Original Article

Where to Grasp a Tool?

Task-Dependent Adjustments of Tool Transformations by Tool Users

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Abstract. Biomechanical and environmental constraints limit body movements and tool use actions. However, in the case of tool use, such constraints can often be overcome by adjusting a tool's tool transformation to the requirements of the intended tool use action. The research presented here examined whether participants grasped a lever at different positions, thus modifying the lever's tool transformation, to accommodate speed and accuracy requirements of different tasks. Participants were asked to quickly track a sequence of targets with the lever. If accuracy requirements were high, participants compensated for limits in the accuracy of hand movements by grasping the lever at a position that enabled precise control of the lever. If accuracy requirements were low, participants compensated for limits in hand speed by grasping the lever at a position that enabled fast lever movements with comparatively slow hand movements. This task-dependent grasp selection was only present after participants had practiced the tasks. The data show that in addition to adapting to fixed tool transformations, participants also actively controlled tool transformations to facilitate tool use actions.

Keywords: tool transformation, end-state comfort, grasping, tool use, anticipation

Almost everyone uses many different tools everyday, be it cutlery, a hammer, or a computer mouse. These tools allow the execution of actions that could not be carried out without them. However, the use of tools requires learning how to control tool movements with movements of the body. For example, when using a computer mouse, one has to learn how far to move the hand holding the mouse in order to move the mouse cursor a desired distance. This mapping from body movements to tool movements is called "tool transformation."

Acquisition of a Predetermined Tool Transformation

In recent years, many studies have investigated the acquisition of visuomotor or tool transformations, which leads to the mastering of various tools (Mosier, Scheidt, Acosta, & Mussa-Ivaldi, 2005; Sailer, Flanagan, & Johansson, 2005; Sülzenbrück & Heuer, 2009b). For example, Sailer and colleagues (2005) showed that the skill to control a novel tool is acquired by initially exploring the effects that body movements have on the tool, and then by the subsequent production and fine-tuning of increasingly goal-directed movements. Once the general skill to control a certain class of tools is acquired, it is often necessary to adapt to different configurations of the tools. For example, although all computer mice behave in roughly the same manner, we have to adapt to different mouse sensitivities when we use different computers. In recent years, numerous studies have scrutinized how human beings adapt to changes in visuomotor transformations (e.g., Abeele & Bock, 2001), the influence of explicit strategies (Mazzoni & Krakauer, 2006; Sülzebrück & Heuer, 2009a), the transfer of visuomotor skills to different tasks and effectors (e.g., Abeele & Bock, 2003; Butz, Lenhard, & Herbort, 2007), and the involved internal models (e.g., Krakauer, Ghilardi, & Ghez, 1999; Tong & Flanagan, 2003).

Adjusting the Tool Transformation

The studies discussed in the previous section showed that participants were able to learn how to realize desired tool movements through body movements. However, in many situations a desired tool movement might require a body movement that is hard or impossible to execute due to biomechanical or psychological limitations. In such situations it is frequently possible to carry out the desired tool movement by adjusting the tool transformation in such a way that an easily executable body movement can realize the tool movement.

Indeed, everyday life offers plenty of opportunities to modify tool transformations. By means as simple as grasping a hammer at different positions, it is possible to adjust the relationship between hand movement and hammer head movement. To generate very fast hammer movements despite limited speed of the hand, the hammer can be grasped at the end of the handle. To control the hammer head with high precision it can be grasped closer to its head. Thus, successful tool use requires anticipating the body

Zeitschrift für Psychologie 2012; Vol. 220(1):37–43
DOI: 10.1027/2151-2604/a000089

movements that are necessary to control the tool and adjusting one's actions to ensure that these body movements can be readily executed.

The ability to anticipate forthcoming movements and to adjust one's actions in anticipation of the requirements of these movements has been frequently documented in the case of object manipulation. Examples of such anticipatory actions are the "end-state comfort effect" and the "grasp height effect" (e.g., Cohen & Rosenbaum, 2004; Herbort & Butz, 2010, 2011a, 2011b; Rosenbaum et al., 1990). For example, when Cohen and Rosenbaum (2004) asked participants to displace a vertical bar, participants grasped the bar at a lower position when accuracy requirements were high than when they were low. The authors speculated that this strategy was used because the lower the bar was grasped, the smaller the effect of unintended hand oscillations on the foot of the bar, and thus the higher the controllability of the object. This behavior can be interpreted as the selection of different tool transformations for movements with high or low precision requirements.

Research Question

Effective tool use requires the acquisition of tool transformations and the adjustment of the tool transformations in anticipation of forthcoming tasks. Many studies have scrutinized the acquisition of a fixed tool transformation. Likewise, anticipatory grasp selection for object manipulation has been extensively studied. However, little is known about how participants anticipatorily select a grasp in tool use actions, and thus influence the tool transformation. I address two questions in this paper. First, do participants adjust the tool transformation associated with a novel tool to task requirements by grasping a tool at different positions? Second, if they do so, do they need practice with the tool or do they immediately grasp the tool task-dependently?

To address these questions, I conducted a study wherein participants were asked to track sequences of targets with the tip of a lever as quickly as possible in two different task setups. In a pointing task, participants were instructed to position the tip of the lever exactly on the targets, requiring precise control of the lever. In a sweeping task, participants were instructed to sweep the lever over the target, requiring little accuracy. Participants could grasp the lever at different positions, which resulted in different transformations of hand movements into movements of the lever's tip. Because human hand movements are limited with respect to movement speed and accuracy, the two tasks could be best performed by grasping the lever at different positions (Fitts, 1954). By grasping the lever close to the joint, very fast lever tip movements were possible despite the limited speed of human hand movements. By grasping the lever closer to the tip, accurate positioning of the lever tip was possible despite the limited accuracy of human hand movements. Thus, given the inherent constraints on the speed and accuracy of hand movements, participants could trade off lever speed and lever controllability by grasping the lever at different positions.

To address the question of whether participants adjust the lever's tool transformation task-dependently, the positions at which the participants grasped the lever for pointing and for sweeping were compared. To address the influence of practice with the lever, grasp positions were recorded in test blocks before and after practice. While participants were free to grasp the lever at any position in the test blocks, in the practice blocks they were instructed to grasp the lever at specific positions. The instruction of different grasp positions served two ends. First, requiring participants to experience the effect of the tool transformations associated with different grasp positions facilitated learning, due to variability of practice (cf. Wulf & Schmidt, 1997). Second, as participants performed both tasks with a variety of grasp positions it was possible to objectively measure which grasp positions yielded the fastest movements.

Method

Participants

Twenty-one students from the University of Würzburg gave informed consent and participated. Three had to be excluded because they did not comply with the instructions. The remaining 18 participants (13 women, 5 men) were between 19 and 31 years old (*m* = 22). According to Coren's (1993) Lateral Preference Inventory, 16 were right-handed and 2 were left-handed. Both left- and right-handed participants used the same experimental setup and executed the movements with the right hand. They received course credit for participation.

Apparatus and Stimuli

Participants operated a light, low-friction, 98 cm long lever on a desk (Figure 1). A start button was placed between the lever and the participant, 20 cm distant from the joint in vertical and horizontal direction. Stimuli and instructions were presented on the desk surface with a projector that was mounted above the desk. Targets were displayed as white circles (diameter 3.2 cm). During the practice phase, a white rectangle (1.6 cm × 6 cm) was projected over the lever to indicate the instructed grasp positions.

Procedure

At the beginning of each trial, the participant was prompted to move the lever to the 0° position if necessary (absolute lever angle larger than 1°). The participant was then asked to press and hold the start button with the index finger of the right hand. Once the start button was pressed, the German word for "point" or "sweep" was displayed for 1,000 ms on the desk between lever and participant, followed by a cross for 500 ms. The first target of the target sequence then appeared. This was the sign for the participant

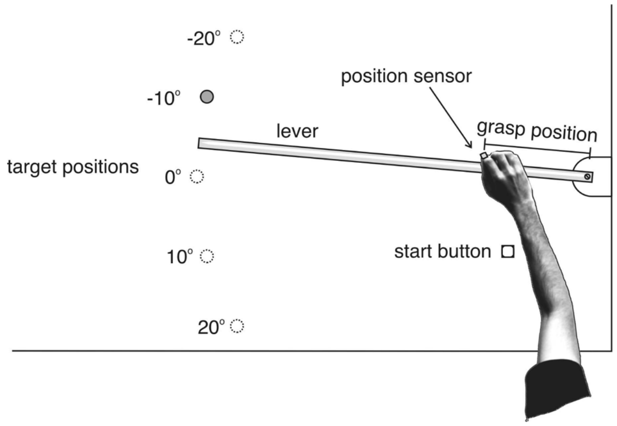

Figure 1. Experimental setup. In the figure, the participant has already grasped the lever (grasp position) and now moves it toward the –10° target. Targets could also appear in four other positions. Before grasping the lever, the hand rested on the start button.

to release the start button, grasp the lever, and hit the target. In pointing trials, a target was considered hit if the lever was within ± 0.7° of the target for at least 150 ms. In sweeping trials, a target was considered hit as soon as the lever was moved over the target. Immediately after the target was hit, the next target was presented. After five targets were hit, feedback was displayed for 2,000 ms based on performance in the previous block with the same task ("good," "very good," or "excellent") and the next trial was initiated. If the movement was not finished within 10 s, the trial was cancelled and the German word for "faster" was displayed. If the participant released the start button before the onset of the first target, the trial was restarted. In practice blocks, the grasp position was indicated by a white rectangle over the lever from the first time the start button was pressed to the first time the lever angle deviated by more than 2° from the 0° position. Video recordings of exemplar sweeping and pointing trials from test and practice blocks can be downloaded from the link provided in the footnote.[1]

The target sequences consisted of five targets, located at 0°, ± 10°, and ± 20° on the imaginary circle, on which the tip of the pointer moved. Only target sequences in which each target was an immediate neighbor of the preceding target were used. As the lever always started in the 0° position, and the first target was always either the 10° or the −10° target, this resulted in 18 different target sequences.

Before the start of the experiment, participants could get used to the experimental setup and the different trial types in eight training trials. Each experimental session consisted of 16 blocks. In each block either only sweeping trials or only pointing trials were presented.

The first two and the last two blocks served as test blocks. In each of these blocks, each possible sequence was presented once in a fixed order to reduce between-participant variance. In the test blocks, no instruction to grasp the lever at a specific position was given.

Blocks 3–14 were practice blocks. In the practice blocks, participants were instructed to grasp the lever at different positions, either 10, 20, 30, 40, or 60 cm away from the lever's joint. In the practice blocks, all combinations of task, target sequence, and instructed grasp position were presented once, resulting in 90 pointing trials and 90 sweeping trials. Each practice block had 15 trials that were randomly drawn without replacement from one of the pools of 90 trials, depending on the task required in the block. Participants were not explicitly prompted to pay attention to the effects of the grasp selection in the practice trials.

In sum, the experiment consisted of two test blocks before practice (1, 2) and two test blocks after practice (15, 16) with a total of 72 trials. The practice phase (blocks 3–14) had 180 trials. Between blocks, participants received feedback on their performance in the preceding block (average movement time, number of errors) and were instructed about the task in the forthcoming block. Participants were randomly assigned to one of two groups, receiving either the pointing trials in the odd-numbered blocks and the sweeping trials in the even-numbered blocks (11 participants) or vice versa (7 participants). The experiment lasted approximately 30 min.

Data Recording and Analysis

Movements of the lever and of the hand were recorded with an Ascension trakSTAR motion tracking system with a sampling rate of 100 Hz. Sensors were attached to the lever and to the middle segment of the participant's right index finger. The motion tracker signal was processed online to control the experiment. In each trial, the position of the index finger was recorded (a) at the onset of the lever movement (the first time the lever angle deviated by more than 2° from the original 0° position) and (b) when the last target was hit. The grasp positions at both moments were defined as the distances between the positions of the index finger sensor and the lever's joint in the desk plane. If the grasp position at movement onset differed by more than 5 cm from the grasp position at the end of the movement, that trial was excluded from analysis (2%). Otherwise, the grasp position at the onset of the movement was used for further analysis and will be denoted as "*grasp position*" in the remainder of this paper. *Movement time* was defined as the time between the onset of the first target and the time the last target was hit. If the movement time in a trial deviated by more than two standard deviations from a participant's mean with respect to the task, instructed grasp position (if any), and part of the session (Blocks 1–2 vs. 3–14 vs. 15–16), the trial was excluded from analysis (4%).

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[1] Video recordings of different exemplar trials can be downloaded from: http://www.i3.psychologie.uni-wuerzburg.de/fileadmin/06020300/user_upload/Herbort/where_to_grasp_a_tool.mov.

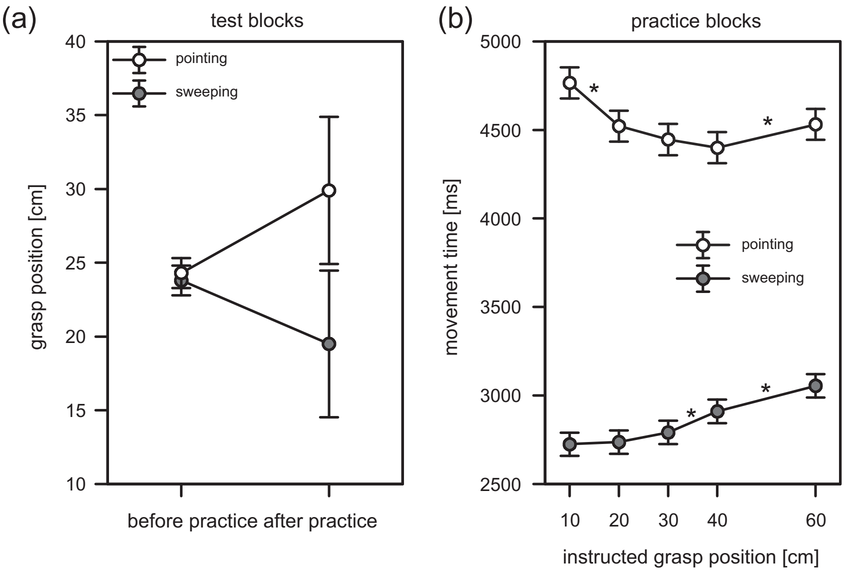

Figure 2. (a) The effect of the task on grasp position in test trials before and after practice. (b) The effect of instructed grasp position on movement times during practice for both tasks. Error bars show 95% CIs for within-subject effects of task (a) and instructed grasp position (b) according to Loftus and Masson (1994). Asterisks show significant differences in movement times within tasks.

Results

As a preliminary analysis revealed that neither the handedness nor the order of task presentation affected grasp position or movement time, these factors were not included in the following analysis of the data.

Test Blocks: Effect of Practice and Task on Grasp Position and Movement Time

To check whether participants adjusted their grasp position to the two tasks, the grasp positions of the test block trials were pooled by task (pointing, sweeping) and practice (before practice, after practice) and submitted to a repeated measures ANOVA with the within-subject factors task and practice. Figure 2a shows average grasp positions before and after practice. The ANOVA revealed a significant effect of task and a significant interaction between task and practice, $F(1, 17) = 11.3$, $p = .004$, $\eta_p^2 = .40$ and $F(1, 17) = 7.8$, $p = .013$, $\eta_p^2 = .31$, respectively. For post hoc analysis, paired two-sided t-tests were conducted. There was no significant difference between grasp positions in pointing trials (24.3 cm) and sweeping trials (23.7 cm) before practice, $t(17) = 0.8$, $p = .437$, $\eta_p^2 = .036$. However, after practice, grasp positions were further away from the joint in pointing trials (29.9 cm) than in sweeping trials (19.5 cm), $t(17) = 3.1$, $p = .006$, $\eta_p^2 = .36$. These results indicate that participants only adjusted the grasp position to the task after practice.

A repeated measures ANOVA with the within-subject factors task and practice revealed that movement times were generally shorter in sweeping trials than in pointing trials, $F(1, 17) = 349.1$, $p < .001$, $\eta_p^2 = .95$. Movement time improved from the blocks before practice to the blocks after practice, $F(1, 17) = 50.0$, $p < .001$, $\eta_p^2 = .75$. Post hoc paired t-test revealed a significant reduction in movement time for both, pointing and sweeping trials, $t(17) = 3.9$, $p = .001$, $\eta_p^2 = .47$; $t(17) = 7.2$, $p < .001$, $\eta_p^2 = .75$, respectively. This improvement was more pronounced in sweeping trials than in pointing trials, $F(1, 17) = 8.0$, $p = .011$, $\eta_p^2 = .32$. The average movement times in pointing trials decreased from 4,483 ms before practice to 4,229 ms after practice. In sweeping trials, movement times decreased from 3,021 ms to 2,532 ms.

Practice Blocks: Effect of Instructed Grasp Position on Movement Time

In the practice blocks, the average absolute difference between the actual grasp positions and the instructed grasp position was below 1 cm, demonstrating that participants grasped the lever as instructed. To examine how different instructed grasp positions affected movement times, the movement times of each of the participants were averaged by task and instructed grasp position and subjected to a repeated measures ANOVA with the within-subject factors task and instructed grasp position.[2] Figure 2b shows that movement times were generally lower for sweeping trials than for pointing trials, $F(1, 17) = 566.3$, $p < .001$, $\eta_p^2 = .97$. Additionally, the instructed grasp position affected movement time, $F(4, 68) = 11.0$, $p < .001$, $\eta_p^2 = .39$. Most importantly, there was a significant interaction between task and instructed grasp position, $F(4, 68) = 35.2$, $p < .001$,

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[2] We report Greenhouse-Geisser corrected p values and uncorrected F values.

$\eta_p^2 = .68$. These results show that the instructed grasp position affected movement times differently in the two tasks. On average, participants performed the sweeping movements fastest if the lever was grasped within 20 cm from the joint, whereas pointing movements were performed fastest if the lever was grasped approximately 40 cm from the joint.

To further analyze the interaction between instructed grasp position and task, 2 × 2 post hoc within-subject ANOVAs for adjacent instructed grasp positions and task were conducted. The three ANOVAs for the comparison of instructed grasp positions 10 cm versus 20 cm, 20 cm versus 30 cm, and 30 cm versus 40 cm yielded significant interactions between instructed grasp position and task, all $F(1, 17)$s > 7.2, all ps $< .015$, all $\eta_p^2 > .30$. Movement times decreased for increasing instructed grasp positions in pointing trials, but increased for increasing instructed grasp positions in sweeping trials for instructed grasp positions between 10 and 40 cm. Additionally, paired *t*-tests between adjacent instructed grasp positions revealed significant differences between the grip positions 10 and 20 cm, as well as 40 and 60 cm in pointing trials, and 30 and 40 cm, as well as 40 and 60 cm in sweeping trials, all $t(17)$s > 4.3, all ps $< .001$, all $\eta_p^2 > .52$.

Finally, to test whether the grasp positions that yielded the fastest movement times changed during practice, a within-subject ANOVA with the within-subject factors instructed grasp position, practice (first half of practice, second half of practice), and task was computed. This ANOVA revealed significant effects of task, practice, instructed grasp position, and a significant interaction between task and instructed grasp position, $F(1, 17) = 569.7$, $p < .001$, $\eta_p^2 = .97$; $F(1, 17) = 10.4$, $p = .005$, $\eta_p^2 = .38$; $F(4, 68) = 11.4$, $p < .001$, $\eta_p^2 = .40$; and $F(4, 68) = 36.2$, $p < .001$, $\eta_p^2 = .68$, respectively. There were no significant interactions with the factor practice, including the three-way interaction, all ps > 0.17, all η_p^2s $< .11$. This shows that the relationship between grasp positions and movement times did not change significantly during training (besides an overall reduction of movement time). In pointing trials the instructed grasp position at 40 cm yielded the shortest movement times in the first and second part of practice. In sweeping trials, the instructed grasp position at 10 cm yielded the shortest movement times in the first half of practice and the instructed grasp position at 20 cm yielded the shortest movement times in the second half of practice.

Discussion

In the present study, participants were asked to operate a simple novel tool – a lever – in two different task setups. By grasping the tool at different positions, participants could adjust the tool transformation associated with the lever to the specific requirements of the tasks. Initially, participants did not grasp the lever task-dependently. However, after practice, participants adjusted the grasp positions to the tasks, thus actively influencing the tool transformation associated with the lever.

Actual and Optimal Grasp Selection

It has been previously reported that human beings optimally adapt their behavior to various motor tasks (e.g., Harris & Wolpert, 1998; Trommershäuser, Maloney, & Landy, 2003). However, in pointing trials from this experiment, participants did not grasp the lever at the position that yielded minimal movement times in the practice blocks. Whereas the grasp position of about 40 cm from the joint yielded the fastest pointing movements in the practice blocks, participants grasped the lever only about 30 cm from the joint after practice.

Different factors could have caused this seemingly inadequate behavior in the reported experiment. First, it is possible that participants were not able to fully adapt their grasp positions to the presumably optimal grasp positions. As participants experienced only 90 practice trials, the limited adaptation could have been due to insufficient practice. Additionally, the small relative differences in movement times resulting from different grasp selections could have resulted in a weak learning signal (cf. Figure 2b). Moreover, participants were not prompted to pay attention to the movement times resulting from the various grasp selection, and it is possible that the actual grasp positions would correspond more closely to the grasp positions that resulted in the fastest movements if other practice procedures had been used.

Second, it is possible that actual grasp positions deviated from those yielding the fastest movements in practice trials because participants employed additional planning criteria. For example, the grasp position yielding the fastest pointing movements required the participant to reach far to the left with the right arm, which may have been considered effortful or uncomfortable by some participants. Hence, some participants may have traded movement speed for ease of reaching for the lever (cf. Rosenbaum, 2008).

Finally, one could argue that the grasp position selections before practice were actually not less suitable than those after practice, because the optimal motor control strategy itself may depend on training (cf. Berthier, 1996). However, the fastest movements resulted from different grasp positions in pointing and sweeping trials in the first and second half of practice. Thus, it seems unlikely that the different grasp selections before and after practice resulted from motor control strategies that were equally well adapted to the respective circumstances. This suggests that grasp selections after training were better adapted to the specific tasks than grasp selections before training.

Outlook on Advance Motor Planning and Tool Use

One of the aims of this paper is to narrow the gap between two prominent topics in the motor control literature: the acquisition of a tool transformation and advance motor planning. Although there is rarely overlap between the two topics in experimental studies, the involved mechanisms seem deeply entangled. An integrated perspective on both topics is necessary to understand advance motor planning and tool use actions.

On the one hand, tool users may benefit in three ways from the ability to consider the requirements of a forthcoming tool use actions when they plan to grasp the tool. First, the reported experiment showed that the ability to plan actions in advance enables the participants to accommodate speed and accuracy requirements of different tasks with respect to biomechanical constraints of the body.

Second, in addition to internal constraints, external constraints may also have to be considered in many situations. A simple example is the control of a computer mouse. In order to move the cursor to a specific position on the screen it is important to know if the associated movement of the hand holding the mouse is possible. For example, the edges of a mouse pad limit effective hand and mouse movements. Thus, before beginning to move the cursor, it is necessary to change the relationship between mouse position and cursor position by repositioning the mouse on the mouse pad.

Third, tool transformations differ with respect to the ease with which desired tool movements can be mapped to body movements (Abeele & Bock, 2001; Kunde, Müsseler, & Heuer, 2007; Massen & Prinz, 2007). Thus, by adjusting the tool transformation, participants may not only facilitate action execution, but also reduce the cognitive requirements of tool use actions. In sum, tool users may benefit from the ability to anticipate the requirements of forthcoming tool use actions with respect to biomechanical, cognitive, or external constraints.

On the other hand, advance motor planning in object manipulation tasks cannot be understood without the acquisition of mappings from desired distal effects to body movements. Whereas the present experiment revealed that participants grasp tools in anticipation of their intended use, participants also frequently align aspects of a grasp, such as the grasp orientation, to forthcoming object manipulations, such as transport or rotation (Cohen & Rosenbaum, 2004; Herbort & Butz, 2010, 2011b; Rosenbaum et al., 1990). Moreover, to be able to adapt the grasp to the intended object manipulation, it is necessary to know how body movements affect object movements. In the present experiment, participants had to consider the effect of the hand position on the position on the lever's tip when planning how to grasp the lever. Likewise, when controlling cursor movements with a control knob and when rotating rigid objects, participants have to map desired cursor or object rotations on the associated forearm and hand rotations in order to be able grasp the object appropriately (Herbort & Butz, 2010, 2011a). From this perspective, any object that is manipulated in a certain way can be viewed as tool, which is associated with a specific tool transformation. It is thus necessary to acquire the tool transformation associated with the to-be-manipulated object to be able to plan a grasp that enables the intended object manipulation.

Conclusion

The present report takes an extended perspective on tool use actions. As a first step, it is necessary to learn how tool movements translate into body movements. Additionally, when using tools, it has to be considered that human beings can influence the tool transformations of many tools in different ways. This ensures that the desired tool movements can be realized by executable body movements. The present data show that participants adjust the grasp position on a lever to the requirements of different tasks, which required either fast or accurate hand movements. The participants selected tool transformations that enabled them to actuate the tool with hand movements that could be (easily) executed. This shows that the tool transformations may be controlled by tool users to facilitate the effective use of the tool. To understand the complexity of human tool use actions, future research should take a broader perspective on tool use, including the adjustment of the tool transformation by the tool users.

Acknowledgments

The author acknowledges funding from the Emmy Noether program of the German Research Foundation (Grant BU1335/3-1). Thanks to Rasty Gabbari, Lars König, Carmen Lai, Pablo Mair, and Juliane Waßmuth for discussion and data collection, and to Albrecht Sebald for technical support.

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