

Brief communication

The influence of attending to multiple locations on eye movements

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Abstract

The present paper reports results of a dual task study in which two locations were endogenously cued as possible target locations, while only one eye movement had to be executed. During the cue period, letters were briefly presented at the saccade goals and at no-saccade goals. Results show that performance was better for letters presented at any of the saccade goals than for letters presented at the no-saccade locations. Furthermore saccades deviated away from the non-saccaded target location, suggesting inhibition of the location to which the eyes should not go. The results indicate that the premotor theory also holds for conditions in which attention is allocated to multiple locations.

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1. Introduction

Saccades are crucial for processing visual information. Over the last few decades there has been a great advancement in our understanding of the processes that control saccades and the underlying neural circuitry (for an overview see Findlay & Walker, 1999; Schall, 1995). It is generally assumed that attention plays a crucial role in the planning, programming and execution of saccades. Most recent findings suggest that covert spatial attention precedes the eye to the saccade goal (e.g. Deubel & Schneider, 1996; Godijn & Pratt, 2002; Hoffman & Subramaniam, 1995; Irwin & Gordon, 1998; Kowler, Anderson, Doshier, & Blaser, 1995; Shepherd, Findlay, & Hockey, 1986; but see Klein, 1980; Remington, 1980; Stelmach, Campsall, & Herdman, 1997). Along these lines the premotor theory of attention has argued for a very strong link between attention and eye move-

ments (Rizzolatti, Riggio, Dascola, & Umiltà, 1987, 1994; Sheliga, Craighero, Riggio, & Rizzolatti, 1997; Sheliga, Riggio, & Rizzolatti, 1994). According to this theory the mechanisms involved in the programming of saccades are basically the same as those involved in spatial attention. It is argued that there is only one mechanism for active interaction with the environment which directs attention and action towards a target goal. According to this viewpoint, visual attention *follows* motor programming, and attention is a by-product of the action of the oculomotor system.

Evidence for this theory was provided by studies looking at saccade trajectories. It is known since von Helmholtz (1909) that the paths of saccadic eye movements are curved and do not take the shortest route from fixation to a target (see also Dodge, 1917; Yarbush, 1967). Recent studies have revealed that the deviation (or 'curvature') of a saccade is a measure for identifying the influence of cognitive processes on oculomotor behavior. For instance, it has been shown that the eyes deviate away from an irrelevant distractor presented simultaneously with the target (Doyle & Walker,

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2001). Furthermore, this deviation away from the distractor is related to its saliency because target-distractor similarity modulates the amount of deviation (Ludwig & Gilchrist, 2003). This shows that the more inhibition has to be applied to the distractor location the stronger the eye curves away from this location. This finding makes saccade deviations a way to determine inhibition differences between conditions.

Consistent with the premotor theory is the notion that the deviation of saccade trajectory away from the distractor location is the result of the inhibition of a saccade programmed towards that location (Sheliga et al., 1994; Tipper, Howard, & Paul, 2001). In the case of a target and a distractor, two eye movements are programmed in parallel to different locations which causes both programs to compete within the same system. Both saccade programs are coded by different populations of neurons, but these populations may overlap, especially in case the target and distractor locations are close. In order to successfully initiate a saccade to the target, the irrelevant saccade program should be cancelled. This process silences the neurons involved in the coding of the distractor location, but it also affects the overlapping neurons involved in the programming of the target location. This then results in a changed saccade deviation when compared to a normal saccade trajectory.

Generally, deviations of saccade trajectories are attributed to competitive interactions of activity within a saccade map (Godijn & Theeuwes, 2002b; McSorley, Haggard, & Walker, 2004). It is typically assumed that the intermediate layers of the superior colliculus (SC) are the neurophysiological correlate of this saccade map because it is the location where the final programming of the saccades is accomplished (Dorris, Pare, & Munoz, 1997; Schall, 1991; Sparks & Hartwich-Young, 1989). Many areas related to oculomotor programming project to this midbrain structure such as the frontal eye fields, the supplementary eye fields and the posterior parietal cortex (Munoz, 2002). The SC computes the size and direction of desired saccades and sends appropriate command signals to the burst generators (Munoz & Wurtz, 1993).

Strong support for the premotor theory comes from studies of Sheliga and colleagues in which they examined whether directing attention to a spatial location influences the trajectory of a predetermined saccade (Sheliga et al., 1997; Sheliga, Riggio, Craighero, & Rizzolatti, 1995; Sheliga et al., 1994; Sheliga, Riggio, & Rizzolatti, 1995). The results showed that saccades curved away from the location to which attention was endogenously directed which indicates that spatial attention leads to activation within the oculomotor system. Functional neuro-imaging studies have provided further evidence for the close link between attention and eye movements by showing that the processes involved in covert shifts of attention and oculomotor processes share the same com-

mon functional areas in the human brain (Corbetta, 1998; Corbetta et al., 1998).

Here we report results of a dual task study in which the influence of spatial attention on eye movements was further examined by adopting a somewhat different approach. Previous studies have focused on the influence on the oculomotor system when attention was allocated to a single location in space. In line with the general notion that spatial attention should be considered to be a unitary small spotlight, it was assumed that attention could only be allocated to one location in space (Eriksen & Yeh, 1985; Posner, 1980). This single location represented the 'spatial code' for the saccade endpoint. However recent evidence suggests that attention can be allocated to multiple locations (Awh & Pashler, 2000; Castiello & Umiltà, 1992; Kramer & Hahn, 1995; McMains & Somers, 2004). From a theoretical point of view, it is therefore important to address whether the premotor theory still holds for situations in which attention is allocated to two different locations in space instead of one.

Results of recent experiments by Godijn and Theeuwes (2003) examining the allocation of attention just before the execution of fast saccade sequences, revealed that attention was not only allocated to the location of the first saccade in the sequence but was allocated to all locations that were part of the saccade sequence. In order to investigate the influence of the allocation of attention to multiple locations on eye movements, the experimental paradigm employed here was very similar to that of Godijn and Theeuwes (2003). In the present experiment, participants did not execute a saccade sequence, but only executed one of two possible saccades. The allocation of attention was examined using a dual-task with a primary saccade task and a secondary forced-choice letter identification task. Two locations were cued as being possible target locations. After the cue period, participants executed an eye movement to one of the two cued locations. During the cue period, letters were presented at the saccade goals and at no-saccade locations. The letters were removed before the eyes started moving to the saccade goal. After executing the eye movement, participants performed a forced-choice letter identification task in which they were required to indicate which of the two letters had been present. See Fig. 1 for an illustration of the display sequence. In order to determine the allocation of attention prior to the saccade execution the performance on the identification task was examined as a function of the location of the target letter. A non-speeded secondary task was used in order to avoid response interference, which may occur when two speeded responses have to be prepared. Another important aspect of the present task was that participants were instructed to give priority to the saccade task and to execute the single saccade as quickly as possible.

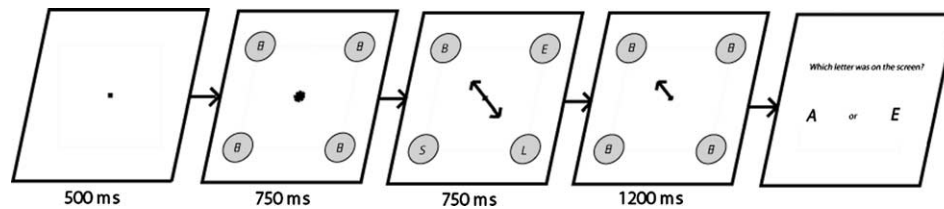


Fig. 1. Sequence of frames on a given trial in Experiment 1. After 500 ms four circles appeared around the central fixation point. After an interval of 750 ms, two central arrows were presented and premasks were replaced by letters. After 750 ms, the letters were masked again and one of these arrows disappeared. Participants were to make an eye movement to the location indicated by the remaining arrow. Participants were required to indicate which letter was presented on the screen by discriminating between two letters.

2. Method

2.1. Participants

Nine observers, aged between 18 and 28 years old, served as paid volunteers. Six of the participants were male. All reported having normal or corrected-to-normal vision and were able to discriminate the colors used in the experiment. They were naïve as to the purpose of the experiment. The experiment was undertaken with the understanding and written consent of each subject. One participant was removed from statistical analysis, since he could not perform the task at hand (mean error percentage of 54%).

2.2. Apparatus

A Pentium II computer with a processor speed of 450 MHz controlled the timing of the events and recorded response times. Displays were presented on a Philips 21" SVGA monitor with a resolution of 1024×768 pixels and an 85-Hz refresh rate. A second computer controlled the registration of eye movements' data on-line. Eye movements were registered by means of a video-based eye tracker (Eyelink SensoMotoric Instruments GmbH, Teltow, Germany). The Eyelink system has a 250 Hz temporal resolution and a spatial resolution of 0.2° . Only data from the left eye was analyzed. An eye movement was considered a saccade either when the movement velocity exceeded $35^\circ/\text{s}$ or when the movement acceleration exceeded $9500^\circ/\text{s}^2$. Although the system compensates for head movements, the participant's head was stabilized using a chin rest. The distance between monitor and chin rest was 75 cm. Participants were submitted to the experiment in a sound-attenuated and dimly lit room.

2.3. Stimuli

Each trial started with the presentation of a 'star' character ($0.38^\circ \times 0.38^\circ$) in the center of the screen for 500 ms. The fixation point was presented in light gray (CIE x, y chromaticity coordinates of .291/.314; 26.4 cd/m²) on a black background (0.0 cd/m²). Around

this central fixation point, four equidistant elements positioned on an imaginary circle of radius 7.07° were then presented. Elements were green (CIE x, y chromaticity coordinates of 0.299/0.600) outlined circles subtending $2.29^\circ \times 2.29^\circ$, and indicated the possible target locations. Pattern masks were presented within each of the elements ($1.60^\circ \times 1.45^\circ$) and were of the same color as the fixation point. After 750 ms the center fixation point changed into a 'plus' character. At the same time, two light gray central arrows appeared, both pointing to one of the two possible target locations. Simultaneously with this change, letter characters replaced the pattern mask within each element. Letters characters had the same size as the pattern masks. Color of the letters was the same as the fixation point and pattern masks. Four letters were randomly sampled without replacement from the set of characters A, B, E, F, G, H, L, and S. The letters were of a sufficient size to identify them without foveating. After 750 ms the letters were removed with a post-mask. At this moment, also one of the two arrows disappeared. The display then remained visible for 1 s. At the end of each trial, two letters were presented to the participant. One of the letters was present at one of the four locations during the trial; the other letter was randomly taken from the set of letter characters that were not presented. The position of the previously shown letter was alternated at random. Participants were required to indicate which letter (the one on the left or the right) was present before the execution of the saccade. By pressing the 'z' key they expressed their belief the left letter had been present, by pressing the 'f' key they expressed their belief the right letter had been present. The display remained visible until a response was made.

2.4. Procedure and design

Participants received written and oral instructions before starting the experiment. They were instructed to fixate the center fixation point until one of the arrows was switched off. Participants were told to move their eyes to the element the arrow was pointing to. It was stressed that one had to make a single accurate saccade towards

this element. Participants heard a short warning tone with a pitch of 300 HZ and duration of 200 ms when the saccade latency was higher than 600 ms. The experiment consisted of a training session of 96 trials and an experimental session of 264 trials. Each session started with a nine-point grid calibration procedure. Participants were required to saccade towards nine fixation points sequentially appearing at random in a 3×3 grid. In addition, simultaneously fixating the center fixation point and pressing the space bar recalibrated the system at the start of each trial. Feedback about the participant's performance on the identification of shown letters was given every 24 trials.

2.5. Data analysis

Saccadic response times below 80 ms were considered too fast. Trials on which the time between offset of the letters and fixation of the eyes on a single target element was below 80 ms were therefore removed from analysis. If the duration between offset of the letters and fixation of the eyes exceeded 600 ms, the trial was removed as well. Moreover, trials were excluded from further analysis in which no saccades, small saccades ($<2^\circ$) or large saccades ($>12^\circ$) were made.

To determine the landing position of the initial saccade the angular deviation from a linear path between the center fixation point and the center of an element on the imaginary circle was calculated. The initial saccade was assigned to a particular element if the endpoint of this saccade had an angular deviation of less than 30° from the center of the element. The saccade was then classified as landed on a target element, on a non-target element, or in between elements. Trials on which the initial saccade was not directed towards one of the target elements were not analyzed further.

We used two different methods of calculating saccade trajectories (for a detailed examination of different measures of saccade trajectories, see Ludwig & Gilchrist, 2002). As the first method, we calculated the mean angle of the actual saccade path relative to the angle of a straight line between the starting point of the saccade and the saccade target. The mean angle of the actual saccade path was calculated by averaging the angles of the straight lines between the fixation point and the different sample points (Godijn & Theeuwes, 2002a, 2002b; Theeuwes, Chizk, & Olivers, in press). See Fig. 2 for an illustration of deviation calculation.

As a second measure of saccade deviation we computed the trajectory's maximum deviation from a straight line from saccade start to end.

As the baseline condition for the measurement of saccade deviations, trials in which the target locations were separated 180° were used. The target locations could either be close (separation between targets of 90°) or re-

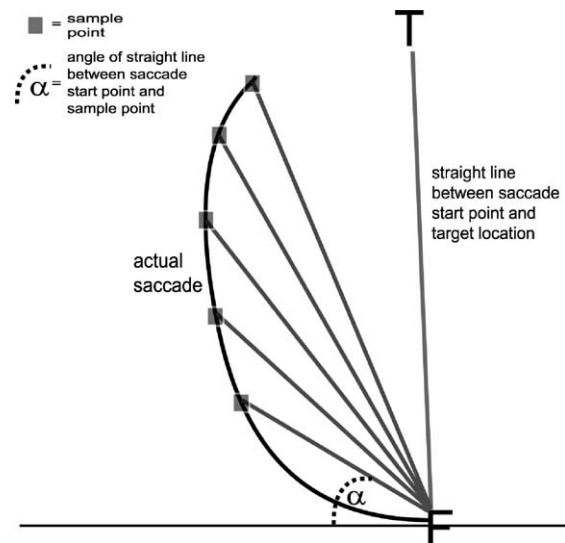


Fig. 2. Illustration of the computational procedure of the saccade deviation. “F” represents fixation, “T” the target. For each sample point of the actual saccade (indicated by the curved line), the angle of the straight line between the start point of the saccade and the current sample point was measured and averaged across the whole saccade. The mean angular deviation was then subtracted by the angle of a straight line from fixation to target.

move from each other (separation between targets of 180°). Because the remote trials were spatially ‘neutral’, no influence on saccade deviation in these trials was expected.

The angular deviation was determined for each participant by calculating the difference between the mean angular deviation on trials in which the target locations were close to each other (experimental condition) and the mean angular deviation on trials in which the target locations were remote (baseline condition). Saccades with an angular deviation 2.5 times the standard deviation away from the mean angular deviation were excluded from the analysis.

The prerequisites made on saccade response time, saccade amplitude, saccade deviation and saccade classification led to the average loss of 28.6% of trials. Of the trials in which a saccade was not directed towards the target element (13.9%), 65.3% of these saccades were directed towards the non-saccaded target letter.

Letter characters that had to be identified at the end of each trial as presented in one of the elements were classified corresponding to the response made. If the character to-be-identified was the saccaded target element, the letter was classified as a saccaded target letter. If the character to-be-identified was one of the other (non-saccaded) target elements, the letter was classified as a non-saccaded target letter. Otherwise, the character was classified as a non-target letter. The proportion correct classification for saccaded target letters, non-saccaded target letters and non-target letters served a measure of visual attention.

3. Results

3.1. Proportion correct

Mean proportion correct is presented in Table 1. An analysis of variance (ANOVA) on proportion correct with the classification of the letter characters to-be-identified (saccaded target letters, non-saccaded target letters or non-target letters) as factor showed a significant main effect, $F(2, 7) = 15.30$, $p < .001$. Planned pair-wise comparisons revealed significant differences between both the saccaded and the non-saccaded target letters with the non-target letters, $p < .02$. The difference between the non-saccaded target and the saccaded target letters reached significance $t(7) = 2.48$, $p < .05$. The identification of non-target letters was performed at chance level, $t(7) = 1.70$, $p > .10$.

A second test was performed in order to determine if the relative position between the target locations interfered with performance on letter identification. No difference was found between performance on trials when the arrows were close and when they were remote, $t(7) = .63$, $p > .50$.

3.2. Oculomotor behavior

Saccade latency was defined as the interval between stimulus display onset and the initiation of a saccadic eye movement. It was determined whether the relative position between the two target elements had an effect on saccade latency. There was no significant difference between saccade latency in the close and remote target conditions (248 ms and 252 ms respectively, $t(7) = 1.30$, $p > .20$).

3.3. Trajectories of saccades to the target

Fig. 3 presents the mean saccade trajectories for the remote and close target conditions. Positive and negative deviations refer to deviations towards and away from the non-saccaded target location, respectively. The first method revealed an overall mean of -0.037 rad (standard error: 0.012 rad) which was significantly different than a mean angular deviation of zero (which is the case if there is no difference between the experimental and the baseline condition), $t(7) = 3.13$,

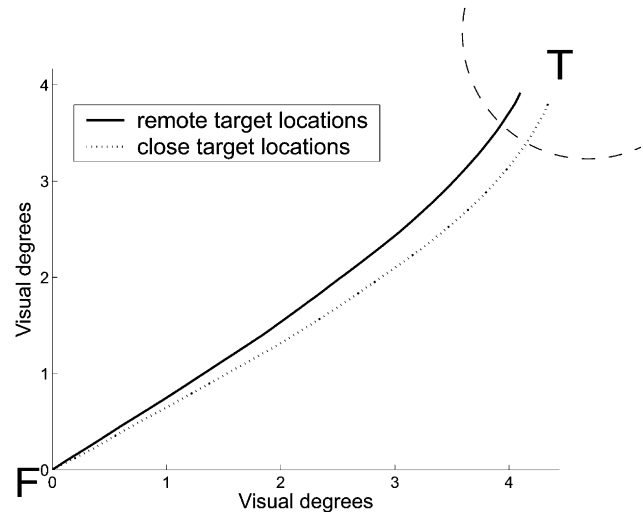


Fig. 3. Eye movement trajectories of the two conditions averaged over all observers (all collapsed and normalized for a non-saccaded target location on the left site). “F” represents fixation (start point of the saccade) and “T” the target location. The target circle is indicated by the dashed circle.

$p < .02$. Furthermore, using the second method, the difference between the mean maximal deviation of the baseline and the experimental condition was significantly different from zero (mean = -0.041 rad, standard error = 0.017 rad, $t(7) = -2.41$, $p < .05$).

The mean endpoint of the saccades in the experimental condition was positioned away from the non-saccaded target location. This was computed by computing the angle between saccade start and saccade endpoint (mean = -0.030 rad, standard error = 0.009 rad, $t(7) = -3.24$, $p < 0.02$).

3.4. General discussion

The main finding of the current experiment is that in a situation in which two locations are cued as possible target locations, saccades to one of these locations deviate away from the other cued location. Letters displayed at both these cued locations were better recognized than letters displayed at the uncued locations, for which performance on the letter identification task was at chance level. This indicates that attention was allocated to both possible target locations during the cue period and that this allocation had an influence on the oculomotor program. This influence is the result of the inhibition of the saccade program to the location to which the eyes should not go (the irrelevant target location). This is in line with the results of Sheliga et al. (Sheliga et al., 1997; Sheliga, Riggio, Craighero et al., 1995; Sheliga et al., 1994; Sheliga et al., 1995).

The present study shows that when attention is allocated to two locations, a subsequent saccade deviates away from the location to which the eyes did not go.

Table 1
Mean proportion correct on the letter character identification task for the close and remote position targets and across both conditions

Letter character identification	Position targets		Mean
	Close	Remote	
Saccaded target letter	.76	.84	.79
Non-saccaded target letter	.71	.75	.72
Non-target letters	.55	.54	.55

The results are consistent and extend the premotor theory indicating that attentional allocation to multiple locations may result in saccade deviation away from either one of these locations. A crucial point is that this not only holds for exogenous attentional allocation but also for conditions in which attention is allocated in an endogenous way.

The premotor theory claims that attentional allocation to a location in space is a by-product of programming an eye movement to that location. In the present experiment attention was allocated to both cued locations which may, according to a strict version of the premotor theory, imply that two eye movements were (at least partially) programmed to these locations. The fact that 65% of the erroneous saccades that were not directed towards the target element were executed towards the non-saccaded target element and not to any of the other locations, seems to indicate that participants were indeed programming eye movements during the cue period. In these trials, the competition between the two eye movements programs was won by the irrelevant program, even though the cue correctly indicated the appropriate target location (see Godijn & Theeuwes, 2002b).

The saccade trajectory deviations reported in the present study are in line with an inhibition account which claims that deviation of the saccade trajectory away from a location is the result of the inhibition of a saccade programmed towards that location (Sheliga et al., 1994; Tipper et al., 2001). Because observers did not know to which location they had to make a saccade, it is plausible to assume that inhibition was applied just before the final saccade was executed.

With respect to the neurophysiological correlate, single cell recordings suggest that saccade deviation either towards or away is a reflection of activity in the SC. For example, McPeck, Han, and Keller (2003) recorded responses of single cells in the SC and found curvature towards a particular location. They showed that this curvature was associated with increased activity of neurons encoding the distractor location just before a saccade was made. The magnitude of the curvature was correlated with the level of distractor related activity. In addition, McPeck et al. (2003) showed that microstimulation of the SC produced a curvature towards the stimulated location. The amount of curvature was correlated with the amount of increased activity. Note that curvature away also has been reported. For example, when a location is deactivated by a localized injection of a neural agonist, muscimol, the eyes curve away from this location (Aizawa & Wurtz, 1998). The conclusion to be made is that it is plausible to assume that finding a modified deviation implies that there is activity (excitation or inhibition) in the SC.

The current observation of saccade deviations away from the location to which an endogenous saccade has been prepared (but not executed) suggests that the

endogenously coded saccade endpoint indeed reaches the motor system, that is, the SC. This indicates that endogenous attentional processing may result in activity in the SC (see also Kustov & Robinson, 1996). In line with recent suggestions by Krauzlis and colleagues, (Krauzlis & Carello, 2003; Krauzlis, Liston, & Carello, 2004) our data suggests that the role of SC is not restricted to the motor control of saccades but instead may represent attentional target selection and may play a role in the endogenous control of spatial attention. This observation is important because it reveals the interaction between the attentional and oculomotor system. Typically, it is assumed that the fronto-parietal network plays a role in spatial attention. Neural activity throughout the ventral and dorsal streams is modulated through attentional allocation (e.g. Moran & Desimone, 1985; Motter, 1993). It is important to note that there is increased activity in parietal and frontal areas for directed attention in the presence and in the absence of visual stimuli (e.g. Kanwisher & Wojciulik, 2000). This suggests that the frontal and parietal activations reflect attentional operations per se and not necessarily reflect attentional modulation in response to visual stimuli. Thus, endogenous, top-down cueing as employed in our study should enhance activity in the fronto-parietal attentional system.

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