Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Vision Research 46 (2006) 4355–4374
Vision Research
www.elsevier.com/locate/visres

Deployment of visual attention before sequences of goal-directed hand movements

Daniel Baldauf *, Martin Wolf, Heiner Deubel

Department Psychology, Ludwig-Maximilians-University, Leopoldstasse 13, 80802 München, Germany

Received 26 April 2006; received in revised form 24 July 2006

Abstract

We examined the allocation of attention during the preparation of sequences of manual pointing movements in a dual task paradigm. As the primary task, the participants had to perform a sequence of two or three reaching movements to targets arranged on a clock face. The secondary task was a 2AFC discrimination task in which a discrimination target (digital **'E'** or **'3'**) was presented among distractors either at one of the movement goals or at any other position. The data show that discrimination performance is superior at the location of all movement targets while it is close to chance at the positions that were not relevant for the movement. Moreover, our findings demonstrate that all movement-relevant locations are selected in parallel rather than serially in time, and that selection involves spatially distinct, non-contiguous foci of visual attention. We conclude that during movement preparation—well before the actual execution of the hand movement—attention is allocated in parallel to each of the individual movement targets.

Keywords: Visual attention; Sequential movements; Selection-for-action; Selection-for-perception; Hand movements

1. Introduction

When we inspect a visual scene, only certain parts or aspects of the visual layout are processed to such a degree as to encode this information in visual short-term memory, and to make it suitable for guiding actions. Visual attention is the mechanism that underlies this selective processing. Thus, on the one hand, attention supports perception in that it facilitates the detection of certain stimuli (e.g., Posner, 1980), enables integration of the features that belong to an object (Treisman & Gelade, 1980), and determines which objects are stored in visual short-term memory and can be identified. This first function of visual attention has been termed "selection-for-perception." On the other hand, visual attention is also involved in the selection of objects that are relevant for goal-directed actions. Here, it is assumed that attention provides the relevant spatial information about the targets of intended movements to the motor system and helps to specify the spatial parameters of the movement (Neumann, 1987). Allport (1987) referred to this second attentional function as "selection-for-action".

Empirically, the functional coupling of selection-for-perception and selection-for-action has been demonstrated most convincingly for saccadic eye movements (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Schneider & Deubel, 2002). In the study of Kowler et al. (1995) participants were presented displays containing eight premasks on a circular array. They were instructed to saccade to the item indicated by a central arrow cue. Simultaneously with the onset of the cue, the premasks were replaced by letters which were masked 200 ms later. It was found that the accuracy of letter report was considerably higher for the letters that appeared at the saccade target, than for the letters at movement-irrelevant locations. Similar results were obtained by Deubel and Schneider (1996; Schneider and Deubel, 2002). In their studies, participants were first shown string-like arrays of premasks left and right of fixation. A central

---

* Corresponding author.
E-mail address: daniel.baldauf@campus.lmu.de (D. Baldauf).

0042-6989/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2006.08.021

colour cue was presented indicating one of the items in the strings as saccade target; the saccade had to be performed when the central cue was removed. Shortly after cue removal, and before saccade onset, a critical discrimination target (digital '**E**' or '**3**') was presented at a certain location in the string among distractors, which was removed after 120 ms. At the end of each trial, participants had to indicate the identity of the discrimination target. The results showed that the discrimination accuracy was considerably higher when the discrimination target was presented at the saccade goal than when it was presented at the adjoining positions. This preferential processing of the saccade target was found even when the participants knew in advance the location of the discrimination target, indicating that the coupling of visual attention and saccade target selection is mandatory.

Recently, similar conclusions were drawn also for the relationship of goal-directed hand movements such as pointing and grasping, and visual attention. Deubel, Schneider, and Paprotta (1998) showed that when participants prepare a pointing movement to a location, perceptual processing is selectively enhanced at the movement goal, already before movement onset. They used a similar paradigm as Deubel and Schneider (1996), cueing participants to point to a certain object in a letter string. Before movement onset, a discrimination target was presented for a short time interval. As for saccades, it was found that when the target fell on the object to which the movement had been programmed, discrimination performance was better than when it fell at other locations, suggesting that attention is coupled to the movement goal also of manual movements. Deubel et al. (1998) showed evidence for such coupling even when the discrimination target occurred at a predictable location; obviously, participants are unable to attend away from the goal of a pointing movement to another location. This indicates that the coupling between pointing movements and attention is mandatory. A recent study has demonstrated that this action-induced selection probably concerns the specific location of the movement goal of the pointing, rather than the whole target object (Linnell, Humphreys, McIntyre, Laitinen, & Wing, 2005).

Other investigations studied attentional deployment for grasping movements. Castiello (1996) showed that distractors relevant to a secondary task that the participants had to perform affected the maximal aperture of the grasping hand. Schiegg, Deubel, and Schneider (2003), and Deubel and Schneider (2004) demonstrated that when an object is grasped, visual attention is largely confined to the to-be-grasped parts of the object. Further evidence for attention-related effect of grasp preparation on perceptual processing was provided by Craighero, Fadiga, Rizzolatti, and Umilta (1998), Bonfiglioli and Castiello (1998), Kritikos, Bennett, Dunai, and Castiello (2000).

Several models have been developed to describe the relationship between selection-for-perception and selection-for-action. The prominent "premotor theory" proposes that the system controlling action is the same system that also controls spatial attention (Rizzolatti, Riggio, & Sheliga, 1994). Simultaneously with the preparation of goal-directed movements, neurons in "spatial pragmatic maps" are supposed to be activated, which results in spatially selective attention. As proposed by a number of authors, different spatial pragmatic maps are activated depending on the type of the action that is to be performed (e.g., Andersen, Snyder, Bradley, & Xing, 1997; Andersen & Buneo, 2002; Colby, 1998; Jeannerod, 1994; Kawashima et al., 1996; Snyder, Batista, & Andersen, 2000).

A second theoretical approach is the Visual Attention Model (VAM, Schneider, 1995). It postulates that selection functions are performed by a single, common visual attention mechanism that is essential for selection-for-action in the dorsal pathway as well as for selection-for-perception in the ventral pathway. When an object is selected, the spatial information that is computed in the dorsal pathway becomes available for setting up motor programs towards the object. This happens independently of whether the action will actually be executed. Similar to the premotor theory, VAM assumes that the preparation of actions in space makes perceptual processing of the objects that are relevant for the movement obligatory. The model predicts that the perceptual representation of the external world during the preparation of a movement should be best for the movement target, allowing for efficient visual processing of the target object. Vice versa, attending to a certain object for perceptual analysis should automatically lead to the implementation of (covert) motor programs towards this object.

Most of the research described previously was characterized by the fact that the movements were directed to a single location in space, a single target object. However, many types of goal-directed movements in the natural environment are more complex in the sense that their preparation requires to consider more than just a single item or location. For example, in order to move to an object, the hand often has to avoid an obstacle. At some point in time during movement preparation, the spatial location of the obstacle and possibly other relevant properties such as its size and orientation have to be computed in order to program a trajectory that leads the hand effectively around the object. Similarly, when we intend to open a bottle of wine we first prepare and perform a grasp to the opener and only then move on to the bottle. The question arises whether in these more complex actions composed of sequential movements the selective processing of the relevant information is also purely sequential, such that processing of the second target would occur only *after* the first movement. Alternatively, the selection (and processing) of further movement goals may already start even before the onset of the initial movement segment.

First evidence for the latter assumption was provided by Henry and Rogers (1960) who showed that in longer and more complex sequences, latencies are prolonged in contrast to simple single pointing movements. Likewise, it was shown that when sequences of saccades have to be performed, the latency of the saccades depends on both the number of targets in the sequence and on the ordinal position of the saccade in the sequence (Inhoff, 1986; Zingale & Kowler, 1987). For manual aiming movements, several studies found that reaction time as well as the movement time of the first sequence compartment increased as the sequence complexity increases (e.g. Fischman, 1984; Fishman & Lim, 1991). For responses consisting of two or three parts Christina and colleagues (Christina, Fishman, Vercruyssen, & Anson, 1982) reported delayed movement initialisation compared to simple one-responses. Similar results were obtained by Smiley-Oyen and Worringham (1996) using much longer sequences of movements. Several authors showed that the kinematics of the first part of a double-step sequence depend on the difficulty of the second part (Gentilucci, Negrotti, & Gangitano, 1997; Lajoie & Franks, 1997; Rand, Alberts, Stelmach, & Bloedel, 1997; Rand & Stelmach, 2000). These findings suggest that both parts of the movement sequence are planned before movement initialisation, considering the properties of the two targets. Assuming that an increase in latencies reflects an increase in preprogramming time these results imply that some aspects of the entire movement sequence may be prepared and stored in advance of the sequence execution, which in turn may require visual attention to be allocated to the movement targets.

More recent investigations that directly studied the allocation of attention during the preparation of saccade sequences yielded partially conflicting results. Gersch, Kowler, and Dosher (2004) analysed attentional allocation during intersaccadic pauses while participants made repetitive saccades on a circular array of squares. The task was to identify the orientation of Gabor test stimuli that appeared briefly along with superimposed noise in one of the squares. They found that attentional resources were dedicated primarily to the goal of the next saccade, leaving only little attention for processing objects at other locations. In contrast, direct evidence for the parallel selection of multiple target positions in saccade control resulted from the investigation by Godijn and Theeuwes (2003). They measured the accuracy of identification of letters presented briefly prior to the execution of a sequence of two saccades in a dual-task paradigm. The results showed that the letter identification was better for letters presented at any of the saccade targets than for letters presented at the movement-irrelevant locations. Moreover, in a matching task where the identity of two briefly presented letters had to be compared, performance was above chance only when both letters appeared at the saccade goals, indicating that attention is allocated to all saccade targets in parallel.

In the present study, the allocation of attention prior to the execution of sequences of pointing movements was examined in a dual-task paradigm in which participants were asked to perform a forced-choice letter discrimination task while preparing sequential pointing movements to several targets. In a first experiment (Experiment 1), participants were required to execute a sequence of two pointing movements on a circular array of characters, arranged like a clock face. While the goal of the initial movement was cued by a central arrow, the second movement goal was defined by the instruction to then move on to the item two clock positions further, in a clockwise direction. We asked whether the preparation of this sequential movement task would involve superior perceptual performance at *both* movement-relevant locations, in comparison to the movement-irrelevant locations. A similar approach was used in a preliminary study reported in Deubel and Schneider (2004). These authors found evidence that attention is allocated to both movement targets, before onset of the initial movement. Also, we were interested in the question of whether a possible facilitation at the first and second movement target is due to a widening of the attentional spotlight over both target positions, or rather due to a division of attention among spatially non-contiguous, distinct attentional locations. Therefore, we also measured discrimination performance at the intermediate location between both movement goals. Experiment 2 and 3 asked whether multiple targets are selected before movement onset even in longer and spatially more complex movement sequences. In Experiment 4, single, double and triple movement sequences were combined, on a trial-by-trial basis. A major question here was whether perceptual performance at the first (and second) movement target position would drop if further movement targets are added to the sequence. This would indicate that the attentional resources used in the task have limited capacity. Finally, we studied in Experiment 5, in a matching paradigm, whether multiple movement targets are selected serially or in parallel.

2. Experiment 1: Double pointing

Experiment 1 was designed to examine the allocation of attention before the execution of a sequence of two manual pointing movements. In a circular arrangement of twelve mask objects, participants were required to first point to the item cued by a central arrow, and then to point to the item two positions further in a clockwise direction. In the movement preparation period, one mask element, at a randomly selected position, changed to the critical discrimination target (digital '**E**' or '**3**'). At all other positions, distractors (digital '**2**' or '**5**') were shown. After a short presentation time, the elements were masked again. At the end of each trial, the participant had to judge, in a two-alternative forced-choice task, which discrimination target had been presented.

2.1. Method

2.1.1. Participants

Six students (three female, aged between 21 and 25 years) were paid for their participation in the experiments. They had normal or corrected-to-normal vision. All participants were right handed. The experiments were undertaken with the understanding and written consent of each subject.

2.1.2. Apparatus

Fig. 1 provides a sketch of the experimental setup. The participant was seated in a dimly illuminated room. The stimuli were presented on a 21-in. colour monitor (Conrac 7550 C21) with a frame frequency of 100 Hz, at a spatial resolution of $1024 * 768$ pixels. The active screen size was 40×30 cm; viewing distance was 58 cm. Pointing movements were executed on a slightly inclined plane in front of the participant. The use of a one-way-mirror between the pointing plane and the participant's face allowed free hand movements without visual feedback about the position of the hand and fingers. The mirror was adjusted such that the visual stimuli appeared to be projected onto the pointing plane. The visual stimuli were presented on a grey background, which was adjusted to a mean luminance of 2.2 cd/m^2. The relatively high background brightness is important to minimise the effects of phosphor persistence (Wolf & Deubel, 1997). The luminance of the visual stimuli was 23 cd/m^2.

Reaching movements were recorded with a Fastrak electromagnetic position and orientation measuring system (Polhemus Inc., 1993), consisting of a central transmitter unit and a small receiver, mounted on the tip of the index finger of the participant's right hand. The sender unit was fixed 60 cm in front of the participant. The device allows for a maximum translation range of 10 ft, with an accuracy of 0.03 in. RMS. The frequency bandwidth of the system is 120 Hz; with a time delay of 4 ms. In order to provide visual feedback about the spatial positions of the fingertip during an initial positioning period, a small red LED (5 mm diameter) controlled by the computer was attached to the sensor. Participants were required to keep strict eye fixation on a central cross throughout the trial. Eye fixation was monitored by a video-based eye tracking system (SensoMotoric Instruments, Eyelink-I). Head movements were restricted by an adjustable chin rest.

2.1.3. Procedure

The sequence of stimuli in a typical trial is shown in Fig. 2. At the beginning of each trial, a display appeared containing a central fixation cross and a circular arrangement of twelve premask characters (resembling a digital '**8**'), positioned on an imaginary circle with a radius of 7.2 deg around the central fixation. The horizontal width of the premask characters was 0.90 deg of visual angle; their height was 1.40 deg. The participant was asked to initially position the right index finger at the screen centre. For this purpose, the LED mounted on the index finger was switched on for 2 s. The active LED was visible through the mirror and allowed the participant to point to the central fixation cross. After a random delay of 1400–1600 ms, the central fixation cross was replaced by a small arrow that indicated one of the surrounding characters as the first movement target (*1st MT*). The participant was required, upon the onset of this movement cue, to make a sequence of two pointing movements with the index finger of the right hand, with the first movement aimed at the cued target. After the completion of the first movement, i.e., after the finger touching the first movement target, the second movement had to be directed to the character located two clock positions further in the clockwise direction (*2nd MT*). Participants were instructed to perform this movement sequence as quickly and precisely as possible.

With a stimulus onset asynchrony (SOA) of 50 ms after the appearance of the central movement cue, 11 of the 12 premask characters changed into distractors (resembling a

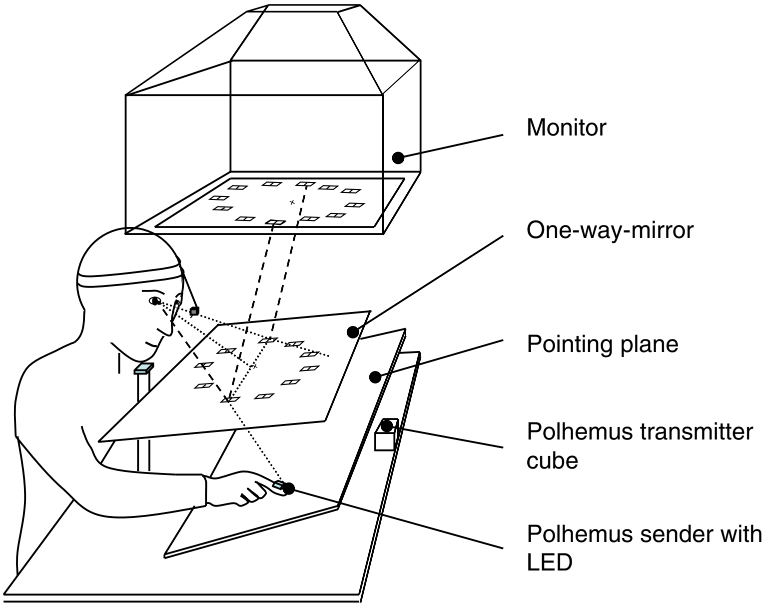

Fig. 1. Experimental set-up. The visual stimuli that were generated on a video display were projected via a half-translucent mirror onto a pointing plane in front of the participant; they appeared at a viewing distance of 58 cm. Movements of the right index finger of the pointing hand were recorded with a Polhemus Fastrack electromagnetic tracking system. Fixation was controlled by an eyetracker.

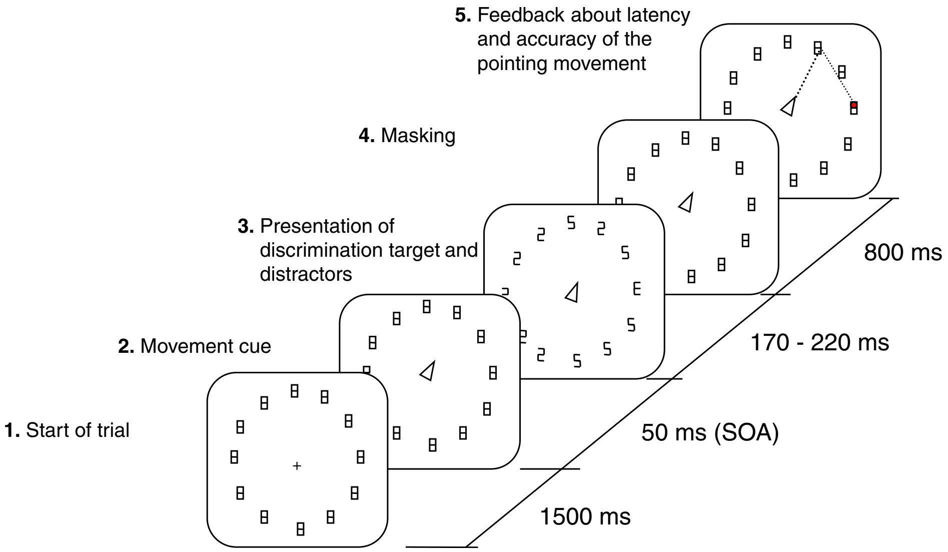

Fig. 2. Stimulus sequence in Experiment 1.

digital '**2**'or '**5**'), while one premask changed into the critical discrimination target (DT) which resembled the character '**E**' or '**3**.' After a presentation time of 160–220 ms (adjusted individually for each participant, see below), the discrimination target and the distractors changed back to the initial mask symbols. At the end of each trial, the participant had to indicate, by pressing one of two buttons, which of both discrimination targets had been presented. This non-speeded response was given on a keypad with the left hand. The trial finished with providing the participant visual feedback about the actual landing position of the pointing finger. For this purpose, a small red dot appeared on the screen, indicating the final landing finger position. Also, acoustic feedback about the latency of the initial pointing movement was provided, based on an online calculation of first point in time where movement speed is above the velocity threshold . A low-frequency tone indicated that the latency in the trial was sufficiently short, whereas an unpleasant, high frequency tone indicated that the latency was too long and that the participant should be faster in the next trial. The feedback about the reaction latency was implemented in order to encourage the participant to perform the pointing movements as quickly as possible after the presentation of the movement cue.

2.1.4. Pretest block

Before the experimental sessions, the participants performed a pretest in which the presentation times for the critical discrimination targets were determined individually for each participant. This was necessary since the participants differed considerably in their ability to discriminate the target letters. For this purpose, a block of 96 trials was run in which each participant was asked to perform single pointing movements to the position cued by the central arrow, and to indicate the identity of the discrimination target, which was always presented at the movement target location. The trials were performed with different presentation times in order to vary the degree of processing demand. From the participant's performance, we estimated the individual presentation times such that each participant reached a performance level of 85% correct responses in this task. The resulting presentation times ranged from 150 to 230 ms ($M = 190$ ms). They were kept the same for each subject in all following experiments.

2.1.5. Design

Initially, each participant performed a training session consisting of three blocks of 96 trials each which were not included in the data analysis. After initial training, the participants performed four experimental blocks, each consisting of 96 trials. Only six out of the twelve mask positions (at 1, 3, 5, 7, 9 and 11 o'clock) were possible movement goals. As the second movement had to be aimed to the item located two clock positions further, both movement targets were separated from each other by an intermediate item. Thus, possible pointing sequences were directed to 1 and 3 o'clock, 3 and 5 o'clock, 5 and 7 o'clock, 7 and 9 o'clock, 9 and 11 o'clock or 11 and 1 o'clock. The critical factor that was varied in this experiment concerned the position where the discrimination target was presented, relative to the instructed movement targets. This factor, "Relative DT position," had four levels: (1) The discrimination target (DT) was presented at the first movement target (condition "*1st MT*"), (2) DT was shown at the second movement target position (condition "*2nd MT*"), (3) DT appeared at the location between both movement targets (condition "*between MTs*"), and (4) DT appeared at any of the four remaining letter positions that were movement-irrelevant in that they were neither targets of the movement sequence in the actual trial nor located between the movement-relevant locations (condition "*other*"). Each of these four conditions occurred with a probability of .25 in the trials. In half of the trials, the discrimination target was the character '**E**', in the other half '**3**' was shown. In total, this led to 48 different conditions (6 MT positions × 4 relative DT positions × 2 types of DT). Each of these conditions was presented twice in an experimental block. The conditions were selected at random in each trial.

2.1.6. Data analysis and rejection of trials

Hand and eye movements were recorded on-line by a PC during sessions and evaluated off-line by custom software. In order to determine latency, amplitude, and duration of the finger movements, an off-line program searched the movement traces for the first point above (or below) the vectorial velocity threshold of 10 mm/s (which is equivalent to about 1°/s). The beginning and the end of the pointing movements were calculated as linear regressions in a 50 ms time window around these threshold points. The analysis of the movement data revealed that the finger sometimes did not completely stop in the phases between the individual movements, probably since the participants were keen to produce very fast movement sequences. In these cases, it was difficult to unequivocally determine the precise end point of the particular movement. From this reason, movement *durations* were not analysed further and will not be reported. The latency of the subsequent movements was calculated as the first point in time when movement speed was above the velocity threshold. The program also analyzed the data from the eyetracker and computed the spatial and temporal parameters of eventual saccades. The algorithm to identify saccades is similar to that used for the detection of the hand movements. The beginning and the end of a saccade were calculated as linear regressions in a 50 ms time window around the first point in time above (or below) the velocity threshold of 15°/s.

In order to ensure that the discrimination target was no longer present when the actual movement started, trials with onset latencies of the initial movement below an individual cut-off time which was 50 ms (= SOA) plus the individual presentation time were excluded from further analysis. We also discarded trials where movement onset latency was above 600 ms, and where the program detected a saccade or a significant deviation of the eye or initial hand position fixation. Finally, trials in which the second pointing goal was missed by more than 3 deg or the movement erroneously was executed toward a non-cued pointing position were classified as pointing errors and were not analyzed further.

The accuracy of the perceptual performance is expressed by the percentage of correct decisions on the identity of the discrimination target; since there were two alternatives, chance level was at 50%. For the analysis of perceptual performance, all possible movement target conditions were averaged for each subject. We computed percent correct for the factor "Relative DT position" which had four levels: (1) The discrimination target (DT) was presented at the first movement target (condition "*1st MT*"), (2) DT was shown at the second movement target position (condition "*2nd MT*"), (3) DT appeared at the location between both movement targets (condition "*between MTs*"), and (4) DT appeared at any of the remaining four letter positions that were movement-irrelevant in that they were neither targets of the movement sequence in the actual trial nor located between the movement-relevant locations (condition "*other*").

Statistical analyses in this and the following experiments included repeated-measure analyses of variance. Post-hoc comparisons were done with *t*-tests. All *p*-values were Bonferroni-corrected or, in case of pairwise *t*-tests, Holm-corrected. Statistical analyses were performed with the "R" statistical package.

2.1.7. "Discrimination-only" control experiment

In a separate "Discrimination-only" control experiment, five participants that did not belong to the experimental group performed the perceptual discrimination task without any pointing. They had not previously served as participants in any of the pointing experiments. These participants were required to position their index finger at the fixation cross position, and to keep the finger there for the whole experiment, ignoring the (irrelevant) movement cue. Otherwise, the stimulus sequence was the same as described before. Also the probability relationship between the arrow direction and the position of the discrimination target was kept the same. The control experiment was performed by a separate group of participants because the participants of our main experiment were all well trained to perform multiple pointing sequences. We wanted to avoid that these participants would eventually reactivate, in motor imagery, their well-trained behavioural pattern of multiple pointing movements.

2.2. Results

2.2.1. Discarded trials

9.0% of all trials in this experiment had to be discarded because of too short or too long movement latencies. Another 5.7% of trials were discarded because of insufficient eye fixation or the occurrence of a saccade. Finally, in 8.2% of the trials pointing errors occurred, these trials were also excluded from further analysis.

2.2.2. Movement performance

After the initial training block, all participants produced pointing movements with consistent accuracy and latency. They reported that they had no difficulties to point quickly to the indicated target items. Fig. 3a displays typical trajectories of the movement sequences of a single subject. Fig. 3b shows the final landing positions of the movement sequence for the six participants. It can be seen that the movement sequences were performed quite accurately. The mean spatial distance between the instructed second target and the final landing position was 1.21 deg.

Mean latency of the initial movement with respect to cue onset was 349 ms (SE = 21.8 ms). The second movement of the sequence was executed with a mean latency of 633 ms (SE = 52.8 ms) after the presentation of the movement cue.

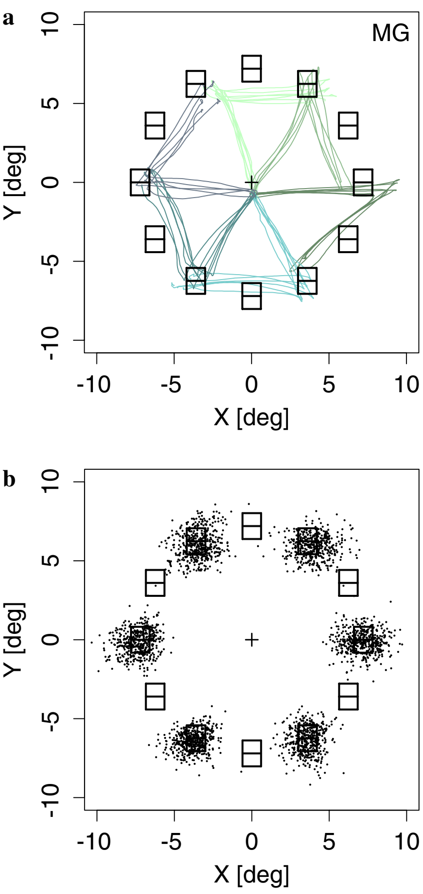

Fig. 3. (a) Typical trajectories of the double movement sequences in Experiment 1 of a single subject. (b) The dots indicate the final landing positions after the double movement sequence for the six participants.

A repeated-measures analysis of variance (ANOVA) showed no significant effect of the factor “Relative DT position” on the latencies of the first and the second movement of the sequence, $F(1, 4) = .1422$, $p > .73$ for the initial movement; and $F(1, 4) = .2595$, $p > .63$ for the second movement. This is important for the interpretation of the results, since it indicates that the pointing task was performed without *specific interference* from the discrimination task. Of course, there might be a general dual-task cost from performing the two tasks and probably onset latencies of the motor behaviour might be influenced by having to perform the discrimination task *in general*. However, the presentation of the discrimination target at a certain position relative to the movement goal does not affect the movement preparation. Obviously, the movement initialisation is not delayed or shortened if the discrimination target is presented at one of the movement goals.

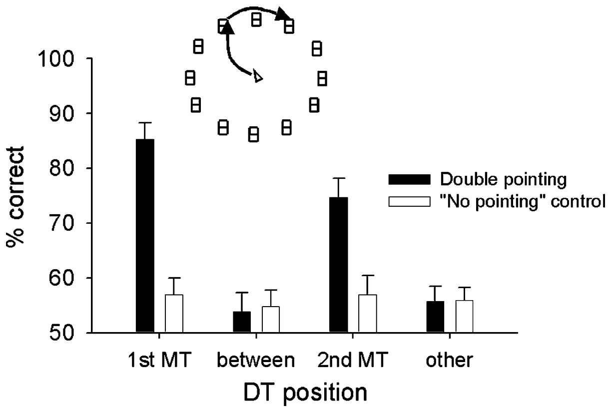

Fig. 4. Solid bars, discrimination performance as a function of the location of the discrimination target; relative to the movement target positions. The inset of the figure presents an illustration of the required double movement sequence. Open bars, discrimination performance in the “*Discrimination-only*” experiment. In this control experiment, participants performed only the discrimination task, without any pointing. The error bars represent standard errors.

2.2.3. Perceptual performance

The accuracy with which participants identified the discrimination target served as our measure of the spatial allocation of attention before movement onset. The solid bars shown in Fig. 4 represent the discrimination performance as a function of the position of the discrimination target relative to the movement target positions. As can be seen, perceptual discrimination was best at the location of the first movement target (condition “*1st MT*”). Performance level in this case is at 86% correct, well above chance level (50%). Discrimination performance at the goal of the second movement (condition “*2nd MT*”) deteriorates to 75%, however, is still well above chance. Thus, at both the first and the second movement goal, the planning of the hand movement causes clear and significant benefits for perceptual processing, as compared to the movement-irrelevant locations. Of particular interest was the discrimination performance at the position between both movement goals (condition “*between MTs*”). The data clearly show that performance drops to chance at this intermediate location, yielding a discrimination performance of only 54% correct. Finally, discrimination is also close to chance level at the remaining movement-irrelevant locations (condition “*other*”), with a performance level of 56% correct.

These findings were confirmed by further statistical analysis. A one-factor within-subject ANOVA revealed a significant main effect of the relative position of the discrimination target, $F(3,15) = 11.95$, $p < .001$. Pairwise post-hoc comparisons showed that the difference between the discrimination performance at the first and the second movement target is only marginally significant, $t(5) = -2.316$, $p < .0626$. However, performance at the first movement target is significantly better than at the movement-irrelevant locations, $t(5) = -6.431$, $p < .001$. Also, discrimination performance at the second movement target position differs significantly from performance at the movement-irrelevant locations $t(5) = -4.116$, $p < .002$. Furthermore, perceptual discrimination at the location *between* both movement targets (condition “*between MTs*”) differs significantly from both the performance at the first movement target ($t(5) = -6.847$, $p < .001$) and at the second movement target ($t(5) = -4.531$, $p < .001$), but it does not differ from the performance at the movement-irrelevant positions, $t(5) = -0.415$, $p > .6823$.

The open bars in Fig. 4 display the discrimination performance in the "*Discrimination-only*" experiment. In this control experiment, participants performed only the discrimination task, without any pointing. Otherwise, the presentation of the stimuli was exactly the same as in the experimental blocks of Experiment 1. As can be seen in the graph, performance was independent of where the discrimination target was presented ($F(3,12) = .594$, $p > .63$), and was not significantly different from chance level, $t(4) = 2.229$, $p > .09$. This demonstrates that the presentation of the central movement cue by itself does not lead to any selective effects, as long as it is not relevant for the planning of a goal-directed movement.

Another interesting aspect of the data concerned the question of whether discrimination performance would be different in sequences where both movement targets were in different hemifields, as compared to sequences in which both targets were in one hemifield. For this purpose, a two-way analysis of variance was performed. First factor was "*Relative DT position*" with the four levels "*1st MT*," "*2nd MT*," "*between MTs*," and "*other*." The second factor was "*change of hemifield*" which had two levels ("*hemifield change*" and "*no hemifield change*"). The data show that there was a significant main effect of the factor "*Relative DT position*," $F(3,15) = 23.25$, $p < .001$, but no main effect of the factor "Change of hemifield," $F(1,5) = .823$, $p > .40$. Also, the interaction of both factors was not significant, $F(3,15) = .7971$, $p > .51$. This result indicates that perceptual performance at first and second movement goal is not affected when the sequential movement targets appear in different visual hemifields.

2.3. Discussion

The results of Experiment 1 show that in double pointing sequences, *both* movement goals are selected even before onset of the initial movement, in a spatially distinct way. The discrimination performance is highest at the first movement target and slightly lower at the goal of the second movement in the sequence. Quite clearly, objects that are not relevant to the programming of the required hand movement sequence are not selected. It can be concluded that before movement onset, attentional selection is spatially highly specific to the pointing goals. This is in line with previous findings of Deubel et al. (1998), who demonstrated a narrow, spatially specific attentional selection of the goal of a single pointing movement.

Interestingly, discrimination performance is also close to chance level at the item located intermediate to both movement goals, i.e., at the item that is located on the movement trajectory of the second partial movement. This striking finding clearly demonstrates that the improved performance at the first and second movement goal does not result from a widening of the attentional focus. Rather, it is consistent with the assumption that the attentional selection can involve spatially non-contiguous positions.

Due to the experimental design of the present experiment, the discrimination target appeared in half of the trials in a block at one of the two movement targets cued by the central arrow. Consequently, the central cue had some validity for predicting the likely location of DT presentation. Therefore, it might be argued that the attentional effects are due to a strategic, endogenous deployment of attention to the movement goals, rather than a consequence of the need to prepare the movement sequence. The data from the "discrimination-only" control experiment however demonstrate that the attentional selection of the movement-relevant targets does not occur under conditions where no motor task is required. Furthermore, the intermediate position in Experiment 1 is at chance even though it had a probability of containing the DT that was equal to that of the *1st MT* and *2nd MT*. This is converging evidence that subjects were not using the probability information provided by the movement cue to allocate attention, because if they were, all three 25% positions would benefit. This indicates that the central arrow by itself has no cueing effect on the peripheral items. We suppose that the validity of the cue for the appearance of the discrimination target (25%) was too small in order to be used effectively. We will address this question further in Experiment 4 where DT positions can no longer be predicted from the central cue.

3. Experiment 2: Triple pointing

Experiment 1 demonstrated that for a sequential movement aimed at two targets, attention spreads to the second target even before the onset of the first movement part. The question arises whether such a perceptual performance advantage at the movement-relevant locations can be also observed at further pointing goals in even longer sequences. Therefore, we extended the movement sequence required in the motor task by another movement, which resulted in a triple pointing sequence along the mask items on the circular display. The focus of analysis was now on the question of whether even three pointing goals would be attended before the onset of the movement sequence, and to what extent this task would improve the perceptual performance at the third pointing goal.

3.1. Method

The five participants in this second experiment were the same as in Experiment 1. The same stimuli were used. The procedure was also similar to the previous experiment except that the participants now were required, after having moved the index finger to the first (cued) and then to the second movement target, to add a third movement, directed to the location two clock positions ahead, in a clockwise direction (an illustration of this movement sequence is given in the inset of Fig. 5). The factor "Relative DT position" had the following four levels: (1) The discrimination

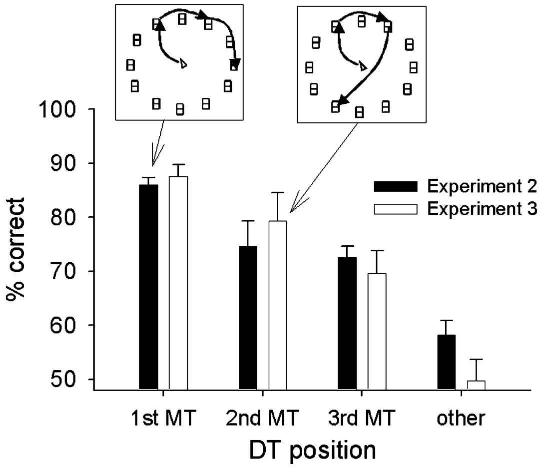

Fig. 5. Solid bars, discrimination performance as a function of the relative discrimination target locations in Experiment 2. Open bars, Discrimination performance in Experiment 3. The figure insets illustrate the required movement sequences in both triple movement experiments.

target (DT) was presented at the first movement target (condition "*1st MT*"), (2) DT was shown at the second movement target position (condition "*2nd MT*"), (3) DT was shown at the third movement target position (condition "*3rd MT*"), and (4) DT appeared at any of the remaining letter positions that were movement-irrelevant in that they were not targets of the movement sequence (condition "*other*"). Each of these four conditions occurred with a probability of 0.25. This led to 48 different conditions (6 MT positions × 4 relative DT positions × 2 types of DT). Each of these conditions was presented twice in an experimental block. The conditions were selected at random in each trial. To become familiar with the new requirements, participants initially performed a training block that was identical to the following experimental blocks. Then, participants performed four experimental blocks with 96 trials each.

3.2. Results

3.2.1. Discarded trials

9.0% of all trials in this experiment had to be discarded because of too short or too long movement latencies. Another 6.7% of trials were discarded because of insufficient eye fixation or the occurrence of a saccade. Finally, 9.4% of the trials were classified as pointing errors and were also excluded from further analysis.

3.2.2. Movement performance

Although one would expect a loss of accuracy over such long movement sequences, landing positions were still close to the locations of the movement target. The mean spatial distance between the final landing position of the sequence and the centre of the instructed movement target was 1.31 deg. Average latency of the initial movement of the sequence was 316 ms (SE = 17.7 ms) with respect to movement cue onset. The second movement followed with a mean latency of 586 ms (SE = 48.5 ms), and the third and final movement occurred with a mean latency of 788 ms (SE = 42.5 ms), measured from the point in time when the cue was presented.

Movement latencies were again analysed as a function of the position of the discrimination target relative to the movement targets. The statistical analysis of the movement data revealed that also in this experiment, the latencies of the sequential pointing movements were independent of the position of the discrimination target. Separate analyses of variance showed no significant main effect of factor '*Relative DT position*' on the latencies of the first, second and third movement, $F(1, 4) = 0.011$, $p > .92$, $F(1, 4) = .0213$, $p > .89$, and $F(1, 4) = 0.0024$, $p > .96$, respectively. It can be concluded that the motor task is not specifically affected by where the discrimination stimulus was presented.

3.2.3. Perceptual performance

The solid bars in Fig. 5 show discrimination performance for the different relative DT locations. As in the previous experiment, it can be seen that perceptual performance was best when the discrimination target was presented at the first movement target. Remarkably, the performance level of 85% in this experimental condition is very similar to the corresponding condition in Experiment 1 (86%), indicating that the requirement to plan a third movement did not hamper discrimination performance at the initial movement location. Perceptual performance dropped to 75% at the second movement position. Finally, and most interestingly for the purpose of this experiment, perceptual performance was still significantly above chance even at the third movement location, yielding 74% correct. In contrast, performance at the remaining, movement-irrelevant positions was close to chance level, similar to the corresponding value in Experiment 1.

Statistical analysis confirmed a significant effect of the factor "Relative DT position" on the discrimination performance, $F(3,12) = 18.71$, $p < .001$. Pairwise t-tests showed that the difference in performance at the first and the second movement target was not significant, $t(4) = -2.410$, $p > .057$. However, there was a significant difference between the performance values at the first and the third movement target, $t(4) = -3.068$, $p < .029$. Furthermore, the performance values at the first, second and third movement targets each differed significantly from the average performance at the movement-irrelevant locations ($p < .0001$, $p < .015$, and $p < .0322$, respectively). The second and the third position do not differ significantly, $t(4) = .659$, $p > .52$.

3.3. Discussion

The results of this experiment show that when pointing sequences consisting of three partial movements are prepared, all three goals are perceptually selected before the initial movement starts. This finding implies that during the period of movement preparation, attention is deployed, in a highly selective manner, to all three movement goals.

Interestingly, the data indicate that the discrimination performance at the first and the second movement goals does not decline in comparison with the results from Experiment 1. This would mean that the requirement to consider three instead of two sequential movement goals does not entail that attentional resources are withdrawn from the first and second target position. We will consider this important aspect further in Experiment 4.

The finding that all three movement goals involved in the sequential motor task are attended already before the onset of the initial movement is quite amazing. However, one possible reason for this effect may be that the demanded movement sequence is too easy to perform. Indeed, after the cue has indicated the first movement target, the following locations can be derived in a relatively simple way ("plus two hours"). Participants could eventually solve this task by the formation of a mental template by which the three movement targets can be effectively selected. In the next experiment, we wanted to study whether the amount of attentional selection of the second and third movement target is affected by the complexity of the motor task. For this purpose, we required the participant to perform triple movement sequences with a spatially more complex arrangement.

4. Experiment 3: Complex triple pointing

The aim of the third experiment was to study whether the high perceptual performance at the second and even the third movement target would also occur in a movement task that is more demanding. For this purpose, the third pointing movement had now to be executed towards the mask element *opposite* to the second target position. Due to this modification, several aspects concerning the spatial properties of the movement sequence were different from the previous experiment: First, the amplitude of the third movement differed from the second. Second, there was a marked change in movement direction included in the sequence that occurred with the third movement. And, finally, in each trial there was involved a movement directed across the stimulus display into the opposite visual hemifield.

4.1. Method

Six students participated in the experiment. They had also participated in Experiments 1 and 2. The experimental setup and the stimuli were unchanged. The procedure was similar to the previous experiment except that the third part of the sequence now consisted in a movement across the circular array, directed towards the item that was located *opposite* to the second goal (see inset in Fig. 5 for an illustration of the movement sequence). The discrimination target appeared with a probability of .25 at either the first, second or third movement target position, and in the remaining 25% of the trials at one of the movement-irrelevant locations. This led to 48 different conditions (6 MT positions × 4 relative DT positions × 2 types of DT). Each of these conditions was presented twice in an experimental block, yielding 96 trials per block. The conditions were selected at random in each trial. Again, participants were first allowed to practice this more complex movement pattern, together with the associated discrimination task, in an initial training block that was identical to the following experimental blocks.

4.2. Results

4.2.1. Discarded trials

7.9% of all trials had to be discarded because of too short or too long movement latencies. Another 1.6% of trials were discarded because of insufficient eye fixation or of the occurrence of a saccade. Finally, in 11% of the trials the third pointing goal was missed; these trials were classified as pointing errors and were also excluded from further analysis.

4.2.2. Movement performance

Participants reported that the task was now more difficult and, at least early in practice, required more effort to perform. In spite of the considerably more complex movement sequence, the pointing movements in Experiment 3 were again relatively accurate, without any significant deterioration of spatial accuracy as compared to the previous experiment. This is reflected in the small mean spatial error of 1.30 deg between the landing positions of the final movement and the centre of the target item.

The initial movement started with a mean latency of 329 ms (SE = 16.7 ms) after cue presentation. The second and third movements had mean latencies of 600 ms (SE = 43.2 ms) and 840 ms (SE = 36.8 ms), respectively, measured from cue onset. We again analysed whether the movement latencies were dependent on the factor "Relative DT position." Three separate within-subject analyses of variance yielded non-significant effects of this factor, $F(1, 4) = .0113$, $p > .92$; $F(1, 4) = .8419$, $p > .41$; and $F(1, 4) = .3273$, $p > .59$, for the first, second and third partial movement. As in the previous experiment this indicates that the movement task is performed without specific interference from the discrimination task.

4.2.3. Perceptual performance

The open bars in Fig. 5 present discrimination performance as a function of the relative DT position, averaged across the five participants. ANOVA yielded a significant main effect of relative DT position, $F(3,15) = 20.481$, $p < .001$. Again, discrimination was superior when the discrimination target was presented at the first movement position (88% correct). Performance decreased at the second and the third sequential pointing goal to 79% and 70% correct responses, respectively. Performance was significantly lower at the remaining, movement-irrelevant positions (50% correct). While a post-hoc comparison showed no significant difference between discrimination performance at the first and the second movement target, $t(5) = -1.336$, $p > .27$, there was a significant performance difference between the first and the third movement target, $t(5) = -2.894$, $p < .027$. However, perceptual performance at the third movement goal located on the opposite side of the array was still significantly better than performance at the remaining, movement-irrelevant positions $t(5) = -3.183$, $p < .019$. Performance at the second and the third target position did not differ significantly, $t(5) = -1.56$, $p > .269$.

4.3. Discussion

The results of this experiment demonstrate that up to three target positions are selected before movement onset, even if they are not part of a simple and possibly automatised movement sequence. In the present experiment, the last movement target was derived by a more complex sequence rule. Also, direction and amplitude of the partial movements differed and had to be computed for each part of the pointing sequence. Finally, the movement-relevant targets now always appeared in both hemifields. Nevertheless, the performance data revealed evidence for an attentional selection of even the final movement goal in the sequence. The results suggest that the selection of several movement goals before movement onset is not restricted to simple and possibly automatised movement patterns but indeed reflects the specification of target positions to prepare the movement sequence.

5. Experiment 4: Capacity limitation

One interesting aspect of the findings of Experiments 1–3 was that perceptual performance at the first and at the second movement target did not decrease from Experiment 1, where only a two-step sequence has to be performed, to Experiment 2 and 3, in which longer and more complex three-step sequences had to be executed. This suggests that adding further movements to the pointing sequence does not interfere with the performance at the first position. Such a finding would be important, since it would indicate that the amount of attentional capacity dedicated to the first movement target is not affected by the requirement to perform longer movement sequences, which, as our results demonstrate, entails attentional deployment also at these additional goals. However, since each participant performed the three experiments one after the other, we could not exclude that training effects, or the acquisition of some strategies may also have been involved. For this reason it is at least arguable whether the experimental results from the first three experiments can be compared directly.

Therefore, in Experiment 4, the number of sequences that had to be performed in each trial was varied within each experimental block. Participants had to execute either a single, a double, or a triple movement sequence. A Roman number presented at the beginning of each trial indicated to the participant which kind of pointing sequence task they were actually asked to perform.

Another important change concerned the design of the experiment. In the previous experiments, the critical discrimination targets appeared with a probability of .75 at one of the three movement-relevant locations, and with a probability of only .25 at one of the three movement-irrelevant locations. This means that the cue was, to some extent, predictive of the likely presentation locations of the discrimination target, and could have induced a strategic shift of attention to the movement goals. In order to exclude any predictability of DT location, the discrimination target could now appear at any of the six possible target positions, with equal probability.

5.1. Method

The same six participants as in Experiments 1 and 3 also participated in Experiment 4. The experimental setup and the stimulus sequence were the same as in the previous experiments, except as follows: In this experiment, a Roman number (I, II or III) was shown for 1700 ms at the beginning of each single trial, at the central fixation position. The long presentation time was selected to ensure that participants were able to prepare the required type of sequence. The Roman number was then replaced by the fixation cross and the trial continued as in the previous experiments. The participant was instructed to execute either a single-step, a two-step or a three-step pointing movement, depending on which Roman number had been presented. The number "I" indicated that a single pointing movement to the item cued by the central arrow had to be performed. If the number "II" had been shown, the participant executed a double point movement, with the second movement goal being the item "two clock positions further in the clock-wise direction," as in Experiment 1. If the number "III" had been presented, the participant performed a triple movement sequence as in Experiment 2. At the end of each trial, the participant was provided with visual feedback about the final finger position. Also, an acoustical signal provided feedback about the latency of the initial movement. Again, the participants were given the opportunity to practice the different trials in an initial training block.

5.1.1. Design

After an initial training block each participant performed four experimental blocks consisting of 108 trials each. As in the previous experiments, only the mask elements at the position 1, 3, 5, 7, 9 or 11 o'clock were possible movement goals. Again, the factor "*Relative DT position*" had the following four levels: (1) The discrimination target (DT) was presented at the first movement target (condition "*1st MT*"), (2) DT was shown at the second possible movement target position (condition "*2nd MT*"), (3) DT was shown at the third possible movement target position (condition "*3rd MT*"), and (4) DT appeared at any of the remaining letter positions that were movement-irrelevant in that they were not targets of the movement sequence (condition "*other*"). The conditions where the discrimination target appeared at one of the three movement-relevant locations (i.e., condition *1*, *2*, or *3*) occurred in half of the trials. In the other half of the trials, the discrimination target was presented at one of the three remaining locations that were irrelevant to the actual movement sequence (condition 4). Thus, the conditions were now balanced such that the movement cue was no longer predictive of the position where the discrimination target would appear. The discrimination targets '**E**' and '**3**' occurred with equal probability. Also, there was the same number of single, double and triple pointing sequence trials in every block.

5.1.2. Discarded data

In the off-line data analysis, 7.9% of all trials were excluded due to too long or too short latencies. The discarding of these trials did not impact the mean latencies in any subtask condition. Moreover, 1.6% of the trials were discarded because the central cross was not appropriately fixated, 11% because the final pointing target was missed.

5.2. Results

5.2.1. Movement performance

The movement data for single, double and triple movement sequences were first analysed separately. Mean movement onset latency for the initial movement to the cued item was 335 ms (SE = 17.6 ms) in the trials where only a single movement was required, 342 ms (SE = 16.1 ms) in trials with double point movements, and 343 ms (SE = 15.2 ms) for the triple movement sequences. These mean values were not affected by the exclusion procedure. Statistical analysis revealed that these differences in latencies were not significant. No single contrast reached significance, neither single- versus double-pointing ($t(5) = -0.505$, $p > .84$), nor single- versus triple-pointing ($t(5) = -0.548$, $p > .84$), nor double versus triple pointing, $t(5) = -0.042$, $p > .96$, indicating that the preparation time for a sequence of pointing movements was independent of its length. In trials which required a second movement part (indicated by "II" or "III") the second movement started with a latency of 647 ms (SE = 51.3 ms) with respect to the go-signal. If a third movement was executed, it had a mean latency of 819 ms (SE = 40.5 ms). As before, the movements were reasonably accurate for all three sequence types. Mean spatial error of the final finger position with respect to the intended goal was 1.07, 1.18, and 1.27 deg for the single, double, and triple movement sequences, respectively. Although the spatial error increases numerically with sequence length, this effect is statistically not significant, $F(1,14) = .0894$, $p > .70$.

5.2.2. Perceptual performance

Again, the accuracy of target discrimination was the measure of the spatial allocation of attention before movement onset. We first analysed the discrimination data by a two-factor ANOVA. The first factor was the relative position of the discrimination target; as in the previous analyses, this factor had the levels "*1st MT*," "*2nd MT*," "*3rd MT*," and "*other*." The second factor was the type of sequence that was required (single, double, or triple movement). As we had expected from the results of the previous experiments, ANOVA revealed significant main effects for both the relative DT position ($F[3,15] = 43.925$, $p < .001$) and for the task type ($F[2,10] = 13.568$, $p < .0014$). Moreover, the interaction between both factors was significant, $F[6,30] = 3.49$, $p < .009$.

Discrimination performance for all conditions is displayed in Fig. 6. The data from the *single movement* trials are presented as black bars, as a function of the relative position of the discrimination target. First, it can be seen that discrimination performance in these trials was superior when DT was shown at the movement goal, yielding 89% correct. At the other DT positions, performance dropped close to chance level. This means that participants were not able to discriminate targets either at the position that would have been the second movement target if a two-step sequence had been required (condition "*2nd MT*," 56% correct), or at the third potential movement target location (condition '*3rd MT*": 54% correct). At the remaining, movement-irrelevant locations, performance was at 51% correct. The performance values for the different conditions were compared in post-hoc tests. These analyses revealed that discrimination performance at the first movement target position was indeed significantly different from the other potential pointing positions ($t(5) = -4.45$, $p < .001$ and $t(5) = -4.79$, $p < .001$), while performance at the potential second and third movement goals were not different from performance at the movement-irrelevant locations, $t(5) = -.731$, $p > .98$ and $t(5) = -.384$, $p > .98$, respectively.

The data from the trials where a *double movement* sequence was required are displayed by the hatched bars in Fig. 6. As in the conditions described previously, performance was superior at the location of the initial movement target (condition "1*st MT*," 96% correct). Now, however, performance at the second movement location was also

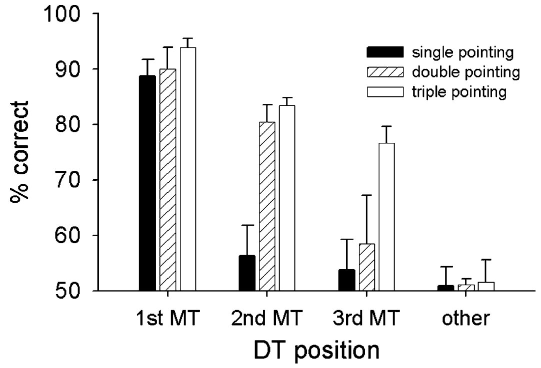

Fig. 6. Discrimination performance for the single, double and triple movement sequences of Experiment 4. Data are shown as a function of the location of the discrimination target.

well above chance (condition "*2nd MT*," 81% correct). Performance at the third (potential) movement target (i.e., the movement target that would have been the third pointing target if a three-step sequence had been required) remained close to chance level (57%). Finally, discrimination performance for the remaining, movement-irrelevant locations was at chance (50%).

Post-hoc analyses revealed that the difference in performance between the conditions "*1st MT*" and "*2nd MT*" was not significant, $t(5) = -1.34, p > .39$. Performance at the first and second movement goal however differed significantly from the discrimination performance at the third (potential) pointing position ($t(5) = -4.34$, $p < .0014$ and $t(5) = -3.061, p < .018$, respectively), and from performance at the movement-irrelevant locations, $t(5) = -5.45$, $p < .0001$ and $t(5) = -4.11$, $p < .0022$, respectively. Performance at the third movement goal was not significantly different from performance at the movement-irrelevant locations, $t(5) = -1.048, p > .392$.

Finally, perceptual performance in the trials in which a *triple movement* sequence was required are indicated by the open bars in Fig. 6. It can be seen that now, all three (movement-relevant) locations were well above chance, yielding performance levels in these trials of 94%, 84%, and 82% correct for the conditions "*1st MT*," "*2nd MT*," and "*3rd MT*," respectively. Post-hoc comparisons showed that the performance values at the (movement-relevant) first, second and third movement target positions differ significantly from the values at the movement-irrelevant locations, $t(5) = -10.67, p < .001$, $t(5) = -8.054, p < .001$, $t(5) = -6.35$, $p < .001$. The gradual decay of performance from the first to the final movement goal is reflected by the fact that performance at the initial movement target differed significantly from performance at both the second and the third movement goals, $t(5) = -2.62$, $p < .03$ and $t(5) = -4.33$, $p < .001$. The drop of performance between the second and the third movement goal turned out to be non-significant, $t(5) = -1.71, p > .10$.

A major purpose for performing this experiment was to study whether attentional processing at the goal of the initial movement would suffer from the requirement to perform longer movement sequences. Interestingly, our data show that discrimination performance at the initial pointing location did not decrease when further pointing movements were added to the first movement; instead, performance values were very similar and numerically even increased (89%, 96% and 94% for the single, double and triple movement task, respectively). Pairwise contrasts between the different types of sequences showed that neither performance difference was significant (single versus double movement: $t(5) = -0.3956$, $p > 0.71$; single versus triple movement: $t(5) = -1.4356$, $p > .21$, and double versus triple movement: $t(5) = -0.7956$, $p > .46$). This indicates that the same amount of attentional resources is deployed to the initial target, irrespective of the required length of the movement sequence. Likewise, when performance at the second movement goal was compared between double and triple movements, performance values were again very similar (81% and 84% for double and triple movements, respectively). A pairwise comparison revealed that these values were not statistically different, $t(5) = 0.9391, p > .390$.

5.3. Discussion

In Experiment 4, sequences of different length were required in randomised order in each single block. The result show, firstly, that in each trial only those items are selected for perception that are movement targets in the *actual* movement task. This indicates that the attentional mechanism always follows the requirements of the movement sequence that is currently to be prepared, rather than selecting, in a more stereotyped way, all three potentially movement-relevant locations. The result emphasizes that attentional selection is closely linked to the actual motor task.

Second, the experiment addressed the question whether the discrimination performance at a certain goal position would depend on how many further positions have to be selected in order to prepare the whole movement sequence. Under the assumption of restricted attentional resources, it would be plausible to expect that performance at the first movement goal should be higher in trials where only this goal has to be selected in comparison to conditions in which participants would have to distribute their attention among several movement goals. Similarly, performance at the second movement goal may be expected to be better in *double* than in *triple movement* trials. In other words, the longer the sequence that is required in the current trial, the worse discrimination performance at the first and the second movement goal should be. The results of the present experiment clearly contradict these assumptions. The data show that when sequences of different length are demanded, the discrimination performance at the first movement target stays the same, demonstrating that the processing capacity at the first movement location is not hampered by having to prepare a second or even a third movement. Similarly, the perceptual processing of the second movement target does not deteriorate when a third movement is required.

6. Experiment 5: Parallel selection

The previous experiments have demonstrated that, during the preparation and before the onset of a sequence of goal-directed movements, all relevant movement goals are attended, resulting in a discrimination performance at each of these positions that is superior to the performance at the movement-irrelevant locations. The important question arises whether the attentional deployment in this situation occurs in parallel, or serially in time. In order to investigate this question, we studied perceptual performance at two spatially separate positions simultaneously in a same-different matching task. In order to be solved, this task requires participants to attend to both stimulus locations simultaneously. In order to ensure that participants would not be able to shift their attention between the discrimination targets while they were present on the screen, the presentation time of the critical discrimination stimuli was reduced to 60 ms (for a similar approach see Godijn & Theeuwes, 2003).

6.1. Method

6.1.1. Participants

Six participants (four female, aged between 24 and 28 years) were tested in this final experiment. Five of them had already participated in Experiments 1–4.

6.1.2. Procedure

The stimulus array and the timing of the stimulus sequence were modified as shown in Fig. 7. At the beginning of each trial, a display consisting of a fixation cross and four mask elements was shown. The mask elements appeared on the diagonals at an eccentricity of 6.4 deg from the central fixation. We decided to use fewer mask elements than in the previous experiments in order to diminish the effects of lateral masking and thus to facilitate the perceptual task (see Bouma, 1970, 1973; Intriligator & Cavanagh, 2001). This allowed us to considerably reduce the presentation time of the critical display that contained the discrimination target, as compared to the previous experiments. After 1500 ms, an arrow appeared at the central fixation that pointed to one of the mask elements. Participants were asked to perform, upon the onset of this movement cue, a double pointing sequence, with the first movement being directed to the indicated mask element and the second movement to the element at the next position, in a clockwise direction. With a SOA of 50 ms after the presentation of this movement cue, two of the mask elements changed into the critical discrimination targets, which resembled a digital ‘**E**’ or ‘**3**’, while distractor stimuli (‘**2**’or ‘**5**’) were shown at the other two locations of the array. This display was presented for 60 ms, then discrimination targets and distractors were replaced by the mask elements.

After performing the movement sequence, participants indicated, by pressing one of two buttons, whether the two discrimination targets that had appeared during the preparation period of the movement had been the same or different. Feedback about the latency and the accuracy of the movements was provided at the end of each trial, as in the previous experiments.

6.1.3. Design

To become familiar with the task, participants initially performed a training session. Then, each participant performed four experimental blocks consisting of 96 trials each. The central arrow cued one of the four target positions, selected at random. Given the four target locations, there resulted six different combinations of where the two discrimination targets could appear on the movement targets. The discrimination targets ‘**E**’ and ‘**3**’ appeared with equal probability. In half of the trials the discrimination targets were the same, in the other half of the trials they were different. Altogether, this led to 96 different conditions (4 MT positions × 6 possible DT arrangements × 2 types of DT × 2 types of DT equality), these conditions were presented in randomised order. The central movement cue had no predictive validity for the presentation location of the discrimination targets.

In the data analysis, we distinguished three experimental conditions, dependent on the position of the discrimination targets relative to the movement targets. In the first condition (condition “*both*”), one discrimination target was presented at the first movement goal, the other discrimination target at the second goal of the sequential movement. In the second condition (condition “*one*”), only *one* of the locations where the discrimination targets were presented coincided with a movement target, while the second

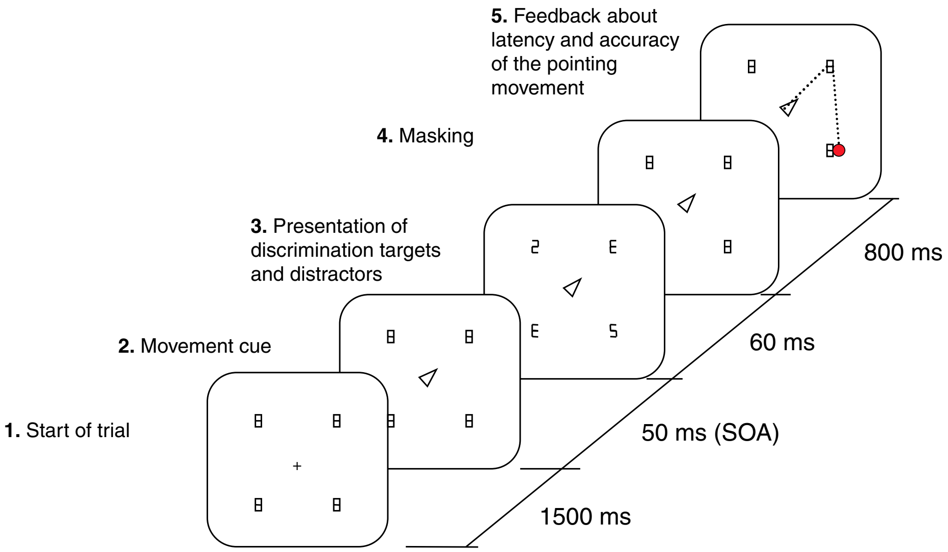

Fig. 7. Stimulus sequence in Experiment 5.

discrimination target was shown at one of the movement-irrelevant locations. Finally, the third condition (condition "*none*") included all those trials where *both* critical discrimination stimuli were presented at locations that were movement-irrelevant.

6.1.4. Discarded data

6.4% of all trials were discarded because of too short or too long latencies. Another 1.1% of data had to be discarded because of insufficient eye fixation or the occurrence of saccades. Finally, in 5.0% of the trials pointing errors occurred, these trials were also excluded from further analysis.

6.2. Results

6.2.1. Movement performance

The analysis of the pointing movements again revealed a relatively high movement accuracy, with the second movement terminating on average 1.28 deg away from the centre of the target item. Average latency of the initial movement was 309 ms (SE = 12.3 ms), the latency of the second movement was 607 ms (SE = 40.7 ms), both latencies measured from movement cue onset. Again, the latencies of the initial and the second movement were found to be independent of the relative position of the discrimination targets, $F(2, 10) = 2.3604$, $p > .14$, $F(2, 10) = .289$, $p > .75$, respectively. This is evidence that the presentation of the discrimination target at a certain position did not specifically affect the pointing movement.

6.2.2. Discrimination performance

Fig. 8 shows discrimination performance with respect to the positions of the discrimination stimuli relative to the movement goals in the three different experimental conditions. Obviously, the matching task could be solved only when both discrimination targets appeared at the movement-relevant locations (condition "*both*"). In this condition, the performance was 69% correct. When only one or none of the discrimination targets were presented at movement-relevant positions (conditions "*one*" and "*none*"), performance levels were close to chance (58% and 57%, respectively), indicating that the comparison could no longer be made, and the participant had to guess.

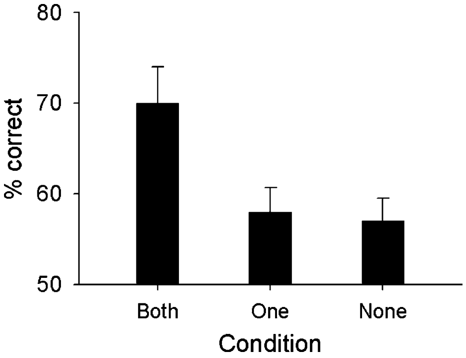

Fig. 8. Discrimination performance in Experiment 5.

A one-way ANOVA revealed a significant main effect of the relative position of the discrimination targets on the performance of the matching task, $F(2, 10) = 7.6062, p < .01$. Pair-wise comparisons showed a significant difference between the perceptual performance when discrimination targets and movement targets coincided and the cases when one or none of the discrimination targets was presented at a movement goal, $t(5) = 3.7$, $p < .007$, and $t(5) = 2.67$, $p < .02$, respectively.

6.3. Discussion

The results of this experiment provide evidence that the attentional selection of the movement goals which occurs during the preparation of the sequential movement can be better described as a parallel allocation to both movement targets rather than as a serial shift of attention between the targets.

The logic of this same-different matching task requires that the presentation time for the critical discrimination stimuli is sufficiently short to prevent the participants to shift attention serially from one discrimination target to the next. In the present approach, the two discrimination targets were present on the screen for 60 ms only. In line with Kramer and Hahn (1995), Hahn and Kramer (1998), and Godjin and Theeuwes (2003) we believe that this time interval is far too short to allow for serial attention shifts. So, there is considerable evidence that it takes about 150–200 ms to identify a stimulus that was indicated by a precue and to subsequently reallocate attention covertly to another position (Eriksen & Yeh, 1985; Krose & Julesz, 1989; Madden, 1992). Ward, Duncan, and Shapiro (1996) even estimated that up to 500 ms may be needed to shift attention endogenously. Evidence for considerably faster attention shifts, so called "express" attentional shifts (see e.g. Mackeben & Nakayama, 1993), are limited to peripheral cueing and to specific experimental settings, such as those involving a gap paradigm (see, e.g., Bekkering, Pratt, & Abrams, 1996; Fischer & Weber, 1993).

The performance in the condition "*both*" of the matching task can in principle be predicted from the probabilities to correctly identify the discrimination performance at the first and the second movement target. Let the probability to correctly identify the discrimination target at the first goal of the movement sequence be p_1, and the probability to identify the discrimination target at the second movement target be p_2. Consider further that a correct decision in the matching task can result either from the *correct* identification of both DTs, or from the *incorrect* identification of *both* DTs. Hence, the probability for a correct decision is $p_1 * p_2 + (1 - p_1) * (1 - p_2)$. Unfortunately, we did not determine perceptual performance in a single-target discrimination task for the stimulus arrangement and the presentation times of Experiment 5. However, assuming that perceptual performance at the first and second movement target were similar to those found in Experiment 1 (0.86 and 0.75, at the first and second movement target, respectively), the predicted probability for a correct decision in a matching task is 0.68 ($=0.86*0.75+0.14*0.25$). This is very close to the value of 0.69 actually found in the matching task in Experiment 5, for the condition where both discrimination targets were presented at the movement-relevant locations.

7. General discussion

7.1. Preparation of sequential movements involves selective processing of the movement-relevant targets

Former results from both saccade and reaching tasks suggested an obligatory coupling between (dorsal) selection for action and (ventral) selection for perception (e.g., Deubel & Schneider, 1996; Deubel et al., 1998). The aim of the present study was to extend these findings to a more complex motor task, namely, the execution of a sequence of pointing movements to two or three predetermined target locations. So, in contrast to the earlier investigations where a single object served as movement target, the tasks presented here involved a more complex computation of motor parameters which included several movement-relevant locations. As the central finding of this study, perceptual performance is found to be significantly better at the locations of *all* movement-relevant targets, as compared to the other, movement-irrelevant locations. This suggests that the second and even the third target position is selected before the onset of the initial movement and processed with higher priority than the task-irrelevant locations. This finding rules out a simple, serial model in which, first, the initial movement is being prepared and executed, and only after its completion, the next part of the sequence is prepared, and so on. Quite surprisingly, this selective perceptual processing of the movement-relevant locations is even present in a task which requires a quite complex movement sequence (Experiment 3). The findings confirm preliminary evidence reported by Deubel and Schneider (2004), who studied attentional deployment in a double pointing task.

The results are evidence that some information about subsequent movement targets is integrated in the initial movement plan. This is in line with a study by Ricker et al. (1999), who measured the latency of the first reaching movement in a rapid sequence of two movements directed to two targets. They found that the latency of the initial movement was longer when a second movement was required. More importantly, blanking of the second movement target during the first movement resulted in longer latencies of the second movement segment. The authors suggested that the preparation of the second movement is completed before the first movement is terminated, and that visual processing prior to movement onset can be used to formulate a movement plan to both targets in the sequence. Our result are also in accordance with several studies on motor control dealing with complex movement sequences (e.g. Christina et al., 1982; Fischman, 1984; Fishman & Lim, 1991; Smiley-Oyen & Worringham, 1996). The main finding of these studies is that the kinematics of the first part of the action sequence are affected by the complexity of the second part. For example, some authors found increased latencies or durations of the first movement part in a double-step reaching task and interpreted this as suggesting that both targets are processed in advance and both sequence parts are programmed before the sequence is initialized (Gentilucci et al., 1997; Lajoie & Franks, 1997; Rand et al., 1997; Rand & Stelmach, 2000).

Our findings are similar to those of Godijn and Theeuwes (2003) for saccadic eye movements. Godijn and Theeuwes demonstrated that prior to the execution of a sequence of two saccadic eye movements, attention is allocated to both saccade locations. As in the present study, they also found that most attentional resources are allocated to the target at the initial movement, yielding best perceptual performance, while less processing capacity is dedicated to the second movement goal. In contrast, Gersch et al. (2004) found no evidence for an attentional allocation beyond the next saccade target while participants performed self-paced sequences of saccades on a circular array of items. Gersch et al. suggested that in sequential saccades attentional resources are dedicated primarily to the goal of the next saccade, leaving little attention for processing objects at other locations. The reasons for the discrepancies between these findings are still unclear. One important factor may be whether the participants are speeded or not in the motor task. In the present study participants had to execute the movement sequence as fast and as accurately as possible. In contrast, Gersch at al. did not require fast saccadic response but rather instructed their participants to scan the target boxes maintaining a steady pace. In the paradigm that Gersch et al. used it is impossible to ensure that the participants really prepared a movement sequence. Instead they might have prepared just the movement to the impending goal. In such an experimental context the participants could choose whether or not to prepare one movement versus a sequence of movements

In more natural tasks it has been shown previously that attentional selection is often restricted to action-relevant objects. For example, Triesch and colleagues (Triesch, Ballard, Hayhoe, & Sullivan, 2003) showed in a change detection paradigm that the detection of feature changes of manipulated objects strongly depends on the momentary task demands. Johansson, Westling, Bäckström, and Flanagan (2001) studied overt attentional selection during the manipulation of objects. They found that participants exclusively fixated certain landmarks that are critical for the manipulation (e.g., object parts that are contacted with the fingertips, or movement-relevant obstacles). The authors claim that the saccades towards such landmarks supports the planning of the hand movement by marking key positions that are crucial for the manipulation.

7.2. Evidence for a division of attention among non-contiguous locations

The analysis of the perceptual performance at the item located in between the first and the second movement target in Experiment 1 showed that discrimination performance is at chance level if the discrimination target appeared between both movement goals. This indicates that no attention was directed to this intermediate position, while the movement targets located closely to the left and to the right were selected with high efficiency. Together with the experimental evidence discussed below that attentional allocation is parallel rather than serial in time, this result demonstrates that attention is divided among the spatially non-contiguous movement targets. The spatial selectivity of the attentional focussing is amazingly high, given the target items were only 3.6 deg apart, and appeared at 7.2 deg in the visual periphery.

The finding clearly rules out the alternative explanation of an attentional zoom lens which assumes a widening of the attentional focus to include both movement target locations (e.g., Eriksen & James, 1986). Rather, the results support a model in which attention can be deployed to multiple non-unitary regions of visual space, so that several objects can be selected individually. The finding that under certain conditions attention can be divided among non-contiguous locations is in line with results of Hahn and Kramer (1998; Kramer and Hahn, 1995). They demonstrated that subjects can concurrently attend to non-contiguous locations as long as new distractor objects did not appear between the target locations. They also showed that hemifield boundaries did not constrain the participant's ability to divide their attention. This is in line with the results of our Experiment 3, demonstrating that even three attentional foci can be distributed in both hemifields.

7.3. Total attentional capacity is not constant across tasks

In Experiment 4 we asked whether the discrimination performance at a certain goal position depends on how many further positions have to be selected in order to prepare the required sequence. Under the assumption that a fixed amount of attentional resources is distributed over the visual field (e.g., Bundesen, 1998, 2002, 1990), the performance at the first movement goal should be better in trials where only this goal has to be selected as a movement target, in contrast to conditions in which participants would have to distribute their attention among several movement goals, as in the double and triple movement trials. Similarly, performance at the second movement target position should deteriorate when an additional, third movement is required. The data of Experiment 4 clearly demonstrate that this is not the case, however. Discrimination performance remains constant at the initial and the second movement position irrespective of the sequence length—additional movements do not entail costs at the initial (and second) movements location. This implies that the total processing capacity that is effective is not constant across the different movement tasks, but increases with increasing sequence length.

The finding that the quality of processing at a given movement location does not deteriorate when longer sequences are required is mirrored in the accuracy of the sequential movements. As shown in Experiment 4, there is no indication that the precision of pointing movements deteriorates if further goals are added—spatial movement errors with respect to the final movement goal do not differ significantly as a function of the length of the required sequence.

These data argue for a mechanism which grants sufficient attentional resources to the current targets so that the required pointing task can be accomplished with sufficient accuracy. For the case of single pointing trials, this means that resources that are not needed for the movement are not further utilized in the visual field. When a double movement sequence is demanded, however, further attentional resources are mobilized and assigned to the second movement, to the extent that this movement will also be sufficiently accurate.

7.4. No evidence for a complexity effect on movement latencies

Somewhat surprisingly, we found no evidence for longer latencies of the initial movement in longer movement sequences (Experiment 4). In line with the assumption of a parallel deployment of attention to the movement goals, this indicates that the required specification of further movement parameters in longer sequences which occurs before the onset of the initial movement does not require additional time. In contrast, several studies have found effects of motor sequence length on reaction times. Henry and Rogers (1960) were among the first to report a complexity effect for increasingly complicated movements. According to their findings, reaction time increases as a function of the number of distinct movement elements (see also Christina et al., 1982; Inhoff, Rosenbaum, Gordon, & Campbell, 1984; Lajoie & Franks, 1997; Rand et al., 1997; Rand & Stelmach, 2000; Stuphorn & Schall, 2002). Inhoff (1986) made similar observations when sequences of saccadic eye movements had to be prepared. The experiments of Zingale and Kowler (1987) also showed that for the execution of longer saccade sequences longer preparation times are needed. These authors estimated an additional preparation time of about 20 ms per additional movement goal. In contrast, however, more recent results from a study on sequences of saccadic eye movements (Pratt, Shen, & Adam, 2004) contradicted these findings. The reasons for these conspicuous differences in the findings is yet unclear. Possibly the response-complexity-effects are less robust than previously assumed. Alternatively, the effects of response complexity may be diminished in very well-trained sequence patterns. The training of sequences like those performed in the present study may allow to automise movements even though the sequence type changed from trial to trial (like in Experiment 4).

7.5. Parallel allocation of attention to the movement-relevant targets

Our experiments show that while a sequence of pointing movements is prepared, attention shifts to all movement-relevant targets. The important question arises whether this attentional deployment occurs in parallel, or serially in time. In Experiment 1–4 of the present study, the critical discrimination target was presented for 180–220 ms, depending on the participants. Due to this rather long presentation time it cannot be ruled out that attention may shift serially from one discrimination target to the next, while these are present on the screen. Our last experiment (Experiment 5) was designed to provide a direct answer to this question. In a same-different matching task target letters (digital '**E**' or '**3**') had to be compared which were presented simultaneously at spatial various positions. Since the discrimination targets were shown for only a very short period of time (60 ms), this task could only be solved when attention was deployed to both targets simultaneously. Indeed, the data showed that the comparison was only possible if both target letters were presented at the goal positions of the double pointing movement. This is direct evidence that multiple movement target positions are selected in parallel when they become relevant for goal-directed actions. Similar results have been reported by Godijn and Theeuwes (2003) for saccadic eye movements.

The results confirm preliminary findings of Deubel and Schneider (2004). In their study, participants performed double pointing movements on a circular letter array as that used in the present investigation. The delay between the presentation of the movement cue and the onset of the critical discrimination stimulus was systematically varied in a range between 80 and 320 ms. While the results suggest that both movement targets are attended before movement onset, there was no effect of the delay on the discrimination performance. This finding is compatible with the present results, suggesting that both movement targets were selected in parallel.

7.6. Neural mechanisms

The posterior parietal cortex (PPC) is an essential neural area for selection in visually guided movements. First, it is crucial for general spatial attention tasks (Corbetta, Miezin, Shulman, & Peterson, 1993; Goldberg, Colby, & Duhamel, 1990). Second, it is essential for preparing goal-directed actions. Spatial information is coded in parallel in various substructures of the PPC for different effector systems (Graziano & Gross, 1994; Konen, Kleiser, Wittsack, Bremmer, & Seitz, 2004; Rizzolatti et al., 1994; Snyder, Batista, & Andersen, 1997). The retinotopically organized lateral intrapariatal area (LIP) is known to be involved both in the programming of saccades as in attentional selection per se (Chelazzi & Corbetta, 2000; Colby, 1998; Colby & Goldberg, 1999; Rizzolatti et al., 1994). Interestingly, LIP is not only connected to the frontal eye fields and the superior colliculus (both important for computing motor commands for saccades) but also to the extrastriate visual area V4, and it seems to be an important interface between sensory processing and action preparation (Corbetta, Miezin, Shulman, & Peterson, 1991). Hahn and Kramer (1998) assumed that LIP is also crucial for the programming of sequences of saccades (see also, LaBerge & Brown, 1989).

Other regions of the PPC are rather related to the control of hand movements (see Kawashima et al., 1996; Kertzman, Schwarz, Zeffiro, & Hallett, 1997). Snyder and colleagues (Snyder et al., 1997) showed that neurons in the parietal reach region (PRR) are active during the delay period of a memory guided reach tasking, but that they are not active during a memory guided saccade task. In a study by Batista and Andersen (2001) monkeys had to perform delayed hand reaches to two remembered targets. The activity of neurons in PRR was found to be related to the reach the monkey was about to perform next. It only rarely represented the remembered target for the second reach (Batista & Andersen, 2001; Batista, Buneo, Snyder, & Andersen, 1998). The authors argued that the observed activity reflects movement intentions, specifying the target for the impending reach, but does not represent a spatial memory of the subsequent reach targets (see also Calton, Dickinson, & Snyder, 2002). MIP and V6A, the likely substrata of PRR are involved in selecting targets for a reach as well as in transforming eye-centred coordinates into limb-centred representations. These structures have connections to (limb-centred) premotor areas in the frontal lobe (Johnson, Ferraina, Bianchi, & Caminiti, 1996; Matelli, Govoni, Galetti, Kutz, & Luppino, 1998). As Batista and Andersen suggest, frontal and parietal regions work in conjunction in order to plan sequences of reaches and converting from eye-centered to limb-centered reference frames. So, Cizek and Kalaska (1999) found physiological evidence that both potential reach targets of a target-selection task are encoded in premotor cortex.

8. Conclusion

We studied the relation of attention and movement preparation in a task where sequential pointing movements had to be directed to multiple targets. Our findings demonstrate that all movement-relevant locations are selected in parallel, involving spatially distinct, non-contiguous foci of visual attention. We showed that during movement preparation, at least three spatially separate targets can be attended, even if they are presented in different hemifields. Discrimination performance is always best at the initial movement position and decreases at further movement goals. When further pointing goals are added to the movement sequence, additional attentional resources are used. Overall, the results are consistent with the view that movement preparation and selective attention are closely related.

Acknowledgments

This work was supported by the Deutsche Forschungsgemeinschaft (Grant De 336/2 to H.D.). We wish to thank Birgitt Assfalg for her help in running the experiments.

References

Andersen, R. A., & Buneo, C. A. (2002). Intentional maps in posterior parietal cortex. *Annual Review of Neuroscience, 25*, 189–220.

Andersen, R. A., Snyder, L. H., Bradley, D. C., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annual Review in Neuroscience, 20*, 303–330.

Allport, D. A. (1987). Selection for action: Some behavioral and neurophysiological considerations of attention and action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 395–419). Hillsdale, NJ: Lawrence Erlbaum Associates.

Batista, A. P., & Andersen, R. A. (2001). The parietal reach region codes the next planned movement in a sequential reach task. *Journal of Neurophysiology, 85*, 539–544.

Batista, A. P., Buneo, C. A., Snyder, L. H., & Andersen, R. A. (1998). The parietal reach region (PRR) employs a predominantly retinal reference frame which updates across saccades, and encodes only the impending reach. *Society of Neuroscience Abtract, 24*, 262.

Bekkering, H., Pratt, J., & Abrams, R. A. (1996). The gap effect for eye and hand movements. *Perception & Psychophysics, 58*, 628–635.

Bonfiglioli, C., & Castiello, U. (1998). Dissociation of covert and overt spatial attention during prehension movements: selective interference effects. *Perception & Psychophysics, 60*(8), 1426–1440.

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*, 177–178.

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research, 13*, 767–782.

Bundesen, C. (1990). A theory of visual attention. *Psychological Review, 97*, 523–547.

Bundesen, C. (1998). Visual selective attention: outlines of a choice model, a race model, and a computational theory. *Visual Cognition, 5*, 287–309.

Bundesen, C. (2002). A general theory of visual attention. In L. Bäckman & C. von Hofsten (Eds.), *Psychology at the turn of the millennium: Vol. Cognitive, biological and health perspectives*. Hove, UK: Psychology Press.

Calton, J. L., Dickinson, A. R., & Snyder, L. H. (2002). Non-spatial, motor-specific activation in posterior parietal cortex. *Nature Neuroscience, 5*, 580–588.

Castiello, U. (1996). Grasping a fruit: selection for action. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 582–603.

Chelazzi, L., & Corbetta, M. (2000). Cortical mechanisms of visuospatial attention in the primate brain. In M. S. Gazzaniga (Ed.), *The new cognitive neuroscience* (pp. 667–686). Cambridge, MA: MIT Press.

Christina, R. W., Fishman, M. G., Vercruyssen, M. J. P., & Anson, J. G. (1982). Simple reaction time as a function of response complexity:memory drum theory revisited. *Journal of Motor Behaviour, 14*, 301–321.

Cizek, P., & Kalaska, J. F. (1999). Neural correlates of multiple potential motor actions in primate premotor cortex. *Society Neuroscience Abtract, 25*, 381.

Colby, C. L. (1998). Action-oriented spatial reference frames in cortex. *Neuron, 20*, 15–24.

Colby, C. L., & Goldberg, M. E. (1999). Space and attention in parietal cortex. *Annual review of Neuroscience, 22*, 319–349.

Corbetta, M., Miezin, F., Shulman, G., & Peterson, S. (1991). Selective and divided attention during visual discriminations of shape, color and speed: functional anatomy by positron emission tomography. *Journal of Neuroscience, 11*, 2383–2402.

Corbetta, M., Miezin, F., Shulman, G., & Peterson, S. (1993). A PET study of visual spatial attention. *Journal of Neuroscience, 13*, 1202–1226.

Craighero, L., Fadiga, L., Rizzolatti, G., & Umilta, C. (1998). Visuomotor priming. *Visual Cognition, 5*, 109–125.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition—evidence for a common attentional mechanism. *Vision Research, 36*, 1827–1837.

Deubel, H., & Schneider, W. X. (2004). Attentional selection in sequential manual movements, movements aroand an obstacle and in grasping. In G. W. Humphreys & M. J. Riddoch (Eds.), *Attention in action*. Hove: Psychology Press.

Deubel, H., Schneider, W. X., & Paprotta, I. (1998). Selective dorsal and ventral processing: evidence for a common attentional mechanism in reaching and perception. *Visual Cognition, 5*, 81–107.

Eriksen, C. W., & James, J. D. St. (1986). Visual attention within and around focal attention: a zoom lens model. *Perception & Psychophysics, 40*(4), 225–240.

Eriksen, C. W., & Yeh, Y. Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 11*, 583–597.

Fischer, B., & Weber, H. (1993). Express saccades and visual attention. *Behavioral Brain Science, 16*, 588–589.

Fischman, M. G. (1984). Programming time as a function of number of movement parts and changes in movement direction. *Journal of Motor Behaviour, 16*, 405–423.

Fishman, M. G., & Lim, C.-H. (1991). Influence of extended practice in programming time, movement time, and transfer in simple target-striking responses. *Journal of Motor Behaviour, 23*, 39–50.

Gentilucci, M., Negrotti, A., & Gangitano, M. (1997). Planning an action. *Experimental Brain Research, 115*, 116–128.

Gersch, T. M., Kowler, E., & Dosher, B. (2004). Dynamic allocation of visual attention during the execution of sequences of saccades. *Vision Research, 44*, 1469–1483.

Godijn, R., & Theeuwes, J. (2003). Parallel allocation of attention prior to the execution of saccade sequences. *Journal of Experimental Psychology: Human Perception and Performance, 29*(5), 882–896.

Goldberg, M., Colby, C., & Duhamel, J. (1990). Representation of visuomotor space in the parietal lobe of the monkey. *Cold Spring Habor Symposia on Quantitative Biology, 55*, 729–739.

Graziano, M. S. A., & Gross, C. G. (1994). Mapping space with neurons. *Current Directions in Psychological Science, 3*, 164–167.

Hahn, S., & Kramer, A. F. (1998). Further evidence for the division of attention among noncontiguous locations. *Visual Cognition, 5*, 217–256.

Henry, F. M., & Rogers, D. E. (1960). Increased response latency for complicated movements and a "memory drum" theory of neuromotor action. *Research Quarterly, 31*, 448–458.

Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics, 57*, 787–795.

Inhoff, A. W. (1986). Preparing sequences of saccades under choice reaction conditions: Effects of sequence length and context. *Acta Psychologica, 61*, 211–228.

Inhoff, A. W., Rosenbaum, D. A., Gordon, A. M., & Campbell, J. A. (1984). Stimulus response compatibility and motor programming of manual response sequences. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 724–733.

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology, 43*, 171–216.

Jeannerod, M. (1994). The representing brain: neural correlates of motor intention and imagery. *Behavioral and Brain Sciences, 17*, 187–245.

Johansson, R., Westling, G., Bäckström, A., & Flanagan, R. (2001). Eye-hand coordination in object manipulation. *Journal of Neuroscience, 21*, 6917–6932.

Johnson, P. B., Ferraina, S., Bianchi, L., & Caminiti, R. (1996). Cortical networks for visual reaching: physiological and anatomical organization of frontal and parietal arm regions. *Cerebral Cortex, 6*, 102–119.

Kawashima, R., Naitoh, E., Matsumura, M., Itoh, H., Ono, S., Satoh, K., et al. (1996). Topographic representation in human intraparietal sulcus of reaching and saccade. *Neuroreport, 7*, 1253–1256.

Kertzman, C., Schwarz, U., Zeffiro, T. A., & Hallett, M. (1997). The role of posterior parietal cortex in visually guided reaching movements in humans. *Experimental Brain Research, 1*(14), 170–183.

Konen, C. S., Kleiser, R., Wittsack, H. J., Bremmer, F., & Seitz, R. J. (2004). The encoding of saccadic eye movements within human posterior parietal cortex. *Neuroimage, 22*, 304–314.

Kowler, E., Anderson, E., Dosher, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research, 35*, 1897–1916.

Kramer, A. F., & Hahn, S. (1995). Splitting the beam: distribution of attention over noncontiguous regions of the visual field. *Psychological Science, 6*, 381–386.

Kritikos, A., Bennett, K. M. B., Dunai, J., & Castiello, U. (2000). Interference from distractors in reach-to-grasp movements. *Quarterly Journal of Experimental Psychology, 53*, 131–151 49.

Krose, B., & Julesz, B. (1989). The control and speed of shifts in attention. *Vision Research, 29*, 1607–1619.

Linnell, K. J., Humphreys, G. W., McIntyre, D. B., Laitinen, S., & Wing, A. M. (2005). Action modulates object-based selection. *Vision Research, 45*, 2268–2286.

LaBerge, D., & Brown, V. (1989). Theory of attentional operation in shape identification. *Psychological Review, 96*, 101–124.

Lajoie, J. M., & Franks, I. M. (1997). Response programming as a function of accuracy and complexity: evidence from latency and kinematics-measures. *Human Movement Sciences, 16*, 485–505.

Mackeben, M., & Nakayama, K. (1993). Express attentional shifts. *Vision Research, 33*(1), 85–90.

Madden, D. (1992). Selective attention and visual search: revision of an allocation model and application to age differences. *Journal of Experimental Psychology: Human Perception and Psychophysics, 18*, 821–836.

Matelli, M., Govoni, P., Galetti, C., Kutz, D. F., & Luppino, G. (1998). Superior area 6 afferents from the superior parietal lobule on the macaque monkey. *Journal of Comparative Neurology, 402*, 327–352.

Neumann, O. (1987). Beyond capacity: a functional view of attention. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 361–394). Hillsdale, NJ: Lawrence Erlbaum Associates.

Polhemus Inc. (1993). *Three-Space Fasttrak user's manual*, Polhemus, Colchester, Vermont, 11.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3–25.

Pratt, J., Shen, J., & Adam, J. (2004). The planning and execution of sequential eye movements: Saccades do not show the one target advantage. *Human Movement Science, 22*, 679–688.

Rand, M. K., Alberts, J. L., Stelmach, G. E., & Bloedel, J. R. (1997). The influence of movement segment difficulty on movements with two stroke sequences. *Experimental Brain Research, 115*, 137–146.

Rand, M. K., & Stelmach, G. E. (2000). Segment inerdependency and difficulty in two-stroke sequences. *Experimental Brain Research, 134*, 228–236.

Ricker, K. L., Elliot, D., Lyons, J., Gauldie, D., Chua, R., & Byblow, W. (1999). The utilization of visual information in the control of rapid sequential aiming movements. *Acta Psychologica, 103*, 103–123.

Rizzolatti, G., Riggio, L., & Sheliga, B. M. (1994). Space and selective attention. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance XV. Conscious and nonconscious information processing* (pp. 231–265). Cambridge, MA: MIT Press.

Schiegg, A., Deubel, H., & Schneider, W. X. (2003). Attentional selection during preparation of prehension movements. *Visual Cognition, 10*(4), 409.

Schneider, W. X. (1995). VAM: a neuro-cognitive model for attention control of segmentation, object recognition and space-based motor action. *Visual Cognition, 2*, 331–374.

Schneider, W. X., & Deubel, H. (2002). Selection-for-perception and selection-forspatialmotor-action are coupled by visual attention: a review of recent findings and new evidence from stimulus-driven saccade control. In W. Prinz & B. Hommel (Eds.), *Attention and performance XIX: Common mechanisms in perception and action* (pp. 609–627). Oxford: Oxford University Press.

Smiley-Oyen, A. L., & Worringham, C. J. (1996). Distribution of programming in a rapid aimed sequential movement. *The Quarterly Journal of Experimental Psychology, 49A*(2), 379–397.

Snyder, L. H., Batista, A. P., & Andersen, R. A. (1997). Coding of intention on the posterior parietal cortex. *Nature, 386*, 167–170.

Snyder, L. H., Batista, A. P., & Andersen, R. A. (2000). Intention-related activity in the posterior parietal cortex. *Vision Research, 40*, 1433–1441.

Stuphorn, V., & Schall, J. (2002). Neuronal control an monitoring of initiation of movements. *Muscle and Nerve, 26*, 326–339.

Treisman, A., & Gelade, G. (1980). A feature–integration theory of attention. *Cognitive Psychology., 12*(1), 97–136.

Triesch, J., Ballard, D. H., Hayhoe, M. M., & Sullivan, B. T. (2003). What you see is what you need? *Journal of Vision, 3*(1), 86–94.

Ward, R., Duncan, J., & Shapiro, K. (1996). The slow time course of visual attention. *Cognitive Psychology, 30*, 79–109.

Wolf, W., & Deubel, H. (1997). P31 phosphor persistence at photopic luminance level. *Spatial Vision, 4*, 323–333.

Zingale, C. M., & Kowler, E. (1987). Planning sequences of saccades. *Vision Research, 27*, 1327–1341.