Advance planning in sequential pick–and–place tasks

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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 this 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 the 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, Altoro, & 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 robust phenomenon that can be observed even in the second and third movement of an action sequence.

The studies presented in the last paragraphs investigated the modification of kinematics when grasping an object with varying action intentions and performing a subsequent action with the very same object (e.g., Cohen & Rosenbaum, 2004; Ansuini et al., 2006, 2008). The question arises whether action sequences are also planned holistically when different target objects and several subtasks are involved. To our knowledge, there has been no study to date investigating the effects of future task demands on movement tasks which are self-contained before the next movement is started. The current study was designed to shed some light on this issue.

Specifically we wanted to test whether the action context effect transfers to situations consisting of different and more or less unrelated motor tasks which are executed in close temporal (and spatial) proximity. If the action context effects persists in such situations this would indicate that the capacity of the motor system is not limited to planning the direct consequences of an action ahead but that it maximizes its efficiency by additionally taking upcoming action tasks into account.

To this end, we designed a sequence of actions in which the orientation of the grip necessary to grasp a target successfully was specified in the last subtask, but not in the intermediate, self-contained pick-and-place task which required the grasping and placing of a cylindrical object. Participants were asked to perform an action sequence which consisted of three movement parts and included two different target objects. They first 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 specifically interested in the effect of the target bar orientation on the grip orientation in the preceding movement segments. Since grasping the cylinder can be achieved with a variety of grip orientations, 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 the CNS takes future task demands into account early during sequence planning and execution even when the actions are not directly related. 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, perhaps 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: $-45^\circ$, $0^\circ$, or $+45^\circ$ 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. In the easy conditions none of the trials had to be repeated whereas in the accurate conditions less than 2% of the trials were repeated because the cylinder was not placed with sufficient accuracy. 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 quickly 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).

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).

Moreover, parameters of the grip aperture profile (difference between index finger and
thumb) were analyzed. The aperture was calculated as the Euclidean distance of the fingers in
3D space. 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° 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
graped (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 test. 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
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°, 0°, 45°) 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.
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 $p>.10$).

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°, 0°, 45°) 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 $p>.42$).

**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 area 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 were analyzed in the same way as for 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, $F(2,30)=3144$, $p<.001$.

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 $539ms \pm 26ms$ to grasp the cylinder in S1, and $949ms \pm 36ms$ 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 $941ms \pm 34ms$ to grasp the bar in S3 when in was oriented to the right, $957ms \pm 31ms$ when the bar was oriented vertically, and $1055ms \pm 41ms$ 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 $250ms \pm 10ms$. Thus, although the movement sequence was even more difficult, the RTs did not increase as compared to Experiment 1. This
finding can be considered as additional indication that the sequence was planned and
programmed sequentially.

**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, 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 than at the end of 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 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 (measured as visual discrimination performance at a 
certain spatial location) 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 (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 the monkeys prepared 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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References


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 ($\alpha$) 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 $\pm$ 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 $-45^\circ$ 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 $45^\circ$ 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 $\pm$ 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.
a) RT → S1 → S2 → S3
- Grasping cylinder
- Placing cylinder
- Grasping bar

b) α α α

- Wrist velocity in m/s
- Aperture in cm

Time in ms

0 200 400 600 800 1000 1200 1400 1600 1800

0 0.5 1.0
a) Movement onset
b) Grasping the cylinder (S1)
c) Releasing the cylinder (S2)
d) Grasping the bar (S3)
Grip orientation:

grasping the cylinder

releasing the cylinder

Participant: A  Participant: B
a) Movement onset

b) Grasping the cylinder (S1)

c) Placing the cylinder (S2)

d) Grasping the bar (S3)
a) Movement onset  

b) Grasping the cylinder (S1)  
c) Releasing the cylinder (S2)  
d) Grasping the bar (S3)