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GRASP
Emergence of Cognitive Grasping through
Introspection, Emulation and Surprise

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Contents

Chapter 1

Executive summary

Deliverable D10 is part of WP1 – "Learning to Observe Human Grasping and Consequences of Grasping". According to the Technical Annexe, It presents the activities in the context of:

- [**Task 1.1**] Exploiting neuroscientific, cognitive psychology findings
- [**Task 2.1**] Definition of the initial ontology

The work in this deliverable relates to the following second year milestone:

- [**Milestone 4**] Analysis of action-specific visuo-spatial processing vocabulary of human actions/interactions for perception of task relations and affordances

Since the seminal studies by Jeannerod (1981) on primate grasping, a particular focus of many studies was on kinematic parameters such transport velocity, time and size of maximal grip aperture, and selected posture. However, normally grasping actions do not occur in isolation, but are part of a larger action sequence by which the actor aims at reaching one or several goals. Indeed, there has been surprisingly little research on how actors move and shape their hands depending on the type of action they intend to perform with the goal object, on whether other objects in the field also need consideration, and on whether the other hand is also somehow involved in the action plan.

Obviously, robotic benchmark tasks such as emptying a dishwasher are characterized by just these complex conditions: objects are grasped in the presence of obstacles, they are moved to other locations, and eventually new objects then have to be picked up. In the light of the envisaged goals of GRASP, according data on human strategies and behaviour in such tasks are urgently required. We therefore focused in the second work period various aspects of human grasping in more complex, though prototypical actions, in several lines of experiments:

1.1. **Effects of obstacles and intermediate goals on reach-to-grasp kinematics** (Attachment A). Simple reach-to-grasp movements are characterized by two largely independent though temporally coupled components: a transport and a hand shaping component. The question arises whether this simple rule also holds in more ecological situations when, e.g., trajectories have to be adjusted such as to consider obstacles or intermediate goals. We investigated this question in several experiments. First, participants were asked to produce trajectories with a varying degree of complexity. The results showed that performing a non-linear trajectory changed the pre-shaping profile such that the grip opening was delayed and the maximum grip aperture (MGA) decreased. In another task we introduced a second object in the workspace and asked participants to either move around this object or to touch it briefly while executing a grasping movement toward the target object. While movements around the intermediate object were executed holistically as characterized by a delayed but smooth grip pre-shaping, movements which involved touching the intermediate object resulted in a segmentation of the pre-shaping pattern. We conclude from these results that not the presence of an obstacle alone determines the sequencing of the movement primitives but that the nature of the sub-task associated with the object plays an important role. We then asked participants to pass over a certain via-position with varying accuracy. The more difficult the sub-task was, the more obvious was the segmentation effect observed in the grasp pre-shaping. The results suggest that the spatial attention which has to be paid to the via-position may cause the shift to sequential performance. This is in line with our findings from the first work period (Baldauf & Deubel, 2009, Baldauf & Deubel, in press).

1.2 **Kinematics of grasping when attention resources have to be shared with a secondary action** (Attachment B) Many grasping situations require a simultaneous coordination of several effectors. Bimanual movements for example can either be cooperative movements meaning that both hands are directed to one single object (e.g., opening a jam jar or folding a newspaper), or may consist of two separate movements which are directed to different objects at the same time (e.g., grasping the dishwasher door with the left and a dish with the right hand). Although these tasks can be naturally performed by humans in everyday life, it is still unknown the bimanual movements are planned, controlled and adjusted by the nervous system. We therefore investigated whether (a) two asynchronous movements can be programmed and executed in parallel and independently of each other resulting in a "standard grasp pre-shaping" of the grasping hand which is unaffected by the asynchronous pointing task, or (b) the movement tasks are sequentialized meaning that the kinematics of the grasping movement are affected by the transport movement of the left hand. The results show that movement control differed fundamentally depending on the fixation condition: If free viewing was allowed, participants tended to perform the task sequentially, as reflected in grasping kinematics by a delayed grip opening and a poor adaptation of the grip to the object properties for the duration of the pointing movement. In contrast, when central fixation was required both movements were performed fast and with no obvious interference. The results demonstrate that movement control is moderated by fixation strategies and respective attentional deployments. By default, humans prefer a sequential behaviour in which the eyes monitor what the hands are doing. However, when forced to fixate, they chose another strategy and do surprisingly well in performing both movements in parallel.

1.3 **Planning of sequential pick-and-place actions** (Attachment C). Obviously, complex actions such as emptying a dishwasher are composed of a series of more simple action primitives. It is still largely unknown from human psychology and neuroscience how precisely these movement primitives are combined in space and time to yield the fluent, smooth and effective behaviour of humans in such tasks. In order to provide prototypical behavioural data for GRASP, we studied grasping kinematics in a sequential pick-and-place task. Participants performed the following sequence: they grasped a cylinder; placed it into a target area; and subsequently grasped and displaced a target bar of a certain orientation. We specifically tested whether the orientation of the target bar, grasped in the last movement sequence, influenced the grip orientation adapted to grasp and place the cylinder in the preceding sequences. Strikingly, the results show that grip orientations chosen to grasp (and release) an object already in the early movement segments were affected by the orientation of the target object which had to be grasped in the very last movement segment. This indicates that the reach–to–grasp movements were not performed in isolation but that the whole action sequence was planned in advance in a holistic manner, taking into account the predicted hand orientation that would be adopted several steps in the future. Our findings emphasize the importance of predictive advance planning and show that this phenomenon extends also to action sequences involving multiple target objects and sub–tasks. The insertion of a difficult movement segment led to a disappearance of the action-context effect suggesting that the action sequence was then decomposed in independently planned and executed movement components. This is in line with our findings from the studies described in 1.1, suggesting that attentional resources are important determinants for the control of grasping.

1.4 **Relation of covert and overt attention in combined eye and hand movements** (Attachment D). Our previous findings have emphasized the role of visual attention in the planning of eye, reach and grasp movements (recently, we extended these findings by demonstrating a close coupling of hand movement preparation and somatosensory attention, see Attachment E). Normally, reach-to-grasp movements are accompanied or preceded by goal-directed eye movements. We therefore asked whether overt and covert attention can focus simultaneously at separate locations. Participants were asked to point and look to different locations while we measured the allocation of visual attention to the movement goals. Strikingly, we found strong evidence for a temporal and spatial independence of attention allocation to the eye and hand movement targets. When participants made simultaneous eye and hand movements to different locations, attention was allocated in parallel at both locations, with no cost arising from the need to plan two movements instead of one. Delaying the eye movement leads to the delay of attentional deployment to the corresponding target object, which indicates that attentional mechanisms for eye and hand may be even dynamically independent. Together, we demonstrate a parallel and independent allocation of attention before eye and hand movements and propose that the attentional mechanisms for those two systems are independent.

1.5 **Gaze direction in grasp preparation and execution** (Attachment F, G). Following our initial studies on gaze behaviour while grasping natural objects, performed in the last work period, we now focused on fixation behaviour while pinch-grasping simple, flat shapes, where both thumb and index finger are visible all through the grasp. Results suggest an interactive pattern of gaze attraction by thumb application point for circular but not for square two dimensional shapes. The interaction pattern is interpreted as an effect of grasp application area size, and a prominent role of the centre of mass of the to-be-grasped objects to attract attention.

1.6. **Grasping irregular shapes and natural objects with 2, 3, and 4 fingers.** In order to study grasping preparation and control in human subjects under different hand embodiments, we currently analyze grasping points and fixation behaviour for a variety of objects in an extensive series of experiments. Participants grasp abruptly appearing, known and unknown objects, either spontaneously with the full hand, or with two, three, or four fingers. The amount of friction is varied by the application of finger thimbles. Subjects also perform a psychophysical judgement of the centre of mass (CoM) of the objects. On some occasions, judgement of the CoM is mislead by attaching additional weights to the objects, eventually leading to a failed grasp and to "surprise". Several questions are addressed in these experiments: How do grip kinematics and grasping points on a given object depend on the number of fingers allowed for the grasp? Is grasp stability related to the appropriate (perceptual) judgement of the CoM or is there evidence for a dissociation? What happens if a grasp is unsuccessful due to a misjudged CoM (leading to "surprise")? And, finally, where do participants attend, and where do they look under all these conditions?

Appendix A

Attached Papers

[A] **Effect of altered transport paths and intermediate movement goals on human grasp kinematics**. C. Hesse, H. Deubel, *Experimental Brain Research,* 201, 93-109, 2010.

[B] **Bimanual movement control is mediated by fixation strategies**. C. Hesse, T. Nakagawa, H. Deubel, *Experimental Brain Research* (in press).

[C**] Advance planning in sequential pick-and-place tasks**. C. Hesse, H. Deubel, *Journal of Neurophysiology* (accepted for publication)

[D] **Parallel and independent allocation of attention to eye and hand movement targ**ets. D. Jonikaitis, H. Deubel, *Neuron* (submitted)

[E] **Action preparation enhances the processing of tactile tar**gets. G. Juravle, H. Deubel, *Experimental Brain Research*, 198, 301-311, 2009.

[F] **Gaze behaviour in grasping of natural objects**. T. Nakagawa, D. Baldauf, H. Deubel. *Journal of Vision* (submitted)

[G] **Gaze direction in pinch grasp preparation**. T. Nakagawa, D. Baldauf, H. Deubel (submitted).

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RESEARCH ARTICLE

Effects of altered transport paths and intermediate movement goals on human grasp kinematics

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Abstract It has been observed that grip opening is delayed when participants are asked to execute complex grasping movements, such as passing over an obstacle or a via-position (Haggard and Wing 1998; Alberts et al. 2002). This finding was proposed to indicate a shift toward sequential performance, meaning that complex movements are carried out in independent motor steps. In our experiments we investigated which aspects of a grasping task determine whether a movement is executed holistically or sequentially. Therefore, participants had to perform different types of curved movements in order to reach and grasp a target object. When only the complexity of the transport paths was varied, no indication of sequential movement execution was found. However, when participants additionally had to either stop at, or pass over a certain via-position the pre-shaping pattern changed considerably indicating a movement segmentation effect. This effect became stronger with increasing difficulty of the sub-task, suggesting that attentional factors are involved.

Keywords Grasping · Trajectory · Obstacle · Kinematics · Motor control · Attention

Introduction

Imagine you are sitting on a well-laid breakfast table and you want to reach out and pick up the sugar bowl. This apparently simple everyday task requires, besides many other processes, to program and execute a complex grasping movement, while at the same time selecting a trajectory which avoids collision with other objects on the table. In this paper we are interested in how such complex grasping movements are accomplished: are they executed holistically or is the movement segmented into several motor steps, and if so under which conditions does movement segmentation occur? But first we will summarize what is known so far about how grasping kinematics change in complex situations.

The basic assumption of the visuomotor channel theory is that grasping movements consist of two relatively independent components, namely the transport and the grasp components, which do not share any information (Jeannerod 1981, 1988). Contrary to the original predictions of this theory, it has repeatedly been shown that alterations of the transport path also result in changes of aperture formation, and vice versa (e.g., Paulignan et al. 1991a, b; Gentilucci et al. 1992; Castiello et al. 1998; Dubrowski et al. 2002). Moreover, the visuomotor channel theory was challenged by studies demonstrating that the grip component is not only influenced by the physical dimensions of an object but also varies with the dynamic aspects and the accuracy constraints of the movement (Wing et al. 1986; Zaal and Bootsma 1993; Bootsma et al. 1994; Wallace et al. 1990). All these findings suggest that the transport and the grasp components are more closely coupled than was originally assumed. Hence, in complex grasping situations, such as grasping a sugar bowl on a crowded table, kinematic changes can most probably be observed in both components.

However, in the example outlined above not only the properties of the object itself have to be considered to execute a successful grasp, but also additionally the configuration of other objects within the workspace must be

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taken into account. Many studies have examined the effect of the presence of non-targets on grasping kinematics (e.g., Jackson et al. 1995; Tipper et al. 1997; Tresilian 1998; Mon-Williams et al. 2001; Chapman and Goodale 2008). The results of these studies show relatively consistent effects on transport and grasp kinematics: when additional objects were placed near the target object, the movement slowed down, tended to veer away from the non-target, and the maximum grip aperture (MGA) was reduced. However, there are two different viewpoints regarding the interpretation of these effects. On the one hand it is argued that non-target objects represent distractors which attract attention, leading to interference effects on movement kinematics when programming and executing a movement to the selected target object (Tipper et al. 1997; Howard and Tipper 1997; Castiello 1996, 1998, 1999). Thus, the distractor object is assumed to evoke a competing response which has to be inhibited by attentional mechanisms. These inhibitory processes lead to changes in the transport path such that the hand veers away from non-targets (Tipper et al. 1997). On the other hand, it is argued that non-target objects represent potential obstacles rather than distractors (Tresilian 1998, 1999; Mon-Williams et al. 2001). According to this view, movements to the target object are planned and executed in such a manner that the probability of a possible collision is minimized. A question that these studies leave unanswered is, however, whether the observed effects on the grasp component (e.g., smaller MGA) result from the fact that distractor objects were physically present (and have to be attended and/or avoided), or whether these effects are simply due to the modifications in the transport component. In the latter case the decrease of MGA would be attributed to the fact that movements in the presence of obstacles are executed slower thereby reflecting a well-known relationship between the components of grasping (Wing et al. 1986; Smeets and Brenner 1999). The finding that the coupling between the grasp and the transport components persists in the presence of other objects in the workspace indicates in turn that these movements are planned and executed holistically.

The studies discussed above have in common that the non-target objects were always placed where they did not physically interfere with the movement path. There are only very few studies in which participants were instructed to move around or grasp above an obstacle placed within the movement path (Saling et al. 1998; Alberts et al. 2002). In these studies the effects on transport and grasp were more pronounced than those observed when the non-target objects were placed outside of the movement path. Besides that the trajectory had to be adjusted when the obstacle was placed inside the movement path, the deceleration phase of the movement was prolonged, the enclosure time of the grip increased, and the MGA was significantly reduced (Saling et al. 1998; Alberts et al. 2002). Additionally, Alberts et al. (2002) found that the typical smooth and monotonic grip opening pattern was disrupted when participants grasped over an obstacle. They suggested that in the presence of an obstacle the grasping movement separates into two parts: a transport phase in which the aperture is opened initially and then remains constant until the obstacle is passed, followed by a standard grasping movement. Thus, the requirement to reach over an obstacle seems to result in a segmentation of the grasping movement. Here the question arises whether the observed segmentation effect is due to the physical presence of the obstacle requiring an adjustment of the movement path, or whether avoiding the obstacle is treated as a sub-task which causes the splitting of the movement into two parts (reach the obstacle and pass it, then execute the grasp).

A similar segmentation effect in aperture pre-shaping was also observed in a study by Haggard and Wing (1998). In this study the path of the hand transport was changed by asking participants to move over a via-point marked on the table. Even though no distractors or obstacles were present in the workspace most of the grip pre-shaping occurred after the via-point was passed. Haggard and Wing (1998) also explained this pattern as a shift toward sequential performance. However, according to their interpretation, the segmentation was caused by the higher complexity of the task (since curved movements require the control of more variables). Alternatively, one could also assume that reaching the via-point constitutes a sub-task which binds attentional resources during movement execution.

In our study we wanted to differentiate between these two possible explanations and to look more closely at the conditions that determine movement segmentation. In particular, we wanted to investigate the effects of: (a) constraining the movement path (Experiment 1), (b) the need to consider additional objects in the working space (Experiment 2), and (c) doing a sub-task, that is attending a specific via-position during movement execution (Experiment 3). The overall aim of the study was thus to determine the factors which lead to the decomposition of a movement into sequential motor steps. Therefore, we asked participants in Experiment 1 to follow a specific trajectory shape which varied in the degree of curvature. If the reasoning of Haggard and Wing (1998) is correct then a higher curvature should lead to a stronger segmentation effect in the grasping movement. In the second experiment we introduced an "intermediate object" and asked participants to either move around this object or briefly touch it with the back of their hand while performing a grasping movement to the target object. We tested in this experiment whether the presence of an additional object in the working space and the task associated with this object (avoiding it during movement execution vs. incorporating it in the movement path) evokes movement segmentation. In the last experiment, participants had to move over a specific via-position with varying accuracy when executing a grasping movement. By changing the accuracy demands, we varied the attentional capacity necessary to do the sub-task, thereby simultaneously withdrawing attention from the actual grasping movement. In all experiments we used two different object sizes in order to check when in time the properties of the target object, i.e., its size is reflected in the grip. This provides us with an additional measure for the specificity of the pre-shaping in the different movement conditions.

Experiment 1

Methods

Participants

As much as 12 undergraduate and graduate students of the Ludwig-Maximilians-University Munich (6 men, 6 women; mean age = 24, SD = 2) participated in the experiment. They were paid 8€ per hour of participation. All participants were right-handed by self report, had normal or corrected-to-normal visual acuity, and were naive with respect to the purpose of the study.

Apparatus and stimuli

Participants sat comfortably on an adjustable chair within a well-lit room. A chin rest was used to maintain a constant head position throughout the experiment. A wooden board (72 × 50 cm) on the tabletop served as presentation surface for the stimuli. Two cylindrical objects made of wood were used as the target stimuli. Both objects had a circular base (diameter of the small object 2.5 cm, and diameter of the large object 5.5 cm) and a height of 5.5 cm. Objects were presented on two different positions marked with a pin upon which each object was affixed (depending on the conditions which are described below). Behind the board, at a viewing distance of 80 cm, a 22″ monitor was used to present the instructions before each grasping trial.

Trajectories of the grasping movements were recorded using a Polhemus Liberty electromagnetic motion tracking system at a sampling rate of 240 Hz. The Polhemus Liberty tracking system provides complete 6-degrees-of-freedom (position and orientation) information at a static accuracy of 0.8 mm RMS for the x, y, z position and 0.15° for sensor orientation. Polhemus sensors were attached to the nails of the thumb and the index finger of the right hand (using adhesive pastels: UHU-patafix, UHU GmbH, Bühl, Germany and medical tape). An additional sensor was attached to the back of the hand in order to measure the transport component of the movement (wrist marker). Prior to the experiment a calibration procedure was used to align the Cartesian coordinate system (x,y,z) of the Polhemus system such that the start position on the board corresponded with the point of origin (0,0,0). Also, the orientation signals of the sensors attached to index finger and thumb were calibrated to a standard orientation. By considering the individual thickness of index finger and thumb, the orientation information allowed us to calculate the grasp touch points of thumb and index finger relative to the sensors, for each sample recorded during the experiment.

Procedure

Participants began each trial with the index finger and thumb at the starting position (marked by a small wooden pin with a height of 1 cm and a diameter of 1 cm). Between all trials participants were asked to keep their eyes closed. This allowed the experimenters to place the target object on the table without it being seen by the participant. After the experimenters had placed the target object, they initiated the trial manually by pressing a key.

Participants wore headphones through which different tones (with a duration of 100 ms) were presented: the first tone signaled them to close their eyes so that the experimenter could prepare a new trial by placing the object. The second tone signaled the participants to open their eyes and to look at the monitor in front of them on which the instruction for the upcoming trial was presented for 2 s. Figure 1 depicts the different instructions which were presented before each trial specifying the shape of the trajectory which participants should produce. Participants were asked to reproduce a trajectory corresponding to this picture: straight, square, round, or complex. The third tone indicated the participants to begin the grasping movement, and also marked the time at which the instructions on the screen disappeared. In response to the third auditory signal, participants moved to grasp the cylinder, lifted it, and placed it roughly halfway between object and starting position on the table. Thereafter, they moved their hand back to the starting position. After 3 s, participants heard another tone which indicated the end of the trial, and they had to close their eyes again. Subsequently, the experimenter returned the cylinder and prepared the next trial. No instructions about the speed of initiation or the speed of the movement were given. When participants had to move straight the distance between starting position and object was about 30 cm. In all other conditions the distance was 20 cm in order to account for the longer movement path. This shorter movement distance was chosen because a test session performed by the first author revealed that the

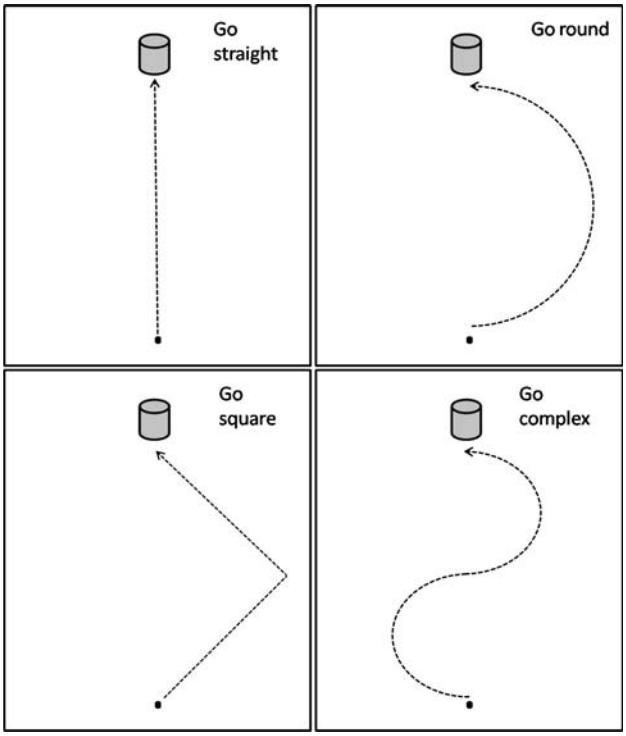

Fig. 1 Experiment 1: the different instructions which were presented to the participants before each grasping trial on the monitor in front of them. Participants were asked to perform a similar trajectory in order grasp the object

curved movements were approximately 10 cm longer than the straight movements.

In all conditions participants were allowed 3 s to execute the movement. If this time limit was exceeded, the trial was classified as an error and repeated later in the experiment at a random moment. Each trajectory was presented 20 times (10 trials per object size). All types of trials were presented in random order. Five practice trials were given before the experiment started (each movement condition appeared at least once) to familiarize the participants with the task.

Data processing

The finger trajectories were filtered off-line using a second-order Butterworth filter that employed a low-pass cut-off frequency of 15 Hz. Movement onset was defined by a velocity criterion. The first frame in which the wrist exceeded a velocity threshold of 0.1 m/s was taken as movement onset. Reaction time (RT) was defined as the time between the auditory signal and movement onset. The touch of the object was defined by a spatial criterion plus a velocity threshold, namely as the first frame after which the maximum distance in y-direction of the index finger from the start position was reached and in which the velocity of the wrist dropped below a threshold of 0.1 m/s. Movement time (MT) was defined as the time between movement onset and touch of the object. Additionally, we calculated the movement distance (MD) traveled by the wrist during MT by calculating the cumulative resultant trajectory lengths (in x, y, z) between two samples of the wrist sensor. Moreover, we determined for the different trajectory types (except for the straight condition) the point of reversal (RP) which was defined as the sample (derived from the wrist marker) with the maximum deviation in x-direction from the start-target axis.

The tangential velocity of the hand transport was determined by differentiating the position signal of the wrist marker at every 5% of movement duration. Movement trajectories were time-normalized and divided into 100 frames. The means and the standard deviations of the X and Y positions of all markers were quantified for each of the normalized frames.

Moreover, different parameters of the aperture profile (difference between index finger and thumb) were analyzed: we determined the size of the aperture at the RP of the trajectory, and the relative time to peak opening velocity (TPV) of the grip (early measures). The grip opening velocity was computed by differentiating the aperture profile. Furthermore, we computed the maximum grip aperture (MGA) as the maximum 3D distance between thumb and index finger during MT (late measure). The time to MGA was analyzed as relative time (time of MGA as percentage of MT). The aperture profile itself was time-normalized to the touch of the object and the size of the aperture was determined every 5% of MT.

Data were analyzed using repeated measures analysis of variance (4 × 2 ANOVA) with the factors movement path (straight, round, square, and complex) and object size (25 mm, 55 mm). If the sphericity assumption was violated and the factor had more than two levels we applied the Greenhouse–Geisser correction (Greenhouse and Geisser 1959) resulting in a more conservative testing. Post-hoc contrasts were carried out using Fisher's LSD (least significant difference) testing procedure. If not stated otherwise, a significance level of $\alpha = 0.05$ was used for the statistical analyses. Values are presented as mean ± standard errors of the mean.

Results

Hand transport

Participants were asked to perform movement paths which differed in their smoothness and complexity. Figure 2 shows the mean path of index finger and thumb for the various trajectory conditions averaged over all participants. Since trajectories and velocity profiles were similar for the two object sizes, we show the data for the small object size (Fig. 2b). As depicted in the figure more curved or angular

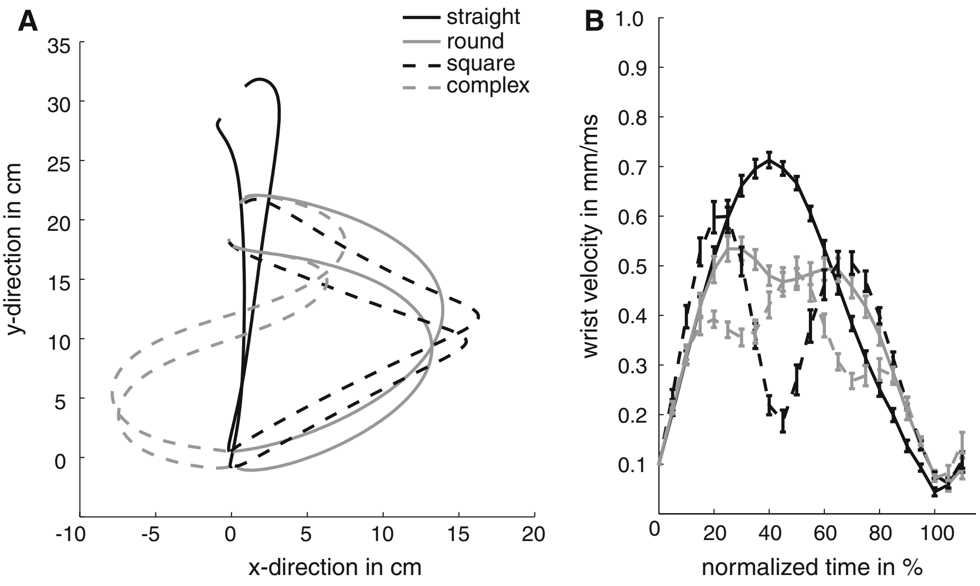

Fig. 2 Experiment 1: **a** Mean trajectories averaged over all participants in the different movement conditions when grasping the small object. **b** Corresponding wrist velocity profiles, time normalized, and averaged over all participants. In the straight condition we observed a single-peaked and bell-shaped profile. In the other conditions a local minimum in the velocity profile occurred at the moment of highest curvature. All error bars depict ±1 SEM (between subjects)

trajectories resulted in slower movements with a drop of velocity at the reversal points of the movement path (as also reported by Flash and Hogan 1985; Haggard and Wing, 1998). On average the reversal points were reached after approximately half of the total movement duration in the round and the square conditions (46% ± 0.6% and 44% ± 0.7%). In the complex conditions the first reversal point occurred after 31% ± 1.0% of MT, and the second after 69% ± 0.6% of total movement duration.

The statistical analysis of the main kinematic landmarks of the transport component revealed a significant effect of movement path on RT, $F(3,33) = 4.9$, $p = 0.008$; MT, $F(3,33) = 67.4$, $p < 0.001$; as well as MD, $F(3,33) = 7.7$, $p = 0.002$. The mean values for the dependent variables are given in Table 1. Post-hoc tests showed that: RT was significantly longer for the squared movement paths than for all other movement paths, MTs differed significantly between all conditions, and MDs were shortest in the straight conditions, of similar length in the round and square conditions and longest in the complex conditions. Although we could partly compensate for longer movement distances in the more complex conditions by placing the object closer to the start position, movement distances still varied for the different movement paths. A significant effect of object size was found only for MT, $F(1,11) = 7.9$, $p = 0.02$, revealing that movements toward the smaller object took longer. For all other dependent variables (RT and MD) the effect of object size was not significant ($p > 0.15$). No significant interactions occurred (all $p > 0.17$).

Hand aperture

Our main interest was in the effect of movement path (curvature) on movement segmentation, which we expected to find in the grasp pre-shaping. Visual inspection of the normalized aperture profiles in Fig. 3a shows that in the straight movements the aperture started to open as soon as the movement began, it opened gradually until the maximum was reached and finally closed in order to match the object size. Furthermore, the aperture profiles differed relatively early in time depending on whether the small object or the large object was grasped. In the aperture profiles of the round conditions (Fig. 3b), the general shape of the aperture profiles seemed to have been preserved even though the profiles for the small and the large object started to separate later. In the square and the complex conditions (see Fig. 3c, d) the initial hand opening appeared to have been delayed with most of the hand opening occurring after the reversal point was passed.

Pre-shaping delay As discussed in the previous section the execution of curved movements came along with lower movement velocities which in turn affect the size of the resulting aperture (e.g., Wing et al. 1986). To quantify the hand opening delay independent of the absolute size of the aperture as well as of MT, we measured when in relative time about half of the total aperture increase (that is the aperture increase between movement onset and MGA) was reached. The 2 (object size) × 4 (movement path) repeated measures ANOVA applied to the data revealed a significant main effect of movement path, $F(3,33) = 20.4$, $p < 0.001$, and object size, $F(1,11) = 9.7$, $p = 0.01$. Post-hoc tests confirmed that 50% of the maximum hand opening was reached earliest in the straight conditions and latest in the square and complex conditions (see Table 1). Furthermore, the 50% of maximum hand opening was reached later in MT when the large object had to be grasped. There was also a significant interaction,

Table 1 Mean values (SE) of kinematic parameters of the reach-to-grasp movements in Experiment 1

Experiment 1	Transport			Grasp			
	RT (ms)	MT (ms)	MD (cm)	Half MGA (%MT)	TPV open (%MT)	MGA (cm)	MGA timing (%MT)
Main effect movement path							
Straight	353 (14)	721 (16)	31.2 (0.9)	41 (2)	30 (4)	7.2 (0.3)	75 (2)
Round	355 (19)	877 (19)	35.1 (1.7)	53 (3)	48 (4)	6.5 (0.2)	84 (2)
Square	379 (18)	967 (25)	36.4 (2.1)	60 (3)	46 (5)	6.1 (0.3)	88 (1)
Complex	335 (16)	1,154 (41)	38.0 (1.7)	59 (4)	57 (5)	6.5 (0.2)	88 (1)
Main effect object size							
Small object	352 (14)	942 (20)	35.1 (1.4)	51 (3)	41 (4)	5.5 (0.3)	81 (1)
Large object	358 (17)	918 (19)	35.4 (1.4)	56 (2)	50 (4)	7.7 (0.2)	86 (1)

Mean values and standard errors (in parenthesis) for the different movement parameters and experimental variations averaged over all participants

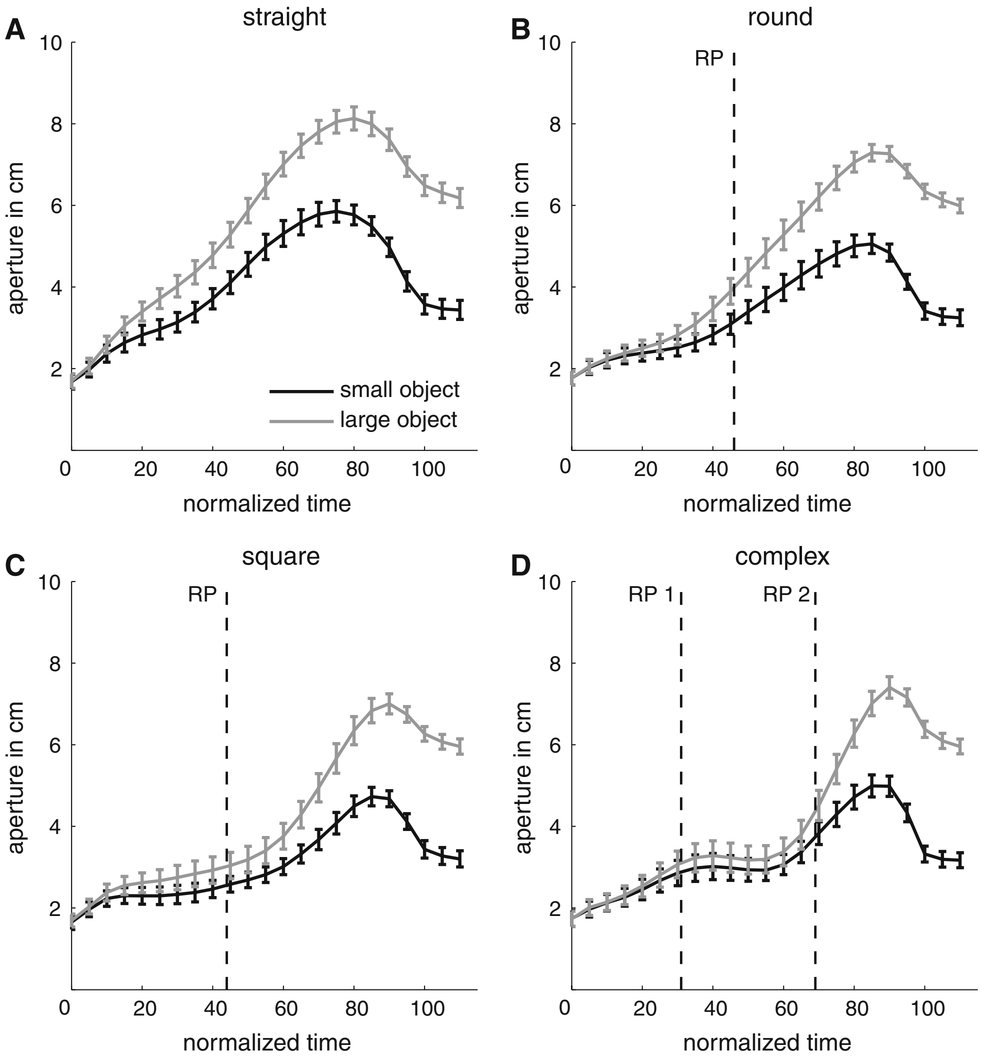

Fig. 3 Experiment 1: Time normalized aperture profiles averaged over all participants. In the straight and the round conditions we observed a gradual opening until MGA is reached. In the two other conditions this typical shape changes to a shallow slope in the first part followed by a steep slope after the reversal point is passed. The *dashed vertical lines* indicate the time of the mean occurrence of the reversal point in the trajectory (RP). All error bars depict ±1 SEM (between subjects)

$F(3,33) = 7.4$, $p = 0.001$, indicating that the effect of object size was stronger for the more complex movement paths. The occurrence of a delayed grip opening with increasing complexity of the movement path was further supported by the finding that the peak opening velocity of the grip occurred earlier in MT in the straight conditions than in all other conditions, $F(3,33) = 15.6$, $p < 0.001$. The relative timing of the peak grip opening velocity was also influenced by object size such that it occurred later for larger objects, $F(1,11) = 12.4$, $p = 0.005$ (all mean values are given in Table 1).

Integration of object size So far we confirmed that the slope of the aperture opening was shallower when participants were asked to execute a curved movement. Additionally, we hypothesized that the differences between the hand opening for the small and the hand opening for the large object might be diminished in these conditions. To check whether the size of the object was already represented in the first part of the movement, we calculated the size of the aperture at the reversal points of the different movement paths for the small and the large object, respectively. The movement paths had to be tested separately since they differed in the number of RPs. We applied a *t*-test on these data and adjusted the *p* values using Bonferroni correction. It turned out that in the round and in the square conditions the aperture size was significantly affected by the object size at the reversal point ($t(11) = 6.0$, $p < 0.001$, and $t(11) = 4.6$, $p = 0.003$). In the complex condition the aperture size for the small and the large object did not differ at the first reversal point ($p = 0.17$). At the second reversal point, however, the difference in aperture size between the large and the small object was also significant ($t(11) = 7.3$, $p < 0.001$). This finding shows that the properties of the target object were taken into account while executing early movement sequences.

MGA: size and timing Finally, we analyzed another important parameter which characterizes the aperture profile: the MGA. This parameter can be regarded as a late component of the movement since it always occurred after all reversal points were passed. A 2 (object size) × 4 (movement path) repeated measures ANOVA revealed, as expected, a significant main effect of object size, $F(1,11) = 937.7$, $p < 0.001$, and also a significant effect of the movement path, $F(3,33) = 25.5$, $p < 0.001$. Post-hoc tests showed that MGA was significantly larger in the straight conditions compared to all other conditions and, as expected, larger for larger objects (mean values are given in Table 1). There was no interaction ($p = 0.30$). Additionally, we calculated the relative timing of MGA. Again, we found a significant main effect of object size, $F(1,11) = 49.5$, $p < 0.001$, confirming the finding that MGA occurs later in time for larger objects (e.g., Marteniuk et al. 1990). Moreover, the relative timing of MGA was also significantly affected by the movement path, $F(3,33) = 54.1$, $p < 0.001$. Post-hoc tests revealed that the MGA occurred earliest during MT in the straight conditions, a bit later in the round conditions, and latest in the square and complex conditions (see Table 1). These findings indicate that the size and timing of the MGA were related to the temporal features of the transport.

Discussion

In this experiment we investigated whether segmentation of a grasping movement occurs when the complexity of the movement path increases. We found that when the movement path from the start position to the object was curved, the pre-shaping pattern of the hand was altered such that the initial hand opening was delayed. Overall, our main findings parallel the results reported by Haggard and Wing (1998). In their study participants were asked to pass over a via-position marked on the working surface resulting in curved movement trajectories. Haggard and Wing (1998) proposed that the higher complexity of the task might have caused a shift toward sequential performance (a pointing movement until the via-position is reached followed by a grasping movement). However, since they also observed "some degree of hand opening" occurring prior to the via-position they concluded that the task was not segmented into two completely independent movement parts. Our study was designed to provide a deeper insight into this matter. By using two different object sizes we were able to check whether the size of the target object was already reflected in the grip after the first movement segment was completed. Alternatively, one could assume that during the first movement part the hand is opened to some "standard-size" without actually incorporating the size of the object to grasp (which would be expected if the movement segments are executed sequentially). Our findings show that the object size is taken into account in the movement parts which are not directly target oriented (i.e., at the reversal points of the trajectory), arguing against a transition to sequential performance.

Moreover, we found that the MGA was smaller when the trajectory became more complex. A similar decrease in MGA was also reported when participants had to reach over an obstacle during grasping (Saling et al. 1998; Alberts et al. 2002). Saling et al. (1998) argued that a longer movement duration may allow for a more careful grip adjustment resulting in a smaller MGA. Additionally, we showed that changes in the trajectory shape led to slower movements which are also known to cause a reduced MGA (e.g., Wing et al. 1986). So the observed decrease in MGA might be due to a combination of both factors: a longer movement path and a slower approach to the target object. The fact that the altered hand transport phase is used by the motor system to set a more accurate aperture gives additional evidence that the movement is not segmented into independent parts.

As discussed above, the effects of changing the shape of the movement path were similar to the effects reported when participants had to adjust their trajectory in order to pass over a specific via-position or an obstacle successfully (Saling et al. 1998; Alberts et al. 2002; Haggard and Wing 1998). However, so far our findings provide no evidence that movement sequencing occurs only due to the fact that the complexity of the trajectory increases (as proposed by Haggard and Wing 1998). In the introduction we hypothesized that movement segmentation might also ensue from the presence of additional objects in the working space which are considered as intermediate goals. According to this hypothesis participants would split their movements (a priori) into two separate parts: (a) reach the intermediate object and pass it, and (b) grasp the target object. Thus, we wanted to test in Experiment 2 whether the introduction of an intermediate object would cause a shift toward sequential performance. Therefore, we asked participants to move around an intermediate object (obstacle) or to briefly touch the intermediate object with the back of their hand when executing the grasping movement.

Experiment 2

Methods

Participants

As much as 10 undergraduate and graduate students of the Ludwig-Maximilians-University Munich (3 men, 7 women; mean age = 26, SD = 4) participated in the experiment. They were paid 8€ per hour of participation. All participants were right-handed by self report, had normal or corrected-to-normal visual acuity, and were naive with respect to the purpose of the study. The data of one female participant had to be excluded from data analysis since one of the markers became loose during the experiment.

Stimuli and procedure

The general procedure of the experiment was similar to Experiment 1. The same target objects were used and the apparatus to measure the grasping movements remained identical. As in Experiment 1, participants heard three tones: after the first tone they closed their eyes and the experimenter placed the object, the second tone signaled the participants to open their eyes, after a preview period of 1 s the third tone signaled them to start their movement, and after another 3 s the first tone again indicated that the trial was over and that they should close their eyes again.

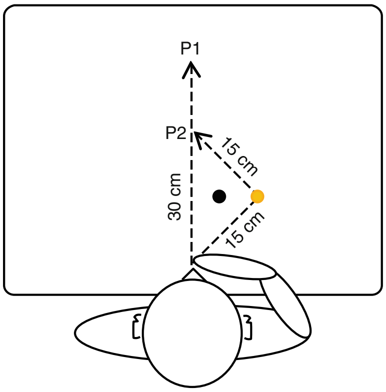

Fig. 4 Top-view of the setup used in Experiment 2. In the "straight" condition the target object was placed 30 cm away from the start position (P1). In the "touch" condition and in the "obstacle" condition the target object was placed closer to the participant (P2). In the "touch" condition an object placed at the position indicated by the *gray circle* had to be touched with the back of the hand. In the "obstacle" condition participants were asked to move around an object which was placed at the position of the *filled black circle*. Further information is given in the text

In this experiment, we used an additional object placed at two different positions depending on the condition (see Fig. 4). There were three different movement conditions: in the "straight condition" participants were asked to perform a normal grasping movement to an object that was placed 30 cm straight ahead from the starting position. In the "touch condition" an obstruction, a cylinder with a height of 5.5 cm and a diameter of 1 cm, was placed to the right side of the movement path (see Fig. 4) so that both the movement distances from the start position to this object and from this position to the target object were 15 cm. In this condition, participants were asked to grasp the target object and to briefly touch the intermediate object with the back of their hand when executing the movement. In the third condition participants were asked to treat the intermediate object as an obstacle and to move around it ("obstacle condition"). In order to keep the movement distance similar to the "touch condition", the intermediate object was placed 6 cm more to the left compared to the previous condition (see Fig. 4). This position was chosen because a test session performed by the first author revealed that this stimulus configuration resulted in similar movement distances for all conditions.

In addition to the different movement conditions we varied the start posture of the participants. This start posture could either require pinching their fingers together (closed-aperture conditions), or grasping them tightly sideways along a small disk with a diameter of 4 cm and a height of 2 cm which was attached centrally to the starting pin (open-aperture conditions). This variation informed us about the location of the adjustment that participants make to their aperture during the movement. More specifically, we were able to determine through this manipulation when in time participants adopted their aperture to properties of the target object independent of the starting aperture size. This should be the case after approximately 50% of movement duration (cf. Hesse and Deubel 2009). If a bias toward the start aperture size lasts longer, for instance until the obstacle is passed or the intermediate object is touched, it might provide further evidence for a segmentation of the movement.

No specific instructions were given about the pre-shaping of the hand. All six conditions ("straight-closed aperture", "straight-open aperture", "touch-closed aperture", "touch-open aperture", "obstacle-closed aperture", and "obstacle-open aperture") were presented in blocks of 20 trials (10 trial per target object size), resulting in a total number of 120 trials. The order of blocks and the order of trials within each block were randomized. The data were analyzed identically to Experiment 1. To test for the statistical significance of the experimental variations 3 (movement condition: straight, obstacle, and touch) × 2 (object size: 25 mm, 55 mm) × 2 (start aperture: closed, open) repeated measures ANOVAs were carried out.

Results

Hand transport

The statistical analysis of the main kinematic landmarks of the transport component (RT, MT, and MD) revealed a significant main effect of movement condition on MT, $F(2,16) = 143.6$, $p < 0.001$, and MD, $F(2,16) = 19.6$, $p < 0.001$. All other main effects and interactions were not significant, and RT was not affected by any of the experimental variations (all $p > 0.12$). The mean values of these dependent variables for the various experimental variations are presented in Table 2. The results show that although the distance traveled by the wrist was shortest in the touch conditions, these movements took longest (as confirmed by post-hoc comparisons). This can easily be explained by the fact that touching the intermediate object resulted in two relatively slow sub-movements with a drop in movement velocity at the moment the intermediate object was touched. In Fig. 5a the wrist velocity profiles are shown for the different conditions (and the small object size exemplary). Visual inspection reveals that the wrist velocity profiles in the touch conditions resembled the velocity profile obtained in the square conditions of Experiment 1, whereas the wrist velocity profiles in the obstacle conditions resembled the profiles of the round conditions of Experiment 1. The reversal point of the trajectory was reached after 44.5% ± 0.8% of MT in the touch condition, and after 45.0% ± 0.8% of MT in the obstacle conditions.

Hand aperture

Figure 5b shows the mean aperture profiles for all movement conditions, both object sizes and both aperture conditions. In the straight conditions we again found a smooth opening and closing of the aperture when the movement began with fingers pinched together. In the open-aperture conditions we observed that the fingers close initially and then reopened. This alteration of the aperture profile due to an open start aperture is in accordance with many previous findings (Saling et al. 1996; Timmann et al. 1996; Hesse and Deubel 2009). In the obstacle conditions the overall shapes of the aperture profiles looked similar to the straight conditions, whereas in the touch conditions the shape of the aperture profiles changed considerably. After an initial

Table 2 Mean values (SE) of kinematic parameters of the reach-to-grasp movements in Experiment 2

Experiment 2	Transport			Grasp			
	RT (ms)	MT (ms)	MD (cm)	Half MGA (%MT)	TPV open (%MT)	MGA (cm)	MGA timing (%MT)
Main effect movement path							
Straight	340 (21)	707 (18)	33.0 (1.1)	32 (3)	27 (5)	7.6 (0.3)	69 (3)
Obstacle	354 (23)	820 (19)	35.0 (0.8)	38 (3)	31 (5)	6.6 (0.3)	77 (3)
Touch	355 (17)	1,062 (20)	30.3 (1.3)	59 (6)	56 (8)	7.4 (0.2)	85 (1)
Main effect object size							
Small object	350 (20)	863 (15)	32.8 (1.0)	42 (4)	38 (5)	6.2 (0.3)	71 (3)
Large object	349 (20)	864 (14)	32.7 (1.0)	44 (4)	38 (6)	8.2 (0.2)	82 (2)
Main effect start aperture							
Closed aperture	342 (22)	861 (15)	33.0 (1.2)	–	–	7.2 (0.3)	81 (2)
Open aperture	357 (19)	866 (14)	32.6 (0.8)	–	–	7.2 (0.2)	73 (3)

Mean values and standard errors (in parenthesis) for the different movement parameters and experimental variations averaged over all participants. *Note*, mean values for the 50% grip opening of MGA and the TPV of the grip opening are only determined in the conditions which began with a closed start aperture because of the changed pre-shaping pattern in the open-aperture conditions (further details are given in the text)

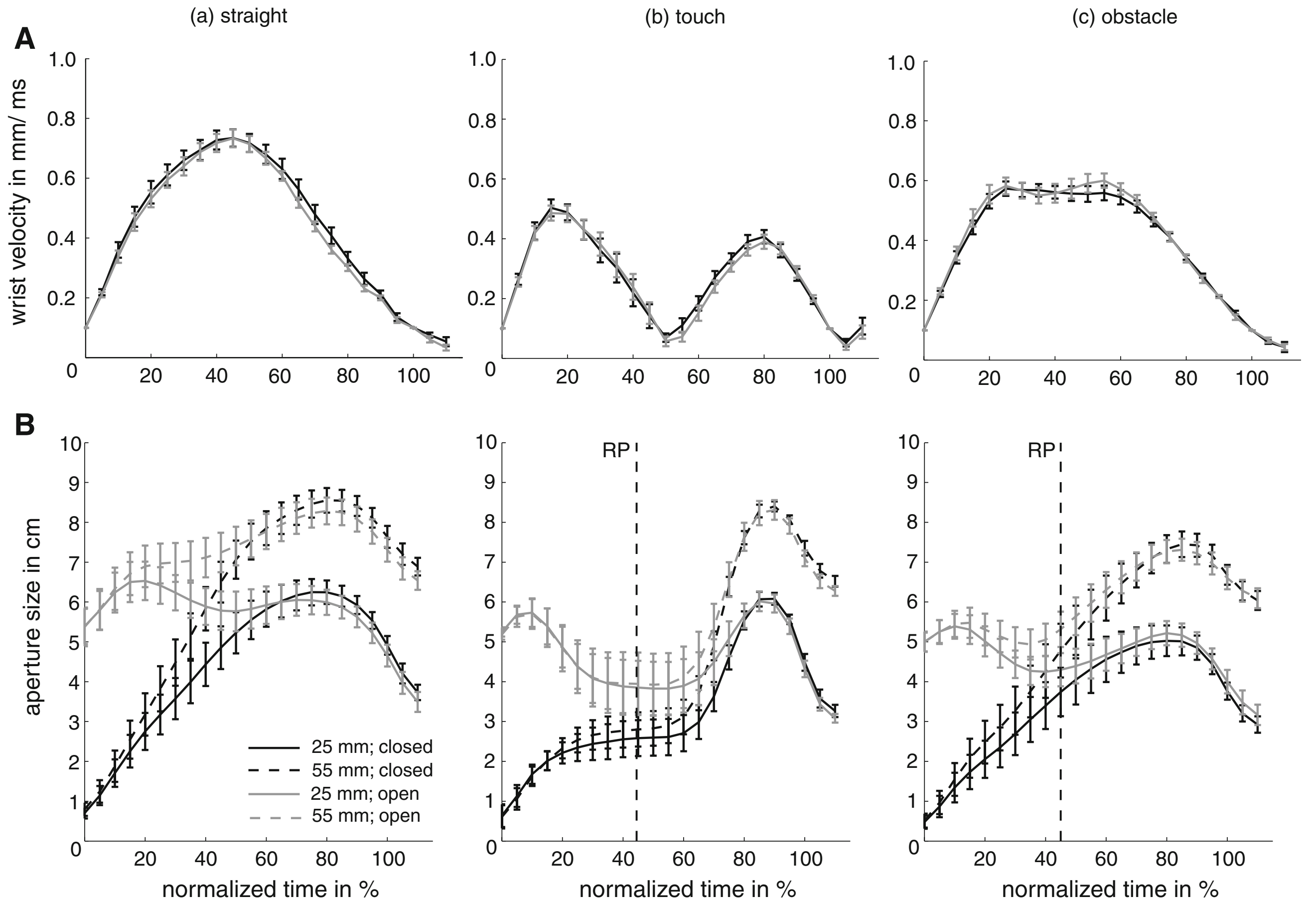

Fig. 5 Experiment 2: **a** Time normalized wrist velocity profiles for the small object size averaged over all participants: *a* straight movements, *b* movements with touch of the intermediate object, *c* movements around an obstacle. **b** Time normalized aperture profiles averaged over all participants for the different movement conditions. All error bars depict ±1 SEM (between subjects)

opening (closed start aperture) or closing (open aperture) the aperture seemed to stay at about the same level until the touch of the intermediate object was completed.

Pre-shaping delay To test these observations statistically we conducted several repeated measures ANOVAs. We determined when in MT half of the increase between start aperture and MGA was reached for the closed aperture conditions, just as in Experiment 1. Because of the changed pre-shaping pattern (the start aperture size corresponded already 50% of MGA) this analysis could not be applied to the open-aperture conditions. We then applied a 3 (movement condition) × 2 (object size) repeated measures ANOVA on the closed-aperture trials. The analysis revealed a significant effect of movement condition, $F(2,16) = 24.6$, $p < 0.001$. There was no effect of object size ($p = 0.18$) and no interaction ($p = 0.77$). Averaged values for the movement conditions are given in Table 2. As in Experiment 1, the aperture opening was delayed when the trajectory was curved (all movement conditions differed significantly from each other). The ANOVA on the relative timing of peak grip opening velocity (also only applied to the closed aperture conditions) also revealed a significant effect of movement condition, $F(2,16) = 17.4$, $p < 0.001$, indicating that the TPV of the grip opening occurred later in the touch conditions compared to the other two conditions (Table 2). There was no effect of object size ($p = 0.92$). and no interaction ($p = 0.18$).

Integration of object size As in Experiment 1, we determined the size of the aperture at the reversal point of the movement path in the obstacle and in the touch conditions by conducting two separate 2 (start aperture) × 2 (object size) repeated measures ANOVAS. In the obstacle conditions we found a significant effect of object size, $F(1,8) = 43.7, p < 0.001$, but no effect of the start aperture size ($p = 0.42$) on the size of the aperture at the reversal point. There was no interaction ($p = 0.68$). The result indicates that at the moment the obstacle was passed, the size of the target object was already reflected in the grip, whereas the start aperture size was compensated. In contrast, in the touch conditions the ANOVA revealed no effect of object size ($p = 0.18$) on the size of the aperture at the reversal point, but the effect of start aperture size was significant, $F(1,8) = 6.1$, $p = 0.04$. There was no interaction ($p = 0.30$). The data imply that when participants had to touch the intermediate object, the size of the target was not integrated in the grip during this first movement part, whereas participants kept a bias in direction to the start aperture size in the first part of the movement.

MGA: size and timing Finally, we determined the size of MGA and its timing as a late measure of the aperture profile. The 3 (movement condition) × 2 (object size) × 2 (start aperture) repeated measures ANOVA revealed a significant main effect of object size, $F(1,8) = 207.7$, $p < 0.001$, and movement condition, $F(2,16) = 9.7$, $p = 0.005$. As expected, MGA was larger for the larger object than for the smaller object (Table 2). More interesting was the effect of movement condition. Post-hoc tests indicated that the size of MGA did not differ between the straight and the touch conditions, but was significantly smaller in the obstacle conditions. Thus, the slower movement execution resulted in a smaller MGA in the obstacle conditions but not in the touch conditions. The size of MGA was unaffected by variations in the start aperture ($p = 0.81$), and there were no interactions (all $p > 0.06$). Regarding the timing of MGA we found significant main effects for all variations: movement condition, $F(2,16) = 19.4$, $p < 0.001$; start aperture, $F(1,8) = 8.9$, $p = 0.02$; and object size, $F(1,8) = 16.4$, $p = 0.004$. Furthermore, the interaction between movement condition and start aperture was significant, $F(2,16) = 5.8$, $p = 0.03$, indicating that the size of the start aperture affected the timing of MGA in the straight and in the obstacle, but not in the touch conditions. The MGA was reached earliest in the straight conditions and latest in the touch conditions (see Table 2). The other two main effects indicated that MGA was reached later when participants started the movement with a closed aperture and that it occurred later when the larger object was grasped.

Discussion

This experiment studied whether movement segmentation occurs in the presence of additional objects placed in the working space which have to be taken into account during movement execution. We varied the task associated with the intermediate object, and thus its relevance for the movement. In one condition the intermediate object had to be considered as an obstacle and participants had to move around it smoothly. In the other condition participants had to integrate the intermediate object in the movement by touching it briefly with the back of the hand while executing a grasping movement toward a target object. To determine in more detail whether the grip is adjusted to the properties of the target object during the first part of the movement (until the obstacle is reached, or the intermediate object is touched) we also varied the size of the start aperture of the hand (open vs. closed).

In the obstacle conditions participants performed a smooth movement around the obstacle with a continuous grip pre-shaping. Although we observed a delayed aperture opening in the closed aperture conditions, the size of the target object was reflected in the scaling of the aperture at the moment the obstacle was passed (similar to the round conditions in Experiment 1). Additional evidence that the grasping movements around an obstacle were executed holistically came from the finding that at the moment the obstacle was passed, participants had fully compensated for the size of the starting aperture. This parallels the findings for normal (straight) grasping movements for which it was shown that the size of the aperture becomes independent of the start aperture size after approximately half of the movement (see Hesse and Deubel 2009). Finally, the size of the MGA was smaller in the obstacle conditions compared to the straight conditions. Like in Experiment 1, this finding can be interpreted as reflecting the relationship between movement velocity and the size of MGA (for review see, Wing et al. 1986; Smeets and Brenner 1999) and therefore may provide another argument against the occurrence of movement segmentation during obstacle avoidance.

A completely different pattern of results was, however, obtained when participants were asked to touch the intermediate object mid-way to the target object. In these conditions the grip kinematics changed suggesting sequential movement execution: the moment the intermediate object was touched the aperture size was unaffected by the size of the target object, and was continually biased toward the size of the start aperture. This finding suggests that the properties of the target object were not taken into account by the motor system until the first task (touching the object) was accomplished. Furthermore, the size of the MGA was not reduced compared to the straight conditions, even though the movements in the touch conditions were much slower. The most likely reason why the size of MGA was not affected in the touch conditions is that in these conditions the actual grasping movement did not begin until the intermediate object was reached. Most of the pre-shaping was thus squeezed into the second movement part resulting in a very short movement distance and therefore much less time to adjust the MGA appropriately. This would also explain the late occurrence of the MGA in time. All these results indicate that the movements in the touch conditions were executed in two relatively independent phases.

In summary, the experiment shows that the presence of an additional object per se does not necessarily determine whether movement segmentation occurs or not. However, the nature of the sub-task associated with this object appears to play an important role. So far, there are two possible explanations for the occurrence of a segmentation effect in the touch conditions. First, in these conditions the movement almost ceases at the moment the intermediate object is touched. In a very recent study, Ansuini et al. (2009) investigated the effect of voluntary interruption of a composite motor sequence (grasping an object and pouring its contents into a container). They showed that when the motor fluency is prevented, the action sequence is no longer planned based on the end goal but is executed in discrete action steps executed independently of each other. From this result they concluded that the temporal contiguity between motor steps is essential to execute fluent action sequences. If we consider the same argument for our experiment, it is possible that the observed segmentation of the grasping movement is a result of the introduction of an intermediate break, thus disrupting the temporal structure of the movement. A counter argument against this interpretation, however, follows from Experiment 1 where movement segmentation was not observed in the square conditions which showed a similar drop of velocity at the reversal point of the trajectory. Thus, we would like to propose a second possible explanation of the observed results. Touching the intermediate object could possibly represent a secondary sub-task, the execution of which may require cognitive (i.e., attentional) resources. These resources are not available for the execution of the main task which is to grasp the target object. So there is an overload of the processing capacity necessary to perform both tasks at hand. If this is true, then a shift toward sequential performance would be expected when the sub-task becomes more demanding. We tested this prediction in a third experiment in which participants were asked to pass over a via-position with varying accuracy.

Experiment 3

Methods

Participants

As much as 13 undergraduate and graduate students of the Ludwig-Maximilians-University Munich (8 men, 5 women; mean age = 25, SD = 3) participated in the experiment. They were paid 8€ per hour of participation. All participants were right-handed by self report, had normal or corrected-to-normal visual acuity, and were naive with respect to the purpose of the study.

Stimuli and procedure

The general procedure of the experiment was similar to Experiments 1 and 2. The same target objects were used and the apparatus to measure the grasping movements remained identical. As in Experiment 1, participants started each movement with their fingers closed around a small wooden pin (closed aperture). Next to the wooden board which served as the working surface as in Experiments 1 and 2, we placed an additional device which was a fixture on which a laser pointer was mounted. The laser pointer was hanging 30 cm above the working surface and pointing to a position on the working surface which was 20 cm away from the starting position and to the right. The distance between the laser point and the target object was also 20 cm. Neither the fixture nor the laser pointer itself physically interfered with the movement path. The target object was placed approximately 28 cm away from the participant and sagitally to the participants' mid-line (see Fig. 6). Participants were again instructed to grasp the target object in response to the auditory signal. There were two different movement conditions: (1) sloppy: participants were instructed to choose their trajectory such that the laser point was shining "somewhere" on their hand when executing the movement, (2) accurate: participants were instructed to choose their trajectory such that the laser point was shining on a marker (diameter: 12 mm) which was attached to the back of the hand between the index and the thumb (it was ensured that the marker was attached such that the laser beam fell on it when a comfortable grasping movement was executed not requiring any unnatural rotation of the hand). The experimenter sitting next to the participant and placing the objects checked in each trial whether the laser point was shining on the hand or on the mark, whichever applied. If not, the trial was classified as error and repeated at a random position later during the experiment. Both movement conditions were presented in blocks of 20 trials (10 trials per target size) resulting in a total of 40 trials. The order of blocks was counterbalanced across participants and the sequence of presentation within each condition was randomized. The data were analyzed identically to Experiments 1 and 2. To test for the statistical significance of the experimental

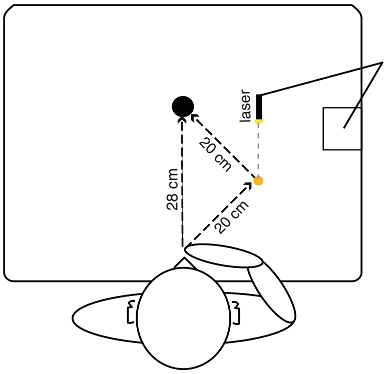

Fig. 6 Experiment 3: Schematic drawing of the setup. The laser pointer was hanging 30 cm above the working surface

variations 2 (movement condition: accurate, sloppy) × 2 (object size: 25 mm, 55 mm) repeated measures ANOVAs were carried out.

Results

Hand transport

The 2 × 2 repeated measures ANOVA applied on the kinematics parameters characterizing the transport component of the movement revealed significant effects only on MT. RT and MD were not affected by the experimental variations (mean values are given in Table 3). When an accurate movement was required, it took the participants significantly longer to execute the grasp, $F(1,12) = 167.7$, $p < 0.001$. The wrist velocity profiles shown in Fig. 7a confirm that accurate movements were much slower with a stronger drop in velocity at the via-position compared to the sloppy movements. There was also a significant effect of object size on MT, $F(1,12) = 21.5$, $p = 0.001$, showing that movements toward the smaller object took longer. The reversal point of the movement was reached at 46% ± 0.8% of MT in the sloppy conditions, and at 50% ± 2.3% of MT in the accurate conditions.

Hand aperture

In Fig. 7b the aperture profiles for the two different movement conditions and both object sizes are shown. In the sloppy conditions the "standard shape" of the aperture profiles seemed to be relatively preserved, whereas in the accurate conditions after an initial opening the aperture stayed of similar size for a fairly long time, followed by an abrupt increase in size after the via-position was passed.

Pre-shaping delay Again, we determined when half of the aperture increase occurred in MT between movement onset and MGA. The 2 (movement condition) × 2 (object size) repeated measures ANOVA applied on these data revealed a significant effect of movement condition, $F(1,12) = 26.9$, $p < 0.001$ (mean values are given in Table 3). There was no effect of object size and no interaction. The finding indicates that the aperture increase was more delayed in the accurate conditions compared to the sloppy conditions. This was also supported by the results obtained for the relative timing of peak opening velocity of the aperture. When participants had to move accurately the peak opening velocity occurred much later than when they could move sloppily, $F(1,12) = 19.7$, $p < 0.001$. Moreover, peak opening velocity was reached later when grasping a large object, $F(1,12) = 6.0$, $p = 0.03$; there was no interaction.

Integration of object size Regarding the size of the aperture at the reversal point the 2 (movement condition) × 2 (object size) repeated measures ANOVA revealed a significant interaction effect, $F(1,12) = 6.0$, $p = 0.03$, and no main effects ($p > 0.10$). Thus, the aperture size at the reversal point differed for large and small objects in the sloppy movement conditions (small: 4.5 ± 1.9 cm; large: 5.0 ± 1.9 cm) but not in the accurate movement conditions (small: 4.1 ± 2.0 cm; large: 4.1 ± 2.1 cm).

MGA: size and timing Finally, we also analyzed the size of MGA and its timing. As expected, the 2 (movement condition) × 2 (object size) repeated measures ANOVA revealed a significant main effect of object size, $F(1,12) = 117.0$, $p < 0.001$, again indicating that the MGA was larger for the large object (Table 3). There was no main effect of movement condition ($p = 0.09$) and no interaction ($p = 0.33$). Furthermore, there was a significant effect of object size on the timing of MGA, $F(1,12) = 50.9$, $p < 0.001$, indicating that MGA occurred later in MT when the larger object was grasped. The timing of MGA was also affected by the movement condition, $F(1,12) = 12.8$, $p = 0.004$. On average the MGA occurred later in the accurate movement conditions than in the

Table 3 Mean values (SE) of kinematic parameters of the reach-to-grasp movements in Experiment 3

Experiment 3	Transport RT (ms)	MT (ms)	MD (cm)	Grasp Half MGA (%MT)	TPV open (%MT)	MGA (cm)	MGA timing (%MT)
Main effect movement path							
Sloppy	351 (14)	974 (42)	37.3 (1.2)	49 (5)	39 (5)	7.4 (0.3)	84 (2)
Accurate	341 (13)	1392 (54)	37.0 (0.9)	57 (5)	52 (5)	7.1 (0.3)	89 (2)
Main effect object size							
Small object	337 (14)	1205 (46)	37.5 (1.1)	48 (4)	37 (5)	6.5 (0.3)	83 (2)
Large object	356 (16)	1161 (45)	36.8 (1.0)	58 (6)	53 (7)	8.1 (0.2)	90 (1)

Mean values and standard errors (in parenthesis) for the different movement parameters and experimental variations averaged over all participants

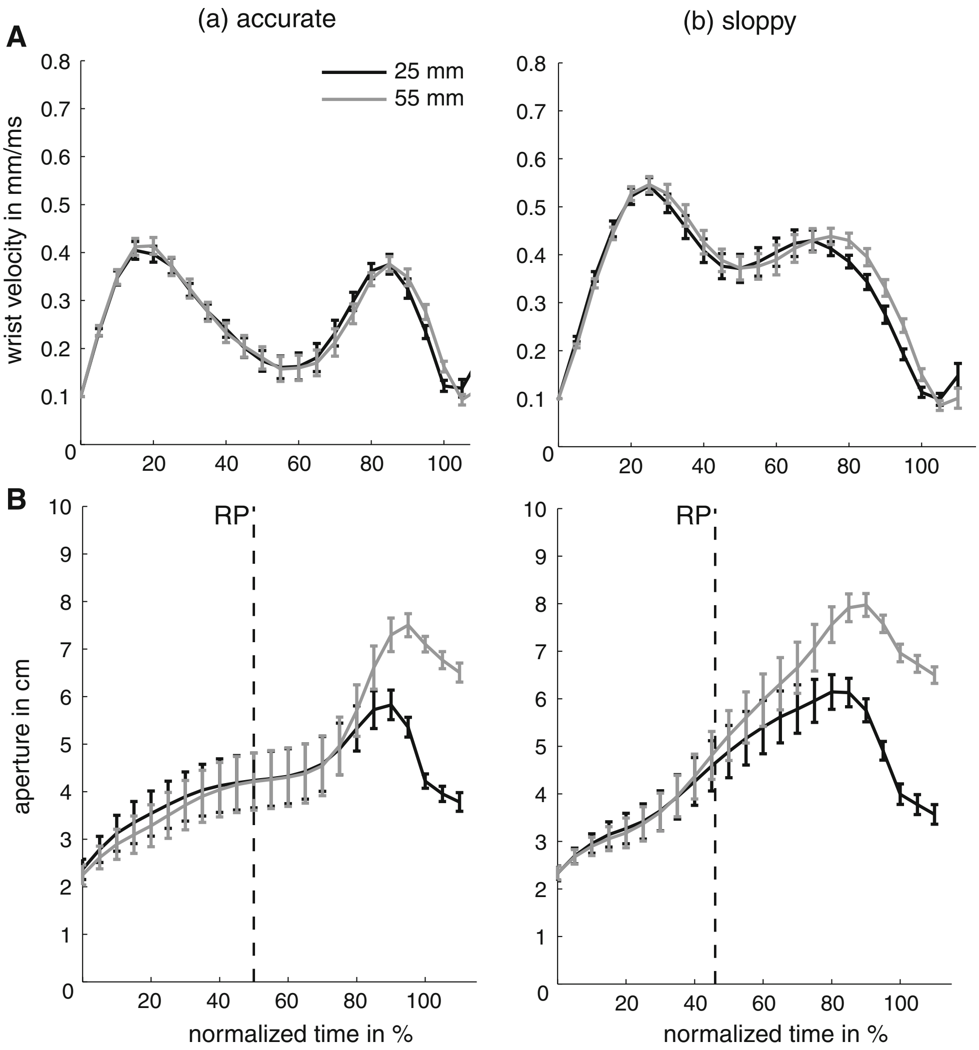

Fig. 7 Experiment 3: **a** Time normalized wrist velocity profiles averaged over all participants: *a* accurate movements, *b* sloppy movements. **b** Time normalized aperture profiles averaged over all participants. All error bars depict ±1 SEM (between subjects)

sloppy movement conditions. There was no interaction ($p = 0.32$).

Discussion

In this experiment we were interested in whether the segmentation of the grasping movement can be explained by the fact that a certain sub-task withdraws cognitive resources from the actual grasping task. We tested this hypothesis by letting participants pass over a via-position with varying accuracy. We expected that with higher accuracy the passing over would become more demanding, resulting in a stronger segmentation effect in the movement. Our results show that when a more accurate passing over of the via-position was required, the aperture opening was more delayed compared to the sloppy conditions. Moreover, the size of the target object was not reflected in the grip pre-shaping until the via-position was passed in the accurate conditions. In other words, the initial hand opening occurred without taking the size of the target object into account, and was followed by a phase with a relatively constant aperture size until the via-position was passed. The actual grasp and most of the pre-shaping occurred in the second movement part which resulted in a later occurrence of MGA in relative time. This finding is in support of a sequential scheduling process occurring when the perceptual motor task is getting more difficult.

The size of MGA was similar in both conditions and corresponded approximately to the size of MGA observed in the straight conditions of Experiment 1 and 2. Thus, the longer movement path and the reduced movement velocity did not result in a decrease of MGA as observed in the curved trajectories conditions of Experiment 1. This finding gives further evidence for a movement segmentation effect occurring when carrying out a cognitive demanding sub-task.

Overall, the design of our study was very similar to the one used by Haggard and Wing (1998). The authors argued in their study that the delayed hand opening observed when passing a via-position may reflect a shift toward sequential performance which is due to the higher computational demands put on the motor system for the execution of curved movements. Our study shows that it is not the degree of curvature of a movement that determines whether a shift toward sequential performance occurs: rather it is the difficulty associated with the sub-task that seems to be the crucial factor for movement segmentation.

General discussion

In this study we investigated the conditions under which segmentation of complex grasping movements occurs. Advancing from grasping studies which reported movement sequencing as a side effect (e.g., Haggard and Wing 1998; Alberts et al. 2002), we derived different hypotheses on when a shift toward sequential performance can be expected: (a) when the complexity of the trajectory increases, (b) when additional objects have to be considered during movement execution, and (c) when a (motoric) sub-task has to be executed. We tested these predictions in three experiments.

In the first experiment participants were asked to produce trajectories with a varying degree of curvature (complexity) which were presented in advance. The results showed that performing a non-linear trajectory changed the pre-shaping profile such that the grip opening was delayed and the MGA decreased. However, there are two reasons to assume that the grasping movements were planned and executed holistically in these conditions: first, we found that the aperture size varied with the size of the target object in the first movement segments (i.e., at the RP), indicating that although these movement parts were not yet directly target oriented, the motor system takes the properties of the target object into account. Second, the decrease in MGA with increasing movement distance indicated that the longer approach path was used by the motor system to calculate and adapt the MGA more precisely to the object size (see also Saling et al. 1998). Thus, although our study confirmed the observation of Haggard and Wing (1998) that the initial grip opening gets delayed in curved movements, we did not find evidence for their prediction that movement segmentation occurs due to the degree of curvature of the movement path. The crucial difference between our experiment and the experiment carried out by Haggard and Wing (1998) is, however, that they did not vary the curvature of the movement path independently of the need to attend a specific via-position in the work space during movement execution (which makes an important difference as discussed below).

Since Alberts et al. (2002) observed indication for sequential movement execution in a grasping task in which participants had to move over an obstacle, we tested in a second experiment whether the presence of an intermediate, movement relevant object causes movement segmentation. For this purpose, we introduced a second object in the workspace and asked participants to either move around this object or to touch it briefly while executing a grasping movement toward the target object (Experiment 2). While movements around the intermediate object were executed holistically as characterized by a delayed but smooth grip pre-shaping, movements which were interrupted due to touching the intermediate object resulted in a segmentation of the pre-shaping pattern: in the first part of the movement the grip was adjusted to some "standard size" which was maintained until the touch was completed. In the second part the actual grip pre-shaping was performed resulting in a very late and relatively large MGA. From these results we concluded that not the presence of an obstacle alone determined the sequencing of the movement but that the nature of the sub-task associated with the object played an important role.

To test this assumption further, in a third experiment we asked participants to pass over a certain via-position with varying accuracy. The more difficult the sub-task was, the more obvious was the segmentation effect observed in the grasp pre-shaping (accurate vs. sloppy conditions). This finding suggests that the spatial attention which has to be paid to the via-position may cause the shift to sequential performance. Indeed, it has been demonstrated that during the preparation of goal directed reaching movements visual attention must be allocated to the movement target, with only small processing capacity remaining for non-target objects (Deubel and Schneider 2004; Baldauf et al. 2006). This may prevent the early perceptual processing of the grasp target, such that the movement relevant spatial parameters of the to-be grasped object cannot be integrated into the early movement phase. The sequential performance manifests in a reaching movement with some standard aperture opening (possibly depending on the start aperture size) and a subsequent final pre-shaping which constitutes the actual grasp. Thus, segmentation effects in grasping are most likely due to the fact that by performing a sub-task attentional resources are withdrawn from the actual grasping task, resulting in sequential performance.

Besides, this reasoning is in agreement with the core assumption of the information processing theory by Broadbent (1982) stating that a transition to sequential performance occurs when the informational capacity of a single processor gets overloaded. Applying this theory to the computational processes required in motor control, one would predict that higher computational demands posed by certain sub-tasks lead to movement sequencing—as observed in our study. Thus, if more than one task is simultaneously assigned to an effector, the motor system seems to respond to the increased planning demands with a shift to sequential performance. This in turn indicates that the motor patterns which can be generated simultaneously (for one effector) may be very limited.

Our findings also have interesting implications for movement planning, and especially for the planning of movement sequences in the presence of a secondary task. As shown in an earlier study simple grasping movements to a single object are planned well in advance (Hesse et al. 2008), i.e., some of the appropriate movement kinematics (e.g., grip orientation) are already determined during the preview period of an object. From the results and the findings of the present study we would expect that introducing a secondary task requiring attentional resources would suppress this early end goal oriented planning process. For example, it has been shown that when executing an action sequence the movement kinematics of the first action part (e.g., grasping an object) are already influenced by the requirements of the second action part (placing vs. throwing the object) indicating that action sequences are planned and executed globally and end goal oriented (Marteniuk et al. 1987; Armbrüster and Spijkers 2006; Ansuini et al. 2008). Based on the findings of our study we would predict that this global planning process gets sequentialized (into concatenated but independently planned and executed motor components) if the first movement part captures excessive attentional resources. This could for instance be the case when the first movement part requires a very precise and therefore difficult movement.

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Bimanual movement control is moderated by fixation strategies

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Abstract

Our study examined the effects of performing a pointing movement with the left hand on the kinematics of a simultaneous grasping movement executed with the right hand. We were especially interested in the question of whether both movements can be controlled independently or whether interference effects occur. Since previous studies suggested that eye movements may play a crucial role in bimanual movement control, the effects of different fixation strategies were also studied. Human participants were either free to move their eyes (Experiment 1) or they had to fixate (Experiment 2) while doing the task. The results show that bimanual movement control differed fundamentally depending on the fixation condition: If free viewing was allowed, participants tended to perform the task sequentially, as reflected in grasping kinematics by a delayed grip opening and a poor adaptation of the grip to the object properties for the duration of the pointing movement. This behavior was accompanied by a serial fixation of the targets for the pointing and grasping movements. In contrast, when central fixation was required both movements were performed fast and with no obvious interference effects. The results support the notion that bimanual movement control is moderated by fixation strategies. By default, participants seem to prefer a sequential behavior in which the eyes monitor what the hands are doing. However, when forced to fixate, they do surprisingly well in performing both movements in parallel.

Introduction

Many grasping situations require the simultaneous coordination of the two hands. Such bimanual movements can either be cooperative movements meaning that both hands are directed to one single object (e.g., opening a jam jar or folding a newspaper), or may consist of two separate movements which are directed to different objects at the same time (e.g., grasping a coffee cup with the left hand and the computer mouse with the right). Although these tasks can be performed effortlessly in everyday life, it is still unknown how bimanual movements are planned, controlled and adjusted by the nervous system.

Most of the studies examining bimanual movements in humans have focused on the temporal coordination of the limbs during aiming tasks (e.g., Kelso, Southard, & Goodman, 1979b, 1979a; Kelso, Putnam, & Goodman, 1983; Keele, 1986). The main finding of these studies was that the reaction times and the movement times of both hands tend to synchronize independently of the corresponding movement amplitudes (Kelso et al., 1979b, 1979a). Other studies challenged these findings by reporting timing asynchronies when the movement distances and task requirements between both hands were varied (e.g., Marteniuk, MacKenzie, & Baba, 1984; Corcos, 1984; Fowler, Duck, Mosher, & Mathieson, 1991). That is, movement times became longer for the hand which had to reach to the more distant or more difficult target. Up to now the bases for these contradictory results remain ambiguous. Almost 20 years ago, Fowler et al. (1991) had already suggested that some of the inconsistent findings in bimanual aiming might be due to differences in fixation strategies. Nevertheless, most studies on bimanual movement control neglected the role of visual information.

In fact there is a specific constraint to bimanual movements: Whereas naturally people tend to look to the target location of the movement (Biquer, Jeannerod, & Prablanc, 1982; Neggers & Bekkering, 2000), it is impossible to fixate two locations at the same time if both targets are spatially separated. In a recent study Riek, Tresilian, Mon-Williams, Coppard, and Carson (2003) showed that eye–movements indeed play an important role in bimanual aiming tasks. According to their results participants adapted a specific strategy when executing bimanual hand movements which was reflected in movement kinematics and the corresponding eye–movements: participants tended to fixate one target after the other, corrected the spatial end–point errors of the hands respectively, and then terminated the movements by moving both hands simultaneously down to the targets. In movement kinematics this strategy led to a steady phase ("hover phase") of the first hand while corrections were made for the second hand. Thus, in order to use visual feedback to correct for the end–point errors of both hands, the movements were partially sequentialized towards the end.

The studies discussed above have all investigated bimanual coordination during simple aiming movements. Compared to aiming movements, grasping movements are of a higher complexity since they consist of two (more or less independent) components: the transport component carrying the hand to the object, and the manipulation component shaping the hand in order to grasp the object successfully (Jeannerod, 1981, 1984, for a different view see, Smeets & Brenner, 1999). That is, in bimanual grasping, in addition to transporting both hands to the object positions, the fingers have to be pre–shaped and adapted to properties of the objects (which can either be the same or different). Concerning the question of whether the transport as well as the manipulation components can be adjusted independently for both hands, results are also ambiguous (Castiello, Bennett, & Stelmach, 1993; Castiello & Bennett, 1997). Besides, there are only very few studies which investigated the coordination of the limbs when reaching and grasping simultaneously to spatially separated target objects (Jackson, Jackson, & Kritikos, 1999; Bingham, Hughes, & Mon-Williams, 2008). Whereas Jackson et al. (1999) reported synchronized movement durations but independent grip adjustment (i.e. maximum grip aperture) for both hands, other researchers observed asynchronous movement times when the objects were separated far enough so that they could not be fixated at the same time (Bingham et al., 2008). Bingham et al. (2008) argued that sequential organization is required to target both movements accurately to the correct end–positions. This reasoning was also supported by the fact that they found at least one gaze shift from one target to the other for each participant in every trial suggesting a serial correction of the end–point errors during the end–phase of the movement. Hence, again the asynchronies are attributed to the need for visual monitoring to guide each hand in the end–phase of the movement (see also, Carlton, 1981; Chua & Elliott, 1993; Binsted, Chua, Helsen, & Elliott, 2001; Winges, Weber, & Santello, 2003).

Contradicting the assumption that resources have to be shared during bimanual tasks (leading to interference effects), it was recently suggested that the human visuo–motor system is well able to simultaneously control two visually guided reaching movements (Diedrichsen, Nambisan, Kennerley, & Ivry, 2004). By using a perturbation paradigm the authors showed that both limbs can be independently and efficiently adjusted to perturbations of object position. This finding was interpreted as evidence for parallel on–line control of bimanual movements. Importantly, participants were asked to maintain central fixation during movement execution in this study thereby suppressing their natural tendency to saccade to a target displacement (as observed in the free–saccade control conditions). Thus, a review of the literature seems to suggest that fixation strategies play a crucial role in bimanual movement control and the occurrence of interference between two simultaneously executed movements.

Up to now, most studies on bimanual movement execution looked at how well the movements are synchronized in time, and which possible reasons for movement desynchronization might exist. In our study we decided to put the cart before the horse, that is, to introduce movement asynchrony and to measure the effects on movement kinematics. Therefore, we asked participants to simultaneously execute a pointing movement with the left hand (which always had to be finished first) and a grasping movement with the right hand. Note that it has been shown that humans are well able to program and execute asynchronous movement times in bimanual tasks if instructed to do so (Spijkers, Tachmatzidis, Debus, Fischer, & Kausche, 1994). To facilitate the task, the length of the pointing movement was much shorter than the accompanying grasping movement. If interference effects between movements are only due to the need for visual information to correct errors at the very end of the movement (as predicted by the studies discussed above), no interference processes between the movements should occur in an asynchronous task, since the movements are intentionally finished in a serial manner. However, one might also argue that bimanual movements require shifts of attention between the targets (e.g., Peters, 1981; Riek et al., 2003) and that the observed eye–movements are an indicator of such (overt) attentional shifts. Since attentional and motor processes are very closely coupled (Deubel & Schneider, 1996; Schiegg, Deubel, & Schneider, 2003; Deubel & Schneider, 2004), one can alternatively hypothesize that the shorter movement captures computational resources, needed for movement planning and control, during the first part of the movement. Thus, the planning and execution of the pointing movement may withdraw computational resources needed for the early visual processing of the grasping target. This lack of planning resources may manifest in altered movement kinematics, for example a poor (early) adjustment of the grip to object properties

In short, we therefore investigated in our experiments whether (a) two asynchronous movements can be programmed and executed in parallel and independently of each other, resulting in a ”standard grasp pre–shaping” of the right hand which is unaffected by the asynchronous pointing task, or (b) there is a tendency to sequentialize the movement tasks meaning that the kinematics of the grasping movement are affected by the transport movement of the left hand (e.g., delayed pre–shaping, mainly occurring after the end of the left hand pointing movement, wit prolongation of movement times (MTs) depending on the duration of the pointing movement). Additionally, we examined whether the occurrence of interference effects depends on the fixation strategies used when performing the task. Therefore, we repeated the same task using a free viewing condition (Experiment 1) and a fixation condition (Experiment 2).

Experiment 1

Methods

Participants

Ten undergraduate or graduate students of the Ludwig–Maximilians–University Munich (six men, four women; mean age = 25, SD = 5) participated in the experiment. They were paid 8 Euro per hour of participation. All participants were right–handed by self report, had normal or corrected-to-normal visual acuity, and were naive with respect to the purpose of the study. All experiments were done with the understanding and written consent of each participant and conformed to the Declaration of Helsinki.

Apparatus and Stimuli

Participants sat comfortably on an adjustable chair within a lit room. A chin rest was used to maintain a constant head position throughout the experiment. A wooden board (72 x 50 cm) was placed on the tabletop and served as the presentation surface for the stimuli. Two cylindrical objects made of wood were used as the target objects for grasping. Both objects had a circular base (diameter of the small object 2.5 cm, and diameter of the large object 5.5 cm) and a height of 5.5 cm. The objects were presented on the right side of the board and 30 cm in front of the start position of the right hand (Figure 1). The object position was marked with a pin upon which each object was affixed. We used two different object sizes in order to check when in time the properties of the target object (i.e. its size) are reflected in the grip. This provided us with a measure of the specificity of the pre–shaping in the different conditions. On the left side of the board four pointing positions (diameter of 12 mm) were marked (see Figure 1). The two "near positions" were 7.5 cm in front of the starting position of the left hand, and 5.5 cm to the left and 5.5 cm to the right. The far positions were 15 cm in front of the starting position, and again 5.5 cm to the right and to the left with respect to the central start position. Behind the board, at a viewing distance of 80 cm, a 22" monitor was used to show the actual pointing position before each trial.

Trajectories of the grasping movements were recorded using a Polhemus Liberty electromagnetic motion tracking system at a sampling rate of 240 Hz. The Polhemus Liberty tracking system provides complete 6-degrees-of-freedom (position and orientation) information at a static accuracy of 0.8 mm RMS for the x, y, z position and 0.15 deg for sensor orientation. Polhemus sensors were attached to the nails of the thumb, the index finger of the right hand (grasping), and the index finger of the left hand (pointing) using adhesive tabs (UHU-patafix, UHU GmbH, Bühl, Germany) and medical tape. An additional sensor was attached to the back of the right hand in order to measure the transport component of the grasping movement (wrist marker). Prior to the experiment a calibration procedure was used to align the cartesian coordinate system (x,y,z) of the Polhemus system such that the start position of the right hand on the board corresponded with the point of origin (0,0,0). Also, the orientation signals of the sensors attached to index finger and thumb were calibrated to a standard orientation. By considering the individual thickness of index finger and thumb, the orientation information allowed calculating the grasp touch points of thumb and index finger relative to the sensors, for each sample recorded during the experiment.

Insert Figure 1 about here

Procedure

Participants began each trial with the index finger and the thumb of the right hand pinched together at the starting position on the right side of the board, and with the left index finger lying on top of the left starting pin (see Figure 1). The starting positions of the left and the right hand were 45 cm apart and equally spaced to the left and right of the participants' midline. Participants were asked to keep their eyes closed between trials. This allowed the experimenters to place the target object on the board without being seen by the participant. After the experimenters had placed the target object, they initiated the trial manually by pressing a key.

Participants wore headphones through which different tones (duration of 100 ms) were presented: the first tone signaled them to close their eyes so that the experimenter could prepare a new trial by placing the object to grasp. The second tone signaled the participants to open their eyes and to look at the monitor on which the pointing instruction for the upcoming trial was presented. This instruction showed the configuration of the four pointing positions. One of these positions was represented by a red filled circle indicating to the participants that they should point to this location. After the instruction was presented for 1.5 s, the third tone signaled to start the pointing movement with the left hand and the grasping movement with the right hand. Prior to the experiment, participants were instructed to try to finish the pointing movement (which was always of a shorter distance than the grasping movement) earlier than the grasping movement. When participants had reached the pointing position they kept their left index finger at this position until they had finished their grasp with the right hand. After they had grasped the cylinder, they lifted it and placed it roughly halfway between object and starting position on the table. Finally, they moved both hands back to the starting positions and waited for the next trial. After three seconds, participants heard a tone again (corresponding to the first tone) which indicated that the trial was over and that they should close their eyes. Subsequently, the experimenter returned the cylinder and prepared the next trial. No instructions were given as to speed of initiation or the speed of the movement. In some trials four empty circles were shown during the instruction meaning that the participants only had to grasp the object with the right hand without performing a concurrent pointing movement. These trials were considered as baseline trials.

In all conditions participants were allowed 2 s to execute the movements. If this time limit was exceeded, the trial was classified as an error and repeated later in the experiment at a random time. Each object size was combined with each pointing position and presented eight times. Additionally, another eight baseline trials for each object size were included. Thus, the experiment consisted of 80 trials which were presented in pseudo–random order. To familiarize with the task, five practice trials were given before the experiment started.

Data Processing

The finger trajectories were filtered off-line by a dual pass through a second-order Butterworth filter that employed a low-pass cut–off frequency of 15 Hz.

Movement onset was defined by a velocity criterion for both hands: the first frame in which the index or the thumb marker of the right hand exceeded a velocity threshold of 0.1 m/s was taken as movement onset of the grasping movement. For the pointing movement the same velocity threshold was applied to the index marker of the left hand. Reaction time (RT) was defined as the time between the auditory signal and movement onset for each hand.

The touch of the object was also defined by a velocity threshold. The first frame in which the velocity of one of the finger markers on the right hand dropped below a threshold of 0.1 m/s was taken as the end of the grasping movement. The end of the pointing movement was determined by the same velocity threshold derived from the index marker on the left hand. Movement time (MT) was defined as the time between movement onset and touch of the object for the right and the left hand respectively.

For the pointing movement the absolute end–point error was defined as the average distance between the position of the index finger at the end of the movement and the center of the target circle. We further analyzed end–point variability (precision) in a Cartesian frame of reference of fingertip positions for all trials using the following formula: Variable Error = Square Root$\{[SD(d_x)]^2 + [SD(d_y)^2]\}$ with SD being the standard deviation, and with d_x, d_y being the differences in the coordinates of the target center and the final pointing position (see also Adamovich, Berkinblit, Fookson, & Poizner, 1998). Standard deviations are an appropriate measure of dispersion since it has been shown that the distribution of endpoints in unconstrained pointing movements tend to be normally distributed (Desmurget, Jordan, Prablanc, & Jeannerod, 1997).

Moreover, different parameters of the grasp (right hand) were analyzed: maximum grip aperture (MGA) was defined as the maximum 3-D distance between thumb and index finger during MT. Time to MGA was analyzed as relative time (time of MGA as percentage of MT). In order to measure the adaptation of the aperture to object size we calculated the mean aperture profiles (in real–time) for each participant in each condition. To quantify when in time the aperture profile for one object size differed significantly from the aperture profile for the other object size, we calculated the difference of the mean "small" aperture profile (grasping the 25 mm object) and the mean "large" aperture profile (grasping the 55 mm object) for each participant. Then t-tests were computed at each time point. If the difference between the small and the large aperture profile became significant ($\alpha = 0.01$, a higher alpha level was chosen because of the multiple comparisons) this was taken as the moment the object size was integrated in the grip. The moment object size was integrated in the aperture pre–shaping was determined in absolute and relative time. Furthermore, the slope of the function relating object size to aperture size was determined at the moment the pointing target was reached with the left hand by calculating a regression analysis. To characterize the transport component of the grasping movement, we calculated the wrist velocity profiles by differentiating the position signal of the wrist marker.

Grasping data were analyzed using repeated–measures analysis of variance (ANOVA) with the factors object size and pointing condition. When comparisons between experiment 1 and 2 were made, the variable "experiment" was introduced as an in–between subjects factor in the standard ANOVA. Values are presented as means ± standard errors of the mean. Post-hoc contrasts were carried out using Fisher's LSD (least significant difference) testing procedure. A significance level of $\alpha = 0.05$ was used for the statistical analysis.

Results and Discussion

Since a pre–analysis of our data showed clearly that there was no effect, neither on the pointing nor on the accompanying grasping movement, dependent of whether the pointing target was to the right or to the left side of the start position, we combined these trials for all data analysis. Hence, we only distinguished between trials in which participants had to point to the near positions from those in which they had to point to the far positions. In the following we will refer to these conditions as "close pointing" and "far pointing". Furthermore, these conditions are compared to the baseline trials in which no pointing movement was executed.

Timing of the movements (RTs and MTs)

Grasping

First of all, we investigated how the execution of a simultaneous pointing movement affected the RTs and the MTs of the grasping movement executed with the right hand. We applied a 2 (object size: small/ large) x 3 (pointing: none, close, far) repeated–measures ANOVA to the data. In accordance with most studies on bimanual movements we found that RTs were slower when a bimanual movement had to be executed, $F(2, 18) = 22.1, p < .001$. There was no effect of object size on RT ($p = .47$) and no interaction ($p = .28$). If no additional pointing was required participants initiated their grasping movement after $321ms \pm 23ms$. With a simultaneous pointing movement the grasp was on average initiated $74ms$ later (after $396ms \pm 28ms$ in the close pointing and after $395ms \pm 27ms$ in the far pointing task). Post–hoc tests revealed no difference between the close and the far pointing condition ($p = .93$).

The MTs were also longer when participants had to execute a simultaneous pointing movement, $F(2, 18) = 39.9, p < .001$. On average it took participants $730ms \pm 26ms$ to execute the grip in the baseline conditions. In the close pointing conditions it took them $909ms \pm 38ms$, and in the far pointing conditions $965ms \pm 44ms$. Post–hoc tests confirmed that the differences between all three conditions were significant (all $p < .005$). Thus, there was a considerable increase in MT of the grasping movement when the pointing movement was prolonged (close vs. far pointing). The fact that the MTs of the grasping movements depended on the MTs of the simultaneously executed pointing movements suggests that some sequencing process between the two movements occurs. There was also a significant effect of object size indicating that movements to the smaller object were executed more slowly,$F(1, 9) = 20.0, p = .002$. There was no interaction ($p = .10$).

To further test our assumption that the movements of the left and the right hand are (partially) sequentialized we correlated the MTs of both hands across the trials of each condition for each participant. Out of 40 possible correlations (four conditions and ten participants), 29 correlations became significant. Table 1 shows the mean correlations obtained for each condition after averaging all correlations across participants using Fisher's z-transformation.

Pointing

The dependent t-test (pointing: close, far) applied on the RTs of the left hand revealed no significant effect of pointing distance, $t(9) = 0.31, p = .76$. Overall, the RTs of the left hand were slower than to the right hand. On average it took participants $420ms \pm 29ms$ to initiate the pointing movement. Hence, although participants were instructed to finish the pointing movement earlier than the grasping movement they tended to initiate the pointing movement later.

There are at least three potential explanations for this finding. First, for all participants the left hand was the non–dominant hand, for which movement initiation has been shown to occur later than for the dominant hand (Swinnen, Jardin, & Meulenbroek, 1996). Second, studies investigating bimanual movements of different amplitudes observed a systematic lead of the hand which had to cover a longer distance (Heuer & Klein, 2005). Since the movements of the right hand in our experiment were always of a larger amplitude than the movements of the left hand this explanation may also apply to our data. Finally, one has to consider the differences between the tasks performed with each hand. Whereas the target position always remained the same for the right hand, there were four different target positions for the left hand which were determined randomly between trials. According to Hick's Law (Hick, 1952; Hyman, 1953) RT varies (increases) with the number of choices which the participant has to make after target onset. Thus, there are several reasons why we observed slower RTs for the left hand and did not replicate a left hand reaction time advantage which was observed in some other studies on bimanual movement control (e.g., Elliott et al., 1993; Mieschke, Elliott, Helsen, Carson, & Coull, 2001).

As expected, the MTs were significantly longer for a far pointing movement ($532ms \pm 21ms$) than for a close pointing movement ($423ms \pm 13ms$), $t(9) = 9.8, p < .001$. Therefore, the close pointing movement was on average finished after 46.5% of the MT of the grasping movement, and the far pointing movement after 55.1%. This clearly shows that participants were able to follow the instructions and to end the pointing movement before the grasping movement.

Accuracy of the movements

Pointing errors

The analysis of the pointing errors revealed that neither the distance error, $t(9) = 0.68, p = .51$, nor the variable error, $t(9) = 1.2, p = .27$, was influenced by the distance of the pointing target. The mean distance error was $7.4mm \pm 1.9mm$ and the mean variable error $4.7mm \pm 1.0mm$. Thus, the pointing movements of all participants were fairly accurate.

Grasp pre–shaping

Our main interest was in the influence of a simultaneously executed transport movement on grip pre–shaping. We hypothesized that the pointing movement might withdraw computational resources from the simultaneously executed grasping movement resulting in a later and possibly less accurate adaptation of the grip to the object size. To test this prediction, we first analyzed the most prominent landmark of aperture pre–shaping, that is, MGA and its timing (for review see, Smeets & Brenner, 1999).

Insert Figure 2 about here

The 2 (object size) x 3 (pointing condition) repeated–measures ANOVA revealed that the MGA was significantly influenced by object size, $F(1,9) = 181.2, p < .001$, as well as by the movement condition, $F(2,18) = 19.7, p < .001$ (see Figure 2a). Post–hoc tests indicated that, as expected, the MGA was larger for larger objects, and increased when an additional pointing movement had to be performed. Significant differences in the size of MGA were observed between the control conditions and both pointing conditions (all $p < .002$) but not between the close and the far pointing conditions ($p = .59$). There was also a significant interaction effect, $F(2,18) = 14.6, p < .001$, revealing that the effect of object size was smaller in the pointing conditions compared to the baseline conditions. Regarding the timing of MGA, we also found a significant effect of object size, $F(1,9) = 33.7, p < .001$, and movement condition, $F(2,18) = 4.1, p = .04$. The MGA occurred later in MT when grasping larger objects (Figure 2b). Post–hoc tests revealed a significant difference in the timing of MGA between the control and the far pointing conditions ($p < .05$) whereas all other differences were not significant ($p > .10$). There was no interaction effect ($p = .24$).

While the effect of movement condition on the size of MGA might be due to an increase of the safety margin in the grip which has repeatedly been observed in bimanual movement execution (e.g., Jackson et al., 1999), the interaction effect between the size of MGA and movement condition indicates that the grip is less well scaled to the object size when executing a simultaneous pointing movement. Therefore, we determined when in time the object size became reflected in the aperture. Figure 3A shows the mean aperture profiles and the corresponding transport velocity profiles, in the baseline and the pointing conditions for one representative participant. When calculating the time at which the aperture profiles for the different object sizes start to differ for all participants, we observed a significant effect of movement condition, $F(2,18) = 16.8, p < .001$, indicating that the aperture profiles separate later in the bimanual conditions. On average the object size became reflected in the aperture after $316ms \pm 51ms$ in the baseline condition (corresponding to $42\% \pm 6.6\%$ of MT), after $629ms \pm 65ms$ ($69\% \pm 6.3\%$ of MT) in the close pointing conditions , and after $640ms \pm 80ms$ ($66\% \pm 6.6\%$ of MT) in the far pointing conditions. The effect also remained significant in relative time, $F(2,18) = 10.6, p = .001$, which indicates that the later adjustment to the object size in the bimanual conditions cannot be attributed to longer MTs. The figure also shows that object size was not integrated in the grip until the late deceleration phase of the transport component of the grip. Interestingly, the typical smooth and bell-shaped velocity profile of the transport component was maintained in all conditions (e.g., Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991).

Finally, we tested whether object size is taken into account at all during the simultaneous execution of the pointing movement by measuring the slope of the scaling function relating object size to aperture size at the moment the left pointing movement was finished. Averaged values over all participants revealed that the aperture scaled to object size with a slope of 0.24 ± 0.06 in the close pointing conditions, and with a slope of 0.36 ± 0.08 in the far pointing conditions. Since both values are significantly different from zero ($p < .003$), this finding indicates that at the moment the left movement is ended, the grip aperture is at least to some degree scaled to object size.

In summary, the experiment provides evidence that there are interference effects between grasping and asynchronously executed pointing movements, suggesting that they are not programmed and executed independently of each other. For the duration of the shorter movement, the movement which ends last seems to be delayed and less well adapted to the task demands.

Insert Figure 3 about here

Control Experiment

In Experiment 1 most participants reported spontaneously that they had chosen the strategy of not looking at the grasping target until the pointing movement was finished (which was also observed by the experimenters sitting next to the participant). We were interested in confirming this assumption by an objective recording of the eye movements during the task. For this purpose, a separate control experiment was conducted since eye movements could not be easily measured in the main experiment. In the control experiment, a head–mounted eyetracker (Eyelink II) was used. A problem with this system was that it had to be attached to the head relatively tightly since participants inclined the head to look down at the working space. Thus, to make the experiment acceptable for the participants, we had to reduce the number of trials compared to the main experiment. Otherwise, the general procedure of this experiment was similar to that used in the main experiment. The control experiment was designed to gain insight into where participants tended to look when doing the task (eye–movements were unrestricted in the main experiment).

Methods and Procedure

Four undergraduate and graduate students of the Ludwig–Maximilians–University Munich (two men, two women; mean age = 24, SD = 2) participated in the experiment (all of them had also participated in the main experiment). All participants were right–handed by self report, had normal or corrected-to-normal visual acuity, and were naive with respect to the purpose of the study.

Eye–movement data were recorded by a head-mounted eyetracker (Eyelink II, SR-Research, Osgoode, Ontario, Canada) measuring both eyes' pupil and corneal reflection at a sampling rate of 250 Hz. A chin rest was used to maintain head position throughout the experiment. Calibration comprised the sequential fixation of nine predefined dots presented on a 19" monitor at 55 cm viewing distance. Calibration was followed by a depth correction using 5 fixation points in different viewing distance planes, to account for parallax changes at different viewing distances of the fixation cross and the object. The rest of the setup was the same as in the main experiment.

The experiment consisted of 30 trials which occurred in random order: 10 baseline trials (five per object size), and 20 bimanual trials (i.e. five trials for each pointing position and a random assignment of object size: each object size was presented 10 times).

Eye data recorded by SR–research recording software (SceneLink Software, SR-Research) were validated and prepared for further statistical analysis using the DataViewer Software (SR-Research). We defined three areas of interest to investigate the participants' task strategies in the free viewing conditions: (1) the left interest area including the pointing targets and approximately the left third of the working space, (2) the central area including the working space between the pointing targets on the left and the grasping target on the right (including the area in which participants had to fixate in Experiment 2) and (3) the right third of the working space including the object to grasp. Eye movements (saccades entering and leaving the interest areas) and fixation times were determined to describe the dynamics of the eye movements. Baseline trials (unimanual grasping) were compared to bimanual trials (grasping and pointing) without distinguishing between close and far pointing movements since the distance of the pointing target did not affect the overall pattern of eye–movements.

Results and Discussion

When examining the looking behavior in the experimental task, we observed that all participants fixated exclusively on the right side of the board in all baseline trials (see Figure 4). A fixation to the left side of the working space occurred in 99% of all bimanual trials. Figure 4 shows the mean entering and leaving times of the pre–defined interest areas (IA). It can be seen that participants left the left IA on average after $589ms \pm 71ms$ which approximately corresponds to the duration of the pointing movement (we assume that the movements took on average slightly longer than in the main experiment because participants tended to move more carefully with the eye tracker affixed on their head). The reason for the finding that in the bimanual trials (on average) the fixation to the right IA occurs earlier than the leaving of the left IA results from the fact that in 16% of all trials a right fixation occurred prior to the left fixation.

Insert Figure 4 about here

Thus, when measuring eye–movements in this task, we observed that participants tended to keep fixation at the left part of the working space for the duration of the pointing movement in most trials. This finding is in accordance with the observation that saccades away from a pointing target cannot be made until the pointing movement is completed (Neggers & Bekkering, 2000, 2001). Knowing that participants adapt the strategy to fixate one target after the other, some of the alterations in movement kinematics observed in Experiment 1, namely the overall increase in the MGA in the bimanual conditions, can well be explained by the fact that the object to be grasped is located in the visual periphery in the first half of the movement (Schlicht & Schrater, 2007; Goodale & Haffenden, 1998). On the other hand, the later occurrence in time of the MGA is contrary to what one might expect in situations of visual uncertainty, since visual uncertainty normally leads to a earlier occurrence of MGA (e.g., Berthier, Clifton, Gullapalli, McCall, & Robin, 1996; Wing, Turton, & Fraser, 1986; Jakobson & Goodale, 1991). Therefore, the delayed occurrence of MGA might be an indicator of a sequencing process between the pointing and the grasping movements which results from a delayed pre–shaping process.

Experiment 2

Methods

Participants

Ten undergraduate and graduate students of the Ludwig–Maximilians–University Munich (seven men, three women; mean age = 29, SD = 8) participated in the experiment. They were paid 8 Euro per hour of participation. All participants were right–handed by self report, had normal or corrected-to-normal visual acuity, and were naive with respect to the purpose of the study.

Stimuli and procedure

The general procedure of the experiment was the same as in Experiment 1. The same target objects were used and the apparatus to measure the grasping movements remained identical. The only difference was that this time participants were instructed to fixate a red dot which was placed in the middle of the working surface between the pointing positions on the left and the grasping positions on the right (see Figure 1). Participants were instructed to look at this point after the instructions on the monitor had disappeared and to keep fixation during movement execution. Participants were motivated to keep fixation by stressing the fact that the experimenter sitting next to the participant was checking fixation behavior. Additionally the experimenter reminded them to keep fixation every twenty trials. All other instructions were identical to Experiment 1. All data analysis was performed in the same way as in Experiment 1.

Results and Discussion

Timing of the movements (RTs and MTs)

Grasping
To examine the RTs and MTs of the grasping movement, we applied a 2 (object size: small/ large) x 3 (pointing: none, close, far) repeated–measures ANOVA to the data. As in Experiment 1, we observed that RTs were significantly slower when a bimanual movement had to be performed, $F(2, 18) = 5.1, p < .04$. There was no effect of object size ($p = .06$) and no interaction ($p = .30$). In the baseline conditions participants initiated their grasping movement on average after

$460ms \pm 57ms$. When an additional pointing movement was required movements were initiated after $517ms \pm 64ms$ in the close pointing, and after $502ms \pm 59ms$ in the far pointing conditions. A comparison between the experiments revealed that RTs tended to be longer when participants had to fixate during movement execution ($371ms \pm 45ms$ in Experiment 1 vs. $493ms \pm 45ms$ in Experiment 2) therefore indicating a tendency for a prolonged planning process in the fixation conditions, $F(1, 18) = 3.7, p = .06$.

Regarding the MTs, ANOVA revealed a significant effect of object size, $F(1, 9) = 13.0, p = .006$ again indicating that movements to the smaller object took longer. We also observed a significant effect of movement condition, $F(1, 18) = 12.6, p < .001$. As in Experiment 1, movements were executed significantly faster in the baseline conditions ($678ms \pm 32ms$) than in the bimanual conditions. However, in contrast to Experiment 1 there was no difference in the MTs between the close and the far pointing conditions ($747ms \pm 29ms$ vs. $741ms \pm 31ms$). There was also a significant interaction effect, $F(2, 18) = 11.0, p = .001$. When comparing the MTs between the experiments, the participants showed significantly shorter movement durations for grasping in the fixation conditions ($722ms \pm 31ms$) than in the free viewing conditions ($868ms \pm 31ms$), $F(1, 18) = 10.8, p = .004$. Moreover, the effect of the simultaneously executed pointing movements on the MTs of the grasping movement was much smaller in the fixation conditions (less than 100 ms) than in the free viewing conditions (more than 200 ms), and unspecific with respect to the duration of the pointing movement. That is, the MTs of the grasping movements did not vary dependent on whether a close or far pointing movement was performed, therefore indicating an absence of a sequencing process between the two movements. As in Experiment 1, we correlated the MTs of both hands across the trials of one condition for each participant. Only 10 out of the 40 possible correlations became significant. Moreover, Table 1 shows that the mean correlations obtained for each condition were considerably lower than in Experiment 1.

Pointing

The dependent t-test (pointing: close, far) applied on the RTs of the left hand revealed no significant effect of pointing distance, $t(9) = 1.4, p = .20$. On average it took participants $535ms \pm 57ms$ to initiate the pointing movement which replicated the finding in Experiment 1 that the RTs of the left hand were slower than for the right hand.

The MTs were significantly longer for far pointing movements ($519ms \pm 26ms$) than for close pointing movements ($430ms \pm 24ms$), $t(9) = 11.9, p < .001$. These values are very similar to those obtained for the duration of the pointing movements in Experiment 1. Since, however, the grasping movements were executed faster in this experiment, the close pointing movement was finished on average after 57.6% of the duration of the grasping movement, and the far pointing movement after 70.0% of the MT of the grasping movement executed with the right hand. Again participants had no problems to follow the instructions and to end one movement before the other.

Accuracy of the movements

Pointing errors

As in Experiment 1 neither the distance errors nor the variable errors were affected by the distance of the pointing target (both $p > .48$). The mean distance error was $13.1mm \pm 1.9mm$ and the mean variable error $8.7mm \pm 1.0mm$. Thus, both the mean distance error and the mean variable error almost doubled compared to Experiment 1. A statistical comparison between the experiments revealed that the distance error was marginally larger in the fixation conditions compared to the free viewing conditions, $F(1, 18) = 4.2, p = .05$, whereas the variable error increased considerably when participants were asked to fixate, $F(1, 18) = 8.1, p = .01$. Thus, fixation was primarily associated with an increase of the end–point variability in pointing.

Grasp pre–shaping

Again our main interest was in the effects of a simultaneously executed pointing movement on grasp pre–shaping. We hypothesized that the grasping movement might be less affected by the execution of a sub–task, since no additional (visual) information can be acquired by sequentializing the tasks.

The 2 (object size) x 3 (pointing condition) repeated–measures ANOVA revealed that the MGA was significantly influenced by object size, $F(1, 9) = 286.2, p < .001$, but not by movement condition, $p = .98$ (see Figure 5a). There was no interaction effect ($p = .43$). Thus, contrary to Experiment 1, the scaling of MGA to object size did not depend on the movement condition. Regarding the timing of MGA, we replicated the finding that MGA occurs later when grasping larger objects, $F(1, 9) = 41.6, p < .001$ (Figure 5b). We observed no effect of movement condition ($p = .52$) and no interaction ($p = .25$).

Insert Figure 5 about here

Figure 3B depicts the mean aperture profiles (and corresponding wrist velocity profiles) of one representative participant visualizing the adjustment of the aperture to object size over time. Contrary to Experiment 1, the aperture profiles separated relatively early in time depending on the object size: after $384ms \pm 48ms$ in the baseline conditions, after $273ms \pm 47ms$ in the close pointing conditions and after $267ms \pm 47ms$ in the far pointing conditions, $F(2, 18) = 2.2, p = .14$. On average the aperture profiles differed after $43\% \pm 6.2\%$ of MT (no effect of movement condition, $p = .06$), which exactly corresponds to the value obtained in the baseline condition of Experiment 1. Furthermore, object size was integrated in the grip before the peak velocity of the transport component was reached in all conditions. The finding suggests that the scaling to object size starts shortly after movement onset, simultaneously with the execution of the pointing movement in the bimanual conditions. A comparison between the experiments revealed a significant main effect of experiment, $F(1, 18) = 12.0, p = .003$, as well as a significant interaction effect between experiment and movement condition, $F(2, 36) = 15.8, p < .001$, confirming that the simultaneous execution of a pointing movement affected the aperture pre–shaping differently in each experiment.

This interpretation is further supported by the slopes determined at the moment the pointing movement was ended: On average the aperture scaled to object size with a slope of 0.47 ± 0.04 in the close pointing conditions, and with a slope of 0.51 ± 0.03 in the far pointing conditions. Both values are significantly different from zero ($p < .001$), and significantly higher than in Experiment 1, $F(1, 18) = 7.0, p = .02$. Overall, we found no indication that the execution of a secondary pointing movement which had to be performed simultaneously but finished earlier, affected the general pre–shaping pattern of the grasp when participants had to keep central fixation.

General Discussion

In this study we investigated the occurrence of interference effects between two asynchronous movements that are executed simultaneously. To that end, we asked participants to execute a short pointing movement with the left and a longer grasping movement with the right hand, and instructed them to end the pointing movement first. Since many studies have suggested that fixation strategies might play a crucial role in bimanual movement control (e.g., Fowler et al., 1991; Riek et al., 2003; Bingham et al., 2008), we asked participants to do the same task either in a free viewing condition (Experiment 1) or in a fixation condition (Experiment 2).

In Experiment 1 we obtained two main findings which are in favor of interference processes occurring between the two movements: First we observed a substantial increase in the MTs of the grasping movements when participants pointed simultaneously. At first glance this finding seems not to be surprising since it is known that bimanual movements sometimes have longer MTs than unimanual movements (e.g., Jackson et al., 1999; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997). However, when reviewing the literature, we found that, if present at all, the increase in MT due to bimanual movement execution is normally less than 100 ms (compared to almost 200 ms in our study). Moreover, the increase of the duration of the grasping movement depended on the duration of the corresponding pointing movement, therefore suggesting a sequencing process between both movements. The second main finding was the observation that the object size was incorporated later in the grip during bimanual movement execution. That is, the aperture profiles for the different object sizes did not separate until the pointing movement was finished.

When measuring the eye–movements in a control experiment, it turned out that participants tended to fixate the target of the movement which had to be finished first for the total duration of this movement. Thus, one could assume that the grip scaling is suboptimal because the object to grasp is located in visual periphery during the first half of the movement. But there are several reasons which make this interpretation relatively unlikely: First, participants were well informed about the size of the object they were going to grasp since there was a preview period of 1.5 s before each trial. Recently, it was shown that object size and shape information are already included during the pre–planning stage of the reach–to–grasp movement (Schettino, Adamovich, & Poizner, 2003; Winges et al., 2003). According to the study of Schettino et al. (2003) the hand pre–shaping is affected by the object's properties well before 50% of the total movement duration regardless of the visual feedback conditions. Second, most studies agree that vision of the hand during goal–directed movements is especially important in the end–phase of the movement, when the fingers come close to the object, since terminal precision depends on a comparison between the position of the seen hand and the target location (Carlton, 1981; Beggs & Howarth, 1972; Chua & Elliott, 1993). This is also supported by the finding that eye–movements during grasping are mainly directed to the target object while the hand is not fixated at all (e.g., Johansson, Westling, Backstrom, & Flanagan, 2001). Thus, the first part of the grasping movement is normally not visually guided suggesting that looking at the pointing targets during this period of time should not affect the grasp pre–shaping. Besides, whereas the absolute size of the aperture is known to depend on the amount of visual information available during grasping (e.g., Wing et al., 1986; Jakobson & Goodale, 1991; Hesse & Franz, 2009), the scaling of the aperture to object size is usually relatively unaffected by a reduction of visual information, as well as by object eccentricity (Jakobson & Goodale, 1991; Hesse & Franz, 2009; Goodale & Haffenden, 1998).

Therefore, the effects on grasp pre–shaping in Experiment 1 may in fact result from sequentialized task processing. Indeed, it has been shown that during movement preparation attention has to be allocated to the movement target which results in only a little processing capacity remaining for non–target objects (Deubel & Schneider, 2004; Baldauf, Wolf, & Deubel, 2006). Thus, one could assume that an allocation of attention to the pointing targets may have prevented the early perceptual processing of the grasp target, such that the movement–relevant parameters of the to-be-grasped object could not be integrated during the early movement phase. In short, we suggest that the serial character of the task might evoke sequential shifts of attention (reflected in eye–movements) which were in turn reflected in movement kinematics.

Interestingly, results changed notably when the same task was done in the central fixation condition (Experiment 2). Apart from the typical effects associated with the execution of bimanual movements, i.e. longer RTs and MTs (increase of less than 100 ms) compared to the baseline conditions, no specific effects of the pointing movement on grasp pre–shaping were observed. Whereas the differences between the initiation times for unimanual and bimanual were of similar size in both experiments, the overall RTs were much longer in the fixation conditions indicating a more demanding planning process. This finding is also in line with other studies showing that under conditions of high uncertainty the movement planning phase is prolonged, as indicated by an increase in RTs (Hansen, Glazebrook, Anson, Weeks, & Elliott, 2006). Besides, the increase in RTs was accompanied by a decrease of total movement duration for the grasping movement compared to the free viewing conditions. The relatively short MTs indicate that the execution of the grasping movement was not substantially delayed when a simultaneous pointing movement had to be performed. However, considering the fact that no additional information could be acquired to adjust the movements more precisely by sequentializing them, movement sequencing seems not to be a functional process in these conditions. Thus, the more efficient way to perform the task (regarding the movement time) was to plan and execute both movements in parallel. As shown by Diedrichsen et al. (2004) the visuo–motor system is well able to control and adjust two visually guided movements in parallel while fixating. However, the authors also showed that the need to keep central fixation undermines the natural tendency of humans to move the eyes to the target locations.

In summary, two important conclusions can be drawn from our findings. First, our study confirms a prominent role of eye–movements and fixational strategies in the control of bimanual tasks. When participants were not restricted in their eye–movements they preferably adapted the strategy to fixate one target after the other and to (partially) sequentialize the movements, resulting in a longer total movement duration but more accurate movement end-points. This finding is also in line with the observations that humans spontaneously look at objects when manipulating them in natural environments (Land, Mennie, & Rusted, 1999; for review see, Hayhoe & Ballard, 2005). Thus, our study gives further evidence that the eyes naturally tend to monitor what the hands are doing, and additionally shows that this strategy might alter movement kinematics when tasks are performed bimanually. Second, the study shows that participants were also able to perform both movements very well when they were asked to fixate. Surprisingly, in the fixation conditions, both movements were executed faster with only very little interference effects (but at the expense of accuracy). We assume that in this task both targets were attended covertly and in parallel. This reasoning would be in line with the observation that in bimanual reaching humans are able to split and allocate processing resources simultaneously to two movement goals which are located at two spatially separated positions (Baldauf & Deubel, 2008).

Thus far there is only basic knowledge about how the (bimanual) online control of reaching and grasping is realized by the brain and which areas may be involved. There is some evidence that reaching and grasping are controlled by separate neuronal subsystems (Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Jeannerod, 1999; Mountcastle, Lynch, Georgopoulos, Sakata, & Acuna, 1975). In patient studies, Binkofski et al. (1998) showed that humans with lesions in the anterior portion of the intraparietal sulcus (aIPS) show impaired grasping movements while reaching remained intact. Other patient studies have shown that bilateral lesions of the posterior parietal cortex result in a strong impairment of automatic online corrections of a pointing movement and the inability to modify the movement path smoothly (Grea et al., 2002; Pisella et al., 2000). Using transcranial magnetic stimulation (TMS) in healthy participants, Desmurget et al. (1999) confirmed that the parietal lobes largely contribute to the online monitoring and adjustment of actions (see also Glover, Miall, & Rushworth, 2005). Furthermore, it was shown that the activity in the posterior parietal cortex increases if multiple targets are presented simultaneously, compared to conditions in which only a single movement target is present (Chapman et al., 2002). The studies discussed so far investigated the brain areas primarily involved in visually guided grasping. Recent studies suggest that (bimanual) movements which are planned and controlled without strong visual guidance result in a pronounced activation of the supplementary motor areas (SMA), whereas the contribution of SMA to visually guided movements is negligible (e.g., Shima & Tanji, 1998). Additionally, the SMA is also known to be activated in the production of asymmetric bimanual movement (Serrien, Strens, & Oliviero, 2002). Thus, it may be possible that the different fixation strategies employed when carrying out bimanual movements in our experiments might have led to the involvement of different brain areas used for movement control: Whereas the posterior parietal cortex is mainly involved in controlling visually guided movements (Experiment 1) and represents the movement targets in gaze–centred coordinates (Medendorp & Crawford, 2002), the SMA is more likely to be activated in (bimanual) conditions which require fixation (Experiment 2), therefore providing less visual information for movement control.

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Figure Legends

Figure 1: Schematic drawing of the experimental set–up used in all experiments (top view). The cross in the middle of the board indicates the location of the fixation point used in Experiment 2.

Figure 2: Experiment 1: The effects of the different movement conditions on a) maximum grip aperture (MGA) and b) relative time to MGA when grasping objects of two different sizes (25 mm and 55 mm). All error bars depict ± 1 SEM (between subjects).

Figure 3: A) Experiment 1: a) aperture profiles for one representative participant averaged over all trials (in real–time) of each movement condition and b) the corresponding wrist velocity profiles. B) Experiment 2: a) aperture profiles for one representative participant averaged over all trials (in real–time) for each movement condition and b) the corresponding wrist velocity profiles. Dashed vertical lines indicate the time at which the aperture size differed significantly from each other. Solid vertical lines indicate the mean end–time of the grasping movements and dotted vertical lines the mean end–time of the pointing movement. All error bars depict ± 1 SEM (within subject). Further details are given in the methods section.

Figure 4: Control experiment: mean latencies of eye–movements when a) entering and b) leaving the areas of interest in the unimanual grasping task (baseline) compared to the asynchronous grasping and pointing task (bimanual). All error bars depict ± 1 SEM (between subjects).

Figure 5: Experiment 2: The effects of the different movement conditions on a) MGA and b) relative time to MGA when grasping objects of two different sizes. All error bars depict ± 1 SEM (between subjects).

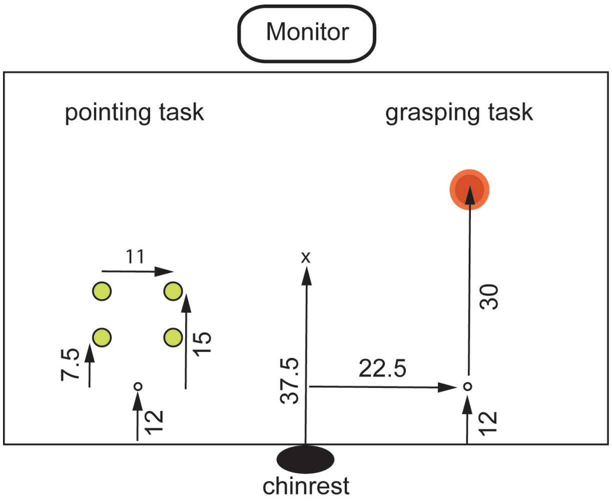

Monitor
pointing task
grasping task
11
7.5
15
12
x
37.5
22.5
30
12
chinrest

Figure 1

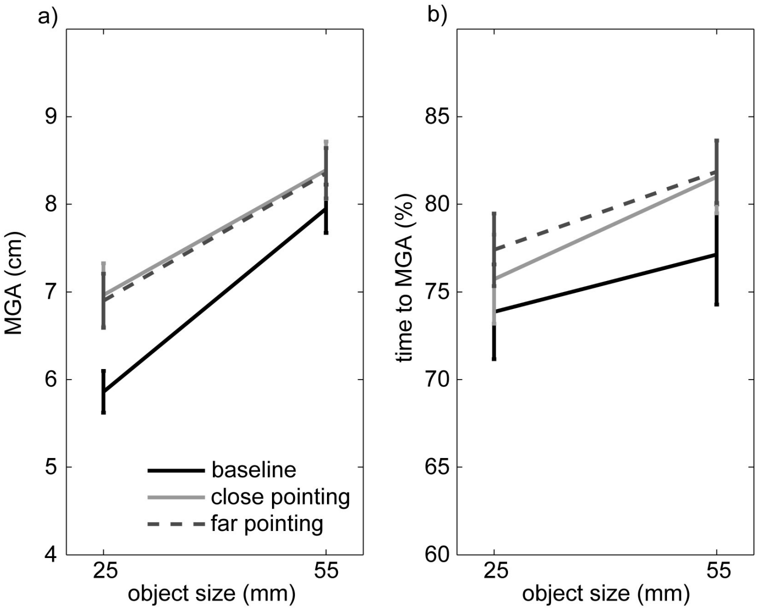
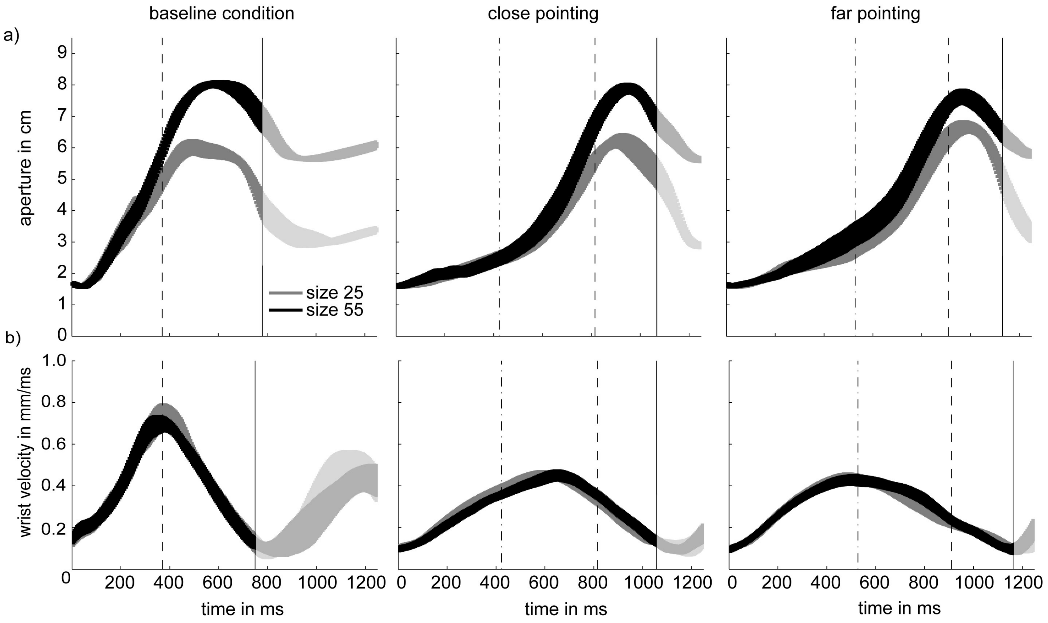

a)
b)
MGA (cm)
4
5
6
7
8
9
time to MGA (%)
60
65
70
75
80
85
25
55
object size (mm)
baseline
close pointing
far pointing

Figure 2

A) Experiment 1: free viewing



B) Experiment 2: fixation

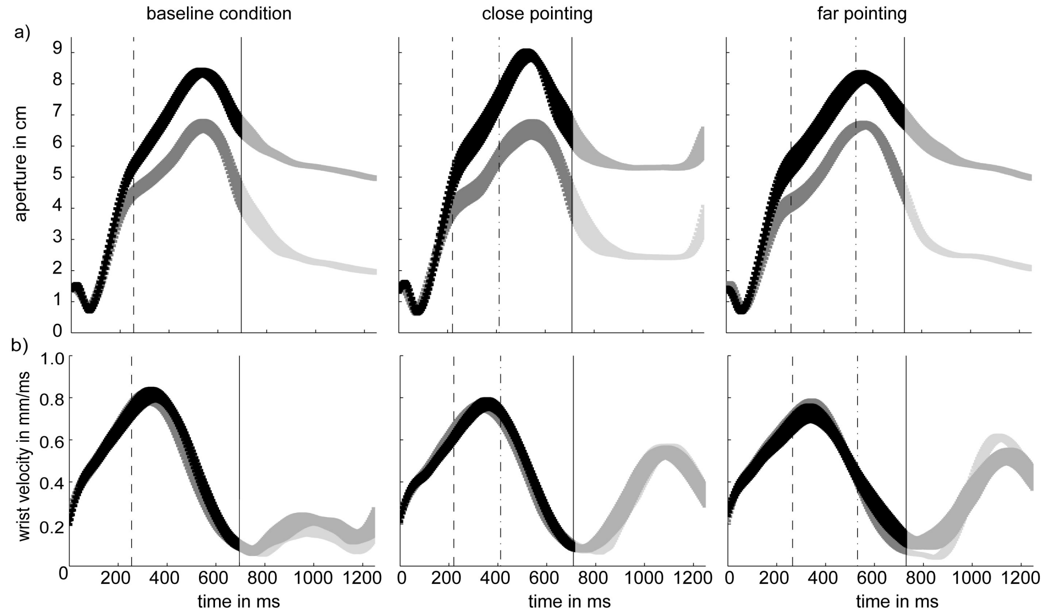


Figure 3

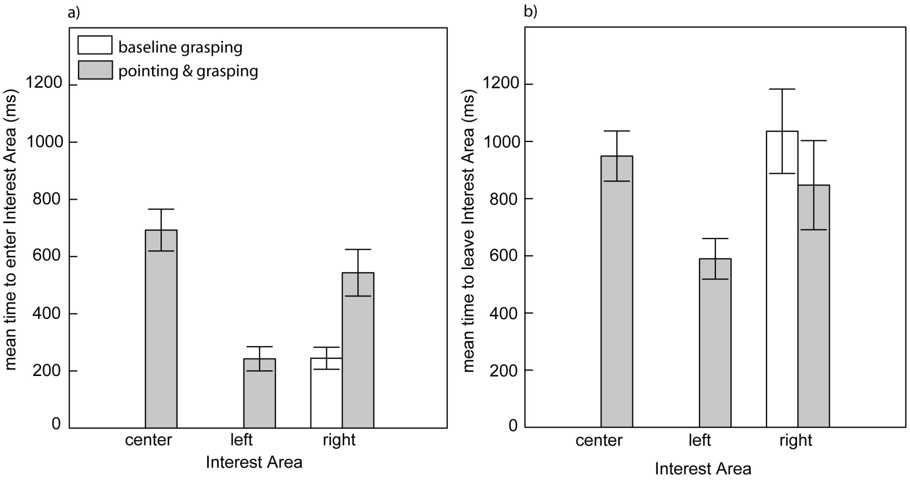

a)
baseline grasping
pointing & grasping
mean time to enter Interest Area (ms)
0
200
400
600
800
1000
1200
center
left
right
Interest Area
b)
mean time to leave Interest Area (ms)
0
200
400
600
800
1000
1200
center
left
right
Interest Area

Figure 4

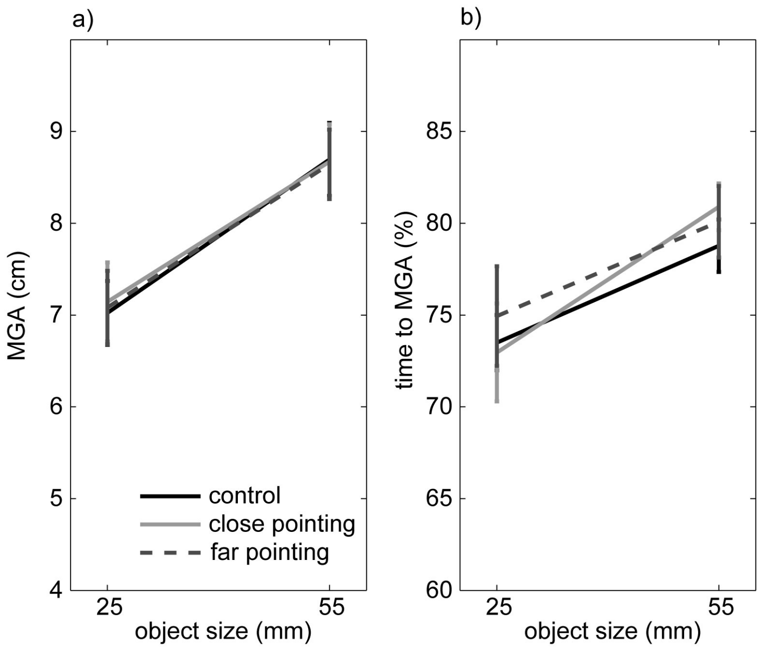

a)
MGA (cm)
4
5
6
7
8
9
25
55
object size (mm)
control
close pointing
far pointing
b)
time to MGA (%)
60
65
70
75
80
85
25
55
object size (mm)

Figure 5

Table 1

grasping	object size			
	25 mm		55 mm	
pointing	distance			
	close	far	close	far
Exp. 1: free viewing	.54	.58	.55	.64
Exp. 2: fixation	.20	.16	.29	.38

Mean correlation coefficients between the MTs of the left hand (pointing) and the MTs of the right hand (grasping) calculated within conditions and averaged over all participants (after Fisher's z-transformation).

Advance planning in sequential pick–and–place tasks

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RUNNING HEAD: "planning action sequences"

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Abstract

It has been suggested that the kinematics of a reach–to–grasp movement, performed within an action sequence, vary depending on the action goal and the properties of subsequent movement segments (action context effect). The aim of the study was to investigate whether the action context also affects action sequences which consist of several grasping movements directed toward different target objects. Twenty participants were asked to perform a sequence in which they grasped a cylinder, placed it into a target area and subsequently grasped and displaced a target bar of a certain orientation. We specifically tested whether the orientation of the target bar being grasped in the last movement segment influenced the grip orientation adapted to grasp and place the cylinder in the preceding segments. When all movement segments within in sequence were easy to perform, results indeed showed that grip orientation chosen in the early movement segments depended on the forthcoming motor demands, suggesting a holistic planning process. In contrast, high accuracy demands in specifying a movement segment reduced the ability of the motor system to plan and organize the movement sequence into larger chunks, thus causing a shift toward sequential performance. Additionally, making the placing task more difficult resulted in prolonged reaction times and increased the movement times of all other movement segments.

Introduction

Most studies investigating the characteristics of grasping movements look at the kinematics of single discrete movements executed under specific circumstances. From these studies, it is well known that grasping kinematics vary depending on the object's properties such as, for instance, its shape (Jeannerod, 1984; Cuijpers, Smeets, & Brenner, 2004), weight (Weir, MacKenzie, Marteniuk, Cargoe, & Fraser, 1991; Johansson & Westling, 1988), fragility (Savelsbergh, Steenbergen, & vanderKamp, 1996), and texture (Weir, MacKenzie, Marteniuk, & Cargoe, 1991). In comparison, there are only few studies which examine the alterations of grasping movements embedded into a larger action context - as they usually occur in our daily life. More specifically, the question here is whether reaching and grasping movements directed toward an object depend on the intention for which the object is grasped, and on the properties of subsequent action segments.

The first evidence that action sequences are not planned and executed as a succession of distinct and independent movement parts came from co–articulation studies investigating speech production (e.g., Fowler, 1980). In these studies it was shown that the articulation of one phoneme is affected by the identity of the upcoming phonemes (for overview see, Rosenbaum, 1991). Following this line of research several studies have examined the influence of the "action context", which is defined by forthcoming movements and/or the intended goal of an action, also on the movement kinematics in reaching and grasping (e.g., Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987; Gentilucci, Negrotti, & Gangitano, 1997; Haggard, 1998; Johnson-Frey, McCarty, & Keen, 2004; Armbrüster & Spijkers, 2006; Ansuini, Giosa, Turella, Altoe, & Castiello, 2008). These studies have shown relatively consistently that grasping movements are not planned in isolation but are altered by the anticipation of future task demands. For example, in the early study of Marteniuk et al. (1987) it was demonstrated that initial grasping kinematics varied depending on whether the grasped disc had to be thrown away or had to be fitted into a similarly sized opening. Both the movement time and the deceleration phase of the movement were especially altered by the type of consecutive action (for similar results, see also Armbrüster and Spijkers, 2006). From these findings it was concluded that the precision requirements of the end–goal modify movement kinematics. In a later study, Gentilucci et al. (1997) showed that initial reach–to-grasp movements were also affected by the distance of a second target, further supporting the notion of a general action plan. Complementary to this, it was demonstrated that not only the initial grasp pre–shaping did depend on the type of subsequent behavior, but that the placing of the fingers on the object also varied depending on the future task demands (Ansuini, Santello, Massaccesi, & Castiello, 2006; Ansuini et al., 2008).

Taken together, it hardly seems a disputed fact that grasping kinematics are modified by the action context. More generally, these action context effects are considered as indication that the CNS plans movement sequences holistically and in advance. Yet the issues of why humans plan actions in advance and what exactly is planned ahead of the impending movement remain relatively unclear. Some experiments of Rosenbaum and colleagues addressed these questions in more detail (e.g., Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992; Cohen & Rosenbaum, 2004). The basic finding of these studies revealed that participants prefer grips that allow them to complete the movement such that all joints are in mid–range at the end of the final transport movement (end–state comfort). For example, they observed that the grasp height of a cylinder was inversely related to the height of the location where the cylinder had to be placed (Cohen & Rosenbaum, 2004). Moreover, adopting the strategy of end–state comfort sometimes resulted in initially highly awkward (underhand) grips of an object for the sake of more easily controlled final postures. Hence, it was assumed that people select movements which minimize fatigue and maximize comfort of the entire action and which are optimal according to some weighted combination of all relevant costs (Rosenbaum, Meulenbrook, & Vaughan, 1996; Haggard, 1998). Interestingly, advance planning does not seem to be limited to the movement segment that immediately follows. Haggard (1998) showed that advance planning is a longer lasting phenomenon that can be observed even in the second and third movement of an action sequence.

All studies presented in the last paragraphs investigated the modification of grasping kinematics when grasping an object with varying action intentions and performing a subsequent action with the very same object. The question arises whether action sequences are also planned holistically when different target objects and several subtasks are involved. Therefore, in our study we asked participants to perform an action sequence which consisted of three movement parts and included two different target objects. In the sequence participants grasped a cylinder, moved and placed it in a target area, and subsequently grasped a target bar. We varied the orientation of the target bar grasped at the end of the movement sequence between trials. We were interested in the effect of the target bar orientation on the grip orientation in the preceding movement segments. Since grasping the cylinder does not require a certain grip orientation, we hypothesized that the grip orientation chosen to grasp (and release) the cylinder might be affected by the target bar orientation. Incorporating the bar orientation in earlier movement segments would in turn indicate that future task demands are taken into account early during sequence planning and execution. In addition, we varied the difficulty of the placing task in the second movement segment. The target cylinder had to be placed either very accurately (difficult) or more sloppily (easy) into the placing area. Using this variation we addressed two further issues: First, studies on sequence effects in pointing showed that the difficulty of one segment determines how the motor system treats adjacent segments of this sequence (Rand & Stelmach, 2000). That is, reaction time (RT) and movement times (MT) of earlier movement segments are influenced by the difficulty of a later movement segments. In our study we were interested in whether these effects also persist in situations which consist of a sequence of grasping movements directed to different target objects. Second, we hypothesized that introducing a difficult placing task might prevent the motor system from planning the action sequence holistically. Recently, we showed that introducing a difficult subtask, as for example moving over a via–position, causes sequential performance in grasping (Hesse & Deubel, in press). Based on these findings we would predict that if one movement segment is very difficult, thus capturing excessive attentional (planning) resources, the global planning process is sequenced into concatenated but independently planned and executed motor components.

Experiment 1

Methods

Participants

Twenty undergraduate and graduate students of the Ludwig–Maximilians–University Munich (six men, fourteen women; mean age = 28, age range: 21–51) participated in the experiment. They were paid 8 Euro per hour of participation. All participants were right–handed by self report, had normal or corrected-to-normal visual acuity, and were naive with respect to the purpose of the study. The experiments were done with the understanding and written consent of each participant and conformed to the Declaration of Helsinki.

Apparatus and stimuli

Two different objects made of wood served as target stimuli. One of the objects was a red cylinder with a circular base, a diameter of 4.0 cm, and a height of 5.5 cm. The other object was a black bar (the target bar) with a length of 5 cm and a width and depth of 2 cm. A wooden board (72 x 50 cm) placed on the tabletop served as presentation surface for the stimuli. On this board four positions were marked (see Figure 1): 1) the start position, 2) the home position of the cylinder, 3) the placing area for the cylinder and 4) the home position for the bar. The distance from one position to the next was always 20 cm. On each trial, both objects were placed at their home positions marked with a short pin upon which the objects were affixed. The target bar could be place in one of three orientations: -45°, 0°, or +45°with respect to the participants' midline. Trajectories of the grasping movements were recorded using a Polhemus Liberty electromagnetic motion tracking system at a sampling rate of 240 Hz. The Polhemus Liberty tracking system provides complete 6-degrees-of-freedom (position and orientation) information at a static accuracy of 0.8 mm RMS for the x, y, z position and 0.15 deg for sensor orientation. Polhemus sensors were attached to the nails of the thumb and the index finger of the right hand (using adhesive pastels: UHU-patafix, UHU GmbH, Bühl, Germany and medical tape). An additional sensor was attached to the back of the hand in order to measure the transport component of the movement (wrist marker). Prior to the experiment a calibration procedure was used to align the Cartesian coordinate system (x,y,z) of the Polhemus system such that the start position on the board corresponded with the point of origin (0,0,0). Also, the orientation signals of the sensors attached to index finger and thumb were calibrated to a standard orientation. By considering the individual thickness of index finger and thumb, the orientation information allowed us to calculate the grasp touch points of thumb and index finger relative to the sensors for each sample recorded during the experiment. During the experiment, participants wore liquid–crystal shutter glasses (Milgram, 1987), which rapidly suppress vision by changing from a transparent to an opaque state.

Procedure

Participants sat comfortably on an adjustable chair in a well–lit room. A chin rest was used to maintain a constant head position throughout the experiment. Before starting the experiment, six practice trials were executed to familiarize the participant with the task. At the beginning of each trial, participants placed their hand at the starting position (marked by a small pin) and the shutter glasses turned opaque. Subsequently, the experimenter placed the cylinder and the bar (in a certain orientation) at their home positions. After the experimenter had placed both target objects, he/she initiated the trial manually by pressing a key. When the shutter glasses became transparent participants looked at the objects in the workspace. After this preview period which lasted for 1 s, an auditory signal with a duration of 100 ms cued the participants to start their movement. Participants were instructed to execute a movement sequence which was composed of three steps (see Figure 1). In the first segment of the action they moved from the start position towards the home position of the cylinder and grasped it (movement segment S1); in the second segment they had to position the cylinder in the placing area, either very accurately or sloppily (S2); and in the third movement segment participants had to grasp the target bar along the 5 cm axis (S3). They were to lift the bar and to put it roughly in the middle of the working space on the table. Thereafter, they moved their hand back to the starting position. The shutter glasses remained transparent during the entire grasping sequence so that participants had full vision of their hand and the target objects. After four seconds, the shutter glasses turned opaque and the experimenter returned the objects and prepared the next trial.

The orientation of the target bar (-45°, 0°, or +45°) was determined randomly in each trial. Furthermore, we varied the accuracy with which participants had to position the cylinder in the placing area (indicated by a colored paper circle); in the accurate conditions (*difficult*) the cylinder had to be placed in a circular field with a diameter of 4.5 cm (0.5 cm larger than the diameter of the cylinder) and in the sloppy conditions (*easy*) the placing area had a diameter of 6.0 cm. After each trial the experimenter who was sitting next to the participant checked whether the cylinder was placed correctly. If not, the trial was marked as an error trial and repeated later in the experiment at a random moment. The accuracy conditions were performed in blocks, and blocks were counterbalanced across participants. Each bar orientation (left, vertical, right) was presented 10 times in each block resulting in a total of 60 trials.

Participants were instructed to initiate and perform the movement sequence as fast as possible while still maintaining their accuracy. Additionally, participants were required to grasp both objects, the cylinder as well as the target bar, with index finger and thumb only (precision grip).

Insert Figure 1 about here

Data Processing

The finger trajectories were filtered off-line using a second-order Butterworth filter that employed a low-pass cut–off frequency of 15 Hz. Movement onset was defined by a velocity criterion. The first frame in which the wrist exceeded a velocity threshold of 0.1 m/s was taken as movement onset. Reaction time (RT) was defined as the time between the auditory signal and movement onset. The end of each movement segment was defined by a spatial criterion plus the velocity of the wrist. When both fingers were in close vicinity to the object positions or the placing area respectively i.e. each finger was less than 3 cm away from the middle of the relevant target position, the frame containing minimum wrist velocity was taken as the end of the corresponding movement segment. Movement time (MT1) for the first segment was defined as the time between movement onset and the first minimum in wrist velocity; the movement times of the other segments were determined by the time between two minima in wrist velocity (for illustration see Figure 2).

Insert Figure 2 about here

Moreover, parameters of the grip aperture profile (difference between index finger and thumb) were analyzed. As the task primarily involved horizontal movements and only the horizontal orientation of the target bar was manipulated, we only analyzed the horizontal orientation of the hand (see also Hesse, deGrave, Franz, Brenner, & Smeets, 2008). Grip orientation is defined as the angle of the horizontal projection of the line connecting the grasping positions of the index finger and the thumb (a sagittal line corresponds to a 0^o orientation of the grip and a clockwise rotation is defined as positive). This angle was determined at movement onset and at the end of each movement segment, i.e. at the end of S1 when the cylinder was touched, at the end of S2 when the cylinder was placed, and at the end of S3 when the target bar was grasped (Figure 2).

The data was analyzed using repeated measures analysis of variance (3x2 ANOVA) with the factors bar orientation (left, vertical, right) and placing difficulty (easy, difficult). Dependent variables were RT, MTs, and the orientation of the hand at different moments in time. If the sphericity assumption was violated and the factor had more than two levels we applied the Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) resulting in a more conservative testing. Post-hoc contrasts were carried out using Fisher's LSD (least significant difference) testing procedure. A significance level of α=0.05 was used for the statistical analyses. Values are presented as means ± standard errors of the mean.

Results

Grip orientation

Our main interest was in the influence of the orientation of the target bar (second object) grasped at the end of S3 on earlier movement segments, i.e. the grip orientation when grasping (S1) and releasing (S2) the target cylinder (first object). Furthermore, we had hypothesized that these effects might differ depending on the difficulty of the placing task. To test these predictions, we analyzed the grip orientation at movement onset and at the end of each movement segment dependent on the orientation of the target bar and the difficulty of the placing task. A 3 (bar orientation: -45^o, 0^o, 45^o) x 2 (placing difficulty: easy/difficult) repeated–measures ANOVA was performed at four different moments during the task (movement onset, end of S1, end of S2, and end of S3). Each panel of Figure 3 shows the grip orientation at one of these moments in time. At movement onset, grip orientation was not affected significantly by the orientation of the target bar, *F*(2,38)=0.24, *p*=.75, therefore excluding the possibility the participants adjusted their grip during the preview period. There was also no effect of placing difficulty and no interaction (both *p*>.20). Quite surprisingly, when grasping the cylinder in the first movement segment (S1), grip orientation was already affected by the orientation of the target bar (-6.1°± 4.7°for the left oriented bar, -0.1°± 3.0°for the vertically oriented bar, and 6.6°± 3.5°for the right oriented bar), *F*(2,38)=6.0, *p*=.02. Post–hoc tests indicated that all conditions differed significantly from each other (all *p*<.05). Additionally we observed a significant main effect of placing difficulty on grip orientation, *F*(1,19)=6.7, *p*=.02, but no interaction (*p*=.23). When the cylinder had to be placed more accurately (difficult condition) the grip was slightly more oriented to the left. Figure 4 shows the mean grip orientations in the different conditions for two representative participants. Although both participants showed the same effect (rotation of the grip orientation according to the orientation of the target bar), the preferred grip orientation varied slightly.

Insert Figure 3 about here

The effect of target bar orientation on grip orientation persisted at the moment the second movement segment was finished and the cylinder was placed in the target area (11.5°± 4.7° for the left oriented target bar, 17.5°± 2.7° for the vertically oriented target bar, and 24.2°± 2.5°for the right oriented target bar), *F*(2,38)=7.2, *p*=.01. Again post–hoc tests confirmed significant differences between all conditions (all *p*<.02). There was again a significant effect of placing difficulty on grip orientation when placing the cylinder, *F*(1,19)=15.8, *p*=.001. As in the first segment, the grip was on average more oriented to the left when the placing of the cylinder was more difficult. There was no interaction (*p*=.54). Finally, as expected, when the target bar was grasped at the end of S3 the grip orientation corresponded to the final orientation of the target bar (see Figure 3d), *F*(2,38)=2068, *p*<.001. At this point in time there was no remaining effect of placing accuracy on grip orientation and no interaction effect (both *p*<.10).

Insert Figure 4 about here

In summary, we observed a significant effect of target bar orientation on the grip orientation applied to grasp and place an object in earlier movement parts. Contrary to our expectations, this effect was not only found when the placing of the second object was easy but also in the difficult conditions. Additionally, the selected grip orientation differed depending on the difficulty of the placing task.

RT and MTs

To test whether RT and MTs of the different movement segments were affected by the difficulty of the placing task and by the orientation of the target bar, we applied a 3 (bar orientation: -45^o, 0^o, 45^o) x 2 (placing difficulty: easy/difficult) repeated–measures ANOVA. Figure 5c shows that, as expected, MTs were considerably longer when the placing of the cylinder was more difficult (S2), *F*(1,19)=90.8, *p*<.001. There was no effect of bar orientation and no interaction (both *p*>.18). Interestingly, the MTs of the segments preceding and following the placing of the cylinder were also affected by the difficulty of the placing task, *F*(1,19)=23.1, *p*<.001 in S1, and, *F*(1,19)=32.2, *p*<.001, in S3 (see Figure 5b and 5d). In the last segment (S3) when grasping the target bar, MT was also influenced by target orientation, *F*(2,38)=23.8, *p*<.001, indicating that it took participants longer to grasped the left oriented bar. All other main effects and interactions were not significant (all *p*>.14). Thus, when the difficulty of one movement segment increased the whole action sequence slowed down.

Regarding the RT of the movement we also observed a significant effect of placing difficulty, *F*(1,19)=6.2, *p*<.02, indicating a more demanding planning process for the more difficult movement sequence. In the easy condition it took participants on average 242*ms*±13*ms* to initiate the movement, and in the difficult condition movement onset was determined after 260*ms*±12*ms*. There was no main effect of bar orientation and no interaction effect (both *p*>.42).

Insert Figure 5 about here

Experiment 2

We had hypothesized that the effect of subsequent movement segments on the kinematics of preceding movement segments may be diminished when one part of the sequence is very difficult to perform. The rationale for this prediction was the assumption that a very difficult sub–task captures more planning resources, therefore preventing the early integration of future action demands.

In a recent study (Hesse & Deubel, in press) we showed that a single grasping movement becomes organized into two separate movement parts (indicated by a delayed aperture pre–shaping), when participants have to perform a difficult subtask while grasping. Therefore, we expected that the planning of a movement sequence containing a difficult movement part may no longer be carried out holistically but in independent motor steps. However, in the previous experiment we found no evidence for this prediction since the effect of the target bar orientation on grip orientations was of similar size independent of the required placing accuracy in S2. Since the placing task in our *difficult* condition was still relatively simple (the placing are was 5 mm larger than the object) we decided to run a second experiment introducing a more demanding placing task.

Methods and Procedure

Sixteen undergraduate and graduate students of the Ludwig–Maximilians–University Munich (eight men, eight women; mean age = 27, age range: 19–47) participated in the experiment (six of them had also participated in Experiment 1). All participants were right–handed by self report, had normal or corrected-to-normal visual acuity, and were naive with respect to the purpose of the study.

The apparatus and the stimuli were identical to that used in Experiment 1, and the general procedure was similar. The only difference was that in the end of the second movement segment, participants had to put the cylinder upon a short pin which was mounted in the center of the placing area of Experiment 1.

The experiment consisted of 30 trials, i.e. 10 trials per target bar orientation (left/vertical/right) which occurred in random order. All data was analyzed identical to Experiment 1. Data were tested for statistical significance using repeated-measures ANOVA with the factor bar orientation (left/vertical/right).

Results

Our main interest was again in the grip orientation at the end of each movement segment. The repeated–measures ANOVA applied at different moments during the action sequence revealed no significant effect of target bar orientation on grip orientation at movement onset, $F(2,30)=1.2$, $p=.33$, and no effect at the moment the cylinder was grasped (S1), $F(2,30)=0.9$, $p=.41$. The mean grip orientation at the end of the first movement segment was $3.9^{\circ} \pm 3.3^{\circ}$ (Figure 6). Thus, contrary to Experiment 1, no effect of target bar orientation on grip orientation was observed at end of the first movement segment. At the moment the cylinder was placed upon the pin (S2) we observed a marginal effect of target bar orientation on grip orientation, $F(2,30)=3.3$, $p=.05$, indicating that the grip was rotated a bit more counterclockwise when the target bar was oriented to the left ($18.4^{\circ} \pm 2.9^{\circ}$). Post–hoc tests revealed no difference in grip orientation for the vertical ($19.5^{\circ} \pm 2.9^{\circ}$) and right oriented bar ($19.4^{\circ} \pm 3.0^{\circ}$). Finally, when grasping the bar at the end of S3, the grip orientation adapted to the target bar orientation, $F(2,30)=3144$, $p<.001$.

Insert Figure 6 about here

Regarding MTs, we found no effect of target bar orientation on the MTs in S1 and S2 (both $p>.30$). On average it took participants 539*ms*±26*ms* to grasp the cylinder in S1, and 949*ms*±36*ms* to affix the cylinder upon the pin in S2. Thus, the MT of S2 was considerably slower than in Experiment 1. As in the previous experiment the MTs of S3 were influenced by the bar orientation resulting in slower MTs when the bar was oriented to the left $F(2,30)=6.9$, $p=.004$. On average it took participants 941*ms*±34*ms* to grasp the bar in S3 when in was oriented to the right, 957*ms*±31*ms* when the bar was oriented vertically, and 1055*ms*±41*ms* when the bar was oriented to the left. Again there was no effect of target bar orientation on RT, $F(2,30)=0.4$, $p=.66$. Average RT was 250*ms*±10*ms*.

General Discussion

Our study investigated whether the planning and execution of early movement segments within an action sequence are influenced by specific task demands - such as orientation of the grasping hand - of later movement segments. We were especially interested in whether these action context effects, which indicate a global planning process, transfer to situations with several pick-and-place subtasks in which more than one target object are involved. Also, we wondered whether, and if so, how the execution of a movement sequence is affected by an increase of the accuracy required for a single motor act within the sequence.

Planning pick–and–place sequences in advance

The results show that grip orientations chosen to grasp and release an object in the early movement segments were affected by the orientation of the target object which had to be grasped in the very last movement segment. The modification of the grip orientation indicates that the reach–to–grasp movements were not performed in isolation but that the whole action sequence was planned in advance in a holistic manner, taking into account the predicted hand orientation that would be adopted several steps in the future. The findings are well compatible with a prominent model of reach–to–grasp planning by David Rosenbaum and colleagues (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). In their posture–based motion planning approach, they propose that movement planning works by first specifying a goal posture and then by specifying a movement to this goal posture. They also assume that movements can be shaped through superposition, i.e. by allowing for simultaneous movements, even in the same effector. In the context of our findings, one may argue that a continuous rotation of the hand to the orientation that is required for the final grasp is superimposed with transport and grip movements of the initial pick-and-place task. However, this assumption would predict that the context effect should be higher at the end of the second segment that at the first segment. This is not the case, as can be seen in the slopes of the curves shown in Figure 3.

There is also an alternative view on the interpretation of the data. So far we have considered the data as an indication of a global planning process carried out by the CNS as part of the movement plan in order to perform an optimal, fluent action. On the other hand, there is some evidence that the mere presence of additional "distractor" objects in the workspace produces automatic interference effects on movement kinematics (e.g., Jackson, Jackson, & Rosicky, 1995). For instance, objects in the visual field were found to elicit competing grasping pattern that cause interference leading to a modulation of the hand shaping during the reach (for review see Castiello, 1999). The phenomenon also corresponds to several neuropsychological studies demonstrating that the mere presence of objects automatically activates associated motor representations in the brain (e.g., Chao & Martin, 2000; Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Grèzes, Tucker, Armony, Ellis, & Passingham, 2003). Consequently, one could argue that the changes of grip orientation observed in our study are due to such automatic motor priming effects, resulting from the simultaneous activation of a movement plan for the cylinder and a movement plan for grasping the bar. Based on the current data we cannot decide which of both alternatives is more likely. In our view, both interpretations (intentional vs. a unintentional effect) are not mutually exclusive, though. In fact, "movement interference" might be an useful mechanism of the CNS in order to plan and execute an optimal movement when action sequences are required.

We also examined the effects of changing the difficulty of an in–between movement segment on RT and MTs. When one part of the sequence was made more difficult, the MTs increased in all preceding and following movement segments. The fact that movement duration varies with movement difficulty is in line with the basic predictions of Fitts' Law (Fitts, 1954). Our results demonstrate that the modulatory effect on movement times transfers also to the adjacent movement segments. This parallels findings obtained in reaching studies indicating that successive segments share similar spatial and temporal characteristics, which in turn gives evidence that consecutive segments are planned and organized in some combined manner (Rand & Stelmach, 2000). Additionally, in our study the RT time increased when a more difficult movement segment was inserted. A similar compensation for action difficulty, i.e. an increase in RT, was observed in studies investigating pointing sequences (e.g., Sidaway, Schoenfelder-Zohdi, & Moore, 1990; Rand & Stelmach, 2005). It was proposed that the relation between RT and complexity of an action gives evidence that the whole action sequence is planned in advance and stored internally before any movement occurs (e.g., Sternberg, Monsell, Knoll, & Wright, 1978). Thus, an action sequence containing a difficult movement segment seems to require a more demanding planning process for the entire action. The findings from our study generalize these previous reports to the case of sequences of more complex pick-and-place tasks, and show that the modulation of movement time extends to both the previous and the subsequent movement segments.

Effect of movement segment difficulty on holistic planning

Our second experiment showed that the grip orientation chosen in the early movement segments was no longer affected by the grip orientation needed to grasp the final object when the in–between task (placing of the cylinder) was very difficult. There are two, though not mutually exclusive explanations for this finding. First, the introduction of a very difficult in-between movement task may capture extensive planning and programming resources of the motor system, therefore preventing a global processing of the action task. The higher demand in specifying an accurate movement termination may reduce the capacity of the motor planning to organize the movement sequence into larger "chunks", linking the adjacent segments functionally. Consequently, an early end–goal oriented planning process is no longer possible, causing a shift toward sequential performance. This explanation is in line with our previous findings showing a segmentation effect in grasp pre–shaping when a difficult subtask was introduced (Hesse & Deubel, in press). A similar phenomenon was observed by Rand and Stelmach (2000) in a study on sequential aiming movements; when the accuracy demands were low, movement durations and peak velocities of adjacent segments were interrelated. This interdependency was reduced or eliminated in tasks with high (spatial) accuracy demands.

The second possibility is that the disappearance of the context effect is due to the break of the action sequence. Putting the cylinder on a pin requires a short stop in movement. In a recent study, Ansuini, Grigis, Massaccesi, and Castiello (2009) investigated the effect of voluntary interruption of a composite motor sequence (grasping an object and pouring its contents into a container). They showed that when motor fluency was prevented, the action sequence was no longer planned based on the end–goal but was executed in discrete and independent action steps. From this finding they concluded that temporal contiguity between motor steps is essential to execute a fluent action sequence. The same argument could hold for our experiment meaning that the action was sequentialized because the temporal structure of the movement was disrupted. Further research is needed to clarify which of these alternatives is valid.

Visual attention in movement sequence planning

In most actions that we perform in everyday life, many objects are present in the environment toward which actions can be potentially directed. Therefore, it is essential for the sensorimotor system to have the capacity to link the planned action selectively with particular objects. Planning sequential, goal–directed movements thus presupposes that all action-relevant objects are attended to at a certain time during movement preparation, allowing the selective visual processing of those object attributes that are action–relevant, such as location, size, and orientation. Indeed, recent investigations have provided striking evidence that before the execution of actions requiring the consideration of more than a single action goal, all action-relevant objects are simultaneously attended. Baldauf and colleagues (Baldauf, Wolf, & Deubel, 2006; Baldauf & Deubel, 2009) for instance studied the deployment of visual attention during the preparation of consecutive manual reaches directed to two or three goals. Their results demonstrate that attention during planning spreads to all action–relevant movement goals. This occurs temporally in parallel, with the amount of perceptual enhancement reflecting the serial order of the required movements. Also, when observers plan to grasp an object, experimental results have demonstrated that perceptual resources are biased toward those locations on the object that will be grasped (Schiegg, Deubel, & Schneider, 2003; Deubel & Schneider, 2004). These studies provide evidence for the assumption that the planning of a complex movement enacts the formation of an "attentional landscape" which tags those locations in the visual lay–out that are relevant for the impending action.

Advance planning of grasping actions in the brain

Neurophysiological evidence from both subcortical and cortical areas also suggests that movement sequences are planned holistically. It was found that neurons in the basal ganglia showed different activation patterns depending on whether a monkey knew an entire movement sequence in advance or performed the same sequence as successive and discrete movement parts (Mushiake & Strick, 1995). As to cortical processing, three specific areas related to grasping have been identified in the monkey cortex: the primary motor cortex (F1), the premotor cortex, the premotor cortex (F5), and the anterior intraparietal sulcus (AIP). Specifically, areas F5 and AIP seem to be involved in a transformation of the intrinsic (visually defined) properties of the to–be–grasped object into appropriate motor actions (Jeannerod, Arbib, Rizzolatti, & Sakata, 1995). Neurons in both areas were found to code for grasping actions that relate to the type of object to be grasped (Murata, Gallese, Luppino, Kaseda, & Sakata, 2000). However, while F5 neurons seem to be concerned with the impending segment of the movement, AIP neurons seem to represent the entire action. For example, Fogassi et al. (2005) reported that a large majority of units in monkey AIP being activated during planning and execution of a grasping movement were strongly influenced by the subsequent motor act. They proposed that single neurons in AIP, more specifically, in area PFG, are selective not just to the current grasping action, but also to the subsequent movements to be performed. This suggests that AIP may represent action goals at a hierarchically higher level, rather than single grasps, providing a neural mechanism for the context effects studied here.

Functional imaging data also suggests that AIP has a role beyond simple grasping. Findings show that the presumed human homologue of AIP is not only activated by object grasping and manipulation, but also by observation of other's grasping movements, and even by the passive viewing of graspable objects - especially of tools that have strong affordances for a complex series of hand actions (Culham & Kanwisher, 2001; Culham, Cavina-Pratesi, & Singhal, 2006). Importantly for the scope of our findings, the question also arises whether the parietal cortex can represent multiple spatial goal positions in parallel. Recently, Baldauf, Cui, and Andersen (2008) recorded from single neurons in the monkey's parietal reach region while they were preparing a sequential reach movement to two peripheral targets. The authors found that most of the cells encoded both the immediately impending reach goal and the subsequent goal. This implies that cells in AIP encode several, action-relevant goals of the planned hand movement sequence in parallel. In line with this reasoning, Culham, Cavanagh, & Kanwisher, 2001 reported in functional imaging studies a gradual increase of parietal BOLD responses by parametrically varying the attentional load in a multiple-object tracking task. Taken together, all this suggests that the parietal cortex can indeed simultaneously represent multiple attended locations in space.

Conclusions

Our study has provided further evidence that people plan their actions well in advance. Forthcoming motor demands such as the prospective orientation of the fingers in a precision grasp are taken into account and become integrated strikingly early in the movement sequence, even when several movement segments and different target objects are involved. However, when one of the movement segments is spatially more demanding, it seems that the functional linkage between the successive movements is weakened, leading to an organization of the movement in separate, rather independent elements. Taken together, our data support the notion that the planning and fluent execution of sequential manipulative actions is based on the functional demands of the entire task (see also Marteniuk et al., 1987), arguing in favor of an important role of anticipatory control in manipulative skills.

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Figure Legends

Figure 1. Schematic drawing of the experimental set–up (top view).

Figure 2. Example of a typical wrist velocity profile (a) and the corresponding grip aperture profile (b) obtained in a single trial. Vertical lines indicate the beginning and end of each movement segment as determined by our calculation routine. At each of these moments in time, horizontal grip orientation was computed (visualized by the alpha sign). c) Grip orientation (α) was measured as the angle of the horizontal projection of the line connecting the grasping positions of the index finger and the thumb.

Figure 3. Experiment 1: Grip orientation (in degrees) as a function of bar orientation in S3, and placing difficulty in S2 at four different moments in time: a) at movement onset, b) at the end of S1 when the cylinder is grasped, c) at the end of S2 when the cylinder is released and d) at the end of S3 when the bar is grasped. All error bars depict ± 1 SEM between subjects.

Figure 4. Data of two representative participants showing the average grip orientation adapted to grasp the cylinder in S1 (upper row) and to release the cylinder in the end of S2 (lower row). Examples are drawn from the *accurate* placing condition. The solid black line indicates the grip orientation chosen to grasp and release the cylinder when the bar was oriented to the -45° to the left, the gray line the grip orientation adapted when the bar was oriented vertically, and the dashed black line depicts the grip orientation chosen when the bar was oriented 45° to the right.

Figure 5. a) Reaction time (RT) as a function of bar orientation in S3, and placing difficulty in S2. b-d) Movement times (MTs) for the three movement segments as a function of bar orientation in S3 and placing difficulty in S2. All error bars depict ± 1 SEM between subjects.

Figure 6. Experiment 2: Grip orientation (in degrees) as a function of bar orientation in S3 at four different moments in time: a) at movement onset, b) at the end of S1 when the cylinder is grasped, c) at the end of S2 when the cylinder is put upon the pin and d) at the end of S3 when the bar is grasped. All error bars depict ± 1 SEM between subjects.

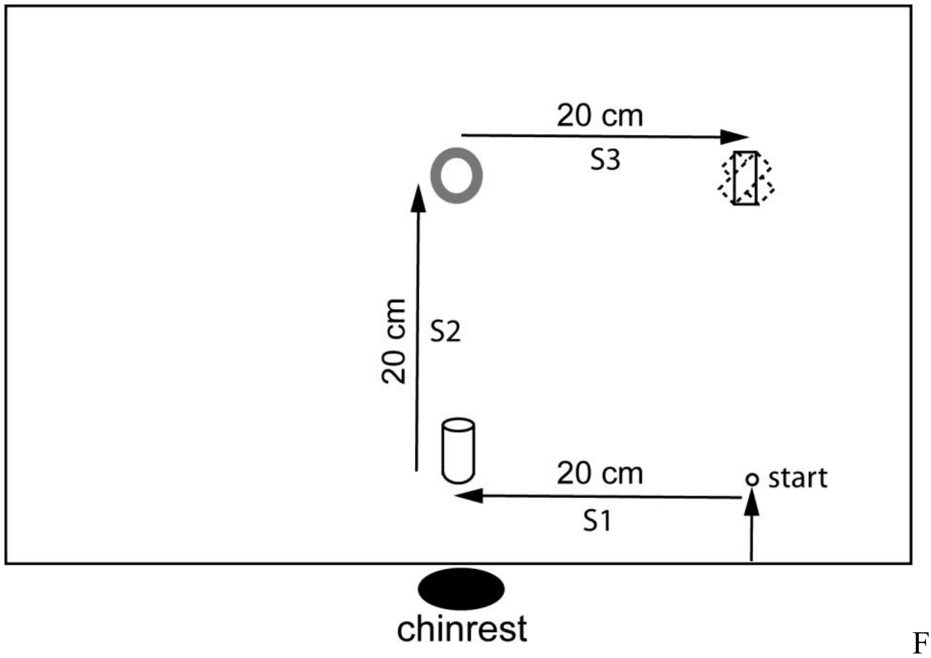

Figure 1

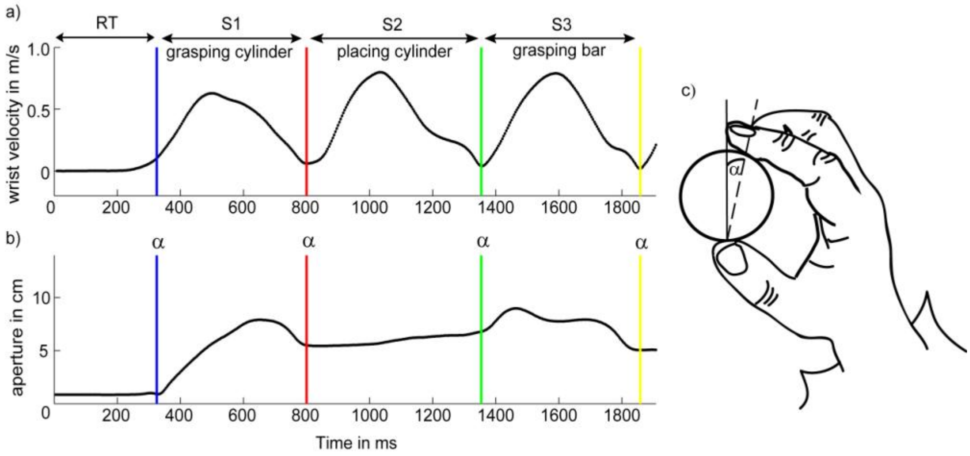
a)
RT
S1
grasping cylinder
S2
placing cylinder
S3
grasping bar
wrist velocity in m/s
1.0
0.5
0
0
200
400
600
800
1000
1200
1400
1600
1800
b)
α
α
α
α
aperture in cm
10
5
0
200
400
600
800
1000
1200
1400
1600
1800
Time in ms
c)
α

Figure 2

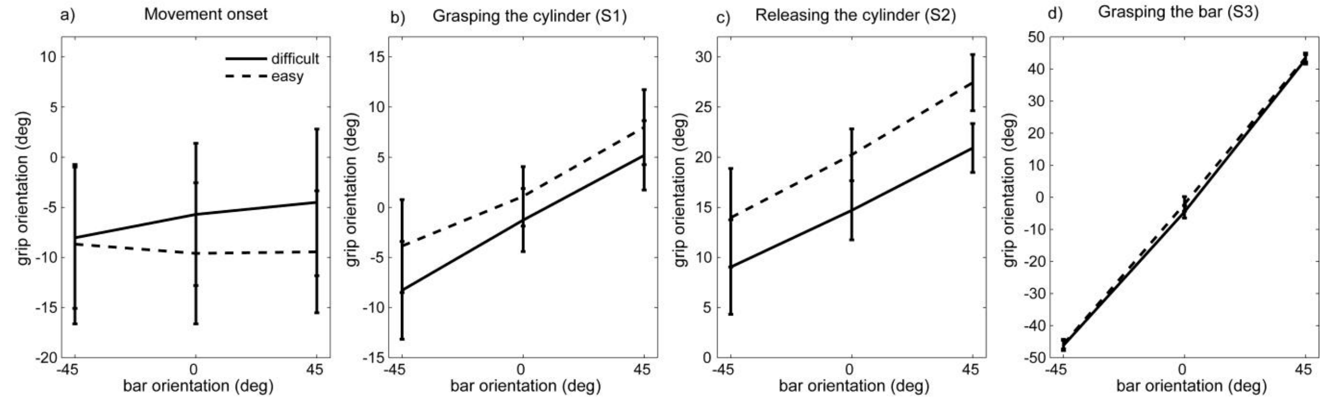
a)
Movement onset
difficult
easy
grip orientation (deg)
10
5
0
-5
-10
-15
-20
-45
0
45
bar orientation (deg)
b)
Grasping the cylinder (S1)
grip orientation (deg)
15
10
5
0
-5
-10
-15
-45
0
45
bar orientation (deg)
c)
Releasing the cylinder (S2)
grip orientation (deg)
30
25
20
15
10
5
0
-45
0
45
bar orientation (deg)
d)
Grasping the bar (S3)
grip orientation (deg)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-45
0
45
bar orientation (deg)

Figure 3

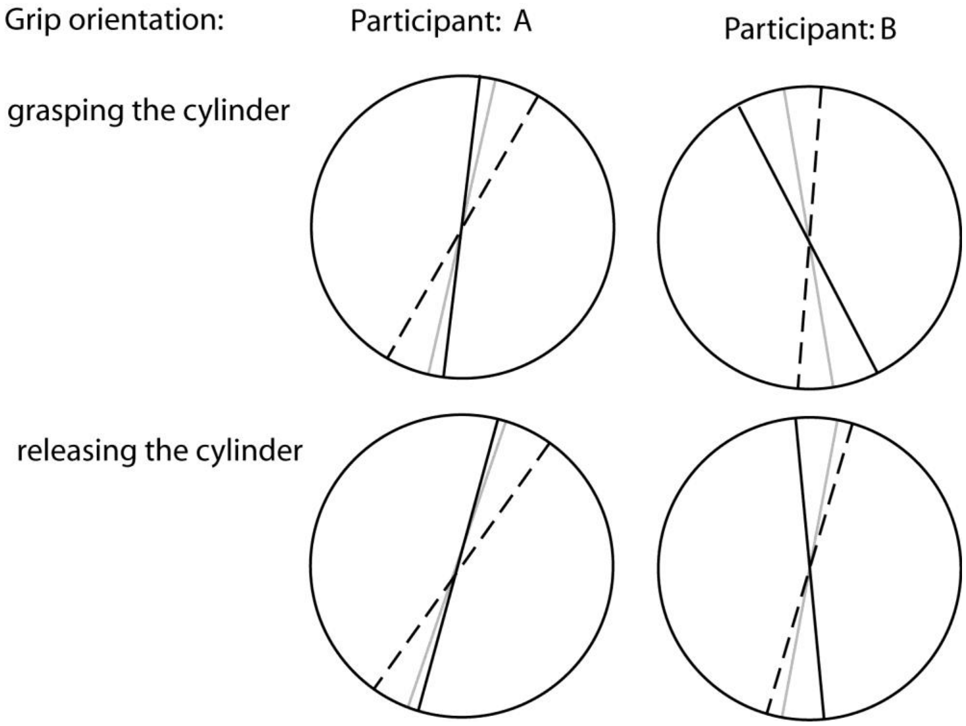
Grip orientation:
Participant: A
Participant: B
grasping the cylinder
releasing the cylinder

Figure 4

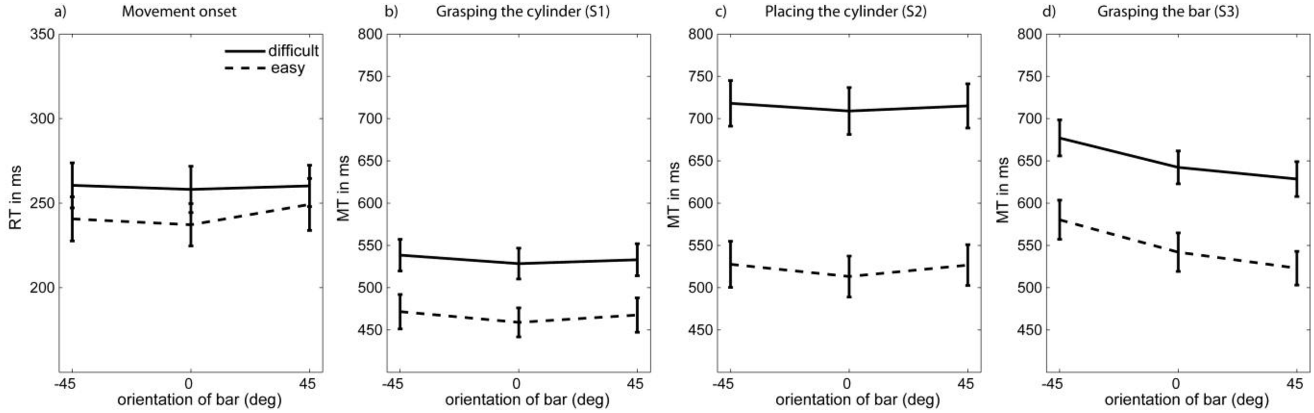
a)
Movement onset
b)
Grasping the cylinder (S1)
c)
Placing the cylinder (S2)
d)
Grasping the bar (S3)
difficult
easy
RT in ms
MT in ms
350
300
250
200
800
750
700
650
600
550
500
450
-45
0
45
orientation of bar (deg)

Figure 5

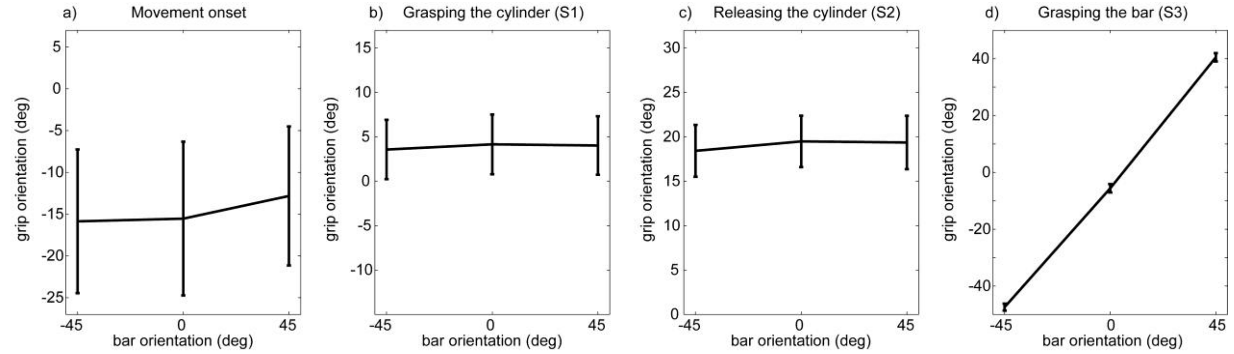
a) Movement onset
b) Grasping the cylinder (S1)
c) Releasing the cylinder (S2)
d) Grasping the bar (S3)
grip orientation (deg)
bar orientation (deg)
-45
0
45
5
0
-5
-10
-15
-20
-25
15
10
5
0
-5
-10
30
25
20
15
10
5
0
40
20
0
-20
-40

Figure 6

(submitted manuscript, please do not communicate)

Parallel and independent allocation of attention to eye and hand movement goals

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When people reach for objects, they tend to look where they reach. This raises the question of whether a common mechanism underlies the selection of saccade and reach goals in combined eye-hand movements. We used the deployment of visual attention as an index of movement target selection and asked observers to reach and look to separate locations while attentional allocation was measured with a perceptual discrimination task. We found parallel allocation of attention to both saccade and reach targets. Target selection for eye and hand interacted synergistically when both movements were directed to a common goal. Delaying the eye movement delayed the attentional shift to the saccade target while leaving attentional deployment to the reach goal unaffected. Together, our findings demonstrate a parallel and independent allocation of attentional resources to eye and hand movement targets during movement preparation and suggest that the goals for these effector systems are selected by separate mechanisms.

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When people reach for an object, their eye movements are organized into a pattern that helps to gather the information that is most important for reaching and manipulating that object[1,2]. Thus people tend to look where they reach[3]. An everyday environment contains many more objects than humans can perceive and act upon, and the observed eye-hand coupling raises the question of what selection mechanisms underlie these coordinated actions. One possibility is that eye-hand movement planning is based on a shared goal selection, resulting in eye-hand coupling at early stages of movement planning[4]. Alternatively, goal selection for eye and hand movements may be implemented separately, with coupling occurring at later stages of movement planning and execution[5].

To address this question we investigated how movement goals are selected before coordinated eye and hand movements. Attention is commonly regarded as a mechanism that selects particular objects for perception and action[7-9], and can be used as an index of target selection in early movement planning. We asked participants to make single or combined eye and hand movements to spatially separate targets while we measured attentional allocation in a secondary perceptual discrimination task. We measured attention at different times during movement planning, which allowed us to chart the temporal dynamics of attention shifts and to observe attentional costs or benefits at eye and hand movement targets.

Results

We first established that attention is allocated to movement goal locations before movement onset. In Experiment 1 (Single movements) participants either made a saccade to a centrally cued target (**Fig 1,** *Saccade-only* task), or they reached towards the cued target without looking at it (*Reach-only* task). We measured covert attentional allocation by briefly presenting a probe at either the movement goal, or at a movement-irrelevant location. Probe discrimination rate at both saccade and reach goals increased gradually before the movement (**Fig 2a**). In the *Saccade-only* task, improvement at the saccade target appeared at around 80 ms after movement cue onset (t(9)=3.30, p<0.01; from that time point probe discrimination was always better than chance, all p<0.05). In the *Reach-only* task, discrimination performance improved at around 140 ms after movement cue onset at the reach goal (t(10)=3.25, p=0.01). Immediately before the onset of the saccade (average latency 250 ± 6 ms) and the reaching movement (average latency 295 ± 12 ms), probe discrimination levels at saccade and reach goals were comparable (p>0.05). These findings demonstrate that, before the saccade or the reach starts, attention shifts to the location of the respective movement goal. In contrast, other locations to which no action was directed were not selected, and participants were at chance level to report probe identity at these locations.

We next asked how attention is distributed when two movements are planned concurrently. In Experiment 2 (combined movement task) participants had to make simultaneous eye and hand movements to two separate locations (with a few trials where both movements were directed to the same location), and we measured attentional allocation again by presenting a brief probe. Strikingly, probe discrimination performance increased at both saccade and reach goals (**Fig 2B**). Thus, before the saccade started (average saccade latency 288 ± 16 ms; average reach latency 300 ± 20 ms), probe discrimination rate was comparable at the saccade and the reach target (p>0.05), indicating that attention was allocated to both movement goals in parallel. This effect did not depend on whether eye and hand goals were close to each other or far away (see **Supplementary Fig 1** available online).

Having found evidence for the parallel allocation of attention to both movement targets, we next determined whether there was a cost (or benefit) in probe discrimination for the combined movement task in Experiment 2 in comparison to the single movement conditions of Experiment 1 (**Fig 3**). Discrimination performance at the saccade goal was not different when the participants made only a saccade as compared to making both a reach and a saccade (77% vs. 75%, p>0.05). The same held for discrimination performance at the reach goal when we compared single and dual movement tasks (73% vs. 72%, p>0.05). Thus, when simultaneous eye and hand movements are planned, there is no reduction in the attentional resources that are available for each of these two systems. This is surprising, given that it has been shown previously that planning a saccade seems to leave only few attentional resources for other, covertly attended locations[8]. However, it seems that preparing a second action - with another effector system - is not liable to this fundamental limitation. In a further experiment involving a same-different judgement task we confirmed that attention is indeed allocated *in parallel* to both movement targets (see **Supplementary note** available online).

We also observed that participants were better at discriminating the probes if both eye and hand movements were directed to the same location, as compared to making eye and hand movements to two different locations (**Fig 3**, rightmost bar; 75% vs. 85%, t(6)=-2.56, p=0.04 for probes at eye movement goal; 73% vs. 85%, t(6)=-3.44, p=0.01 for probes at reach goal). This increase in probe discrimination indicates that separate attentional resources are used in the selection of eye and hand targets.

We next asked to what degree the attentional selection of the saccade target and the reach target are dynamically independent. For this purpose we performed a median split of the data of each participant according to whether saccade latencies were short or long. Attention was allocated earlier to the saccade goal if saccade latency was short and later if latency was long. Faster (short latency) saccades started on average 112 ± 6 ms earlier than the slower saccades, and this temporal difference was also reflected in the time course of attentional allocation (**Fig 4A**). It took participants 105 ms longer to reach

75% correct probe discrimination if their saccade latencies were slower (determined by fitting probe discrimination for fast and slow latency saccades with a sigmoidal function). These results demonstrate the close relationship between attentional allocation and saccadic initiation.

In contrast, the time course of attentional allocation at the reach goal was the same for fast and slow latency saccades, and was thus independent from attentional allocation at the saccade location (**Fig 4B**). In other words, no matter how early or late attention was allocated to the saccade goal, this did not affect attentional allocation at the reach goal. Therefore, it cannot be argued that the parallel allocation of attention to saccade and reach goals is the result of a coupling of the signals to shift attention to those locations. Rather, the finding suggests that attentional allocation at both locations is dynamically independent.

Experiment 3 was aimed at confirming the dynamical independence of attentional allocation to eye and hand movement targets. In this task, two movement cues were presented one after the other – a first cue indicating the reach target, and a second cue indicating the saccade target. The cues appeared with a stimulus onset asynchrony (SOA) of 150 or 200 ms., There was no difference between probe discrimination rates at the reach goal for the two SOA condition (**Fig 5,** all $p>0.05$). By contrast, probe discrimination performance at the saccade target was modulated by the SOA. The later the saccade cue appeared, the later discrimination improved at the saccade target. If the saccade cue in one condition appeared 50 ms later (SOA=150 vs. SOA=200), discrimination at the saccade target rose above chance level 80 ms later, correspondingly.Notably, probe discrimination was better than chance at the saccade location for the 150 ms asynchrony condition, which was before the reach movement started (latency 272 ± 15 ms), meaning that the selection of the saccade goal was not delayed until after the reach started, and rather depended on the movement cue onset. These results demonstrate the temporal independence of attentional allocation to the two movement targets, and rule out the possibility that the parallel allocation of attention observed in our previous experiment was due to the pre-cueing of the saccade target.

Discussion

Although humans can easily coordinate eye and hand movements, the mechanisms underlying the selection of targets for these movements are relatively unknown. We addressed this question by asking participants to reach and look to different locations while we measured the allocation of visual attention to the movement goals. Strikingly, we found that when participants made simultaneous eye and hand movements to separate locations, attention was allocated in parallel at both locations, with no cost arising from the need to plan two movements instead of one. Therefore, even though eye and hand systems are linked, this is probably not due to attentional limits when selecting the targets for both movements. Furthermore, we demonstrated that delaying the eye movement led to an according delay in the attention shift to the corresponding target while leaving attentional deployment to the reach goal unaffected. This indicates that the attentional control mechanisms for eye and hand are dynamically independent. From these results we propose that separate, effector-specific attentional controllers might be involved in distributing visual attention to multiple task-relevant locations, instead of a single system. The finding that perceptual performance improves further when eye and hand are directed to the same spatial location further argues against explaining the results by a single attentional system that selects eye and hand movement targets.

In line with this assumption, our results show that before combined eye and hand movements are executed, attention is split and allocated in parallel at both the eye movement target and the reach goal. While classical theories of attention assumed a single focus of selection, multifocal attention has been demonstrated in various perceptual tasks, such as in multiple target tracking[10,11]. Moreover, recent studies have provided compelling evidence that multiple attention foci are also important during the preparation of complex goal-directed motor tasks in which several locations are relevant to the intended action. For example, studies in which observers prepared a sequence of eye or hand movements to two or three targets revealed that during sequence planning attention spreads in parallel to all action-relevant goals, establishing spatially separate attentional foci[12,13].

The suggestion that separate systems may be involved in movement goal selection is supported by neurophysiological studies which have suggested that separate regions in the posterior parietal cortex (PPC) are responsible for selecting targets for eye and hand movements, respectively[14,15]. Single cell recordings show that the majority of cells in the monkey parietal reach region (PRR) are active before memory-guided reaching movements, whereas the majority of cells in the adjacent lateral intraparietal (LIP) area are active before memory-guided saccades[16]. Similar specificity has been demonstrated in human parietal cortex, where posterior parts of the intraparietal area are found to be more selective to saccades whereas anterior parts are more selective to reaching and grasping[17-19]. Additionally, it has been shown that separate parietal regions are involved in decisions on whether eye or hand movements have to be performed[14].

The observed independence of target selection for saccades and reaching is unexpected given that a number of studies have reported coupling between eye and hand systems[5,6,20]. However, previous investigations have focused on indirect measures of target selection - latencies, trajectories and amplitudes of saccades and reaching movements - as measures of the coupling between eye and hand systems. Using probe discrimination task we directly measured attention, instead of relying on other measures. Note that crosstalk between eye and hand movements can still arise at later stages of movement planning. It has been demonstrated that information related to eye and hand movements is shared in a number of cortical and subcortical areas[21,22]. So, interactions observed in movement trajectories or latencies could still occur, but we propose that they occur at processing stages separate from (and probably later than) movement goal selection.

In conclusion, we here demonstrate that selective attention is allocated in parallel to the targets of eye and hand movements and propose that the attentional control mechanisms for these two effector systems are largely independent. This highlights the flexibility of the visuomotor system to simultaneously select and process multiple objects relevant for different actions, and suggests the existence of separate sources of signals related to target selection for different effectors.

Methods

Observers. Between six and eleven observers took part in each experiment. With the exception of one of the authors (DJ), all observers were naive with respect to the purpose of the study. They had normal or corrected-to-normal visual acuity, and their age ranged between 16 and 28 years (mean of 23 years).

Eye and hand movement recording. Participants sat in a dimly illuminated room with their right hand on a slightly inclined reaching plane, under a mirror. Stimuli for reaching movements and saccades were projected from a monitor above onto the mirror. This setup allowed the projected visual stimuli to appear on the reaching plane, while participants could not see the reaching hand. In order to provide visual feedback about the hand position a LED was fixed to the fingertip and could be switched on and off during the experiment. Stimuli were presented on a 21 inch Conrac 7550 C21 display with frame frequency of 100 Hz, at a display resolution of 1024*768 pixels. Visual stimuli were shown on a gray background with a mean luminance of 23 cd/m2.

Reaching movements were recorded with a Fastrack electromagnetic position and orientation measuring system (Polhemus Inc., 1993), consisting of a central transmitter unit and a small receiver which was mounted on the tip of the participant's right index finger. The device allows for a maximal 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. Eye movement were recorded with a video-based eye tracking system (SensoMotoric Instruments, Eyelink-I) with an accuracy of better than 0.1 degree. Head movements were minimized by an adjustable chin rest.

Experiment 1 - Single movements. Figure 1 depicts the stimulus sequence. During each trial a central fixation cross and twelve mask elements (size 0.9 x 1.4 deg, composed of randomly generated lines) were presented on a uniform gray background, arranged on an imaginary circle with a radius of 6.5 deg. Participants first directed the index finger of the right hand and their gaze to the central cross. 580 to 880 ms later, the central cross changed into an arrow which pointed towards one of the mask stimuli. In one version of the experiment participants made a saccade towards the cued location ("saccade-only" task), whereas in another version they reached with the index finger of the right hand to the cued location while maintaining central fixation ("reach-only" task). Participants were instructed to reach or look as fast as possible while still remaining accurate. Visual feedback about reaching accuracy on each trial was given 1500 ms later.

While performing the saccade or reaching task, participants had to detect a brief probe stimulus shown at any of the locations occupied by the mask elements. At a random time between 200 ms before movement cue onset and 600 ms after cue onset, 11 of the 12 mask stimuli abruptly changed into distractors (digital "2" or "5"), while one mask stimulus changed into the probe letter (digital "E" or "3"). The probe was presented for 80 ms and then was again masked. After finishing the eye or hand movement participants reported whether they had perceived an “E” or “3”. Responses were made non-speeded with the left hand on a response pad. After that button press the next trial started.

Each participant performed at least 4 experimental blocks of 192 trials each. During the block any of the 12 locations occupied by the mask stimuli could be used as the movement goal. On half of the trials the probe appeared at the movement goal (valid trials). On the other half of trials the probe was presented elsewhere (at one of the movement-irrelevant locations); however, the probe never appeared directly besides the movement goal.

Experiment 2 - Combined movements. Before the experiment, participants were informed about the saccade location which was kept constant (at clock positions of 2,4,8 or 10 o’clock) for a block of 190 trials. Stimuli were identical to the single movement experiment. When the movement cue appeared, participants were asked to make two movements simultaneously - a manual reach to the cued location and a saccade to the remembered location. We used a fixed saccade location because it is known that even when a saccade is planned to a known location, saccades are always preceded by attention shifts to the target[23]**.** We used three different spatial distances between the saccade and the reaching goals: the arrow instructing reaching could point to the location besides the saccade goal (“Distance 1”), to the location 3 elements away from the saccade goal (“Distance 3”), or to the location 5 elements away from the saccade goal (“Distance 5”). In some cases reaching and saccade goal locations coincided. Probe probability was 33% at the saccade goal, 33% at the reaching location, and 33% at the movement-irrelevant locations. Each participant performed at least 6 experimental blocks.

Experiment 3 - Asynchronous movement experiment. Stimuli and procedure were the same as in the combined movement experiment (Experiment 2) except for the following differences: the movement cue was presented for 100 ms and participants had to reach as quickly as possible to the instructed location; 50 or 100 ms later a second movement cue appeared for 100 ms, instructing the saccade location - thus, stimulus onset asynchrony between the first and second movement cue was either 150 or 200 ms; the distance between saccade target and the reach goal could be either 2 or 4 items; each participant performed at least 6 blocks of 144 trials.

Data analysis. Probe discrimination rate was used as a measure of attentional allocation. Since the probe was presented at variable times, we were able to analyze the time course of attentional deployment to the probe locations. For each time point (every 30 ms) we calculated the proportion of correct probe discrimination. Repeated measures t-tests and independent samples t-tests were used for comparisons of attentional allocation within and between experiments. We searched for the first point in time for which the probe discrimination performance differed significantly from chance ($p<0.05$). Discrimination rates at all later time points were also better than chance ($p<0.05$). For comparisons in Figure 3 probe discrimination was compared between all trials in which the probe appeared within 100 ms before the saccade or the reaching onset.

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Figure legends

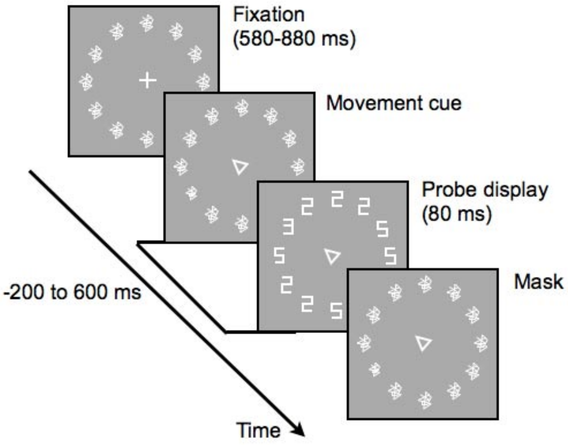
Figure 1 Experimental procedure**.** In *Experiment 1, p*articipants quickly looked (saccade-only task) or reached (reach-only task) to the object indicated by the centrally presented movement cue. After the movement they reported the probe identity (the probe was a digital letter “E” or “3”). The probe display could appear -200 to 600 ms with respect to the movement cue onset. In Experiment 2*,* the cue was the signal to initiate both the reach to the location indicated by the cue, and a saccade to a location that was prespecified within an experimental block.

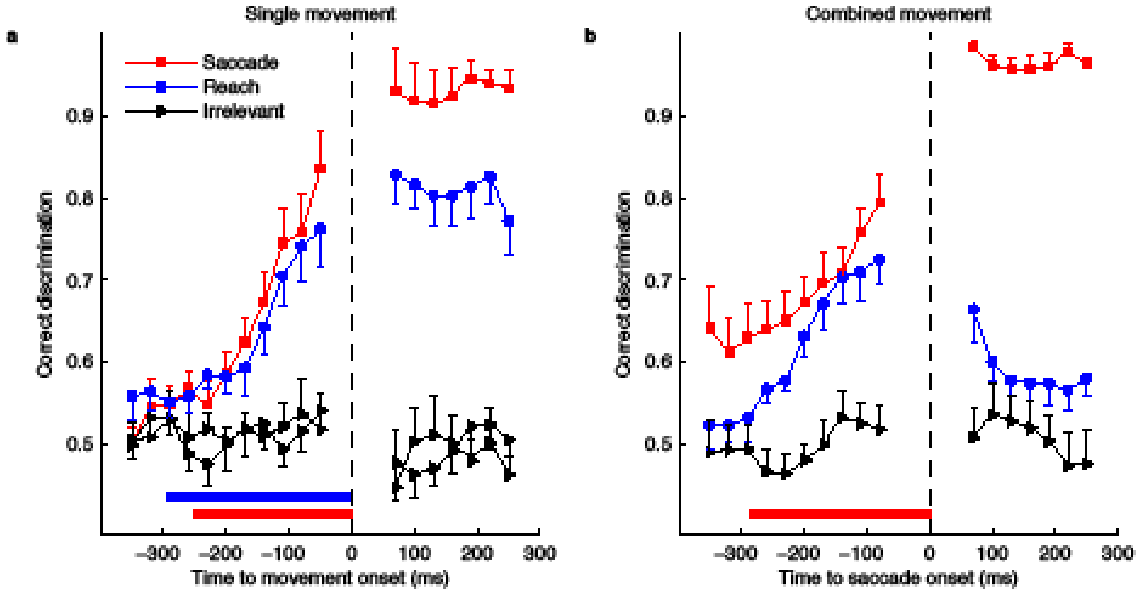
Figure 2 Attention shifts before movement onset. (**a**) Experiment 1 - *saccade-only* and *reach-only* tasks. After movement cue presentation probe discrimination rate increased at the saccade target (red curve) and at the reaching target (blue curve; horizontal red line - saccade latency; horizontal blue line - reach latency; vertical dashed line - saccade and reach onset). Participants were at chance to discriminate probes at movement irrelevant locations (black curves for two single movement tasks). (**b**) Experiment 2 - combined movement task. Probe discrimination increased in parallel at both saccade and reaching goal locations. After saccade onset (vertical dashed line), probe discrimination decreased at the reaching goal.

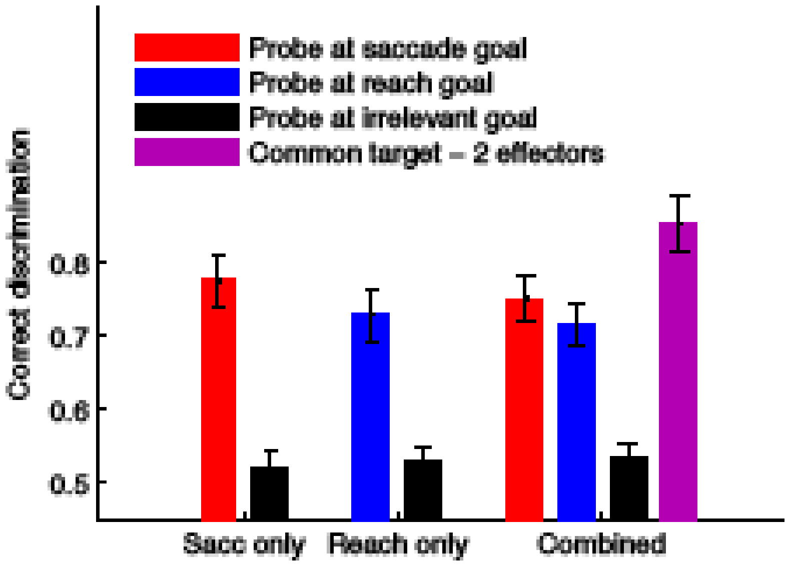
Figure 3 Comparison of discrimination rates in single and combined movement experiments. Discrimination rates were determined for probes occurring within 100 ms before movement onset. Discrimination was comparable between the single and combined movement tasks. Discrimination was best if saccade and reach were made simultaneously to the same location.

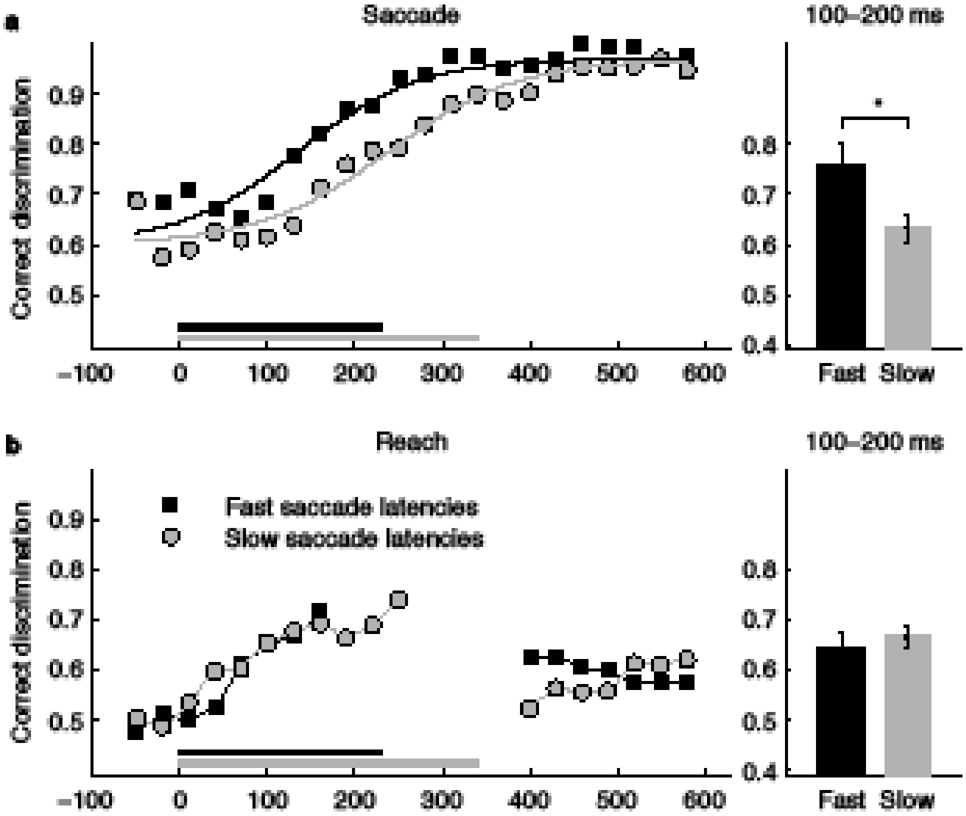
Figure 4 Experiment 2. Independence of attention for eye and hand movements**.** Data for each participant was split into trials with slower or faster saccades by means of a median split. (**a**) Attention shifted to the saccade location earlier (black curve) when saccade latencies were faster. Horizontal black line denotes the mean of these faster saccade latencies. Accordingly, attention shifted to the saccade location later (gray curve) if saccade latencies were slower (horizontal gray line is average of the slower latencies). In a temporal interval of 100 to 200 ms after the movement cue participants were better to discriminate the probes presented at the saccade location if saccade latencies were faster (right panel). (**b**) Attention deployment at the reaching goal for trials with slow and fast saccades. Attention did not shift faster the reaching location if saccade latencies were faster (black curve) and did not shift slower if saccade latencies were slower (gray curve). Thus, regardless of saccade latency, there was no difference in how attention was allocated to the reach targets (right panel).

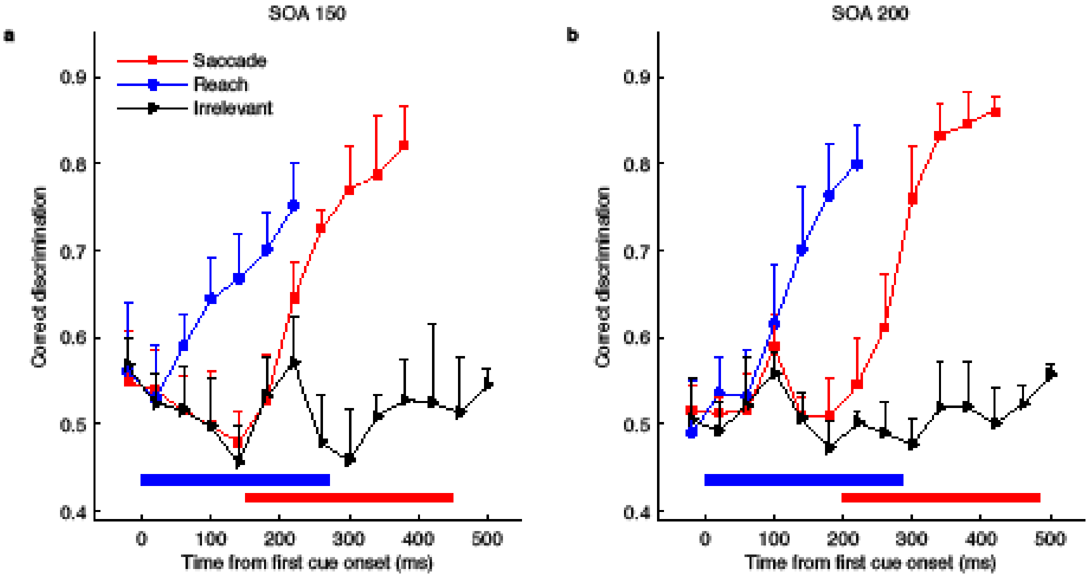
Figure 5 Attention shifts before delayed eye movements. (**a**) Time between movement cue onsets - 150 ms. Horizontal blue bar - time from the first movement cue onset to the reach onset; horizontal red bar - time from the second movement cue onset to the saccade onset. Attention shifted to the reach goal after the first movement cue, and in parallel shifted to the saccade target after the second movement cue appeared. (**b**) Same as (a), but time between movement cue onsets is 200 ms.


Fixation
(580-880 ms)
Movement cue
Probe display
(80 ms)
Mask
-200 to 600 ms
Time


a
Single movement
Saccade
Reach
Irrelevant
Correct discrimination
0.5
0.6
0.7
0.8
0.9
−300
−200
−100
0
100
200
300
Time to movement onset (ms)
b
Combined movement
Correct discrimination
0.5
0.6
0.7
0.8
0.9
−300
−200
−100
0
100
200
300
Time to saccade onset (ms)


Probe at saccade goal
Probe at reach goal
Probe at irrelevant goal
Common target – 2 effectors
Correct discrimination
0.8
0.7
0.6
0.5
Sacc only
Reach only
Combined


a
Saccade
100–200 ms
Correct discrimination
0.9
0.8
0.7
0.6
0.5
0.4
−100
0
100
200
300
400
500
600
*
Fast
Slow
b
Reach
100–200 ms
Fast saccade latencies
Slow saccade latencies
Correct discrimination
Fast
Slow


SOA 150
a
Saccade
Reach
Irrelevant
0.9
0.8
0.7
0.6
0.5
0.4
Correct discrimination
0
100
200
300
400
500
Time from first cue onset (ms)
SOA 200
b
0.9
0.8
0.7
0.6
0.5
0.4
Correct discrimination
0
100
200
300
400
500
Time from first cue onset (ms)

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RESEARCH ARTICLE

Action preparation enhances the processing of tactile targets

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Abstract We present two experiments in which we investigated whether tactile attention is modulated by action preparation. In Experiment 1, participants prepared a saccade toward either the left or right index finger, depending on the pitch of a non-predictive auditory cue. In Experiment 2, participants prepared to lift the left or right index finger in response to the auditory cue. In half of the trials in both experiments, a suprathreshold vibratory stimulus was presented with equal probability to either finger, to which the participants made a speeded foot response. The results showed facilitation in the processing of targets delivered at the goal location of the prepared movement (Experiment 1), as well as at the effector of the prepared movement (Experiment 2). These results are discussed within the framework of theories on motor preparation and spatial attention.

Keywords Attention · Tactile · Sensory facilitation · Movement

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Introduction

A large body of research over recent decades has been concerned with the distribution of spatial attention within one modality (especially vision) and more recently within other modalities such as audition or touch, or across modalities, with vision still as a primary modality of interest. Generally, touch and consequently tactile attention were studied at a behavioural level from the point of view of their connection with other modalities. For example, recent studies have demonstrated links from vision to touch and from touch to vision, as well as from vision to audition and vice versa (for reviews see Spence and Driver 2004). Such crossmodal links between tactile and visual attention have traditionally been shown for covert shifts of attention, meaning that no eye movements were permitted in these studies.

In the visual domain, shifts of spatial attention have been closely linked to the preparation of goal-directed actions. This has become particularly clear in studies involving goal-directed saccadic eye movements which strongly suggest that saccades are always preceded by a shift of attention to the saccade target (Hoffman and Subramaniam 1995; Kowler et al. 1995; Deubel and Schneider 1996). Similar discrimination paradigms showed significantly higher accuracy for visual targets presented at the goal location of a manual reaching movement (Deubel et al. 1998; Baldauf and Deubel 2006, 2008), also arguing in favour of an obligatory coupling between visual attention and goal-directed movements. In this context, it is interesting to note that the overt direction of the gaze to one's hand was shown to improve detection (Tipper et al. 1998) and discrimination (Kennett et al. 2001) of *tactile* targets, although vision of the hand was otherwise non-informative for the task.

The question therefore arises as to whether the programming of a saccade to a part of the body would lead to an enhancement of tactile processing at that location. To our knowledge, also only one behavioural study has reported enhanced discrimination performance for tactile stimuli delivered at the location of a saccade (Rorden et al. 2002). In a series of three experiments, they asked participants to saccade either to the left or right side in response to a central cue. They were also asked to make a speeded verbal response as to whether they felt a tap to the proximal or the distal location of either hand. The authors demonstrated that tactile discrimination is faster at the location of an upcoming saccade and that this effect occurs even when the participants perform the task with their hands crossed. They concluded that when a saccade is planned, tactile attention is biased to the location of the intended oculomotor response. Visual–tactile interaction is dictated by where the eyes look, but can be modulated by expectations.

The first experiment reported here was designed to reconfirm the finding of tactile attention shifts to the goal location of a saccade (Rorden et al. 2002) with a different experimental setup. We used a detection task (adapted from Whang et al. 1991) in which participants had to respond to a tactile target defined as an increase in the intensity of a base vibration presented to the participants' index fingers throughout the trial. Contrary to Rorden et al. (2002), who asked their participants to make vocal responses to the tactile target, our participants responded to the increase in tactile vibration intensity by means of a foot pedal. Another differing methodological aspect was the type of cueing: While in Rorden et al.'s (2002) study a central array of LEDs was used to cue the saccade direction and to trigger the saccade, our participants were cued as to the direction of the saccade that had to be executed from the pitch of an auditory signal presented at the beginning of each trial; the offset of the tone served as go-signal to initiate the saccade. Moreover, another point of interest in running the first experiment was to be able to compare, by using the same experimental setup and the same experimental procedure, the effect sizes of saccade preparation (Experiment 1) with simple finger lifting preparation (Experiment 2) on tactile attention.

Therefore, in a second experiment, we tested whether the planning of a finger movement would also lead to a similar shift of tactile attention to the movement effector. Several recent studies indeed point toward a modulation of tactile sensation when movements are prepared, however, with partially contradictory findings. For example, Voss et al. (2006) delivered cutaneous stimulation to both index fingers of their participants. They measured the point of subjective equality between the perception of the stimuli at the left finger (which was used as a reference and always remained stationary) and the right finger, which, depending on the condition, the participants either had to lift in time with three auditory tones or to keep still. The results showed that in the moving finger, the tactile stimulation had to be 2.69 times stronger than the one in the reference finger for the participants to perceive it as being equal in intensity to the stimulation applied to the resting finger. This effect was referred to as sensory suppression. In some of the trials, they applied transcranial magnetic stimulation (TMS) over the left primary motor cortex at the offset of the sound (when the movement would have normally started) which caused a twitch in the right finger, followed by a silent period with no activity in the finger and the delayed planned movement. The tactile stimulation in this silent period after the TMS pulse once again showed the same suppression effect. So, the mere command to move rather than the real movement itself was sufficient for sensory suppression.

In contrast to these findings suggesting that tactile perception is attenuated shortly prior to and during the execution of an action, Event-Related Potential (ERP) studies have provided evidence in favour of facilitatory tactile attention orienting effects to be elicited during the covert preparation of manual responses. In a go/no-go experiment, Eimer et al. (2005) presented participants with a visual cue which was followed either 520 or 920 ms later by a tactile probe. A go/no-go visual signal presented 1,100 ms after the onset of the cue instructed participants to lift or not the index finger of the cued hand as fast as possible while ignoring all tactile events. Their results showed enhanced amplitudes of early somatosensory components such as P90 and N140 when the tactile probes were delivered to the response-relevant hand as compared to the opposite, non-relevant hand, and therefore argue in favour of a spatial modulation of the tactile information processing when unimanual responses are covertly prepared. Convincingly, N140 was shown to be enhanced for tactile stimuli presented at the goal location of a saccade in a task very similar to the one used in the present study—participants prepared and executed a saccade toward either spatial locations of the hands (hands occluded) following the presentation of an auditory cue (Gherri and Eimer 2008). Moreover, Forster and Eimer (2007) dissociated between the effector of the movement and the goal location of the movement by asking their participants to touch the index finger of a stationary hand (goal location) with the index finger of the other hand (effector hand), following a visual cue that defined the hand to be moved. The same somatosensory N140 was significantly enhanced for tactile probes presented to the effector hand in the time of the movement preparation, as compared to the opposite resting hand that served as a movement goal. As it appears, in the neurophysiological domain, the preparation of different motor responses—eye movements (Gherri and Eimer 2008) and finger movements

(Eimer et al. 2005; Forster and Eimer 2007)—is reflected in similar changes on tactile sensitivity. It is therefore interesting to note for the purpose of the present study that, although tactile processing is facilitated not only when the finger is the goal of the saccade, but also when the finger itself is the effector of the prepared movement, different attentional mechanisms may be involved in the preparation of the two motor responses.

In our second experiment, participants prepared a lifting movement of the right or left index finger, depending on the pitch of an auditory signal presented at the beginning of each trial. Participants were instructed to execute the movement at the offset of the auditory cue. They were also required to respond to a suprathreshold tactile stimulus, which appeared in only half of the trials at the time when the auditory signal was turned off and therefore prior to the movement onset. We monitored both eye movements and finger movements, to ensure effects reflected consequences of covert orienting of attention: participants were required to fixate on a central fixation cross.

If there is an obligatory coupling between visual/tactile attention and planned movements, we should expect our participants to more rapidly detect tactile targets presented at the goal location of the saccade (Experiment 1) or at the finger they intended to lift (Experiment 2). On the other hand, if tactile sensation is suppressed while performing a self-initiated finger movement (Voss et al. 2006), then we would expect tactile detection to be attenuated in Experiment 2 and therefore the finger-lifting preparation should have an inhibitory effect on tactile detection performance.

Experiment 1

Methods

Participants

Eight paid participants (one male, one left-handed) participated in this experiment. They had a mean age of 25 years. All reported normal or corrected to normal vision and normal touch. The experimental session lasted approximately 70 min. All participants gave their informed consent for participation and the experiment was conducted in accordance with the Declaration of Helsinki.

Apparatus

The experimental setup is depicted in Fig. 1. The participants were seated at a table in a darkened room, with their hands on top of an inclined plane above the plane of the table and their chin resting on a chin rest. A colour monitor with a resolution of 1024 × 768 pixels was placed above the inclined plane and displayed the fixation cross centrally. The grey display background had a mean luminance of 2.2 cd/m^2 and the viewing distance was 58 cm. In between the inclined plane and the monitor, a semi-translucent mirror was positioned and adjusted such that the fixation appeared to be projected onto the inclined plane. The participants wore a pair of headphones for auditory stimulation. Furthermore, the participants had their eye movements monitored with a video-based eye-tracking system (SensoMotoric Instruments,

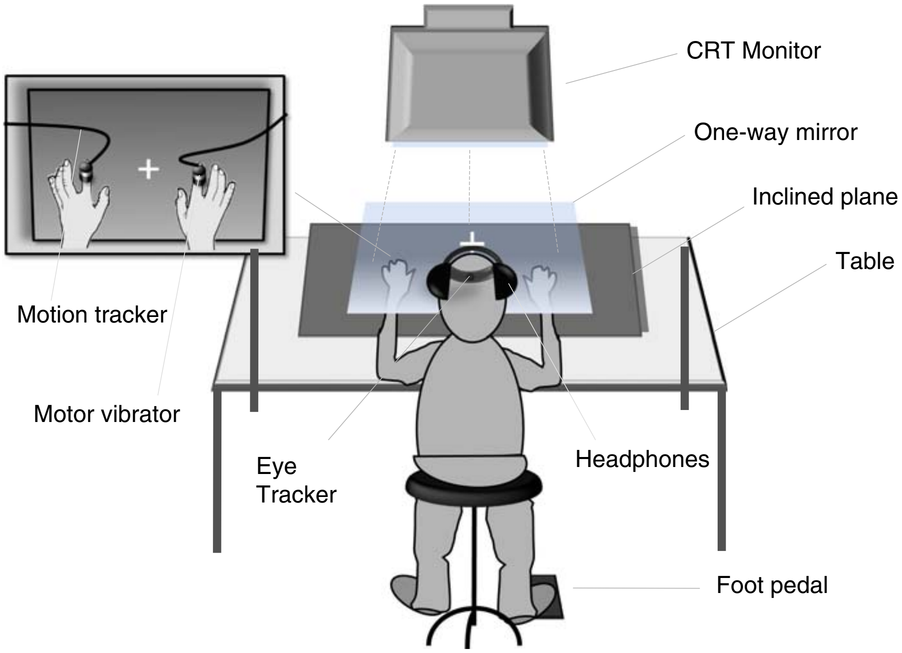

Fig. 1 Experimental setup for Experiments 1 and 2

Eyelink-I). Participants rested their hands on the inclined plane to the left and right of the fixation cross at 15 cm eccentricity each. Tactile stimulation was provided to the left and right index fingers by means of two motor vibrators connected to the computer. They were attached with velcros to the participants' fingers. In order for the hands to be clearly visible, we placed two rectangular pieces of styrofoam on top of the inclined plane and asked the participants to rest their hands on them throughout the experiment. The distance from the body to the tip of the fingers was of 60 cm and given the inclined plane, the distance from the chin to the tip of the fingers was of 50 cm. The responses were given by means of a foot pedal connected to the computer.

Design

Participants performed four blocks of 120 trials each. In half of the trials in each block no tactile stimulus was presented (*target absent* trials), they required only a saccade to the cued finger. The other half of the trials was composed of *target present* trials, requiring a speeded foot response to the tactile target, in addition to the execution of the planned saccade. In *target present* trials, there was an equal chance for the target to appear on the left or the right index finger and also an equal chance for the tactile target to appear at either the location congruent with the planned saccade destination or at the opposite, incongruent location. The crossing of the goal location of the planned eye movement and the location of the tactile target delivery resulted in a congruency "tagging". We refer to congruent trials as the trials in which the saccade was directed to the location of the tactile target delivery and incongruent trials as the trials in which the saccade was directed to the opposite side of the tactile target.

Procedure

The participants were instructed to maintain fixation on the fixation cross which was continuously illuminated throughout the experiment. A *target absent* trial began with both motors that the participants wore on their index fingers turned on at a base vibration intensity (0.63 V, 60 Hz) for a variable period of 1,000–1,500 ms. At the same time, an auditory signal (65 dB), either *high* or *low*, required them to plan a saccade to the *left* or *right* finger, respectively, and to execute the eye movement as soon as the auditory signal was turned off. The offset of the sound came after a random time interval of 50–500 ms to assure that no accurate anticipation was possible. In a *target present* trial, at the same time as the sound offset, a tactile target appeared at one of the two fingers. Participants were told that if the tactile target is presented, their main task is to respond to this stimulus as quickly as possible by pressing the foot pedal with the right foot, but nevertheless still to execute the planned saccade to the finger. The tactile target was a strong increase in the vibration intensity (2.9 V, 140 Hz) and lasted for 100 ms. The increment in the base vibration intensity was the same for all participants in the study. After the delivery of the tactile target the motors returned to the base intensity vibration for another 300 ms. The next trial started 800 ms after participants made a response. They were encouraged to react as fast as possible to the tactile stimulation, to avoid erroneous pedal responses in the *no target* trials and to produce correct direction saccades (see Fig. 2 for a depiction of the trial timeline).

Data analysis

Two participants were excluded from the final data analysis as they mostly saccaded to the left finger after a low tone and to the right finger after a high tone. Trials in

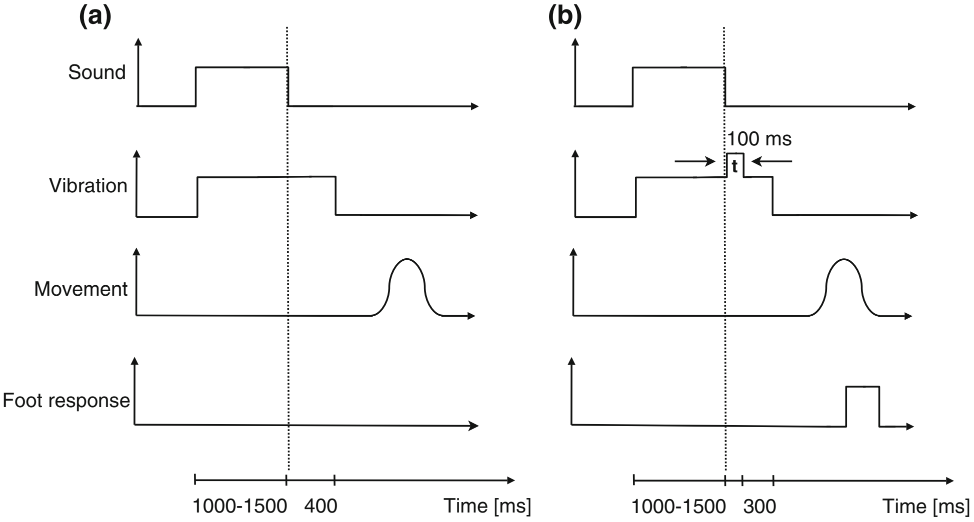

Fig. 2 Timeline of a *target present* trial (**a**) and *target absent* trial (**b**) in Experiments 1 and 2. The vibrators were turned on at the same time as the auditory signal and a movement (saccade in Experiment 1 and finger-lifting movement in Experiment 2) was required at the offset of the sound. Participants made speeded responses to tactile targets (*t*) in half of the trials

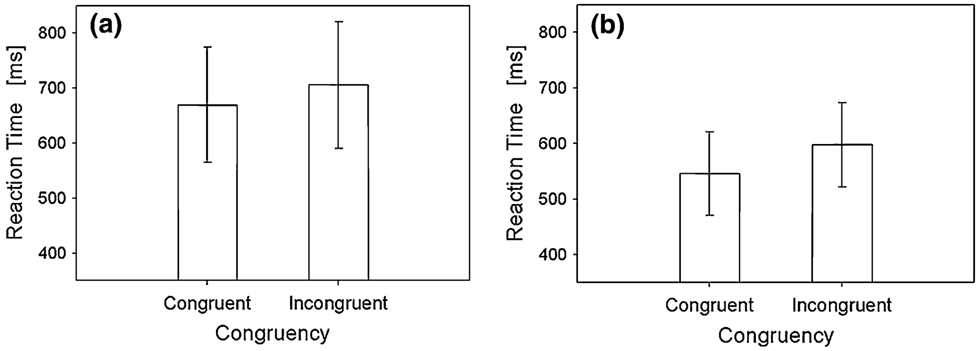

Fig. 3 **a** Mean reaction times for *target present* trials in Experiment 1. **b** Mean reaction times for *target present* trials in Experiment 2. Trials in which the tactile target was presented at the location of the planned movement were considered *congruent* and trials in which the target was presented at the opposite location, *incongruent.* The *vertical error bars* represent standard error bars of the means

Table 1 Mean foot reaction times, mean movement latencies and mean error percentages split into tactile *target present* trials (congruent and incongruent) and tactile *target absent*/movement only trials for both Experiments 1 and 2

Foot RTs (ms)	SE (ms)	Movement latency (ms)	SE (ms)	Error (%)
Experiment 1 (saccade preparation)				
Target present				
Congruent				
669.24	104.7	341.28	49.26	6.54
Incongruent				
705.56	114.75	339.21	54.47	8.12
Target absent				
		447.58	38.93	12.24
Experiment 2 (finger-lifting preparation)				
Target present				
Congruent				
545.73	75.36	445.87	144.45	5.48
Incongruent				
597.57	75.96	603.16	183.69	5.71
Target absent				
		548.81	107.87	8.05

which participants did not saccade (2.38%); saccaded to the wrong finger (16.94%); saccaded, but had saccades too small in amplitude—that did not end on the finger—(6.02%); or had reaction times faster than 150 ms and slower than 2,000 ms in the tactile detection task (1.56%) were excluded from the final analysis. Participants made 26.92% errors on average. For the *tactile detection task*, an overall repeated measures analysis of variance (ANOVA) was run on the *target present* trials with a within-subjects factor *CONGRUENCY* (congruent vs. incongruent finger) and a second factor *LATERALITY* (left vs. right target). For the *motor task*, another ANOVA was run on the saccade latency data with the factor *TYPE* (*target absent* vs. *target present* trials). Separate analyses with the same factors were run on the error data for both the tactile detection task and the motor task.

Results

Tactile detection task

Foot reaction times to the tactile stimulus are shown in Fig. 3a. Numerical values of foot reaction times, saccadic reaction times and error percentages in the various conditions are presented in Table 1. Results showed a main effect of CONGRUENCY [$F(1,5) = 14.98$; $P < 0.02$]. Participants detected tactile targets presented at the finger toward which they planned an eye movement faster as compared to the incongruently cued finger. No significant LATERALITY effect was found [$F(1,5) = 0.14$; $P < 0.72$].

The error data analysis revealed no main effects for either CONGRUENCY [$F(1,5) = 5.74$; $P < 0.063$] or LATERALITY [$F(1,5) = 0.162$; $P < 0.71$], as well as no interaction between the two factors [$F(1,5) = 0.50$; $P < 0.84$].

Motor task

There was a significant difference of saccadic latency between *target absent* trials (saccade only) and *target present* trials (saccade plus speeded tactile response) [$F(1,5) = 15.99$; $P < 0.02$]. Participants initiated the saccade faster in *target present* trials as compared to *target absent* trials. A further ANOVA showed the difference between saccade latencies in congruent versus incongruent *target present* trials to be non-significant [$F(1,5) = 0.005$; $P < 0.95$], as well as no significant difference between left and right saccade trials [$F(1,5) = 5.92$; $P < 0.06$].

The error analysis conducted on the saccade latencies showed no effect of TYPE of trials [$F(1,5) = 4.73$; $p < 0.083$]. There was no significant difference in the error pattern between *target absent* trials (saccade only) ($M = 12.24\%$; SE = 2.34%) and *target present* trials (saccade plus speeded tactile response) ($M = 14.67\%$; SE = 2.69%).

The present results provide evidence for tactile attention being shifted toward the final location of a saccade, prior to the eye movement initiation and reconfirm Rorden et al.'s (2002) results using a tactile detection paradigm. In Experiment 2, we were interested in whether we would find the same pattern of tactile facilitation for the preparation of a finger-lifting movement.

Experiment 2

Methods

Participants

Nine paid participants (two men, one left-handed) took part in this experiment. Four participated in the first experiment as well. They had a mean age of 23 years. All reported normal or corrected to normal vision and normal touch. The experimental session lasted approximately 70 min.

Apparatus and design

The apparatus and design were similar to Experiment 1. However, participants were now instructed to maintain central fixation throughout the trial and to plan a lifting movement of the *left* finger given a HIGH tone is provided, or of the *right* finger if a LOW tone is given. The finger lifting movements were tracked with a Fastrak electromagnetic measuring system (Polhemus Inc., 1993). The rest of the procedure was identical to that used in Experiment 1 (see Fig. 1).

Data analysis

Three participants were excluded from the final data analysis as they did not lift the finger or they lifted the opposite finger and this resulted in an error trial, or they showed excessive eye movements. Trials in which participants failed to fixate throughout the trial or did not move the expected finger (14.6%), or had reaction times faster than 150 ms (3.12%) and slower than 2,000 ms (1.53%) were excluded from the final analysis. The remaining participants made 19.25% errors on average. For the tactile detection task, a repeated measures ANOVA was run on the *target present* trials with a within-participants factor of CONGRUENCY (congruent vs. incongruent location) and the factor LATERALITY (left target vs. right target). In the motor task, an additional ANOVA was conducted on the finger movement latencies with the factor *TYPE* (*target present* vs. *target absent*). Separate analyses with the same factors were run on the error data for both the tactile detection task and the motor task.

Results

Tactile detection task

Figure 3b depicts mean reaction time to the tactile stimulus as a function of CONGRUENCY in Experiment 2. The ANOVA revealed a significant main effect of CONGRUENCY [$F(1,5) = 26.69$, $P < 0.01$]; participants detected tactile targets presented at the finger that they planned to lift more rapidly as compared to the opposite finger.

On the error data analysis, no main effects of either CONGRUENCY [$F(1,5) = 0.078$; $P < 0.80$] or LATERALITY [$F(1,5) = 0.546$; $P < 0.49$] were found: consequently, there was no interaction between the two factors [$F(1,5) = 1.2$; $P < 0.32$].

Motor task

There was no main effect of LATERALITY [$F(1,5) = 0.19$; $P < 0.69$]. Finally, there was no significant difference in the finger movement latencies between *target absent* trials (finger lifting only) and *target present* trials (finger lifting plus speeded tactile response) [$F(1,5) = 0.10$; $P < 0.77$]. Further analyses showed a significant difference in finger-lifting latencies between congruent and incongruent *target present* trials [$F(1,5) = 15.49$; $P < 0.02$], but no significant difference with respect to laterality on *target present* trials [$F(1,5) = 4.86$; $P < 0.08$].

The error analysis conducted on the finger-lifting latencies showed no effect of TYPE of trials [$F(1,5) = 2.73$; $P < 0.16$]. There was no significant difference in the error pattern between *target absent* trials (saccade only)

($M = 8.05\%$; SE = 2.56%) and *target present* trials (saccade plus speeded tactile response) ($M = 11.19\%$; SE = 2.26%).

Experiment 2 provides novel evidence in favour of a modulation of tactile processing by the preparation of a simple finger-lifting movement. Prior to the initiation of the planned movement, covert tactile attention shifts to the location of the movement effector and facilitates the processing of upcoming tactile targets.

Discussion

Facilitation of tactile processing at the goal of a planned saccade

Experiment 1 provided behavioural evidence for visual–tactile spatial attention shifts to be triggered by goal-directed saccades. Participants detected a tactile target more rapidly when it appeared at the location toward which they planned a saccade. With this primary result of the first experiment, we were able to confirm previous findings on tactile attention shifts at the location of an upcoming saccade (Rorden et al. 2002).

Nevertheless, some considerations on discrimination versus detection tasks have to be made. One effect worth mentioning is the crossmodal congruency effect (Spence et al. 2008). The crossmodal congruency task is similar to the up/down tap discrimination task used in Rorden et al.'s study (2002). Participants make speeded elevation (upper vs. lower) discrimination responses to tactile targets, while simultaneously trying to ignore irrelevant visual distractors, which most usually occur 30 ms prior to the onset of the tactile targets. The crossmodal congruency effect results from the difference in performance (in both the RT and error data) between relevant and irrelevant distractor trials; participants are usually slower to discriminate the tactile targets when the visual distractors are incongruent with the elevation of the visual targets (for example, a tactile target appearing "up" and a visual distractor appearing at a lower location). If exogenous crossmodal cueing effects are usually in the range of 20–30 ms, the crossmodal congruency effect brings in a considerably higher RT difference between same and different distractor sides.

Another effect worth mentioning here is the fact that in simple speeded saccade experiments, it has been shown that saccade accuracy can be improved by the continuous illumination of an LED at the end-point of the saccade (Groh and Sparks 1996a). One could therefore argue that as in Rorden et al. (2002) study the saccade goal location was signalled throughout the experiment by means of an yellow LED, this could therefore have acted as a relevant distractor facilitating crossmodal spatial attentional cueing effects to be more likely taking place at the location closest to the distractor light. Additionally, the difference between tactile RTs between congruent and incongruent trials in their study was of 61 ms as compared to 36 ms in the present tactile detection study. We therefore replicated Rorden and colleagues results on the facilitation of tactile processing at the location of an upcoming saccade in a detection paradigm that excludes a possible crossmodal congruency explanation.

The results of Experiment 1 yielded faster saccade initiation in *target present* trials. The shorter saccade latencies for *target present* trials may be due to a trivial alerting signal from the tactile stimulus, which speeded up the already prepared oculomotor response (Diederich et al. 2003). However, as no significant difference in saccade latencies between congruent and incongruent *target present* trials was found, one could argue that the two tasks—saccade to the finger and speeded response to the tactile target—were performed in parallel and an alerting effect (Diederich et al. 2003) could account for the present difference.

When we prepare a saccade to a given location, shortly prior the execution, visual attention shifts covertly to the goal location (Hoffman and Subramaniam, 1995; Kowler et al. 1995; Deubel and Schneider, 1996), resulting in higher discrimination performance at the given spatial location. Therefore, a crossmodal explanation for tactile detection facilitation at the location of an upcoming saccade points toward an attentional interconnected network between the oculomotor and somatosensory system.

Facilitation of tactile processing due to the preparation of a finger movement

Experiment 2 provided the first behavioural evidence for tactile attention to be modulated by the preparation of finger-lifting movements. We hypothesized that if tactile perception is attenuated/suppressed during the execution of a planned movement, then our participants should not show a facilitatory effect in responding to tactile targets presented at the finger that they planned to lift as compared to the opposite finger. However, if there is a coupling between tactile attention and motor preparation, then our participants should be faster to detect a target presented at the finger that they previously planned to lift. Participants were indeed faster to detect a tactile target when this appeared at the finger that they previously planned to lift.

The results of Experiment 2 showed faster finger lifting initiation in congruent *target present* trials, as opposed to incongruent *target present* trials. It appears therefore that when the tactile stimulus was delivered at the finger that was preparing to move, the tactile stimulation speeded up the movement initiation. In such a case, an automatic response to the tactile stimulation could account for the present effect (Diederich et al. 2003), which in turn would require inhibition of the response when the stimulation is delivered at the incongruent finger. However, as the error data do not support the finger movement latency data, with no significant difference in error behaviour across congruent and incongruent trials, one can consider tactile stimulation to have indeed caused reflexive finger movement responses in *target present* trials, but further experiments are needed to test the robustness of this effect.

Our findings are well in line with the results of the ERP studies by Eimer and colleagues (Eimer et al. 2005; Forster and Eimer 2007) showing enhanced processing of early somatosensory components during the preparation of a manual response. However, they seem to be at variance with the findings of Voss et al. (2006) demonstrating a considerable attenuation of tactile sensitivity in the moving finger. Indeed, further investigations have also pointed toward a suppression of somatosensory information during self-produced movements. For example, Blakemore et al. (1999) asked participants to self-produce tactile stimulation or to receive it from an external robot and to rate the intensity of the tickling. Results showed that participants rated the self-produced sensation as being less tickly than the one externally produced by the robot. In another study (Shergill et al. 2003), participants were asked to match a force applied to their finger by means of a force transducer either by using a computer-controlled joystick or their own finger and again the force generated by using their own finger was perceived as being weaker.

So how can the differences between the two types of experimental findings be explained? In our opinion, the timing of the target delivery either in the response-preparation period or else in the response-execution period is the crucial delineator between the different results and the different theoretical claims. Our experimental manipulation involved the instruction to lift the finger at the offset of an auditory cue. In half of the trials, at the same time with the offset of the cue, a tactile target was delivered and participants had to make a speeded response to it. Accordingly, with a lifting movement latency of 524 ms on average, the tactile target was therefore delivered very early during the preparation of the movement and not during the movement-execution period.

Motor control involves the constant estimation of one's body state, sensory predictions for filtering out unnecessary sensory information, as well as context estimation which, based on previous experience, helps to rapidly select the controller of the action (Wolpert and Flanagan 2001). In order to classify sensory stimulation as self-produced, the predicted sensory feedback has to be equal to the actual sensory feedback. If there is a discrepancy between the predicted and the perceived actual feedback, such as a short time delay, the sensory stimulation will be attributed to an external cause and therefore its salience will be increased. Timing appears to be a critical factor in motor control. Bays et al. (2005) provide a time window for sensory attenuation. In the movement trials of their task, participants press a button with their right index finger and hold their left index finger beneath a force sensor. At an auditory go-signal, they are instructed to release the button held with their right finger and make a speeded movement to press a second force sensor (*active tap*) placed above their left index finger. At a variable delay interval, they receive a force tap in their resting left index finger (*test tap*), which is followed at a short interval, by a *comparison tap* of variable amplitudes. Participants are asked to rate which of the two taps they perceived as being harder. Their results show that sensory attenuation is maximal when no time delay is present between the active and the test taps. Moreover, this effect decreases with increasing the time distance between the two taps, such that already at 300 ms difference the attenuation is not present any longer (the rating is not significantly different from the control no-movement condition).

These studies indicate that when we engage ourselves in goal-directed actions, our tactile perception should be decreased shortly prior and during the execution of the action as a result of signals coming from the central nervous system, related to the preparation of motor commands. When planning an action, the motor system sends a motor command to the effector of the action. As the motor command is sent through the central nervous system, the efference copy is used to predict the expected sensation that should occur. If the resulting sensation corresponds to the predicted one, then this sensation will be attenuated. However, if a time delay is inserted in between, the sensation is enhanced because it will more likely be attributed to an external cause and not to one's own movement.

With regard to the present data, the absence of a sensory attenuation effect indicates that attenuation is more prone to be present in the case of tactile stimuli delivered shortly prior or during the actual movement execution. As the tactile stimuli in the present Experiment 2 were always delivered in the response-preparation period and not during the actual finger-lifting execution, our data argue in favour of an early attention orienting effect toward the location of the planned movement, which occurs well before the actual response execution and leads to a faster tactile detection performance at the specified movement location.

It therefore points toward tactile attention shifts to the location of a planned finger-lifting movement and supports the premotor theory of attention (Rizzolatti et al. 1994). In the present study, we found tactile enhancement at the location of a planned saccade and at the location of a self-initiated finger-lifting movement. The attentional shifts took place in the motor-preparation period, before the actual execution of the intended motor act and we propose that they reflect the coupling between tactile attention and motor preparation, as predicted by the premotor theory. According to this theory, the mechanisms responsible for spatial attention are located in spatial pragmatic maps. Facilitation occurring in neurons in the spatial pragmatic maps brings in spatial attention and this facilitation is dependent on the preparation to perform goal-directed movements. Different pragmatic maps become active according to the task requirements. Therefore, the theory claims that the preparation of goal-directed movements and shifts of spatial attention are closely linked, as they are controlled by shared sensorymotor mechanisms.

Mechanisms of attentional control: interlinked modalities versus supramodal accounts

An interesting way to look at the data from both experiments in the present study is underlining the fact that different types of motor preparation elicit similar shifts of attention in different modalities. Accordingly, the saccade preparation data in Experiment 1 could argue in favour of attentional facilitation on tactile processing due to crossmodal links between visual and tactile attention. In Experiment 2, the finger-movement preparation task elicits a similar attentional facilitation on the processing of tactile stimuli. However, visual attention may be involved in the results of Experiment 2, especially if taking into account that shifts of attention within one modality could trigger analogous shifts of attention into other modalities as well.

The mechanisms of selective spatial attention have to be considered as they may play a role in the interpretation of the present data. To date, several theoretical accounts with regard to the architecture of selective spatial attention have been proposed. Their claims spread from a supramodal view to a modality-specific view of attention. For example, a supramodal, unitary attentional account would predict similar preparatory attentional shifts to locations in space independently of the modality of the stimuli (Farah et al. 1989), whereas an interconnected modality-specific control account would be reflected in systematic preparatory attentional shifts within such modalities (Spence and Driver 1996; Spence et al. 2000). The latter account is based on the existence of different attentional systems which can be individually influenced by various top-down factors, such as the paradigm used, the type of cueing or the importance of spatial coordinates for the chosen task. Moreover, each modality is characterized by a specific localizability of stimuli in space, as well as individual time needed by the sensory information to travel from the sensory epithelia to the appropriate brain centers. This account does not exclude the existence of a supramodal mechanism; still it has to be tuned in conformity with the specific spatio-temporal characteristics of each modality. Therefore, according to Spence and Driver, there are separate modality-specific attentional systems for the various representations of auditory, visual, and tactile inputs, but they are interlinked so that they contribute to attention shifts in the different modalities toward the same spatial location.

One possibility could be that attention spreads supramodally across modalities to locations in space irrespective of the modality of stimuli presented at the given locations, as documented by patient (Farah et al. 1989) and neurophysiological studies (Eimer 2001; Eimer and Van Velzen 2002; Eimer et al. 2003). Another possibility could be that although dependencies may exist between the investigated modalities, the system is not purely supramodal. In this respect, behavioural (Spence and Driver 1996; Spence et al. 2000; Lloyd et al. 2003) and TMS (Chambers et al. 2004) evidence shows that attention in different modalities can shift simultaneously to different spatial locations. Nevertheless, our behavioural data cannot clearly disentangle between only visual, only tactile, visual–tactile crossmodal links or a pure supramodal account, although the tactile detection task used definitely increases the probability of a higher involvement of tactile attention. Further neurophysiological studies are needed to shed light into the problem.

Lastly, we were interested where in the brain the coupling between tactile input and motor preparation takes place. Several brain structures are involved in the preparation, generation and the control of movement. In the following, we will try to delineate those brain structures that are also exhibiting tactile and visual neuronal activity.

Neural structures for multimodal interaction

The tactile facilitation effects elicited during the motor-preparation period reported in this study imply that up to some degree the sensory information coming from different senses must be integrated such that they are attributed to a common location. However, this is an intricate process, as different regions in the posterior parietal cortex (PPC) are involved in distinct motor behaviour and moreover, different reference frames are used to code stimuli from different modalities. For example, visual stimuli are coded retinotopically and tactile stimuli are coded somatotopically, meaning that there is not a common location across modalities at the level of the sensory input. Therefore, in order to use the sensory information collected via one reference frame, the motor system has to recode the representation of the given sensory stimulus into one that is suitable for the intended motor act. The PPC is generally thought as a mediator between sensation and action as it receives input from visual, auditory and somatosensory areas together with motor areas, in order to project further to frontal motor areas (Cohen and Andersen 2004). PPC is also involved in representing target locations in a common reference frame (Colby 1998; Cohen and Andersen 2004). Evidence for this complex sensorymotor transformation comes from single-cell recording studies.

Several multimodal regions have been identified in the primate brain, such as the polysensory zone (PZ) in the pre-central gyrus, parietal VIP and area 7b, as well as the deep subcortical putamen region (Graziano and Gross 1996; Graziano et al. 2004). If neurons in the PZ have matched visual and tactile receptive fields (RFs) and provide a body-part-centered representation, as we move caudally to parietal areas (VIP and 7b), neurons exhibit the same RFs characteristics, only that the majority of visual RFs in these areas are retinocentric. On this basis, it has been argued that the multimodal parietal areas are an intermediate step in the sensorymotor transformation, especially since moving ventrally to the basal ganglia, tactile and voluntary movements responsive neurons are found, which follow a somatotopic organization of the body and have again matched visual and tactile RFs for the face and arms. Therefore, a hierarchical organization was proposed with multimodal information gathered in VIP and consequently activating the PZ depending on the proximity of objects to certain body parts and finally projecting to the motor structures and triggering the action towards an object (Graziano et al. 2004).

Another brain structure that represents the location of tactile stimuli (but also visual and auditory) with respect to the eyes is the midbrain superior colliculus (SC). In primates, the proposed functional role of the activity in sensory-motor SC neurons is to signal the presence and position of the saccade target with respect to the eyes, as these neurons discharged more closely in time to the tactile stimulus onset than to the saccade movement onset (Groh and Sparks 1996b). Considering the behavioural results in the present study, one could argue that such a difference in the timing of the firing found in SC sensorymotor neurons for the time period close to the stimulus onset as compared to the one closer to the required saccade onset to be an indicator of attention allocated to the target.

A human fMRI experiment (Bremmer et al. 2001) presented participants on separate trials with tactile, visual or auditory stimuli. Their results showed significant activations from baseline in certain brain regions to be triggered by any of the three employed stimulation modalities: first on the floor of the intraparietal sulcus (IPS) (matching the VIP in the primate brain), second located in front of the central sulcus in the frontal lobe (matching the PZ) and a third region in the upper bank of the lateral fissure (possibly matching part of area 7b in the primate brain). These findings draw a parallel between primate and human brain and suggest that the human brain might have a system of multimodal areas similar to that found in the primate brain.

Furthermore, human ERP studies bring evidence for the neural substrates of motor preparation and support our behavioural results in the present study. For example, the finding that the early somatosensory N140 component is enhanced for tactile probes delivered in the movement-preparation interval (Eimer et al. 2005; Forster and Eimer 2007) supports the present behavioural results and points toward a link between motor preparation and tactile attention as mediated by fronto-parietal brain circuits taking part in the sensorymotor transformation during action planning (Rizzolatti et al. 1998; Fogassi and Gallese 2004).

In summary, different frontal, but mostly parietal and also deep brain areas in both the human and the primate brain are activated in response to sensory stimulation prior the execution of a planned movement. Overt gaze shifts toward a tactile target involve the transformation of the tactile target representation from body-centered coordinates into eye-centered coordinates. This process takes place in the PPC and is governed by fronto-parietal brain circuits.

Conclusions

The present findings provide behavioural evidence in favour of a coupling between tactile attention and motor preparation. Overt gaze orienting, as well as the preparation of simple finger-lifting movements under conditions of covert attention elicited an enhanced performance in detecting tactile targets delivered at the movement congruent location. These facilitatory effects were found for stimuli delivered in the movement-preparation period, before the start of the planned movement and confirm our hypothesis of a coupling between tactile attention and motor preparation, as predicted by the premotor theory (Rizzolatti et al. 1994). However, further experiments, both behavioural and neurophysiological, involving a finer distribution of tactile events in the temporal interval between response preparation and response execution may shed light on the exact border between attentional facilitatory effects (Deubel and Schneider 1996; Deubel et al. 1998, Rorden et al. 2002; Eimer et al. 2005; Forster and Eimer 2007, Gherri and Eimer 2008) and attenuating inhibitory effects (Blakemore et al. 1999; Wolpert and Flanagan 2001; Shergill et al. 2003; Voss et al. 2006; Bays et al. 2005) on tactile perception.

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Gaze Behavior in Grasping of Natural Objects

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Grasping an object is an activity performed many times each day. This study was conducted to investigate where gaze is directed on everyday objects during grasp preparation phase as compared to during viewing. Two grasp types and three objects (a box, a cylinder and a cup) were used. Participants grasped either from the top (spherical) or from the side (cylindrical) with their thumb in the front and the other fingers on the backside of the object. During viewing, Center of Gravity (COG) was mainly fixated. During grasping, participants mainly fixated the area of the thumb's grasp application point. No attraction of gaze by COG could be found. In conclusion, in natural grasps as used in this study, fixations in grasp preparation are directed to the grasp application points fast and efficiently.

Keywords: gaze, grasp preparation, eye movements, fixation location

Introduction

The present study aims to pilot detailed investigation of gaze behavior during grasping of three-dimensional objects. While it has been known that objects are fixated in preparation of their being grasped or manipulated in various natural tasks such as making a sandwich (Hayhoe, M. M., Shrivastava, A., Mruczek, R., & Pelz, J. B., 2003, Land & Hayhoe, 2001) or making tea (Land, M., Mennie, N., & Rusted, J. 1999), surprisingly little is known about the exact location and dynamics of fixations on (to be) grasped objects. Task demands can strongly influence eye movements and detailed investigation of gaze behavior in object manipulation may tell us more about the underlying cognitive processes, such as selection processes or visual guidance.

Studies investigating fixation location on objects can coarsely be divided into three categories: viewing tasks not involving any direct motor interaction with the object, pointing tasks, and grasping tasks. The effects of these task-types on gaze behavior are summarized in the next sections to outline the rationale of the present study.

Factors influencing gaze in viewing

Bottom-up visual features including local contrast, high variance, (Reinagel & Zador, 1999), high local symetry (Privitera & Stark, 2000) and 2-d image features such as curved lines, edges, occlusions, etc. (Krieger, Rentschler, Hauske, Schill, & Zetsche, 2000) are known to attract observers fixations. Another well investigated factor attracting fixations is an object's or shape's center of gravity (COG; see He & Kowler, 1991; Kowler & Blaser, 1995, McGowan, Kowler, Sharma, & Chubb, 1998; Melcher & Kowler, 1999; Vishwanath, Kowler & Feldman, 2000)). The COG even attracts fixations when it lies outside of the objects boundaries. Depending on task, fixation position may be biased to either visual features or COG. Vishwanath & Kowler (2003, 2004) found landing position onto an L-shape biased from the COG towards the intersection of the two legs when subjects were to make a single saccade, while in a task involving sequential targets no such bias could be found. Using a virtual scene, they also found that three-dimensional cues may shift fixation targets to the 3D-COG, although interindividual differences were apparent.

In addition to visual features, task demands can be shown to affect gaze behavior as shown by a well known study by Yarbus (1967), who instructed his participants to answer different questions about the same scene. Fixation patterns varied with the questions asked and prominently illustrated task influence on gaze behavior.

Factors influencing gaze in pointing

While in viewing several factors may influence fixation locations, the most salient fixation location in pointing is, of course, the pointing goal location. Gaze in pointing has been well studied, and results suggest that poining errors increase if the target is not fixated (Bekkering, Adam, van den Aarssen, Kingma, & Whiting, 1995; Bock, 1986; Enright, 1995; Henriques, Klier, Smith, Lowy, & Crawford, 1998; Medendorp & Crawford, 2002; Neggers & Bekkering, 1999; Vercher, Magenes, Prablanc, & Gauthier, 1994), and errors in fixating and pointing are often correlated (Soechting, Engel, & Flanders, 2001, Admiraal, Keijsers, and Gielen, 2003), but not under all conditions (see Binsted, Chua, Helsen, & Elliot, 2001; Binsted & Elliot, 1999; de Grave, Brenner, & Smeets, 2004; de Grave, Franz, & Gegenfurtner, 2006; de Grave, Smeets, & Brenner, 2006; Mack, Heuer, Villardi, & Chambers, 1985). Consequently, gaze and pointing location cannot be said to always and necessarily coincide under all conditions, but in free viewing and good performance, this would generally be the case as no other location in a scene would compete in drawing attention.

Conflict is added to the situation when subjects are asked to simultaneously point to two different locations at the same time with both hands. Riek, Tresilian, Mon-Williams, Coppard, and Carson (2003) found that in this task, both targets were fixated sequentially with the later fixated target mostly being the left target (in right-handed participants), or the smaller of two targets, suggesting that the later fixated target is the one needing more visual monitoring.

Factors influencing gaze in grasping

First to closely investigate gaze behavior in grasping of a 3-dimensional object, Johansson, Westling, Bäckström, and Flanagan (2001) had participants grasp a 2x2x8 cm bar with the thumb and the index finger as part of their task. They found that participants fixated the visible contact region of the bar before grasping it. The fixation location correlated with the actual grasp location of the thumb on a trial by trial basis, suggesting a tight linking of fixation location and grasping location. This finding, however, may or may not represent a general mechanism, as participants were asked to grasp a ‘parking bar’ of the same dimensions as the grasping bar in between trials, which featured distinct to be grasped contact locations (‘bumps’) on the bar. This might have implicitly led participants to aim precisely for the same contact location on the grasping bar and would explain the close fixation & grasping location link.

Brouwer, Franz & Gegenfurtner (2009) argued that, with only one visible contact location, it comes to no surprise that subjects will fixate where they grasp, so they made the contact location of the index finger visible by using two-dimensional shapes presented in a vertical viewing pane in front of the subject and have it either be grasped or viewed.

Unlike in double pointing (Riek et al, 2003), they did not find fixations centered around the contact locations of the fingers sequentially. Rather, in the grasping task, an attraction of gaze to the COG was apparent, shown by Brouwer and colleagues with different geometrical shapes. In experiment two, they also found an attraction of gaze by the index finger, arguing with the index finger’s path to the target being more variable and thus needing more online visual guidance. This attraction, however, could only be seen for the second saccade relative to the first saccade, and not for both saccades relative to the COG. Indeed, the graphs suggest overall mean fixation location to be on the side of the thumb (best visible in the square shape) unless the pointed side of the triangle has to be grasped by the index finger.

In conclusion, in grasping of two-dimensional objects, factors attracting gaze for mean or first fixation location may include COG and thumb contact location while the second saccade may be attracted by index finger and smaller contact area.

Rationale of the present study

Both Johansson et al. (2001) and Brouwer, Franz, & Gegenfurtner (2009) applied a ‘pinch’-like grasp type in their tasks, that is, objects had to be grasped between thumb and index finger only. In everyday life, however, we usually pick up objects by grasping them either from the top or from the side with the thumb on one side of the object and several (two to five) fingers on the opposite side of the object. This adds stability to the grasp and less visual guidance may be necessary to securely grasp and pick up an object. Thumb contact location can still be expected to be a likely fixation target, but other fixation locations may be advantageous to extract object information, such as general object shape geometry, depth, symmetry, 3-D center of gravity, or expected object weight. These locations could be added to, or compete with, fixation of the grasp application points.

The present study was conducted to gain a first insight of fixation locations and dynamics in speeded grasping of natural three-dimensional objects. Objects consisted of common shapes, namely a box, a cylinder, and a drinking cup, and were to be grasped either from the top (spherical) or from the side (cylindrical, grasping of handle for the cup). In another condition, participants were asked to simply look at the objects. As the objects differed in their characteristics, different effects were expected for them. For the rather large box, distinct fixations on the application points away from the COG were expected, while for the cylinder, cylindrical grasp application point overlapped with COG and they were not effectively distinguishable. For the cup, the handles’ grasp location is quite distinct from the center of the cup, and needs more visual guidance to be contacted than e.g. the boxes’ (rather arbitrary) application point, but it does not give much information about the objects center of gravity.

Therefore, effects of object and application point/grasp type on fixation locations were expected. Analysis was limited to the pre-grasp period operationalized by the first 500 ms of each trial.

Methods

Participants

Six Different Participants (2female and 4 male) took part in the experiment and were paid 8€ per hour for their participation. All had normal or corrected to normal vision and normal hearing. Informed consent was obtained before the beginning of the experiment. All participants were self declared right-handed and between 22 and 25 years old.

Apparatus and stimulus materials

Stimulus objects consisted of a rectangular box (14x7.5x14.5 cm), a cup (height 9 cm, diameter 8 cm, handle protruding 3 cm from the side of the cup and handle height 6.5 cm), and a cylinder (height 14.5 cm, diameter 6 cm). The objects were presented on an empty workspace area in front of the participant between the chinrest used to maintain viewing distance and the monitor on which calibration was performed. The object were always placed in the same viewing distance, with the front edge 41 cm from the base of the chinrest to the one side and 14 cm from the base of the monitor on the other side.

The height of the chinrest was 22 cm, so that subjects eyes remained close to 36 cm higher than the workspace, causing the subjects to look slightly downward during the experiment, as can be seen in fig.1.

Eye data were recorded by a head-mounted, video based eye tracker (Eyelink II, SR-Research, Osgoode, Ontario, Canada[1]), measuring both eyes at 250 Hz in pupil + corneal reflection mode. The tracker featured a Scene-camera (Scenecam, SR-research), filming the scene viewed by the subject, which was attached to the front-bar of the eye-tracker, allowing for recording of eye-data independent of the monitor. Calibration was performed on the monitor and head-referenced eye position data was overlayed automatically to the scene camera by the recording Software SceneLink (SceneLink Software, SR-research). Calibration was done by the sequential fixation of nine predefined dots presented on a 19” monitor at 55 cm viewing distance. Calibration was followed by a depth correction using 5 fixation points in different viewing distance panes, to account parallax changes at different viewing distances of the fixation cross and the object. The overlay resulted in eye data being recorded in reference to the video frames of the scenecamera video. To keep video coordinates of the scene (and the herein included object) constant during and over trials of one recording session, head movements had to be avoided. This was achieved by fixating the metal band (supporting the front bar and eye cameras) to the chinrests vertical bars in such a way that the head could only be angled by moving the chinrest back and forth in its sliding mechanism but could not freely moved by the participant. After calibration at the beginning of each recording session, during which subjects looked straight at the monitor, the chinrest was moved back some centimeters, so that the scene camera scene center was shifted from the monitor to the workspace. A drift correction to compensate for headbandslipping during the angling of the head and depth calibration were performed at this point.

The scenelink II head mounted eyetracker is connected to one “tracker pc” and one “display pc”, the latter running the scenelink software used for calibration and control of recordings done with the scene camera. As in the scenelink software recordings can only be controlled manually from the display pc but automatically controlled via the parallel-port, a third pc running ExperimentBuilder Software (SR-research) was used. This pc sent recording start and stop signals to the port, controlled the timing of trial sequence and provided an initial fixation cross (22cm above the workspace) for each trial.

Fig 1: Trial sequence and apparatus setup

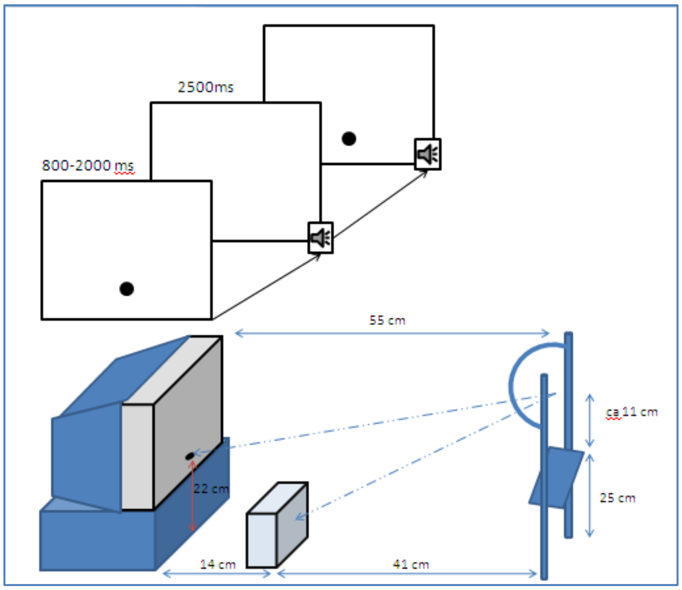

Fig. 1: After a random interval, a sound started the 2.5s recoding sequence as the fixation cross disappeared.

Design and procedure

The experiment consisted of 2 grasp types and one viewing condition for each of the three objects, resulting in a total of 9 conditions times 10 repetitions = 90 trials. In a first block, Participants were asked to either grasp the presented object from the top (spherical grasp) or from the side (cylindrical grasp, in case of the cup, this was the han-

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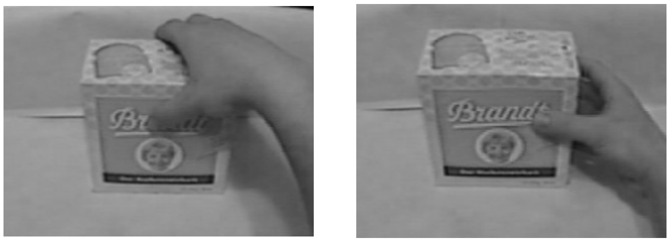
[1] Reffered to in the following as „SR-Research“

dle of the cup). Subjects were instructed to grasp the object at a brisk speed but with a secure grasp, lift the object into the air, and place it back to the exact position from which they picked it up from. After this block, subjects were asked not to grasp, but simply to look at the object. No further instructions about how or where to look at the object were given. Object identity - and grasp type in the first block - was randomized over trials.

On a single trial, participants started by fixating the fixation cross that was presented at the beginning of each trial while the experimenter exchanged the object and read out loud the grasp type ("cylindrical" or "spherical") to the participant. The experimenter then pressed a button and after a random interval between 800 and 2000 ms, the fixation cross disappeared and a beep signalled the subject to grasp the object with the indicated grasp type and lift it up. A second beep 2.5 s after the first beep signalled the end of the recording, by which time subjects were to have put back the objects to its original place. For the viewing condition, subjects were asked to 'freely look at the object' until the second beep appeared, upon which they were to look back at the fixation point on the monitor.

Fig 2: Exampes for "spherical" and "Cylindrical" Grasps



Analysis

One of the six participants' eye data could not be recorded due to technical problems with the TTL-signal controlling EyeLink recording. Another subject had to be excluded due to insufficient quality of eye data. 9 Of the remaining 300 grasping trials and 7 of the remaining 150 viewing trials were rejected due to insufficient quality of eye data.

Graphical data validation preparation for further statistical analysis was done with DataViewer Software (SR-research). For each trial, data validation and offline drift correction was performed manually by aligning the first fixation of every trial with its corresponding fixation cross. As hand movement data was not recorded, movement preparation period was operationalized by the first 500 ms time period of each trial, to which all statistical analysis was limited.

Fixations and saccades were automatically recognized by the DataViewer software with default filter options.

The first fixation of each trial was the fixation on the fixation cross. To account for different head angling (and therefore video referenced coordinates) across participants, fixations x and y values of all fixations were adjusted and the fixation cross used as new origin, with negative horizontal and vertical values representing values to the left and below the fixation cross, respectively. For this and further statistical analysis of the data, R software (R Development Core Team, 2008) was used.

For further analysis of gaze behaviour on the object, areas of interest (AI) were defined in DataViewer by circles of appr. radius 3 cm centered around the relevant visible grasp application points and object COG, respectively (see fig.). For each fixation of a trial, it was registered whether or not it was contained in an AI. Accumulated time and number of fixations spent in a certain AI were calculated for each trial and compared between conditions (spherical grasp, cylindrical grasp, viewing) by use of 2factorial repeated-measures ANOVA and t-tests.

Fig 3: Interest Areas

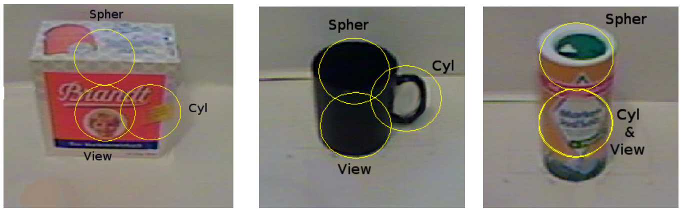


Fig 3: Interest areas (denoted Spher for spherical grasp, Cyl for cylindrical grasp and View for No grasp (Viewing condition)

Results

Number & latency of fixations per trial

Figure 4 shows the total amount of fixations made in the first 500 ms of each trial. The mean (SD) amount of total fixations inside this time period was 2.36 (0.87). The first fixation was the fixation on the fixation cross on the monitor. The mean number of fixations until the grasp-type-relevant interest area was reached (when reached), was 1.2 fixations.

Fig.4: Fixations per trial

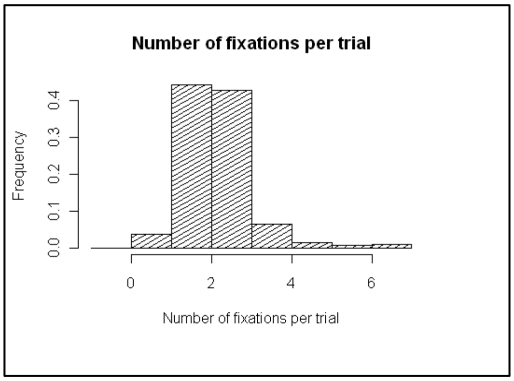


Fig. 4: Percentage of Trials as function of number of fixations in the first 500 ms per trial.

Fig.5: Heat maps for one Participant based on fixation duration during the first 500 ms of each trial.

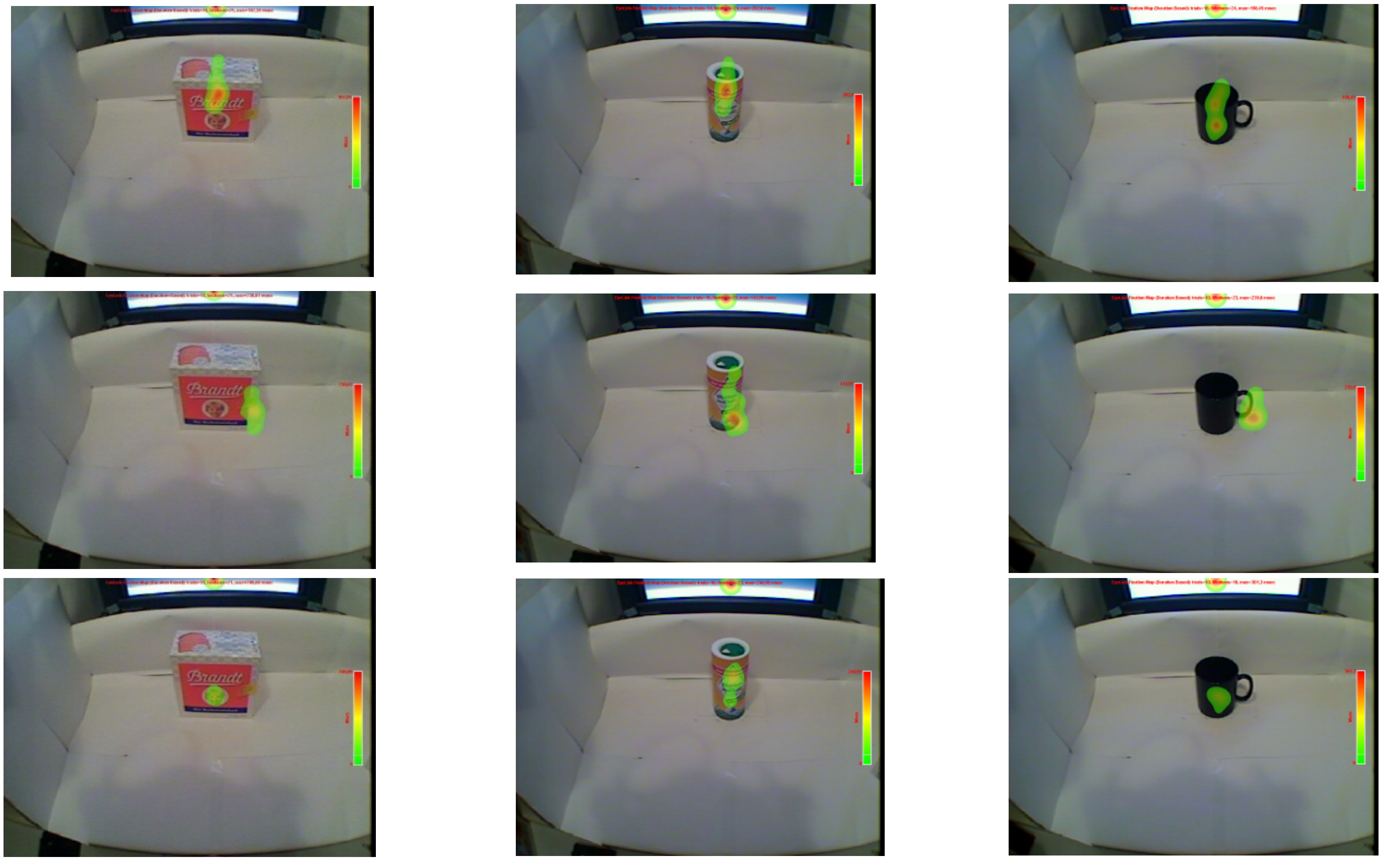


Fig.5: First row: “Spherical Grasp” condition, second row: “Cylindrical Grasp”, last row: “Viewing” condition

Fig. 6: X and Y Coordinates of fixations for objects and grasp-types

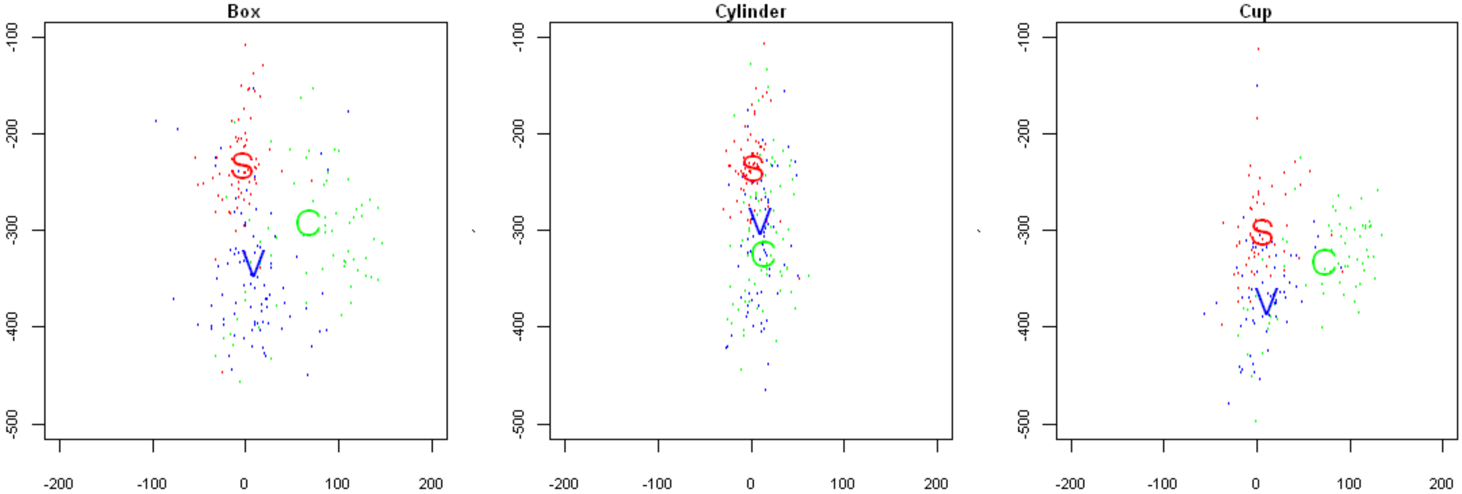


Fig.6. Fixation locations of all fixations during the first 500ms of each trial, averaged over participants. The symbols give the average fixation location for each grasptype. “S”: spherical grasp, “C”: Cylindrical grasp, “V”: No grasp/viewing condition. Fixations at the fixation cross for each trial (Origin; x,y=0,0)

As only the first 500 ms of each trial were analyzed, The latency of the second and third fixations can be seen in fig. 7, as trials with two or three fixations make up over 85% of all trials. Mean (SD) latency for fixation 2 and 3 were 272.01 (94,00) ms and 381.58 (63.97) ms, respectively. (It has to be noted, however, that the right end of the distribution is cut off for fixation 3).

Fig. 7: Fixation latency distribution

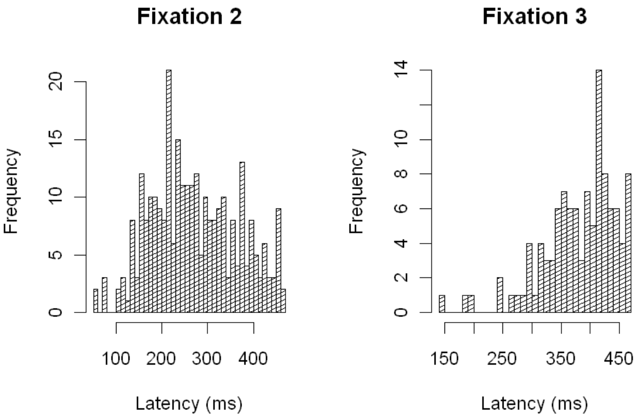


Fig. 7: Frequency of fixations as function of latency for the second and third fixation of each trial's grasp preparation phase.

Location of fixations

Heat maps based on fixation duration for the grasp preparation for one participant can be seen in fig. 5. (See appendix for other particpipants) and give a first glance confirmation on grasp type effect on gaze behavior.

Average fixations X and Y position split by object and condition can be seen in Fig. 6. X and Y positions are referenced to the fixation cross (0,0). To further investigate fixations with respect to differences in object-centered coordinates, AI's were deployed to pool fixations in critical areas and tested against each other (AI see fig.3) with respect to the mean time and number of fixations spent in each interest area. Two-factor repeated measure ANOVAs calculated for each AI revealed main effects of both object and grasptype as well as Interaction effects in AI 2 and 3 (see table 1.

One tailed paired t-tests were performed to test whether these differences were conform to the hypothesis that participants fixate more and longer in the AI centered around the corresponding grasp application point than in other AI. This could be shown for AI "Spher" ("Spherical Grasp" > "Viewing" (t(3)=5.00, p<.05) and "Spheric Grasp" > "Cylindrical Grasp" (t(3)=4.44, p<.05) as well as for AI "Cyl" ("Cylindrical Grasp" > "Spherical Grasp" (t(3)= 2.41, p<.05) and "Cylindrical Grasp" > "Viewing" (t(3)=2.46, p<.05). For the AI "View" the difference between "Viewing" and ""Spherical Grasp" (t(3)=5.40, p<.01) was significant.

Table 1: ANOVAs for summed up fixation time and number of fixations spent in each of the Areas of Interest

	AI "spher"			AI "cyl"			AI "view"		
	Object	Grasp	Inter-action	Object	Grasp	Interaction	Object	Grasp	Interaction
Fix-Time	F(2,6)=6.0 p<.05	F(2,6)=21.3 p<.01	-	F(2,6)= 16.4 p<.05	F(2,6)= 6.2 5<.05	F(2,6)= 7.3 p<.01	F(2,6)= 6.8 p<.05	F(2,6)= 15.3 p<.01	F(2,6)= 4.4 p<.05
Fix-Num	F(2,6)= 29.6 p<.01	F(2,6)= 45.8 p<.01	-	F(2,6)= 8.8 p<.05	F(2,6)= 14.6 .01	F(2,6)=4.9 p<.05	F(2,6)=6.6 p<.05	F(2,6)=21.8 p<.01	F(2,6)=3.6 p<.05

Fig. 8: Summed up fixation time in Areas of Interest

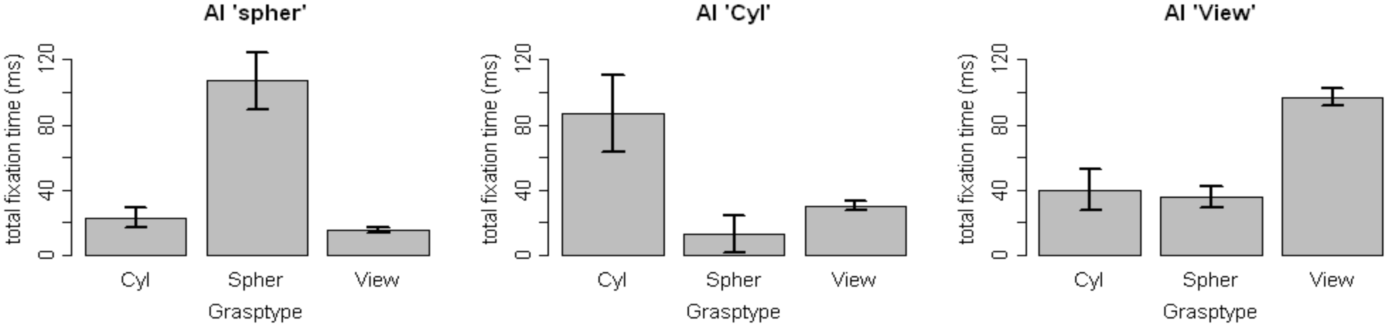


Fig. 7: Mean summed up fixation time for Areas of Interest as function of condition. Error bars represent SE of mean.

Discussion

The results of the present study show that participants effectively prepared the action of grasping an object by fixating relevant areas on the object surface before grasp application. As in the vast majority of trials, the grasp preparation period featured either one or two fixations after the initial fixation on the fixation cross, and the locations of these fixations were distinctly different for the different grasp types, subjects seem to directly have aimed for grasp application points rather than first to look at or near the COG and then towards the to-be grasped locations. This finding is in line with Johansson's et al. (2001), who found that subjects fixated precisely the area of a small bar that had to be grasped rather than its COG or edges.

In the present study, the investigation of fixations on a to-be grasped object was extended over different object types (box, cylinder & cup) and grasp types (spherical and cylindrical).

Visual feedback to calculate and correct future hand position and movements, as investigated by e.g. Binsted & Elliot (1999), Binsted, Chua, Helsen, & Elliot (2001), Lünenburger, Kutz, & Hoffmann, (2000) is only relevant before the grasp location is actually reached, at the moment of grasping, the next movement goal may already be fixated. Therefore, analysis was limited to the pre-grasp period of each trial as this is the time period in which the grasp areas are critical areas for the next manipulation action.

The fixation landing in the grasp application area and not near the COG mainly took place after the first saccade onto the object already, so that an attraction of fixation by the COG as found by Brouwer et al. (2009) did not show in the present study. This might have to do with the familiarity and variability of the properties of the used setup. While Brouwer et al. used relatively small, two-dimensional objects; the present study featured only three well known objects of larger proportions. Variability and size of object shapes might account for differences in attraction of the objects COG on gaze. While in the present study, application points of the grasps were not prespecified and multiple fingers were used, participants still mainly fixated the grasping site. The high familiarity of the objects might have made further gathering of object shape, weight, or symmetry information obsolete, that could otherwise have affected gaze behavior.

The fact that overt attention directly jumped from the fixation cross directly to grasp location sites in this experimental setup suggests covert attention preallocation at the grasp application point, similar to the allocation of attention found by Baldauf & Deubel (2008) in a bimanual pointing task. They found higher discrimination performance in multiple sequential saccade goals. For grasping an object, possibly the object as a whole (with attention centering on its COG) could first be selected covertly, and fixation goal then selected at the probable grasp location. This would implicate higher discrimination performance at COG than at grasp application area, then shifting (or "saccading" to fixation goal) before saccade preparation. Another possibility is, that in our setup, fixation goals at grasp application sites were remembered due to lack of variability of object location. Spatial information has been found to be retained over saccades. (Karn & Hayhoe, 2000; Aivar, Hayhoe, Chizk & Mruczek, 2005). Saccadic and focal attention dynamics remain to be investigated in grasping of objects in variable locations.

Conclusion

This study for the first time investigated gaze dynamics in natural, 3-d objects during the hand movement preparation phase in natural, grasping, resembling everyday grasping of various objects in perspective and type of grasp. When simply viewing the object, Particpiants showed to mainly fixate the object as a whole shape and gaze duration around COG was much higher than at the two possible grasp sites. For Grasping conditions, results advocate fast and efficient fixation of grasp application point when the grasp type is predetermined with no or little attraction of gaze by (task-irrelevant) COG.

Other studies that suggest close monitoring and planning ahead of actions found systematic fixations on objects that were to be manipulated next in tasks, such as the studies mentioned in the Introduction in which naturalistic tasks were used (Hayhoe et al, 2003; land & Hayhoe, 2001; Land, Mennie, & Rusted, 1999). In the present study, these action guiding fixations were now found to not only take place on specific objects but also to depend on which area of an object is to be manipulated/contacted in grasping.

As this was a first study in the study of gaze dynamics in the grasping of three-dimensional objects in a naturalistic three-dimensional scene setting, results will have to be replicated and expanded by future research. Object shape, texture, perceived weight, location, familiarity and fragility are just some of the factors that are worth investigating. A thorough knowledge of visual guidance in grasping can help us understand the most critical features and error sources in grasping and may even be useful in guiding technical systems to better manipulate various objects.

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Gaze direction in pinch grasp preparation

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While visual guidance in object manipulation has been studied for decades, gaze behavior in grasping of objects has received little attention so far. Brouwer, Franz & Gegenfurtner (2009) have found attraction of gaze by index finger grasp application point on saccades following the first saccade on an object. Based on the thumb providing most information for hand to target transport, the current study was conducted to investigate whether in early grasp preparation attraction of gaze by thumb contact area on the object could also be found. Results suggest an interactive pattern of gaze attraction by thumb application point for circular but not for square two dimensional shapes. The interaction pattern is interpreted as an effect of grasp application area size.

Keywords: gaze, pinch grasp, grasp preparation, eye movements, fixation location

Introduction

Visual Guidance & Grasping

Grasping and lifting up an object is a task executed many times each day and so well practiced that we perform it quite automatically and do not feel like we need a lot of mental effort or attention for this action. While being occupied with another task, such as e.g. reading the newspaper or text from a computer screen, one might reach over to the side of the table and try to grasp a pen. In many cases, it will suffice to take note of the object in our visual periphery to grasp it without missing, even though our eyes will stay on the screen, as we concentrate on what is written there. Many of us, however, know the occasional sensation of grasping e.g. too short and only reaching the pen in a second attempt. This time we probably look up from what we were reading to more precisely grasp the object in question. To securely grasp an object, how do we control our gaze on the object to gain most information important for securely grasping it?

Visual guidance in motion

As humans are visual creatures, many of our actions and motions are guided visually. Various studies have underlined the importance of the amount o visual information available to effectively and precisely control our motor systems. Neural evidence for visual guidance and overlapping control systems for visual input and motor control has been found in macaques (Taira, Mine, Gergopoulos, Murata & Sakata, 1990). Visual guidance has been shown to be important in various tasks including locomotion (Marigold, 2008), climbing stairs (Warren, 1984), catching (Savelsbergh, Whiting, Pijpers & van Santvoord, 1993), and many other tasks. The influence of accessibility of visual information has also been shown in pointing (e.g. Bekkering, Adam, van den Aarssen, Kingma, & Whiting, 1995; Bock, 1986; Enright, 1995; Henriques, Klier, Smith, Lowy, & Crawford, 1998; Neggers & Bekkering, 1999) and grasping (DeGrave, Hesse, Brouwer & Franz, 2008) of objects.

Overt attention in visual guidance

Due to the organization of the retina, visual features can best be extracted from the fovea, the area directly surrounding the center of the retina. So if visual information of high acuity has to be extracted, the corresponding area has to be fixated. As this area is limited in size, humans use shifts of fixations to construct an image or scene of adequate representation of the real surroundings. Fixation locations in these shifts depend on what kind of information is to be extracted from a scene. This has originally been shown by Yarbus (1967), who asked participants different questions about the same picture. In trying to answer the different questions, participants showed different fixation patterns.

Without further instructions or tasks, areas of high visual saliency such as lines, edges or occlusions (Krieger, Rentschler, Hauske, Schill, & Zetsche, 2000) as well as Center of Gravity in shapes , both for 2D (COG; He & Kowler, 1991; Kowler & Blaser, 1995, McGowan, Kowler, Sharma, & Chubb, 1998; Melcher & Kowler, 1999; Vishwanath, Kowler & Feldman, 2000)) and 3D (Vishwanath & Kowler; 2003, 2004)) have been found to attract gaze when fixating objects “as a whole” and in visual search.

Task-dependent gaze shift effects are not limited to picture or scene viewing, though. They can also be observed when information has to be extracted from objects for effective interaction with them.

Gaze behavior in motor tasks

Gaze behavior has been studied in various settings involving active motor control of the subject in his environment, such as preparing a sandwich (Hayhoe, M. M., Shrivastava, A., Mruczek, R., & Pelz, J. B., 2003, Land & Hayhoe, 2001), making tea (Land, M., Mennie, N., & Rusted, J. 1999), or car driving (Land & Lee, 1994). Many studies have investigated the effect of gaze behavior in pointing tasks, finding that fixation of the pointing target increases accuracy (Bekkering, Adam, van den Aarssen, Kingma, & Whiting, 1995; Bock, 1986; Enright, 1995; Henriques, Klier, Smith, Lowy, & Crawford, 1998; Medendorp & Crawford, 2002; Neggers & Bekkering, 1999; Vercher, Magenes, Prablanc, & Gauthier, 1994). Riek, Tresilian, Mon-Williams, Coppard, and Carson (2003) investigated gaze behavior in a bimanual double pointing task. They found that subjects tend to sequentially fixate both pointing targets (ending at the smaller target or the target of the non-dominant hand) suggesting more need for visual monitoring of this latter pointing target.

So while we have known about the dynamics of eye movements in complex behaviors such as shopping decision making (e.g. Russo & Rosen, 1975) or simultaneous pointing to two distinct spatial locations, visual guidance of one-handed grasping has received little attention in attention research so far. One study by Johansson, Westling, Bäckström, and Flanagan (2001) found that participants fixated the visible contact region of the bar before grasping it. The fixation location correlated with the actual grasp location of the thumb on a trial by trial basis, suggesting a tight linkage of fixation location and grasp location. This finding, however, may or may not represent a general mechanism, as participants were asked to grasp a 'parking bar' of the same dimensions as the grasping bar in between trials, which featured distinct to be grasped contact locations ('bumps') on the bar. This might have implicitly led participants to aim precisely for the same contact location on the grasping bar and would explain the close fixation & grasping location link.

Brouwer, Franz & Gegenfurtner (2009) argued that with only one visible contact location it comes to no surprise that subjects will fixate where they grasp, so they made the contact location of the index finger visible by using two-dimensional shapes presented in a vertical viewing pane in front of the subject and have it either be grasped or viewed. Unlike in double pointing (Riek et al, 2003), they did not find fixations centered around the contact locations of the fingers sequentially. Rather, in the grasping task, an attraction of gaze to the COG was apparent, that is, subjects generally tended to fixate shapes near the COG. The finding that in the setup used, subjects generally fixated higher than the target shapes' COG could either be interpreted as undershoot of the saccade from the initial fixation point, a general upward tendency, or attraction of gaze by the index finger.

To disentangle this finding, Brouwer et al. (2009) conducted a second experiment in which the fixation point was on the side of the shape and a general upwards tendency of fixations could not anymore be explained by undershoot of saccades from the initial fixation point. Now using either hand to pick up a square, a leftward facing triangle or a rightward facing triangle using both index finger and thumb, participants showed an attraction of gaze by the index finger in the case that the index finger had to grasp the point of the triangle.

Rationale of the present study

Gaze behavior during pinch grasping (i.e. with thumb and index finger) of flat shapes seems to follow a more complex pattern than central fixation or serial fixation of grasp application points. Additionally to undershoot from initial fixation point, attraction of Gaze by COG and of smaller grasp application point, Brouwer et al. (2009) found an attraction of gaze by the index finger affecting the second fixation falling on the object. The effect in the experiment, however, was not visible when the thumb had to grasp the tip of a triangle. This could be due to the thumb application point in this case coinciding with the smaller grasp application point, just as with a square, the overall side of fixations is that of the thumb and at the same time of fixation undershoot.

To separate the effects of undershoot, grasp application point size and side of thumb/index finger, we decided to use shapes of equal application area size for both fingers and to set the side of thumb and index finger not on a line with, but to the sides of the connection between initial fixation point and the shapes COG. Even though Brouwer, Franz & Gegenfurtner (2009) found an attraction of the second saccade (relative to the first saccade) by the index finger, their data also suggests that the overall gaze direction might not be determined by the index finger grasp location but by the thumb (see Brouwer et al., 2009; Fig. 9b, Fig. 11 – square shape). This might even be more visible in situations when we grasp flat shapes from a horizontal working space as we often do in daily life. Grasping three-dimensional objects, we can often not see our fingers at the back of the object, and, as we found in a recent study (Nakagawa, Baldauf & Deubel, unpublished data), in these cases fixations tend to land around the thumb application point. In a study measuring attention to different locations of an “X” shape that was to be grasped with thumb and index finger, Schiegg, Deubel & Schneider (2003) found that attention was first allocated to thumb and then to index finger application area. From 500 ms SOA, no better discrimination performance for a probe could be found for either of the two grasped arms over the non-grasped arms, suggesting preparation of movement was finished at this time.

Brouwer and colleagues argue that if fixations’ function is to provide visual feedback about the approaching hand to enable online corrections (see also Binsted et al., 2001; Helsen, Elliott, Starkes, & Ricker, 1998; Lünenburger, Kutz, & Hoffmann, 2000; Riek et al., 2003), fixations should be attracted to the index finger’s contact location “as this finger describes a more variable trajectory and thus requires more visual feedback in order to guide it to its contact location” (Brouwer, Franz & Gegenfurtner, 2009). Schiegg, Deubel & Schneider (2003) hold a different view based on results by Wing & Fraser (1983), proposing that the thumb is more important for the transport component of the hand as its less variable position may serve as a stable reference point used for guiding the transport of the hand to the object. They also note that, as maximum grasp aperture is reached only after ca. 80% of hand movement duration, the hand transport component seems likely to be prioritized over the manipulation component early in movement preparation.

We therefore expect the thumb, not the index finger, to be associated with the function of providing visual feedback for online correction of the approaching hand’s path; at least for early fixations in grasp preparation. This could also explain why in their study, Brouwer and colleagues found an attraction of fixation by index finger only in the later, second, fixations on the object.

In summary, the current study was conducted to investigate gaze behavior in the grasp preparation phase more closely in a setting with equally large contact areas for thumb and index finger. As argued above, additionally to attraction by COG, we expected attraction of fixations by thumb contact area in early grasp preparation, as this area provides most feedback information for hand transport computation.

Methods

Participants

8 Participants (4 female and 4 male), took part in the experiment and were paid 8€ per hour for their participation. All had normal or corrected to normal vision and normal hearing. Informed consent was obtained before the beginning of the experiment. All participants were self declared right-handed and between 19 and 26 years old.

Apparatus and stimulus materials

Stimulus objects consisted of a flat disc (and a flat square shape of the same size (11 cm radius / width). A smaller disc (7,5 cm radius) was included to investigate possible shape size effects. The objects were presented on an empty workspace area in front of the participant between the chinrest used to maintain viewing distance and the monitor on which calibration was performed. The objects were always placed in the same viewing distance, with the front edge 35 cm from the base of the chinrest to the one side and 25 cm from the base of the monitor on the other side.

The height of the chinrest was 22 cm, so that subjects’ eyes remained close to 25 cm higher than the workspace, causing the subjects to look a proximally 54° downward during the experiment, as can be seen in fig.1.

Eye data were recorded by a head-mounted, video based eye tracker (Eyelink II, SR-Research, Osgoode, Ontario, Canada[1]) measuring the right eye at 250 Hz in pupil + corneal reflection mode. The tracker featured a Scenecamera (Scenecam, SR-research), filming the scene viewed by the subject, which was attached to the front-bar of the eye-tracker, allowing for recording of eye-data independent of the monitor. Calibration was performed on the monitor and head-referenced eye position data was overlaid automatically to the scene camera by the recording Software SceneLink (SceneLink Software, SR-research). Calibration was performed by the sequential fixation of nine predefined dots presented on a 19” monitor at 55 cm viewing distance. Calibration was followed by a depth correction using 5 fixation points in different viewing distance panes, to account parallax changes at different viewing distances of the fixation cross and the object. The overlay resulted in eye data being recorded in reference to the video frames of the scenecamera video. To keep video coordinates of the scene (and the herein included object) constant during and over trials of one recording session, head movements had to be avoided. This was achieved by fixating the metal band (supporting the front bar and eye cameras) to the chinrests vertical bars in such a way that the head could only be angled by moving the chinrest back and forth in its sliding mechanism but could not freely be moved by the participant. After calibration at the beginning of each recording session, during which subjects looked straight at the monitor, the chinrest was moved back some centimeters, so that the scene camera scene center was shifted from the monitor to the workspace. A drift correction to compensate for headband slipping during the angling of the head and depth calibration were performed at this point. Drift correction was repeated in the beginning of each trial.

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[1] Referred to in the following as „SR-Research“

The scenelink II head mounted eye tracker is connected to one “tracker pc” and one “display pc”, the latter running the scenelink software used for calibration and control of recordings done with the scene camera. As in the scenelink software recordings can only be controlled manually from the display pc but automatically controlled via the parallel port, a third pc running ExperimentBuilder Software (SR-research) was used. This pc sent recording start and stop signals to the port, controlled the timing of trial sequence and provided an initial fixation cross (11 cm above the workspace) for each trial.

Fig 1: Trial sequence and apparatus setup

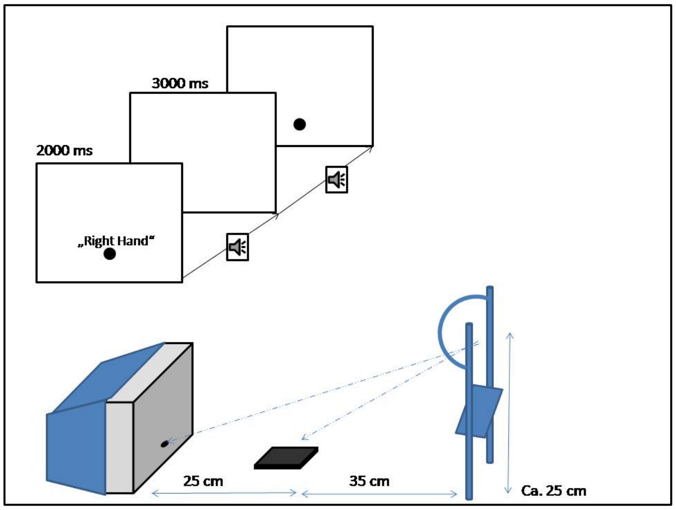

Fig. 1: After drift correction, grasp condition (“Left Hand” or “Right Hand”) was shown on the screen for 2000 ms. The grasping interval lasted 3000 ms.

Design and procedure

The experiment consisted of 2 grasp types for each of the three objects, resulting in a total of 6 conditions times 15 repetitions, totalling 90 trials. In a first block, participants were asked to grasp the presented object with either their left hand or their right hand, in both cases using their thumb and their index finger to spread diagonally over the object, and, in the case of the square shape, to grasp the upper corner of the same side as the grasping arm with the index finger and the lower corner of the opposite side with the thumb. Subjects were instructed to grasp the object at a brisk speed but only so fast as they could still securely grasp the object without it slipping away, lift the object into the air and place it to the left side of the table when grasped with the left hand and to the right when grasped with the right hand. No further instructions about how or where to look at the object were given. Object identity and grasp type were randomized over trials.

A single trial started with a drift correction, followed by a beeping sound signalling the subject to fixate the fixation cross on the screen, where the grasp type (either “left hand” or “right hand”) was presented. After 2000 ms, another beep signalled the subject to grasp the object with the indicated grasp type, lift it up, and place it to the indicated position. A third beep, 3000 ms after the second beep, signalled the end of the recording by which time subjects were to have put down the objects to their intended position.

Fig 2: Stimuli and grasp types

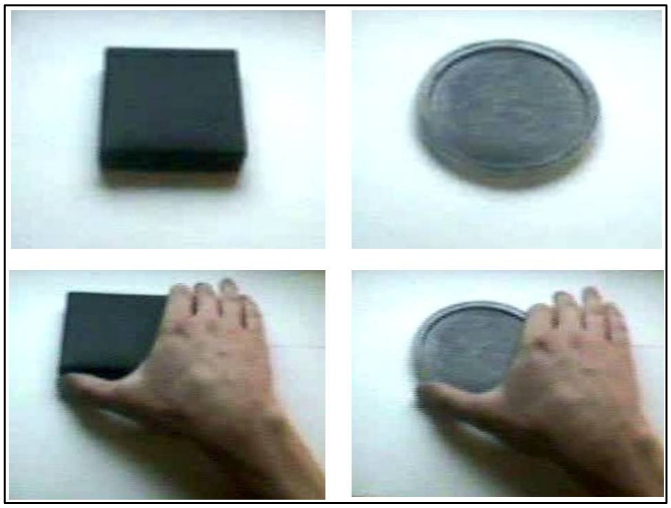

Fig. 2: Examples for Square shape, circular disc shape, and their being grasped (right hand shown).

Analysis

Graphical data validation for further statistical analysis was performed with DataViewer software (SR-Research).

As hand movement data was not recorded, movement preparation period was operationalized by the first 500 ms time period of each trial, to which all statistical analysis was limited. To account for subjects anticipating the start signal, the interest period started 100 ms before and ended 400 ms after the signal. Trials with missing eye coordinates, unsuccessful drift correction or fixations only on the initial fixation point were excluded. Fixation reports were created and exported to R software (R Development Core Team, 2008) for further analysis. To reduce noise, Fixations and saccades were automatically recognized by the DataViewer software with default filter options, however, fixations with duration smaller than 40 ms and outliers greater 2.5 times the standard deviation were excluded from the analysis.

To investigate attraction of gaze by thumb and index finger, respectively, fixation locations during the interest period (the initial 500 ms interval) of each trial were analyzed with repeated measure ANOVA and t-tests. X- (horizontal) and y- (vertical) coordinates were referenced to the shapes COG. Positive x-values reflect rightward fixations, positive y values upward (or on the workspace more distant) fixations

Results

Number & latency of fixations per trial

Figure 3 shows the total amount of fixations made in the interest period. The mean (SD) amount of total fixations inside this time period was 1.22 (0.44). Participants made one fixation in 71,1% and two fixations in 27,7% of the trials, leaving less than 1% with more than 2 fixations in the time period analyzed.

Fig 3: Number of fixations per trial

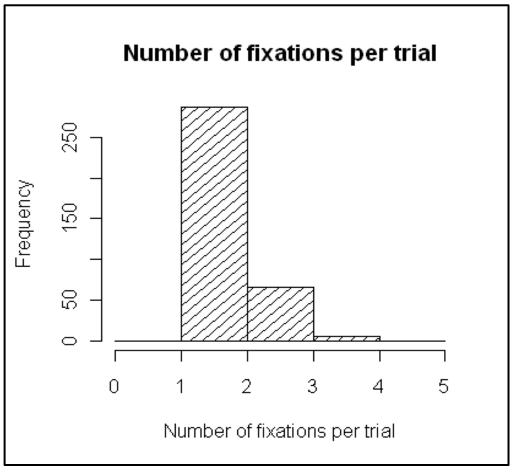

Fig.3: Number of fixations inside the 500 ms interest period interval per trial in absolute frequencies.

The latency distributions of fixations 1 and 2 inside the interest period are shown in figure 4, peaking at 50-100 ms for the first fixation and showing only the part of the distribution for the second fixation that lies within the interest period. (Peaking at 500-550 ms outside of the interest area)

Fig. 4: Latency distribution

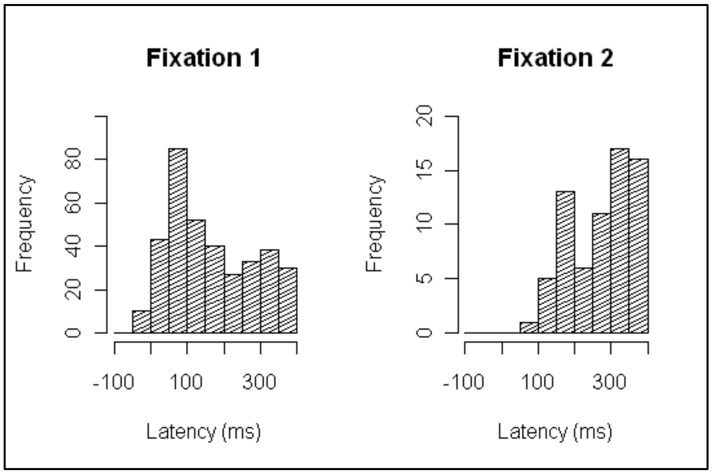

Fig 4:Histograms for Fixation latencies inside the interest period for first and second fixations on the object in absolute frequencies.

Total durations of fixations 1 and 2 were analyzed for all fixations beginning in the interest period. As can be seen in Fig. 5, Duration distributions markedly show multiple local maxima at around 200 and 700 ms for both Fixations 1 and 2.

Fig. 5: Duration distributions

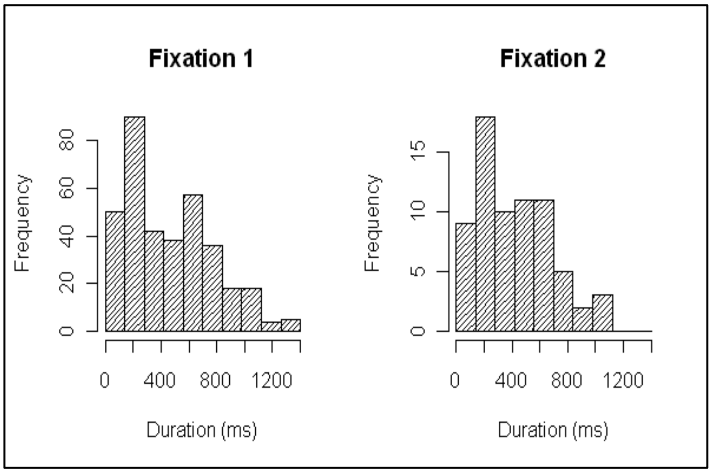

Fig 5: Durations of Fixations with latencies falling inside 500 ms interest period interval for first and second fixations.

Fixation location & Dynamics

2-factor repeated measures ANOVA over all shapes' y-values revealed no significant main or interaction effects. Mean y coordinates were greater zero for all shapes, yielding a combined measure of saccadic undershoot and index finger application area. As x-coordinates did not suffer from such a confoundation, we based our further analysis on fixations horizontal location (x-values).

As for y values, a 2-factor repeated measures ANOVA revealed no main effect for either shape (F(2,14=.15,p=.86) or grasptype (F(1,7=.05, p=.83) for x coordinates, however, a significant interaction between the two factors was evident (F(2,14=4.36, p<.05). Fixation locations did not differ significantly between the small and large size disc (ANOVA: shape: F(1,7)=.27,p=.62, grasp type: F(1,7)=1.46, p=.23, Interaction: F(1,7)=1.54, p=.25), so for better comparability, lateral gaze locations were further investigated for the large disc and the square shape, as these shapes were of equal pinch grasp aperture. Mean fixation coordinates can be seen in figure 6.

The two same sized shapes yielded a significant interaction (F(1,7)=13.4, p<.01) with no significant main effects (shape: F(1,7)=.005, p=.94; grasp type: F(1,7)=.02, p=.88). t-tests showed a marginally significant difference between left hand and right hand grasp for the disc (t(7)=2.33, p=.05) but no such difference for the square shape (t(7)=-1,14, p=.29).

Fig. 6: Fixation locations on shapes for conditions

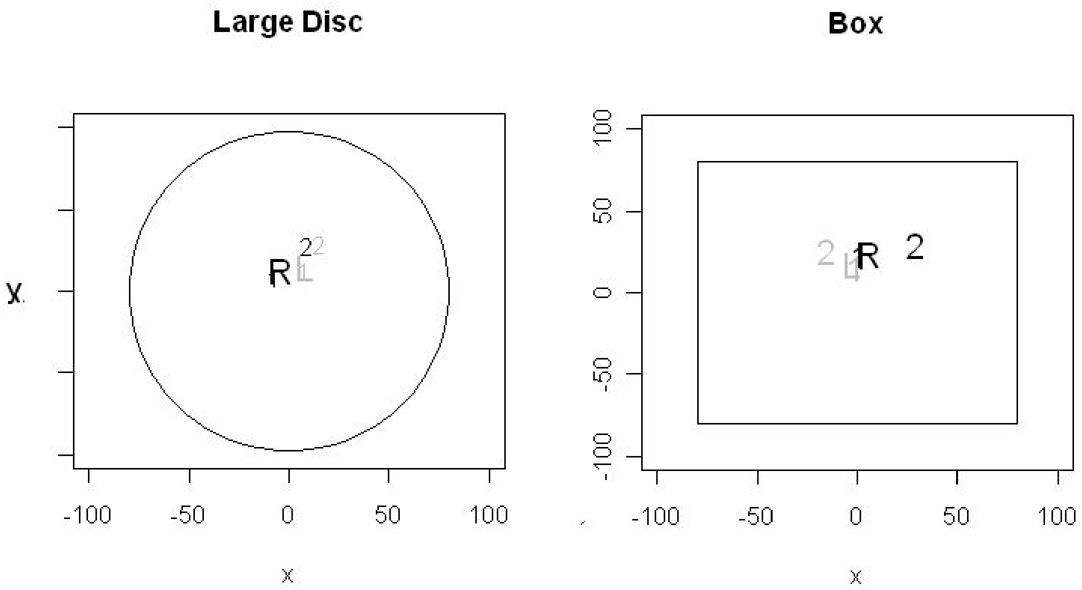

Fig.6: x and y coordinates for fixations on circular disc and square shape for left hand (grey) and right hand(black) grasp. Numbers refer to fixations of the number's index, letters to mean fixation coordinates.

Fig.7: x values for large Disc and Box for grasp type

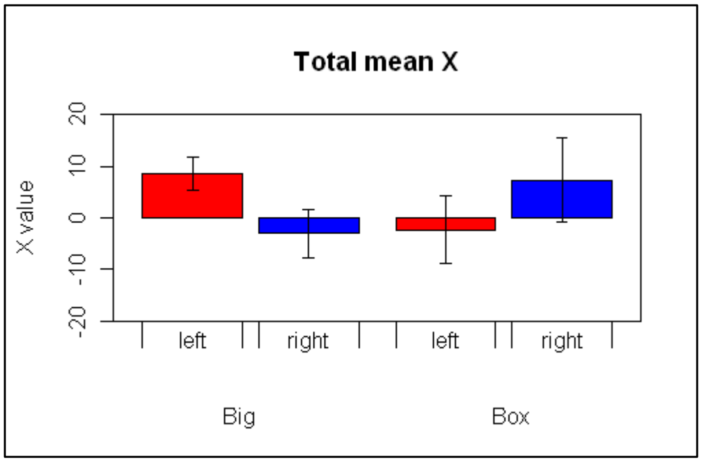

Fig. 7: Mean x values for large Disc ("Big") and square shape ("Box") for left and right hand grasps

As visible in fig. 7, the mean fixation location pattern, albeit not significant for the square shape, numerically mirrors the discs pattern. For the disc, right hand grasp led to more leftward fixations than left hand grasp. For the box, right hand grasp numerically lead to more rightward fixations than left hand grasp. Therefore, in grasping the circular disc shape but not in grasping the square shapes' corners, participants fixated more towards the thumbs' side.

Discussion

The present study was designed to investigate gaze attraction of thumb vs. index finger during pinch grasp preparation on two-dimensional shapes. We expected gaze to be attracted by thumb application location in early grasp preparation, as the thumb guides the hand to the object (Wing & Fraser (1983)) and therefore the thumbs' contact location should provide most information for visual guidance.

Our results did not show clear main effects of grasp type (left hand or right hand) or shape (disc or square shape). Further analysis revealed that while for the circular shape early (mostly primary) saccades were directed more leftward when using the right hand than when using the left hand, suggesting an attraction of gaze by thumb. This pattern was mirrored numerically by the square shape, suggesting that gaze attraction of the fingers may not only depend on relative size of contact application area. Even if contact application area for both index finger and thumb are of equal size, their absolute size may affect gaze behavior. With larger grasp application points, guidance of the hand to the object, best monitored by thumb application point, may be of prime importance.

With smaller grasp application points, though it may be more crucial to monitor the index finger's approach, as the index finger's path is more variable and carries more degrees of freedom, as argued by Brouwer, Franz & Gegenfurtner (2009).

In the current study, the initial fixation point was spatially over the objects, and in all shapes and grasp types, saccades landed slightly higher than the COG, suggesting saccadic undershoot from the fixation point (see fig. 6).

This hypothesis is derived from an analysis of the initial 500 ms interval of grasp preparation and was not combined with motion tracking. In our study, we therefore mainly investigated early, primary fixations on the objects. Results showed the same pattern when analyzing all saccades in the interest period or only primary fixations. There were not enough cases in all cells to perform statistical analysis for secondary fixations only. Early secondary fixation locations (marked by a "2" in fig. 6) do reflect attraction by index finger though. This would be in line with the findings of Brouwer, Franz & Gegenfurtner, (2009).

It must be noted that fixation location on shapes feature high intra & interindividual variability, so gaze attraction can only be interpreted as a probabilistic effect. The fixations mostly do not leave the COG of a shape so far as to actually center around grasp application point of thumb or index finger may be due to attraction by COG, saccadic undershoot or a combined attraction by both fingers' application points. The two fingers' 'attraction force' may be weighted according to setup and shape of the object, as both fingers' application points carry some information, and the further one fixates towards on application point, the less accurate vision of the other application point will become. Such a weighting mechanism would also result in most fall fixations only part of the way between COG and actual grasp application point.

Finally, not only contact application area size or shape may play an important role for gaze in grasp preparation, grasp preparation may also easily be influenced by setup. An object laying on a table or workspace may be pushed/pulled some way with one finger only, giving tactile feedback about the objects' weight, COG, center line, etc. When shapes are fixed vertically in front of the subject, this is impossible and therefore grasping, and especially index finger's application point may have to be guided more closely.

Conclusion

Investigation of gaze behavior in grasp preparation may be affected by different variables, such as saccadic undershoot, gaze attraction by COG, grasp application point size and finger used. The current experiment found attraction of gaze by thumb application point in a circular disc shape, and suggested attraction of gaze by index finger in a square shape grasped on diagonal corners. These measures are not confounded with saccadic undershoot from initial fixation point and suggest that both thumb and index finger application point may attract gaze in grasp preparation, depending on shapes and setup used. As results were in part only marginally significant or tendencies, they will have to be replicated and amended by future research. It appears that in grasp-gaze investigation, many factors have to be regarded and controlled for. Nonetheless it is worthwhile investigating this topic, as a thorough knowledge of visual guidance in grasping may help us understand basic cognitive processes underlying motor control and may be useful for guiding technical systems to better manipulate various objects.

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