Delayed Saccades, but Not Delayed Manual Aiming Movements, Require Visual Attention Shifts

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ABSTRACT: Several studies have shown that during the preparation of a goal-directed movement, perceptual selection (i.e., visual attention) and action selection (the selection of the movement target) are closely coupled. Here, we study attentional selection in situations in which delayed saccadic eye movements and delayed manual movements are prepared. A dual-task paradigm was used which combined the movement preparation with a perceptual discrimination task. The results demonstrate a fundamental difference between the preparation of saccades and of manual reaching. For delayed saccades, attention is pinned to the saccade target until the onset of the response. This does not hold for manual reaching, however. Although fast reaching movements require attention, reaches delayed more than 300 ms after movement cue onset can be already performed "off-line"; that is, attention can be withdrawn from the movement target.

KEYWORDS: attention; saccade; reaching; manual movements; delayed movements

INTRODUCTION

Visual attention, the ability to select a portion of the visual world for further processing, has since long been viewed to play a central role in visual perception. Attention is seen to facilitate detection,[1] to integrate features from different visual modules into "object files," [2] to allow for object recognition,[3] and to regulate entry into visual short-term memory.[4] In contrast with this classic view of visual attention as a mechanism-supporting perception, the important role of visual attention in the control of action was emphasized only by the end of the 1980s.[5,6] Goal-directed actions such as grasping an object are normally directed to a single target and imply a mechanism that selects the target from competing distractors in the scene. Also, humans typically make many eye movements when examining a scene. Given that the visual scene often is crowded with many different stimuli, there must be a mechanism which

selects one particular stimulus as the target of the saccade. The question arises how this "selection-for-action" relates to the perceptual functions of visual attention.

As to saccadic eye movements, a now well-established hypothesis is that the saccade target is chosen by allocating attention to it. A growing number of studies have supported this view.[7–10] In the study by Deubel and Schneider,[10] subjects were confronted with a dual-task situation which required a perceptual discrimination (discriminating the letter "E" from a reversed "E") while preparing a saccadic eye movement. The spatial relationship between the saccade target and the discrimination target (DT) was systematically varied. The DT disappeared before the actual eye movement started so that perceptual performance was measured during the saccade preparation phase only. If visual attention for perception and saccade target selection can be controlled independently, discrimination performance should not depend on the location of the saccade target. On the other hand, if both selection processes are coupled via a common selection mechanism, discrimination performance should be best when DT appears at the saccade target location. The results of this study indeed revealed a high degree of spatially selective coupling between saccade target position and DT position. Discrimination performance was good when both referred to the same object while performance for an object that appeared only a degree of visual angle away from the saccade target location was close to chance level. Further related experiments revealed that the coupling between perceptual processing and the selection of the saccade target is obligate; it is not possible to attend to one location in space while preparing a saccade to another.[10,11] From these studies, the question arose whether a manual reach or grasp also would bind the attentional mechanism in visual perception to the movement target. This was tested in various dual-task paradigms in which subjects had to make a fast manual pointing movement to a centrally cued item while performing a discrimination task at that or at a different location.[12–14] The results showed that perceptual performance again depended strongly on the position of the movement target, with best perceptual performance when the movement was directed to the DT. Further evidence for the relevance of a visual selection process in manual movement programming comes from several studies which analyzed the effect of task-related distractors on the preparation of manual movements. In a study by Castiello,[15] subjects had to grasp an object while counting the number of times a distractor object was illuminated by a spotlight. The results showed that the type of distractor influenced the amplitude of the peak grip aperture to the target, that is, the manipulation component of the movement. When the distractor was smaller/bigger than the target, the peak aperture was also smaller/bigger than in trials without a distractor. Craighero and colleagues[16] investigated whether a nonrelevant prime picture influenced the latency of the following grasping movement. They found a reduction of grasping latency when the prime picture depicted the object to be grasped compared with the condition when the prime depicted a different object. Hence, visual perception of an object, here the prime, influenced the programming of a movement that immediately followed the perception.

Taken together, these studies point to an important role of attentional deployment in the preparation phase, both for saccadic and manual movements: they suggest that visual attention has to be focused on the movement target and cannot be withdrawn before the onset of the movement. However, in all these previous experiments, subjects had to saccade or reach to the target immediately after the presentation of a movement cue, and they were encouraged to perform a fast response. Consequently,

it remains an open question whether attention could be withdrawn from the target before movement onset, given the subject had sufficient time to completely prepare the movement. Therefore, the present study analyzed selective discrimination performance before delayed saccades and before delayed manual reaching movements, while the subject tried to attend at the movement goal or at other spatial locations.

METHODS

The first experiment investigated attentional deployment for delayed manual aiming. The experimental setup is sketched in FIGURE 1. The stimuli were presented on a 21-inch color monitor with a resolution of 1024 by 768 pixels; the frame rate was 100 Hz. Visual information was presented via a half-translucent mirror at an effective viewing distance of 60 cm. This setup made it possible to present movement targets and discrimination stimuli on the working plane in front of the subject without seeing the hand movement or having the hand obstructing the DTs during the movement. Eye fixation was controlled by an SMI-Eyelink Infrared Eye Monitoring system (SensoMotoric Instruments, Teltow, Germany). Manual movements were recorded with a Polhemus Fastrak electromagnetic position and orientation measuring system. This system provides the spatial position of a small position sensor that was mounted on the fingertip of the subject's right index finger. Attached to the sensor was a small red light-emitting diode which allowed visual feedback about the spatial position of the fingertip at the beginning of each trial.

The sequence of stimuli and the experimental task is illustrated in FIGURE 2. The subject was asked to keep fixation in the center of the screen throughout the experi-
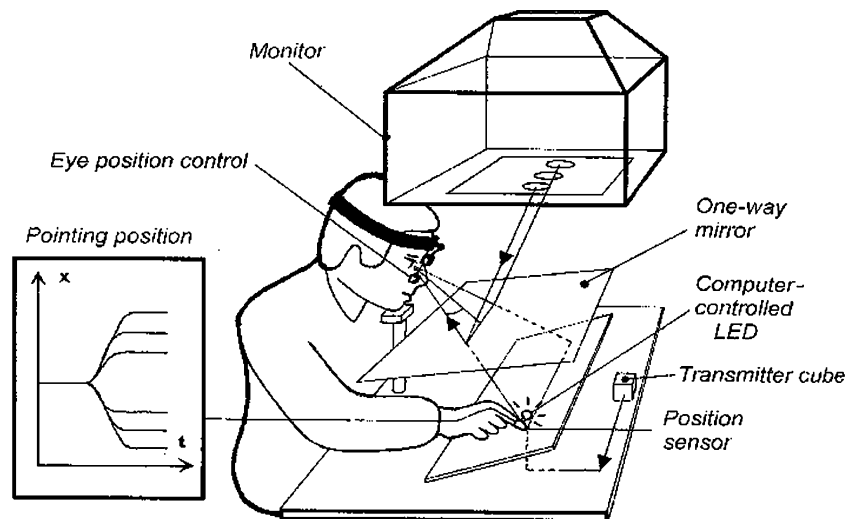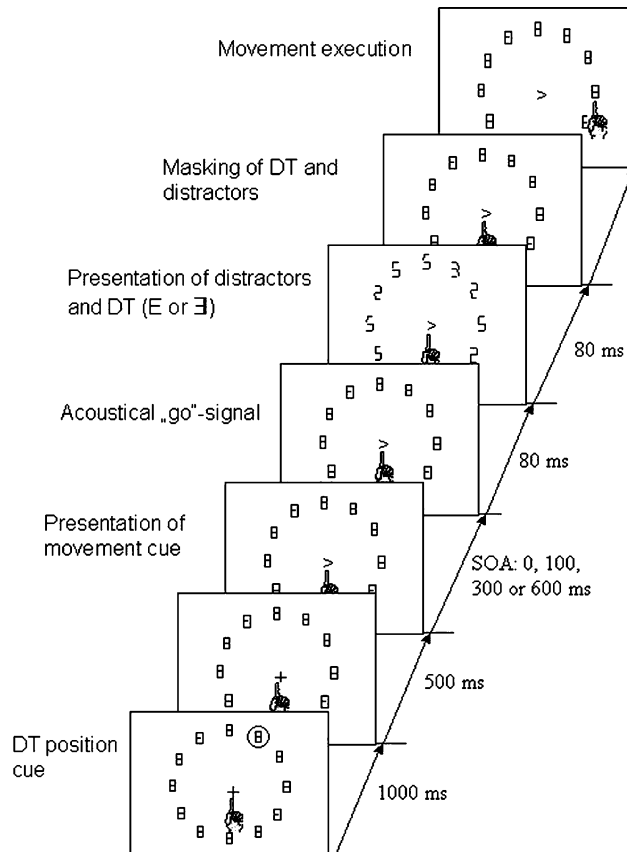

FIGURE 1. Experimental setup.

FIGURE 2. Stimulus sequence in experiment 1. See text for explanation.

ment. A circular array of 12 masking letters initially was displayed at an eccentricity of 7.2 degrees. At the beginning of each trial, the subject put her finger on the small cross in the center of the screen. At one of the letter locations, a circle was presented which served as a valid cue indicating the future location of the critical discrimination stimulus. The circle disappeared after 1000 ms. Five hundred milliseconds later, a central arrow appeared which indicated the position of the movement target. The subject was instructed to perform a pointing movement to this target, but to start the movement only after an acoustical "go" signal which was given at a delay of 0, 100, 300, or 600 ms after the presentation of the movement cue. Eighty milliseconds after this go signal, 11 of the masking letters changed into distractors (which resembled "2" or "5"). At the position cued by the circle at the beginning of the trial, however, the critical DT was presented. The DT consisted of either an "E" or a reversed "E" which was shown for 80 ms. Then, the DT and the distractors changed back to the

masking letters. Because typical movement onset latencies in this experiment were in the range of 250 to 300 ms, it is obvious from the timing of stimulus sequence that the critical discrimination stimulus normally appeared and disappeared before the onset of the movement. At the end of each trial, the subject received feedback about the movement accuracy by means of a red dot displayed at the landing position of the second movements. In 50% of the trials, the position of DT coincided with the location of the movement target. Otherwise, position of DT and the location of the movement target were selected randomly from 6 of the 12 clock positions. Six paid, naïve subjects participated in the experiments. Each subject performed two experimental blocks; each block contained 120 trials.

In the second experiment, subjects were asked to produce an eye saccade, instead of a manual aiming movement, to the indicated movement target. The stimulus sequence was similar to that shown in FIGURE 2, except that three different values of Stimulus Onset Asynchrony (SOA; 100, 500, and 1200 ms) were used. Eye movements were recorded with a SRI Generation 5.5 Dual Purkinje-image eyetracker and sampled at a rate of 500 Hz. Further details of experimental setup, eyetracker calibration, and eye movement analysis are given in Deubel and Schneider.[10] Again, six subjects (different from those of experiment 1) participated.

RESULTS

FIGURE 3 provides perceptual performance (given as percentage correct) as a function of the SOA between the onset of the movement cue and the acoustical go signal. Note that a performance level of 50% would indicate chance level, whereas 100% would indicate perfect performance. The data for the manual movements (experiment 1) are displayed on the left graph; the data for the saccadic eye movements (experiment 2) are shown on the right. The data points indicate the means over the participating subjects; vertical bars indicate standard errors. Data are presented separately for those trials where DT and the movement target coincided (open squares) and for the conditions in which DT appeared at a position which was not the target for the movement (filled circles).

As expected from previous work,[9-14] perceptual performance depended on whether DT was shown at the movement target location or at a different spatial location. For the cases where movement target and DT position coincided (open squares), performance was close to perfect and independent of SOA, for both saccades and manual reaching. For the incongruent case in the reaching experiment, however, discrimination performance strongly depended on the SOA. For zero and short SOA (SOA = 0 and 100 ms), performance was significantly lower than in all congruent conditions. Note that because of the presentation of the valid DT position cue, the subjects were perfectly informed about the location of the DT. Nevertheless, subjects were not able to intentionally keep their focus of attention on the discrimination stimulus, as indicated by the inflated perceptual performance in these conditions. This implies that attention had to be focused on the movement target to prepare the manual reach. For longer SOA values, however, performance improved considerably and reached the performance level of the congruent conditions for SOA values of 300 ms and above. This indicates that for these sufficiently delayed
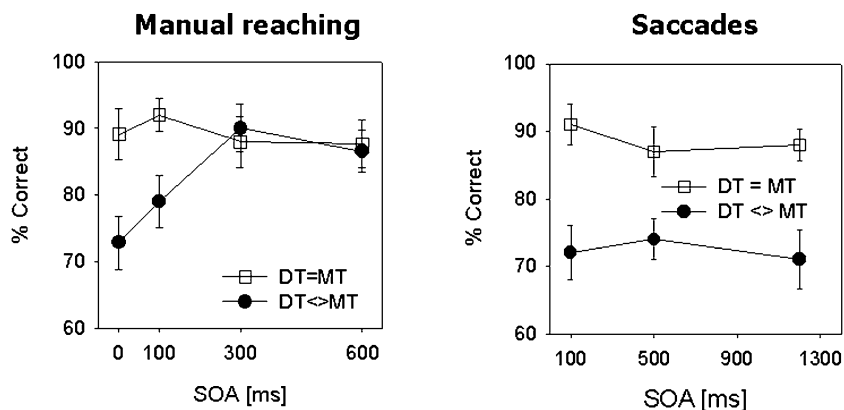
FIGURE 3. Perceptual discrimination performance in the manual reaching task (experiment 1, *left*) and in the saccade task (experiment 2, *right*). The data are shown as a function of SOA (see FIG. 2) and are plotted separately for the cases where the movement was directed to the location of the discrimination stimulus (*open squares*) and for the incongruent conditions (*filled circles*).

movements, attention can be already withdrawn from the movement target and can be deployed onto the location of the DT, allowing for DT identification.

In contrast, there is no indication of performance improvement for the case of delayed saccades, even for the longest SOA (right graph). Although discrimination was perfect at the location of the target of the planned saccade (open squares), it remained at a consistently lower performance level at the other locations (filled circles). This finding implies that even when saccades are delayed by more than a second, attention still remains bound to the saccade target in an obligatory manner. Therefore, whereas manual movements can be prepared and finally started "off-line," that is, without attentional deployment, saccade preparation is always "on-line" in the sense that attention stays at the target location until movement onset.

DISCUSSION

The data presented here reveal an obligatory coupling of visual attention to the saccade target, even when a temporal delay should allow preparation of an internally generated, stereotyped movement. The finding that it is not possible to withdraw attention from the target before saccades adds to former findings on the relation of attention and saccade programming studied in a variety of experimental situations.[9–11] Investigations on the role of attentional in manual reaching have suggested that the same strict coupling also may hold for manual reaching and grasping.[12–14] The present findings qualify this assumption, however, demonstrating a basic difference between the control of saccades and manual movements. Whereas saccades always require attention, manual reaches can be preprogrammed, allowing to specify the movement parameters and store the motor program for use in a delayed movement. It is interesting to see that this attention-mediated parameter specification can be completed within less that 300 ms. The remarkable dissociation between mechanisms of the

preparation of saccades and manual reaches is in line with another recent finding on the role of attention in the control of sequential movements.[14] In this study, subjects had to prepare a sequence of either two saccades or two sequential reaching movements to separate targets. Analysis of perceptual performance revealed that in the saccade case, only the target of the initial saccade experienced processing by attention, whereas performance at the second location was close to chance level. For the manual reaches, however, both the first and the second movement target were simultaneously selected before the onset of the initial movement.

The present findings have some implications for the ongoing discussion on the functional role of neural activity in the posterior parietal cortex. Several studies have shown that the activity of neurons in the lateral intraparietal area (LIP) is enhanced when a behaviorally relevant stimulus is presented in the neuron's receptive field, relative to when this stimulus is unimportant. This enhanced response traditionally has been interpreted as evidence that LIP is involved in the generation of attention to the stimulus. However, an alternative view has been that the activity of LIP neurons may reflect motor intention, more specifically, the intention to perform a saccade to the object on the neuron's receptive field, rather than (effector-independent) attentional focusing.[17] Because, as shown in the present and other work,[8–11] visual attention is normally pinned to the spatial location of a saccade goal until the onset of a saccade, one cannot distinguish a priori whether LIP activation before saccades is related to attention or to a motor plan. The strongest evidence for LIP activity representing motor intentions came from an electrophysiological study showing that the activity of LIP neurons is greater when the neurons are activated by the target of a saccade than when they describe the target of a simultaneously generated arm movement, directed to a different location.[18] When this finding is interpreted in the light of the current results, however, it is plausible to assume that when delayed, simultaneous hand and eye movements to different locations are required, visual attention may first move to the hand movement target to establish the spatial movement parameters of the manual move. After a short temporal interval (possibly <300 ms), attention then would be free to move on to the saccade target, which ultimately would lead to the enhanced saccade-related response until saccade onset. This hypothesis is in line with a recent study demonstrating a significant correlation of the activity of LIP neurons with a perceptual measure for the monkey's selective spatial attention.[19]

In summary, the present work demonstrates that even for delayed saccades, attention is pinned to the saccade target until the onset of the response. This does not hold for manual reaching, however; reaches delayed by more than 300 ms after movement cue onset can be already performed "off-line," that is, without attention.

ACKNOWLEDGMENT

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