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Visual attention during the preparation of bimanual movements

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Abstract

We investigated the deployment of visual attention during the preparation of bimanually coordinated actions. In a dual-task paradigm participants had to execute bimanual pointing movements to different peripheral locations, and to identify target letters that had been briefly presented at various peripheral locations during the latency period before movement initialisation. The discrimination targets appeared either at the movement goal of the left or the right hand, or at other locations that were not movement-relevant in the particular trial. Performance in the letter discrimination task served as a measure for the distribution of visual attention during the action preparation. The results showed that the goal positions of both hands are selected before movement onset, revealing a superior discrimination performance at the action-relevant locations (Experiment 1). Selection-for-action in the preparation of bimanual movements involved attention being spread to both goal locations in parallel, independently of whether the targets had been cued by colour or semantically (Experiment 2). A comparison with perceptual performance in unimanual reaching suggested that the total amount of attentional resources that are distributed over the visual field depended on the demands of the primary motor task, with more attentional resources being deployed for the selection of multiple goal positions than for the selection of a single goal (Experiment 3). © 2007 Elsevier Ltd. All rights reserved.

Keywords: Visual attention; Selection-for-action; Bimanual movements; Hand movements; Split attention

1. Introduction

The coordinated use of both hands is a key motor skill in primates. From an evolutionary point of view, it is the likely basis for the development of many cognitive functions like gesturing or the effective use of tools (Wiesendanger, 1999), and the advantages bimanual skills had in coping with the daily demands in hominids' life presumably caused the upright stand of man (Festinger, 1983). Many of the daily actions we perform involve the simultaneous coordination of both hands. In previous studies it has been shown that the movement patterns of both hands are highly synchronized and well aligned with each other. For example, the movements of the left and right hand begin and end at approximately the same time, although they may have different amplitudes (Kelso, Southard, &

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Goodman, 1979a, 1979b). Further, several studies showed that there are strong performance limitations during bimanual movements. To some extent this seems to cause problems in the planning or execution of independent movements with both hands at the same time (Diedrichsen, Ivry, Hazeltine, Kennerley, & Cohen, 2003). This is not only true for timing constraints in performing complex polyrhythm in cyclic bimanual coordination tasks like bimanual finger tapping or pendulum swinging by the hands (Kelso, 1995; Schöner & Kelso, 1988). In addition there are also spatial constraints (Franz, Eliassen, Ivry, & Gazzaniga, 1996; Lee, Almeida, & Chua, 2002; Swinnen, Dounskaia, Levin, & Duysens, 2001). Non-symmetric actions with different spatial characteristics for the left and the right hand sometimes give rise to prolonged latencies (Franz et al., 1996; Spijkers & Heuer, 1995; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997; Spijkers, Heuer, Steglich, & Kleinsorge, 2000), and cause high error rates or distorted trajectories (Franz, Zelaznik, & McCabe, 1991). These effects were traditionally explained by inter-

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ferences during the motor programming (Rosenbaum, 1980; Rosenbaum & Kornblum, 1982) or, more recently, by conflicts during the selection of the appropriate response or of the stimulus–response mapping (Diedrichsen, Hazeltine, Kennerley, & Ivry 2001; Diedrichsen et al., 2003).

Aside from these interesting findings of interferences during asymmetrical movements with the left and right hand, commonly performed bimanual movements in which both hands are used in a very orchestrated manner also pose a challenge to the cognitive system. For example, when bimanually grasping for an object, two spatially distinct contact points for the left and the right hand have to be prepared. In order to plan such a visually guided action the relevant visual information about the operandum has to be processed effectively. The mechanism of selective visual attention plays a prominent role in filtering the information about movement-relevant parts of the scene from other distracting visual input. As Allport (1987, see also Neumann, 1987) pointed out, visual selection in action preparation is a fundamental function of the attentional system. Accordingly, the premotor theory of attention describes how the intention to move an effector causes covert shifts of the attentional focus (Rizzolatti, Riggio, & Sheliga, 1994).

It has been demonstrated for unimanual reaching movements that visual attention is deployed to the goal position well in advance of movement initialisation, and little room is left for the visual processing of action-irrelevant items in the visual field (Castiello, 1996; Deubel, Schneider, & Paprotta, 1998). This resulted in the view that only one (actionrelevant) object at a time is processed before the next goaldirected action. However, more recent studies have suggested that this picture may require some modification as soon as actions are considered which involve more than a single action goal. So, when the reach requires to avoid potential obstacles, attention seems to be flexibly distributed among several objects of interest (Deubel & Schneider, 2004). In the context of more complex (yet still unimanual) actions such as grasping for an object, Schiegg, Deubel, and Schneider (2003) observed attentional effects that specifically facilitated visual processing at the two grasping points, i.e., at those parts of the object where thumb and index finger were going to contact the surface. Finally, our previous studies on the preparation of movement sequences showed that the visual system does not select only a single goal position of the impending very next movement, but that up to three goals of the subsequently performed reaches are selected even before the first movement starts (Baldauf, Wolf, & Deubel, 2006). In this series of experiments participants had to perform a dual-task. The primary task was to point with the index finger to two or three centrally cued goal positions in the periphery. The reaches had to be executed in fast sequence. Right after the 'go'—signal for the pointing sequence—but well before the actual movement started-a target letter was tachistoscopically presented (resembling a digital 'E' versus '3') among distractors ('2's or '5's) at one randomly selected position in the periphery. The non-speeded secondary task was to discriminate the target letter ('E' versus '3') by button press at the very end of each trial. The results showed that the participants' ability to discriminate the target letter was superior if the discrimination target had been presented at the first or second reach goal, compared to discrimination performance at chance level in those trials, in which the target letter did not coincide with any of the movement goals (for similar results regarding the preparation of *eye movement* sequences see also Baldauf & Deubel, in press).

In a second study (Baldauf & Deubel, submitted) a dotprobe paradigm was used to provide electrophysiological evidence for the hypothesis that attention splits into distinct foci as to cover two goal locations of an intended double-reach sequence. Here a task-irrelevant visual transient (dot probe) was flashed in the visual field while subjects prepared for a rapid double-reach sequence. The dot probe could be presented at the first or second movement goal or at irrelevant positions. The analysis of the visual potentials that were elicited by the onset of the dot probe revealed increased N1 amplitudes in response to dot probes that were flashed at either movement goal (first or second) indicating enhanced visual processing of both goal locations before movement onset.

Also, little interest was paid until recently to the spatial selection of multiple goal position in actions that involve more than a single effector. In the case of bimanual actions, when contact points for the left and right hand have to be selected, the visual processing of *both* goal locations may be enhanced. Riek and colleagues (Riek, Tresilian, Mon-Williams, Coppard, & Carson, 2003) tracked gaze position during the execution of precise bimanual aiming movements. They described how eye gaze shifts in the end phase of the reach from one target to the other in order to serially correct for spatial end-point errors of the left and right hand. This kind of overt allocation of visual attention may play a major role in the appropriate use of visual feedback, helping to minimise the spatial error that accumulates during the transport phase of the movement (Riek et al., 2003). However, programming of the transport of both hands towards the two targets may also involve covert selective processing-well before the movement actually starts. So, the question arises whether the preparation of a bimanual action requires both target zones, at which the hands are intended to contact the object, to be attended before action initialisation. Indeed, the tight synchronization that is observed in the movement kinematics of both hands (see Kelso et al., 1979) may be an indication for a parallel pre-programming of both reaches, which may entail visual attention to be simultaneously deployed to both movement goals. Alternatively, attention may shift covertly back and forth from one goal position to the other while preparing for the coordinated action, in a manner as alike the serial overt attention shifts reported by Riek and colleagues (2003).

In a series of three experiments we studied the deployment of visual resources while participants prepared bimanual reaches to two distinct goal positions in the periphery. Letter discrimination was used as secondary task in order to determine the distribution of visual attention during the planning phase. The analysis of discrimination performance in Experiments 1 and 2 revealed that, when bimanual reaches are prepared, both goal positions are attended well before movement initialisation. This selection process involves the *parallel* allocation of visual attention to both target zones, and is not an artefact of the type of cue that was used to indicate the goal positions (Experiment 2). In Experiment 3 the participants performed unimanual reaches as primary task. The comparison of the discrimination performance under this condition with the performance in bimanual reaching suggests that the total amount of visual resources that is deployed in the visual field is not fixed but varies with the demands of the motor task.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Six students of the Ludwig-Maximilians-University, aged between 24 and 27 years (three males), participated as consenting, paid volunteers in all of the following three experiments. They had normal or corrected-to-normal vision and were right handed.

2.1.2. Experimental apparatus

Fig. 1 provides a sketch of the experimental set-up. The participant sat in a dimly illuminated room. The stimuli were presented on a 21-inch colour monitor (Conrac



Fig. 1. Experimental set-up. The visual stimuli were generated on a video display and were projected via a half-translucent mirror onto a slightly declined pointing plane in front of the participant. The mirror was adjusted such that the visual stimuli appeared in the centre of the manipulation space. Movements of both index fingers were recorded with a Polhemus Fastrak electromagnetic tracking device. Eye fixation was controlled with a video-based eye-tracker.

7550 C21) at a frame frequency of 100 Hz with a spatial resolution of 1024 * 768 pixels. The active screen size was 40×30 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 for 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 luminance of the visual stimuli was adjusted to 23 cd/m^2 . The stimuli were presented on a grey background, which was adjusted to a mean luminance of 2.2 cd/m^2 . The moderate background brightness is important to minimise the effects of phosphor persistence (Wolf & Deubel, 1997). Effective viewing distance was 58 cm.

The movements of the left and right index fingers were recorded with a Fastrak electromagnetic position and orientation measuring system (Polhemus Inc., 1993), consisting of a central transmitter unit and two small receivers mounted on the tips of the participants' left and right index fingers. The sender unit was fixed 60 cm in front of the participant. The device allows for a maximum translation range of 3.0 m, with an accuracy of 0.08 cm RMS. The frequency bandwidth of the system was 120 Hz, with a delay of 4 ms. Eye position was monitored by a video-based eye tracking system (Eyelink-I, SensoMotoric Instruments). An adjustable chinrest helped to reduce head movements. At the base of the chinrest, between the pointing plane and the participant's trunk, two keys were placed to allow for the manual responses to the secondary discrimination task.

2.1.3. Stimuli and procedure

Fig. 2 shows the stimulus sequence in a typical trial. The screen contained a continuously visible fixation cross at its centre and a star-like configuration of three crossing elements. The three elements had differently coloured margins (red, blue and green). At the six endings of this configuration white mask elements that resembled digital '8's were shown; they appeared at an eccentricity of 7.2°. Their horizontal width was 0.90° of visual angle; their height was 1.40°. The visual presentation of the coloured star-like configuration corresponded to a real, 1 cm thick wooden object with similar shape and spatial extent that was mounted on the reaching plane. Therefore, whenever the participant reached for the visually presented configuration, he/she also obtained tactile information about the object. This helped to provide a more realistic interaction with the object, but without visual feedback about the finger positions during the reaching period. Also, the wooden object provided some tactile feedback about the accuracy of the reaches. The participants were required to fixate the central cross throughout the trial. At the beginning of each trial they positioned their left and right index fingers at the base of the chinrest. The distance between the hands' start positions and the reach goals was 24° of visual angle for the close goals, 31° for the goal positions on the



Fig. 2. Sequence of stimuli in Experiment 1. After a random delay a centrally presented coloured dot cued the ends of one of the coloured branches of the configuration as the movements goals of the next bimanual reaching movement. After a SOA of 50 ms the premask characters changed into a critical discrimination target (resembling digital '3' or 'E') and distractors (resembling digital '2' or '5'). After a presentation time of 100 ms, all symbols were masked. At the end of each trial, the participant indicated by button press which of the two discrimination targets had been presented.

horizontal (red) bar and 36° for the farthest goals (i.e., the upper ends of the tilted bars).

In each trial the participants had to perform a dual-task. The primary task was to perform bimanual reaching movements. The secondary task was designed to measure the deployment of visual attention and consisted in a letter discrimination task. Participants were asked to focus on the motor task, by encouraging them to react quickly and accurately. The perceptual task was stressed to a lesser extent, by explicitly informing the participants that they would quite often be unable to perceive the discrimination target.

After an initial delay of 600–1000 ms the central fixation cross was replaced by a small coloured dot (red, green or blue). The colour of the dot cued one of the three branches of the surrounding star configuration. Upon the appearance of this colour cue the participant had to perform a bimanual reaching movement to the mask elements at the endings of the cued branch.

With a SOA of 50 ms after cue onset five of the six mask elements changed into irrelevant distractors (resembling digital '2' and '5'), while one randomly chosen mask element switched into a discrimination target (DT), resembling either a digital 'E' or '3'. Distractors and discrimination target were presented for 100 ms and then changed back into mask elements, again resembling digital '8's. At the end of each trial the participant indicated, by pressing one of two buttons which of both discrimination targets had been presented. This non-speeded response was given via two response keys mounted at the base of the chinrest. The next trial started with a delay of 1600 ms after the key-press.

2.1.4. Design

Each participant performed an initial training block of 108 trials which was not included in the data analysis. After the initial training, the participants performed five experimental blocks, each consisting of 108 trials. The coloured cue indicated the ends of either of the three branches as movement goals. DT was randomly presented at one of the six mask element positions and could be either a digital 'E' or '3'. In total, this led to 36 different conditions (three possible movement goal configurations * 6 DT positions * 2 types of DT). Each condition was presented three times in an experimental block. The conditions were selected at random in each trial.

2.1.5. Data analysis

The positions of both index fingers were stored together with the eye movements during the sessions on a PC 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 points in time when the vectorial velocity reached a threshold of 10 mm/s (which is equivalent to about 1° /s). The beginning and end of the pointing movements were calculated as linear regressions in a 50 ms time window around these threshold points. The program also analysed the data from the eye-tracker and computed the spatial and temporal parameters of eventual saccades.

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 150 ms (equivalent to 50 ms SOA plus 100 ms presentation time), were excluded from further analysis. We also discarded trials where movement onset latency was above 600 ms, or where the program detected a saccade or a deviation from eye fixation that exceeded 2° . Trials in which the pointing goal of the left or right hand was missed by more than 3° or the movement was erroneously executed toward a non-cued pair of pointing goals were classified as pointing errors and were not analysed further.

The accuracy of the perceptual performance can be expressed by the percentage of correct decisions on the identity of DT; since there were two alternatives, chance level was at 50%. For the analysis of perceptual performance in relation to the movement task, we computed percent correct discrimination as a function of the position of the discrimination targets with respect to the movement targets (MT) in the particular trial (factor 'relative DT position'). Two conditions were of special interest: (1) DT was presented at one of both movement goals, or (2) DT appeared at any of the remaining character positions that were movement-irrelevant because they were not a movement goal in the particular trial.

Statistical analyses in this and the following experiments were performed with the 'R' statistical package (Ihaka & Gentleman, 1996) and included repeated-measure analyses of variance. Post hoc comparisons were done with *t*-tests. The results were Holm-corrected if multiple comparisons were performed on a single data set.

2.2. Results

2.2.1. Discarded trials

6% of all trials in this experiment were discarded because the movement latencies were too short (see Table 1). In these trials, the presentation of the discrimination target had not yet been masked by the time the reach was initialised. In another 4.5% of trials movement initialisation was delayed by more than 600 ms—these trials were excluded because movement latencies were too long. 1% of trials were discarded because saccadic eye movements or other significant deviations of central fixation occurred. Finally, in 9.0% of trials one movement goal was missed by more than 3° of visual angle. These trials were also excluded from further analysis.

2.2.2. Movement performance

Fig. 3a shows the endpoints of the bimanual reaches for all six participants, demonstrating that the pointing movements were performed quite accurately. The mean spatial distance between the instructed left target and the landing positions of the left hand was 0.78° ($SE = 0.03^{\circ}$). The accuracy of the right hand was slightly superior with a mean spatial error of 0.69° ($SE = 0.02^{\circ}$). Fig. 3b shows some exemplary trajectories of the bimanual reaches of one participant.

The bimanual reaches were initialised after 231 ms on average (see Table 1). Both hands moved in a coordinated

Table 1

Percentage of trials that were discarded due to various criteria in each of the four experiments

	Experiment 1	Experiment 2a	Experiment 2b	Experiment 3
Task				
Primary task	Bimanual reach	Bimanual reach	Bimanual reach	Unimanual reach
Secondary task	Singe letter discr.	Letter comparison	Letter comparison	Singe letter discr.
Discarded data				
Eye movements	1.0%	0.5%	1.8%	0%
Too short latency	3.3%	4.0%	2.1%	0.1%
Too long latency	0.3%	0.4%	0.5%	4.3%
Movement parameters				
Left/right hand				
Latency left hand (ms)	227 (11.9)	231 (15.8)	272 (22.1)	440 (23.9)
Latency right hand (ms)	236 (12.9)	250 (19.6)	280 (20.4)	444 (20.6)
Duration left hand (ms)	401 (9.2)	426 (13.4)	411 (10.4)	400 (13.5)
Duration right hand (ms)	393 (11.1)	413 (13.3)	405 (12.1)	396 (12.5)
Reach accuracy left (deg)	0.78 (0.03)	0.91 (0.07)	0.76 (0.02)	0.83 (0.02)
Reach accuracy right (deg)	0.69 (0.02)	0.66 (0.02)	0.92 (0.05)	0.62 (0.02)
Far/short reaches				
Latency far reaches (ms)	230 (11.3)	248 (18.8)	275 (20.8)	457 (32.4)
Latency interm. reaches (ms)	231 (12.1)	251 (19.4)	280 (21.2)	452 (35.3)
Latency short reaches (ms)	228 (11.4)	250 (19.9)	276 (20.7)	455 (30.5)
Duration far reaches (ms)	417 (14.3)	400 (19.9)	420 (9.7)	395 (11.6)
Duration interm. reaches (ms)	387 (12.5)	393 (22.1)	393 (10.6)	359 (12.8)
Duration short reaches (ms)	346 (11.4)	318 (12.2)	385 (10.2)	340 (9.2)

The lower part lists the observed latencies and durations of the left versus right hand as well as the respective movement accuracy (means and standard errors).



Fig. 3. (a) Final landing positions of the left and right index finger in bimanual reaching movements of Experiment 1. (b) Typical movement trajectories of a single participant. The colours (red, green and blue) indicate the trajectories that were executed towards the, respectively, coloured parts of the configuration. (c) The spatial variance of the reaching amplitudes as a function of the distance of the reach goals from the starting position. The dashed lines represent the values of the six participants; the solid line indicates the means across the participants. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fashion and were well synchronized in initialisation. There was no significant difference between the left and right hand in respect of movement latency, nor in movement durations (for an overview over the movement parameters see Table 1). In 2/3 of the trials, namely, when the blue or green branches of the configuration were cued, the movement goals for the left and right hand appeared at different distances from the starting position. For instance, if the green, right-tilted bar was cued the left hand had to reach shorter (24° of visual angle) than the right hand (36°). We analysed the movement latencies and durations for the subset of trials, in which the goal distances for both hands differed. Movement latencies did not significantly differ between reaches to distant versus close goals, with means of 228 ms (SE = 11.4 ms) and 230 ms (SE = 11.3 ms), respectively. However, an one-way ANOVA revealed a significant main effect of the reaching distance (levels 'far', 'intermediate' and 'near') on the duration of the movements, F(2, 10) = 4.48, p < .04. The reaches to distant goals took on average 70 ms longer than those to close-by goal locations (346 ms versus 417 ms, t(5) = -3.89, p < .012). The mean variances of the amplitudes of reaches to distant versus close goals were rather similar (1.07° for far reaches and .99 for short reaches, see Fig. 3c). An one-way ANOVA revealed no significant main effect of the reaching distance (levels 'far', 'intermediate', 'near') on the variance of the respective movement amplitudes, F(2, 10) = .98, p > .4.

Additionally, we wanted to assert that the presentation of the discrimination target at certain positions relative to the movement goals did not specifically interfere with the movement initialisations. Since the letter discrimination task is supposed to be a measurement of attention during the movement initialisation, the presentation of the discrimination target at a goal position should not prolong or shorten the latencies of the intended reach in comparison to reaches that were aimed at positions where no discrimination target was presented. An one-way ANOVA indeed showed no significant effect of the factor 'DT position' on the latency of the left or right hand (F(2, 10) = 2.23, p > .16 and F(2, 10) = .53, p > .60, respectively), nor on the duration of the movements of the left or right hand, F(2, 10) = .64, p > .54 and F(2, 10) = .86, p > .45.

2.2.3. Perceptual performance

The accuracy with which participants identified the discrimination target at any of the six mask positions served as the measure of the spatial allocation of attention before the onset of the bimanual reach towards two goals. Fig. 4 represents the discrimination performance as a function of the relative position of the discrimination target with respect to the movement targets. The discrimination performance was close to chance level if DT was presented at any position that was movement-irrelevant in that particular trial (condition 'other'), with a pooled performance level of 53% correct (SE = 3.7%). In contrast, perceptual discrimination was superior at the movement target locations of the bimanual reaches with 69% (SE = 5.3%) correct discriminations (68% at the right versus 70% at the left MT).

A one-way ANOVA showed a significant effect of the factor relative position of the discrimination target ('DTposition', with the levels 'DT at left MT', 'DT at right MT' and 'other') on the performance in the letter identification task, F(2,10) = 11.1, p < .002. Pairwise post hoc comparisons showed that performance at the movement goals were significantly better than at the movement-irrelevant locations, t(5) = 4.28, p < .007 and t(5) = 4.58, p < .005, for the left- and right-hand side, respectively. Perceptual discrimination performance was not significantly different at the left versus the right hand's goal, however, t(5) = 1.18, p > .28. Interestingly, discrimination performance was superior at the goals of the far reaches, i.e., at the upper ends of the blue (right-tilted) and the green (left-tilted) branches with on average 70% correct (SE = 5.2%), in comparison to performance at the closer reach goals at the lower ends of the two tilted bars, with 62% (SE = 5.6%) correct on average (t(5) = 2.02, p < .05, one-tailed). Performance values at the distant and the close reach goals were both significantly higher than at the taskirrelevant locations, t(5) = 4.03, p < .01 and t(5) = 3.08, p < .03, respectively.

2.3. Discussion

The results from this first experiment revealed significant benefits for perceptual processing at the movement goals of both the left and the right index finger, as compared to the discrimination performance at the locations that were movement-irrelevant in the particular trial, showing that the preparation of a bimanual reach movement leads to improved visual perception at both intended movement goals. However, an alternative explanation for this finding is that the participants may have attended to the left-hand side in some trials and to the right-hand side in other trials. By averaging across the individual trials this would lead to a similar pattern of aggregated results. Experiment 2 will address this caveat in more detail and test whether both movement goals are indeed attended simultaneously in each trial.

When both effectors were directed to goals with different distances from the starting point, the hand that had to reach for the more distant goal terminated about 70 ms later than the other hand. The observed movement durations for distant, intermediate and close goals were in accordance with Fitts' Law (Fitts, 1954; Fitts & Peterson, 1964), predicting longer movement times for more distant targets. The variances of the movement amplitudes were approximately constant for the different movement amplitudes (see Fig. 3c). This indicates that the participants tried to land within the cued mask element, which is more difficult to achieve for the more distant locations. In Fitts' law, the difficulty of a



Fig. 4. Discrimination performance in the letter discrimination task of Experiment 1. Data are presented as a function of the relative position of the discrimination target with respect to the cued movement goals. Vertical bars indicate standard errors.

movement is theorized to be a logarithmic function of the ratio of the target distance and its width (see Fitts, 1954; Fitts & Peterson, 1964). Thus, following Fitts' conceptualisation the distant goals in our paradigm have a higher '*index of difficulty*' than the close ones.

This may be related to the finding that during movement preparation the more distant goals were better attended than the close goals. The data suggest that the goal with the higher distance-to-width ratio (equivalent to a higher *index of difficulty*) is attended to a higher degree during the preparation period of a bimanual movement (see Section 5).

3. Experiment 2

The first experiment demonstrated that the movement goals of the right and left hand were both attended while preparing for a bimanual reach. This resulted in superior discrimination performance at each of these locations, as compared to the perceptual performance at the movement-irrelevant locations. The second experiment addressed whether attention was deployed to the reach targets in parallel or serially in time. In order to examine this question, we used a same-different matching task. This task required participants to compare two discrimination targets appearing briefly at different locations with each other. Since the short presentation time precluded serial attention shifts, the participants could successfully compare the target letters only if they were able to attend simultaneously to both locations. In accordance with others (e.g., Logan, 2005) we assume that a presentation interval of 100 ms is too short for participants to shift their focus of attention between the two positions (for a similar approach see Hahn & Kramer, 1998; Kramer & Hahn, 1995).

In a second version of this experiment (Experiment 2b) we used a numeric cue instead of a colour cue in order to assure that the visual facilitation found is a consequence of the movement preparation, rather than caused by the specific cue characteristics.

3.1. Methods

3.1.1. Participants, stimuli, and procedure

The same six students as in Experiment 1 participated. The procedure and the stimuli used were similar to the previous experiment except for the secondary task (see Fig. 5). In Experiment 2a, the participants again performed bimanual reaches to the mask elements at the ends of the branch instructed by the colour cue. As secondary task participants now had to perform a letter comparison (match-mismatch) task. For this purpose *two* discrimination targets were shown simultaneously for 100 ms, replacing the two mask elements at the ends of one of the three coloured

branches. During the presentation of the discrimination stimuli, the other elements switched into distractors ('2's and '5's), as in the previous experiment. Discrimination targets and distractors were then masked by digital '8's. The particular branch on which the two discrimination targets appeared was chosen randomly. After performing the movement, participants indicated, by pressing one of two buttons, whether the two discrimination targets had been the same or different.

Experiment 2b was aimed at controlling for possible effects of the type of cue on selective attention. This experiment was similar to Experiment 2a except for the way the movement targets were cued. In this experiment, the star-



Fig. 5. (a) Sequence of stimuli in Experiment 2a. The secondary task was a letter comparison task (match/mismatch-task). After a SOA of 50 ms two discrimination targets (each of them resembling either a digital '3' or 'E') were presented simultaneously for 100 ms only. (b) Sequence of stimuli in the Experiment 2b. Movement goals were cued by a central roman numeral.

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like configuration was defined by a white outline instead of a multi-coloured contour. In order to define two mask elements on a particular branch as reach goals, a roman numeral ('I', 'II', or 'III') was presented at the central fixation point. If a roman 'I' was presented the participants were instructed to reach with both hands to the mask elements at the endings of the branch that was tilted to the right (i.e., the right upper and left lower mask element). In case of a roman 'II' they were instructed to reach to the ends of the horizontal bar. If a roman 'III' appeared they had to reach to the mask elements at the ends of the left-tilted bar, i.e., to the left upper and the right lower mask element. Participants were instructed to reach as fast as possible after presentation of the central numeral.

3.1.2. Design

Each participant performed four experimental blocks of Experiment 2a and four blocks of Experiment 2b, in an order balanced across the participants. Each block consisted of 108 trials. The central cue (colour or numeric, respectively) indicated the ends of one of the three branches as goal positions. The discrimination targets 'E' and '3' appeared with equal probability. In half of the trials the discrimination targets were identical, in the other half of the trials they were different. Altogether, this led to 36 different conditions (3 MT positions \times 3 DT arrangements \times 2 types of $DT \times 2$ types of DT equity); these conditions were presented in randomised order. The central movement cue had no predictive validity for the presentation location of the discrimination targets. Now, two experimental conditions were of special interest in the data analysis, indicating the location of the discrimination targets relative to the movement goal positions: The discrimination targets could either appear at the two positions that were cued as movement goals (condition 'DTs at MTs') or at two positions that were not movement goals in the particular trial (condition 'other').

3.2. Results

3.2.1. Movement performance

In Experiment 2a, 4.9% of trials had to be excluded from further analysis due to insufficient movement performance; 4.3% had to be excluded in Experiment 2b (for details see Table 1). In Experiment 2a, the mean spatial distance between the final landing position and the centre of the instructed movement targets was 0.83° (mean across both hands). Average latency of movement initialisation was 231 ms (SE = 15.8 ms) for the left hand and 250 ms (SE = 19.6 ms) for the right hand. The movement durations were similar to those observed in Experiment 1 (see Table 1). As can be seen from Table 1, the movement parameters in both versions of Experiment 2 (colour movement cue in Experiment 2a and numeric movement cue in Experiment 2b) were rather similar. On average the latencies were slightly prolonged in the version using the numeric cue (Experiment 2b). Movement latencies and durations in both versions of Experiment 2 were again analysed as a function of the position of the discrimination targets relative to the movement targets in order to assert that the movement performance was not affected by where the DTs were presented. Two-way ANOVAs with the factors Experiment ('Experiment 2a' versus 'Experiment 2b') and DT position ('DT at a movement goal' versus 'DT at other position') were computed for the movement latencies and durations separately. For the latencies, the ANOVA revealed a significant main effect of factor Experiment (F(1,5) = 16.7, p < .05), but no significant main effect of factor *DT* position (F(1, 5) = 0.0133, p > .9) and no significant interaction (F(1,5) = 0.25, p > .5). A second ANOVA revealed no significant main effect of Experiment (F(1,5) = 1.17, p > .3), and no effect of the factor *DT posi*tion (F(1,5) = 1.409, p > .25). Also the interaction of both factors was non-significant (F(1, 5) = 0.22, p > .6).

3.2.2. Perceptual performance

The solid bars in Fig. 6 present the discrimination performance for two different relative arrangements of both discrimination targets with respect to the movement goals. If the discrimination targets appeared at movement-irrelevant positions, i.e., at the ends of a branch that were not movement goals in that particular trial, the comparison of both target letters failed and the participants performed at chance level (51% correct). However, if the locus of discrimination target presentation coincided with the movement goals of the current trial, performance in the match-/mismatch comparison task improved to 63% correct comparisons. A *t*-test confirmed this difference to be significant, t(5) = 3.11, p < .027.

The striped bars of Fig. 6 represent the discrimination performance in Experiment 2b where a roman numeral cued the movement goals in each trial. Target letters that had been presented at both reach goals were compared successfully in 65% of trials. If the discrimination targets appeared at movement-irrelevant positions, performance in the comparison task was close to chance level with 52% correct discriminations. A *t*-test confirmed that the difference between these two conditions was significant, t(5) = 3.94, p < .011. Importantly, performance in both



Fig. 6. Perceptual performance in the letter comparison task of Experiment 2a (solid bars) and Experiment 2b (striped bars).

versions of Experiment 2 did not differ significantly. *T*-tests confirmed a non-significant difference between the performance in both versions of the experiment, for both the condition "*DTs at MTs*", t(5) = -0.30, p > .77, and the condition "*other*", t(5) = -0.45, p > .67.

3.3. Discussion

The results of the letter comparison task in Experiment 2 provide evidence for the assumption that the preparation for a bimanual reach involves a parallel distribution of spatial attention to both movement targets. This rules out the alternative hypothesis that attention shifts serially between the reach goals in order to select information about the two goals of the index fingers, and that attention may have been deployed randomly to either action-relevant target in Experiment 1. Experiment 2b was designed to ensure that the effects were not caused by the use of a specific type of cue. The results suggest that the better visual processing at both goal positions does not result from the fact that both are surrounded by the cued colour but from the movement preparation. The intention to reach to both positions with the right and left hand causes the selection-for-action of the intended points of contact - independently of how the reaches are instructed.

4. Experiment 3

In this final experiment participants were asked to perform unimanual reaches with either the left or the right hand. It is important to compare the distribution of attention during the preparation of bi- and unimanual reaches for at least two reasons. First, we wanted to exclude an alternative interpretation of the results obtained so far. It may be argued that attention is deployed to both locations not because both are the movement goals for the right and left fingers, but because these locations are perceptually grouped since they belong to the same object part, e.g., the horizontal bar (Duncan, 1984). Following this line of argument, the preparation for a reach to a single mask element-either the left or the right one-may have been sufficient to facilitate processing of the whole object part. Alternatively, only those goal locations may be selected that are relevant for the planned action. If this is true the preparation of unimanual reaches should result merely in unilateral facilitation.

A second aspect was to compare, within the same participants, the overall perceptual performance in the two different tasks. It is a widely accepted assumption that there is a constant capacity of visual resources, which are distributed by the mechanism of selective attention (see, e.g., Bundesen, 1990; Bundesen, Habekost, & Kyllingsbaeck, 2005). This implies that when two targets have to be selected in parallel (as for a bimanual reach), perceptual performance at each target location should be inferior to perceptual performance at the movement target when just one goal location is action-relevant (as for the unimanual reach).

4.1. Methods

4.1.1. Participants, stimuli and procedure

The same six students as in the previous experiments participated in this study. Stimuli and procedures were the same as in Experiment 1 except for the primary motor task. Simultaneously with the presentation of the colour cue that indicated one of the branches as action target, an acoustical cue indicated whether the participant had to reach with the left or the right hand. The goal for the left- or right-hand reach was defined as the ipsilateral mask element on the cued branch. If a high-frequency beep accompanied the colour cue, the participant had to reach with his/her left hand to the left-sided mask element of a particular branch. If a low-frequency beep was presented, the participant had to move his/her right hand to the respective mask element on the right-hand side of the branch. The participants were asked to perform the reaches as fast and as accurately as possible.

4.1.2. Design

Every participant performed four experimental blocks, each consisting of 144 trials. The coloured dot at the centre cued one of the three branches of the wooden cross. The acoustic signal could be either a high- or low-frequency beep specifying to use either the left or right hand. The discrimination target (DT) was randomly presented at one of the six mask element positions and could be either an 'E' or a '3'. In total, this led to 72 different conditions (3 movement goal configurations \times 2 possible effectors \times 6 DT positions \times 2 types of DT). Each condition was presented two times in an experimental block. The conditions were selected at random in each trial.

4.2. Results

4.2.1. Movement performance

Table 1 provides an overview of the proportions of trials that had been excluded due to various criteria. In general the latencies and durations as well as the accuracy of unimanual reaches were similar to the corresponding parameters of bimanual actions in Experiments 1 and 2.

4.2.2. Perceptual performance

Perceptual discrimination was analysed with respect to three relevant conditions: (1) the location of DT presentation coincided with the movement target ('DT at MT'), (2) DT was presented at the location opposite to MT, but on the same branch ('*opposite*'), and (3) DT was flashed at any other position that was not on the branch the participant reached for ('*other*'). Fig. 7 depicts the results of the perceptual task. As in the previous experiments discrimination performance was close to chance level if the discrimination stimulus was presented at a branch that was not relevant for the particular reach (condition '*other*', 53% correct, SE = 1.9%). However, when the target was shown at the reach goal (as defined by the combination of the cen-



Fig. 7. Discrimination performance in Experiment 3 (unimanual reaching) as a function of the relative position of the discrimination target with respect to the movement goal.

tral colour cue and the acoustic cue) discrimination performance improved to 75% correct (SE = 5.5%). Of specific interest in this experiment is the discrimination performance in those cases, in which the target letter had been presented on the cued branch but at the location opposite to the reach goal (condition '*opposite*'). The data reveal that discrimination performance in this condition was as poor as the performance at the movement-irrelevant locations on the non-cued branches, with 52% correct decisions (SE = 4.1%).

ANOVA showed a significant effect of the relative DT position on the performance in the letter identification task, F(2, 10) = 8.82, p < .01. Planned contrasts revealed that discrimination performance at the movement goal was significantly better than the pooled performance at other, non-cued locations, t(5) = 3.96, p < .011, and better than the performance at the opposite location of the cued branch, t(5) = 2.70, p < .04.

4.3. Discussion

The results of this last experiment have two important implications. First, they show that the attentional selection that occurs during the movement preparation period is spatially specific and limited to the movement-relevant locations. In the present paradigm the preparation for a single reach to only one end of a coloured bar did not lead to perceptual facilitation at the opposite end of the very same bar, demonstrating that attention did not spread across the whole object, or a particular part of the object. This is converging evidence that the processing advantages at multiple locations that we observed before the bimanual reaches of Experiments 1 and 2 were a consequence of the intention to simultaneously move two effectors to two distinct goal locations, but did not result from perceptual grouping by a common same-coloured surrounding or from object-based attention.

Second, perceptual performance in the last experiment may be quantitatively compared to the performance in Experiment 1. In Experiment 3, the preparation for a unimanual reach caused an improvement in discrimination performance at the goal location from 53% at movementirrelevant locations to 75% at the movement goal. A model that assumes a constant amount of resource would predict that this facilitation, which occurs before unimanual reaches, should be apportioned in case of preparation for bimanual movements and should therefore facilitate both goals in a significantly less efficient manner. In Experiment 1, however, the participants prepared for a bimanual reach resulting in a perceptual facilitation of 69% (SE = 5.3%) at the goal location of the right *as well as* the left-hand goal (compared to again 53% at non-goals). This may indicate that the total amount of attentional resources that are distributed over the visual field may not be constant across both tasks.

5. General discussion

5.1. Preparation of bimanual reaches involves allocation of attention to both goal locations

In this study we used a dual-task paradigm in order to probe the deployment of visual attention during the preparation of bimanual reaches directed to two goals. Experiments 1 and 2 showed that both goal locations were attended before the movements were executed. At both goal locations the discrimination of target letters was significantly better than the discrimination performance at positions that were not goals for a reach in that particular trial. This main result is in line with previous studies on the involvement of visual attention in action preparation. It agrees with the general idea of the 'premotor theory' of attention (Rizzolatti et al., 1994), which postulates that the programming of a movement causes attention to shift to the intended destination of the movement. Experimentally this has not only been shown for eye movements (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995) but more recently also for manual reaches. Deubel and colleagues (Deubel et al., 1998; Deubel & Schneider, 2004) for example investigated how visual attention is shifted to the intended target location of a single hand movement. These former studies suggested that only one target is selected at a given point in time. Our study adds an important perspective to this 'one-target-at-a-time' conception. It provides novel and strong evidence for the notion that attentional shifts precede not only simple, singular reaches to one single goal but also more complex actions that involve multiple movements with several effectors towards various goals. If several locations are intended goals of a complex action, attention splits and facilitates visual perception at each of the goals. This happens at an early stage of action planning while the action is still in preparation. We therefore conclude that attentional facilitation is not restricted to a single location but can be flexibly distributed according to the demands of the motor task.

This matches the results of a recent study where we (Baldauf et al., 2006) asked the participants to execute sequential pointing movements to several peripheral goal locations and measured with a secondary letter discrimination task how attention is distributed in the visual field during the preparation period. The results demonstrated that attention also splits among multiple locations if participants intended to reach to these locations in a rapid sequence of manual pointing movements. This suggests that the attentional system plans multiple steps ahead in time and is not restricted to facilitating only immediate goals.

5.2. Parallel selection of both reach goals

Experiment 2 used a secondary match-/mismatch task. Participants had to decide at the end of each trial whether the two discrimination targets that were presented briefly during movement preparation either at the reach goals or at reach-irrelevant positions had been the same or different. In order to correctly perform in this secondary task both stimulus locations had to be attended. The discrimination targets were presented for only 100 ms and pre- as well as post-masked. The question arises here as to whether this time interval would allow for a serial shift of attention between both targets. There is substantial evidence in the literature that it takes at least 150-200 ms to first encode a spatial cue, then attend to the cued location, identify a stimulus at this location and subsequently reallocate attention to a another location in order to identify a second object. Logan (2005) provided an estimation of the time required to encode a cue and then to shift attention to a peripheral location. He argued that encoding the cue requires about 70 ms and that the subsequent attention shift to the cued location may take another 90 ms (see also Eriksen & Yeh, 1985; Krose & Julesz, 1989; Madden, 1992). Ward, Duncan, and Shapiro (1996) estimated that even up to 500 ms may be needed to shift attention endogenously to two peripheral positions. Therefore, in accordance with previous investigators (see also, e.g., Hahn & Kramer, 1998; Kramer & Hahn, 1995), we believe that 100 ms presentation time is too short to allow for serial shifts of covert attention between both goal locations. Given this conjecture, our findings demonstrate that participants simultaneously pay attention to both reach goals before they start the movement.

Our Experiment 3 showed that attention does not spread throughout the whole object part if only one end is intended to be reached by an unimanual hand movement. This means that the selection of both goal positions as observed in Experiments 1 and 2 results from the intention so reach to both goals rather than from any kind of perceptual grouping. Thus, our results strongly suggest that the preparation for a bimanual action involves the parallel distribution of visual attention to both the goals of the left and the right hand.

5.3. Manual and attentional asymmetries

While there was no significant difference in movement initialisation times nor in movement durations between the left and the right effector, all four experiments revealed longer movement durations for reaches to more distant goals. This means that for the bimanual reaches the velocities of both hands were not rescaled such as to result in synchronized movement termination. In fact, the farther reaches end on average 60 ms later than the reaches to the close targets. Therefore, our data are in line with the predictions of Fitts' Law—stating that the movement to a more distant goal takes longer than the aiming for a closer target (given that both targets have the same size). The law is not violated in our data. Since the width of the goals was kept constant in our paradigm, the *difficulty* of the reaches varied as a function of the goal's distance (see Fitts Law, Fitts, 1954; Fitts & Peterson, 1964).

The finding of differing movement times contradicts some former studies reporting that in bimanual aiming movements of mixed difficulty the velocity of the reach with smaller difficulty (for example the reach with smaller amplitude) is rescaled in order to guarantee highly synchronized movement termination (see, e.g., Jackson, German, & Peacock, 2002; Jackson, Jackson, & Kritikos, 1999; Keele, 1986; Kelso, Putnam, & Goodman, 1983; Kelso et al., 1979b). Keele (1986) reported that the synchronization of both effectors occurs automatically even if the participants are not explicitly instructed to do so. Other studies investigating bimanual reach-to-grasp movements however did not find any evidence for movement synchronization (Castiello & Bennett, 1997; Castiello, Bennett, & Stelmach, 1997).

The perceptual data of Experiment 1 demonstrate that these manual asymmetries were accompanied by corresponding perceptual asymmetries *before* the movements started. The visual processing at both goal locations was significantly facilitated during the movement preparation, however with a strong bias to better identify target letters at the goal of the farther reach. This provides some evidence that movement difficulty as defined in Fitts' law may be reflected in the amount of attentional resources deployed to the movement targets. If one of the intended targets is farther away from the starting point, it is more difficult to accurately reach towards this goal (given the movement goals are equally sized, see Fitts, 1954); this goes in line with a better perceptual performance at this location. The target difficulty (which is a function of the ratio of a goal's distance and its width) not only predicts the time it takes to reach for a certain goal but may also be a determinant for the relative attentional weight that is deployed to the goals before the movement starts.

5.4. Independence of the type of cue

One critical argument against our interpretation of the data obtained in Experiments 1 and 2 may be that the observed facilitation in discrimination at the various goal locations does not result from the instruction as movement goals. Alternatively, the superior processing at these positions may be caused by the colour cue itself. The colour

cue that indicated the goal locations in Experiments 1, 2a and 3 might also have a cueing effect independently of the movement goal instruction, in the sense that it facilitates perception on the whole same-coloured branch of the configuration. Some studies have shown that human observers can selectively attend to stimulus colour under certain conditions (e.g., Moore & Egeth, 1998). In visual search for example the prior knowledge of the colour of the search target can improve response speed and/or response accuracy (Kapstein, Theeuwes, & Van der Heijden, 1995). Also during eye fixation attention can be distributed to parts of the visual field on the basis of common features (see, e.g., Lu & Itti, 2005; Melcher, Papathomas, & Vidnyanszky, 2005; Saenz, Buracas, & Boynton, 2002; Saenz, Buracas, & Boynton, 2003).

In order to rule out this alternative explanation we designed Experiment 2b which used a numeric cue to indicate the reach goals. It replicated the findings of Experiment 2a, suggesting that the intention to bimanually reach to the ends of a particular branch facilitates perception at the goal locations-independently of how the reaches are instructed. The view that the observed selective perception of movement-relevant parts of the scene is due to action strategies rather than common colour features of cue and targets is also supported in our last experiment in which participants performed unimanual reaches. Here the colour cue indicated one branch of the star-like configuration while an acoustic signal cued the effector to be used. The participants had to combine the colour and the acoustic cue in order to prepare the correct motor response. The data revealed that visual attention was then selectively deployed only to the reach goal of the respective effector (left or right side). If cueing in this last experiment had occurred by the common colour feature (as opposed to movement instruction), the colour cue would have been effective for *all* positions on the same-coloured branch, i.e., not only for the goal of the chosen effector but also for the location at the opposite ending of the same-coloured branch.

5.5. Bimanual actions involve more attentional capacities than unimanual actions

A common assumption in the literature it that attention allows for the selective allocation of a limited (see, e.g., Cavanagh, 2004; Kahneman, 1973; Posner, 1978) and possibly *constant* amount of visual resources (e.g., Bundesen, 1990; Bundesen et al., 2005). For example, Posner (1978) stated that the system's 'efficient utilization for the processing of a signal code will usually reduce the efficiency with which it can process any other signal code'. Whether attention is focused on just one single object or broadly distributed among several items—the sum of attentional weights assigned to the various objects in the scene is assumed to be a constant (e.g., Bundesen, 1990; Bundesen et al., 2005).

The results of several recent studies have questioned this widespread assumption. In one study, for instance, we

explored the attentional preparation of multiple goals before the execution of movement sequences (Baldauf et al., 2006). Here, a comparison of single- versus doubleversus triple-reaches showed that the more goals a motor sequence contained, the more resources were distributed before sequence initialisation. The attentional weight per goal stayed constant, whereas the overall amount of visual resources that were deployed in the visual scene increased with sequence length. Also a fMRI study by Chapman and colleagues (Chapman et al., 2002) found the BOLD activity in the posterior parietal cortex (PPC) is increased if multiple potential targets are presented simultaneously, compared to a condition with only a single target. The authors claimed that the PPC activity that is related to a selection-for-action process may increase under conditions where the motor planning is more demanding.

Results like these are incompatible with a model of constant visual resources. Instead, they speak in favour of an alternative model of attentional deployment in action control: planning of a goal-directed movement recruits a certain amount of visual resources to process the intended goal to such an extent as to grant a sufficiently successful execution of the motor response. Actions that involve multiple movement components or sub-movements (e.g., either sequentially guiding one effector to multiple locations or simultaneously guiding two effectors to two separate goals) flexibly recruit more visual resources and deploy these to the various targets. A possible interpretation of our findings is that the amount of attentional resources that are recruited depends on the specific task, such that they are used flexibly and economically to ensure the successful programming of the goal-directed movement(s).

Some results from the present study fit to this alternative view. When participants prepared for an unimanual reach to a single goal position (Experiment 3) the secondary letter discrimination was selectively facilitated at this single goal location, yielding a discrimination performance of 75% correct (as compared to 53% at the other, movement-irrelevant positions). The preparation of bimanual movements in Experiment 1 also lead to selective deployment of attention to movement-relevant parts of the visual field. Here, however, discrimination performance was facilitated at both target locations to a similar extent. This seems to indicate that the attentional resources that were deployed to prepare for a simple reach with one hand accreted when a bimanual action was required. So, there is no evidence in our data that attention is a limited and constant resource.

5.6. Conclusions

We explored the role of visual attention during the preparation of coordinated bimanual movements to two distinct goal locations. Our results demonstrate that well before the movements started both reach goals were attended in parallel. If both goals had different distances from the starting position more attention was deployed to the farther goal. In comparison to unimanual movements bimanual reaches seemed to recruit additional attentional resources. The results are in line with the view that complex movement preparation and selective attention are closely related.

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