RESEARCH ARTICLE

Habitual and goal-directed factors in (everyday) object handling

Oliver Herbort · Martin V. Butz

Abstract A habitual and a goal-directed system contribute to action selection in the human CNS. We examined to which extent both systems interact when selecting grasps for handling everyday objects. In Experiment 1, an upright or inverted cup had to be rotated or moved. To-be-rotated upright cups were more frequently grasped with a thumb-up grasp, which is habitually used to hold an upright cup, than inverted cups, which are not associated with a specific grasp. Additionally, grasp selection depended on the overarching goal of the movement sequence (rotation vs. transport) according to the end-state comfort principle. This shows that the habitual system and the goal-directed system both contribute to grasp selection. Experiment 2 revealed that this object-orientation-dependent grasp selection was present for movements of the dominant- and non-dominant hand. In Experiment 3, different everyday objects had to be moved or rotated. Only if different orientations of an object were associated with different habitual grasps, the grasp selection depended on the object orientation. Additionally, grasp selection was affected by the horizontal direction of the forthcoming movement. In sum, the experiments provide evidence that the interaction between the habitual and the goal-directed system determines grasp selection for the interaction with every-day objects.

Keywords Habitual system · Goal-directed system · Grasping · End-state comfort effect · Object handling

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Introduction

Each moment offers a myriad of possibilities for interaction with other people, animals, or objects. To select beneficial actions, a habitual, stimulus-driven and an intentional, goal-directed system are employed by the central nervous system (Balleine and Dickinson 1998; Yin and Knowlton 2006). The habitual system associates stimuli with responses that were rewarding in the past. The goal-directed system, on the other hand, selects actions dependent on the match of anticipated action outcomes and current needs. Both systems differ functionally and in their neural substrates (Packard and Knowlton 2002; Owen 1997; Waszak et al. 2005) but need to work in concert to enable effective behavior (Daw et al. 2005).

In this paper, we address which roles both systems play in manual action, focusing on the selection of the grasp orientation based on external stimuli and the overarching object manipulation intentions of our participants. Whereas many findings show the involvement of goal-directed processes in object handling, also evidence for the involvement of the habitual system has been provided. On the one hand, many experiments demonstrate that the selections of object-directed grasps are controlled mostly by the goal-directed system, because the kinematics of these movements depends specifically on the intended interactions with the objects (Cohen and Rosenbaum 2004; Gentilucci et al. 1997; Haggard 1998; Herbort and Butz 2010, 2011; Johnson-Frey et al. 2004; Rosenbaum et al. 1990, 1992, 1996). On the other, it has been shown that objects may evoke those motor responses that are habitually associated with them more or less independently from current intentions (Creem and Proffitt 2001; Masson et al. 2011; Tucker and Ellis 1998). However, the influence of both systems has so far mostly been studied in isolation. Hence, in this paper,

we aim to explore the interaction of the habitual with the goal-directed system when interacting with objects.

In the following, we review isolated lines of research for both claims and highlight possible intersections. After that, we present three experiments, demonstrating the interaction of both processes in grasp orientation selection for object handling. A discussion concludes the paper.

Goal-directed actions

A classic example of the influence of the goal-directed system on grasp orientation selection is the end-state comfort effect (Rosenbaum et al. 1990). The end-state comfort effect refers to the finding that participants adjust the orientation of the hand when grasping an object to the intended interaction with the object. For example, if participants intend to rotate an object, they counter-rotate the hand before grasping, thus avoiding extreme arm postures after rotation (e.g., Haggard 1998; Herbort and Butz 2010, 2011; Rosenbaum et al. 1990, 1996). Likewise, if participants want to transport a vertical rod to a high or low shelf, they grasp the rod at a low or high position, respectively, thus facilitating transport of the rod (Cohen and Rosenbaum 2004). The finding that such anticipatory effects are modulated by the precision requirements at the end of the movement sequence further supports the notion that these movements are controlled by the goal-directed system (Cohen and Rosenbaum 2004; Rosenbaum et al. 1996; Short and Cauraugh 1999). Besides the hand orientation, also other parameters of prehension movements depend on anticipated object interactions (Gentilucci et al. 1997; Johnson-Frey et al. 2004).

These anticipatory effects in grasp orientation selection seem generally very robust. For example, in Rosenbaum et al. (1990), participants obeyed the end-state comfort principle in virtually every single trial (c.f. Weigelt et al. 2006; but see Rosenbaum et al. 1996). Furthermore, the effect has been reported in young children (Thibaut and Toussaint 2010; Weigelt and Schack 2010) and even in monkeys (Weiss et al. 2007). Finally, in bimanual actions, the end-state comfort effect even persists if it requires the execution of different rotations with the left- and right-hand (Weigelt et al. 2006). From these findings, one could conclude that the grasp orientation selection for object interaction is mostly determined by the goal-directed action selection system.

Habitual actions

In contrast to this conclusion, recent studies have also provided support for an involvement of the habitual action selection system in the control of grasping movements. For example, experiments using the stimulus–response compat-

ibility paradigm provide evidence in this direction. In a study of Masson et al. (2011), participants had to grasp either a vertical or a horizontal bar in response to an imperative stimulus. It was found that pictures of handled objects could prime the orientation of the hand in a subsequent grasping movement. For example, vertical grasps were executed faster if they were preceded by the presentation of a vertical beer mug rather than a horizontal frying pan. Additionally, a priming effect only occurred when the response, if applied to the prime stimulus, would correspond to the normal, functional use of the displayed object. This suggests that everyday objects evoke those actions that are habitually directed to them.

Tucker and Ellis (1998) reported comparable results from an experiment that required wrist rotations. In their Experiment 3, participants had to respond to the orientation of an image of an everyday object with a clockwise or counterclockwise wrist rotation, depending on an arbitrary counterbalanced stimulus–response mapping. Reaction times were lower when the response coincided with the wrist rotation that would be necessary to functionally grasp the object than when the response coincided with the wrist rotation that would result in a non-functional grasp. Both experiments suggest that the perception of an object automatically evokes actions that are habitually applied to grasp the object.

More direct evidence for stimulus-driven grasp selection has been provided by Creem and Proffitt (2001). Participants, who had to grasp and transport handled objects, such as a hammer or a screwdriver, grasped the objects according to their normal use in most cases (about 75% of the time in the control condition). This was surprising because the object transport did not require the usual grasps, which were even rather cumbersome because the objects' handles faced away from the participants. In sum, these experiments provided evidence that the presentation of everyday objects may automatically activate those actions that are habitually used to grasp them, independent of the current intentions of the participants. This could be interpreted in favor of a strong involvement of the habitual system in grasp (orientation) selection.

Interaction between the goal-directed and habitual systems

The apparent contradiction of evidence favoring a strong involvement of the goal-directed and the habitual systems in grasp selection may be partially due to the experimental methods used, which usually manipulate factors that tap only into one of the systems. For example, most experiments that report a strong involvement of anticipatory factors in grasp orientation selection use "neutral" objects, such as bars or control knobs, which do not afford a specific grasp in everyday life and thus cannot be associated with a

habitual grasp (e.g., Haggard 1998; Herbort and Butz 2010, 2011; Rosenbaum et al. 1990, 1996; Thibaut and Toussaint 2010; Weigelt et al. 2006; Weigelt and Schack 2010). Likewise, in the experiments that showed the influence of the habitual system, the participants always performed the same action with the object or did not intend to interact with the object. Thus, no differentiating influence of the participants' intentions could be observed.

Nevertheless, several findings hint at the interaction of the goal-directed with the habitual systems in grasp orientation selection. Rosenbaum et al. (1992) described the tendency to grasp a pointer with the thumb toward the tip. This "thumb-toward bias" (Rosenbaum et al. 1992, p. 1059) was attributed to the creation of an attentional overlap between the tip of the pointer and the thumb and index finger. However, this finding could also be interpreted as a habitual bias because also most tools are usually grasped with the thumb toward the functional end of the tool (e.g., toothbrushes, knifes, and rackets). Both accounts are not exclusive because the repeated selection of grasps that create attentional overlap could result in the formation of a habitual thumb-toward bias. Other support for a possible involvement of (short-term) habitual factors in grasp orientation selection comes from the finding that grasp orientation selection depends on recent (successful) grasp orientation choices and not entirely on intended object interactions (Kelso et al. 1994; Rosenbaum and Jorgensen 1992; Weigelt et al. 2009). This shows that grasp orientation selections could be determined by simple stimulus–response mappings at least as long as the response remains effective.

Further evidence for the involvement of the habitual system comes from a developmental study (McCarty et al. 1999). Nineteen-month old children had more difficulties selecting a suitable grasp for transporting the functional end of a handled toy (e.g., a rattle) to the mouth than doing so with a spoon. The authors suggested that this discrepancy arose because the spoon was more clearly associated with a specific grasp (i.e., grasping the spoon at the handle with the thumb toward the bowl) than the handled toys. From these and other observations, the authors concluded that the control of grasping movements toward frequently used objects shifts from a goal-directed to a habitual strategy during development.

To conclude, isolated evidence for the involvement of goal-directed and habitual factors in grasp orientation selection has been provided. Several findings hint at a possible interaction of both systems in grasp orientation selection but so far, this interaction has been rarely examined directly.

Here, we address how the goal-directed and the habitual systems interact when selecting grasps for handling everyday objects. We consider goal-directed action selection as a process that selects actions based on the match of antici-pated action outcomes with the current explicit goals of an individual, independent of the actions that are usually carried out in the presence of current external stimuli. Habitual action selection is considered a process that selects actions that are usually executed in the presence of the current external stimulus and which does not dependent on current explicit intentions. In this paper, we focus on the influence of external stimuli and the associated habitual actions as well as on the overarching object manipulation intentions on the selection of the grasp orientation.[1] Experiment 1 reveals that grasp orientation selection depends on both, the intended interaction with an object and the habitual actions associated with the object. Experiment 2 replicates Experiment 1 for actions of the dominant and non-dominant hand in right-handed participants. Experiment 3 explores the influence of the object-grasp association strength on grasp orientation selection.

Experiment 1

To assess the contribution of the goal-directed and habitual system to grasp orientation selection, we asked participants to grasp and transport a cup. We used a cup because almost every one uses a cup every day and because it is habitually grasped with a thumb-up grasp (supine) before being used for drinking. However, additional ways to grasp a cup exist, such as a thumb-down grasp (prone).

To test the involvement of the goal-directed system, we manipulated the movement that the participants had to carry out with the cup. In some trials, the cup had to be moved to another position; in other trials, the cup had to be additionally rotated by 180°. It can be expected that participants use a thumb-up grasp more frequently for transport than for rotation movements if the goal or end-state of the entire movement sequence is taken into account during grasp orientation selection (e.g., Rosenbaum et al. 1990). Moreover, for the execution of the required tasks, only the geometrically and physical properties of the cup (e.g., inertia and friction) have to be considered. As these properties are almost identical for the upright and the inverted cup, one would not expect an influence of cup orientation on grasp orientation selection if only the goal-directed system would be employed.

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[1] Please note that the selection of a grasp posture itself can be considered as setting the (sub-) goal to assume a specific posture at the moment of grasping. Thus, also habitually selected grasping postures may result in necessarily goal-directed grasping movements. This apparent contradiction arises because the selection of the grasp posture may be considered as the result of an action selection process when observed from the task perspective (e.g. rotating an object) but as a goal itself when observed from the movement perspective (e.g. grasping an object with prone forearm orientation).

Table 1 Frequency of grasp selections dependent on trial type in Experiment 1

Task	Cup orientation		Presumed grasp preference		Grasp selection			
	Initial	Target	Goal-directed system	Habitual system	Thumb-down	Thumb-up	Top	Error
Rotation	Upright	Inverted	Thumb-down	Thumb-up	15	9	0	0
	Inverted	Upright	Thumb-down	None/thumb-down	23	1	0	0
Transport	Upright	Upright	Thumb-up/top	Thumb-up	2	18	4	0
	Inverted	Inverted	Thumb-up/top	None/thumb-down	2	16	5	1

To test for the involvement of the habitual system, the cup was presented either in its canonical upright orientation or inverted. As upright cups are most frequently grasped with a thumb-up grasp in everyday life, for example for drinking, we expect a strong link between the upright cup and the thumb-up grasp. In contrast, inverted cups are less likely to afford a specific grasp orientation, because they are seldom directly used for drinking but are rotated to pour liquid inside or stowed away. Thus, inverted cups may not afford a specific grasp orientation or may afford a thumb-down grasp. As the external stimulus situation was identical in all trials with the same initial cup orientation, one would not expect that the intention of the participants played a role in grasp orientation selection, if only the goal-directed system was employed. Table 1 lists the presumably preferred grasp orientations of the habitual and the goal-directed system for all experimental conditions.

The most interesting experimental condition is the rotation of an upright cup because here the habitual grasp (thumb-up) is in conflict with the goal-directed grasp (thumb-down). This condition can be compared with both transporting an upright cup, in which both systems act in concert, and rotating an inverted cup, in which the habitual system can be assumed to either play only a minor role or bias grasp selection in the same direction as the goal-directed system does.

If the habitual system was involved in grasp orientation selection, we would expect that upright cups are more frequently grasped with a thumb-up grasp than inverted cups—independent of the participant's intention. Moreover, we expect that the influence of the intended movement on grasp orientation selection is larger for inverted cups than for upright cups, because, in this case, the habitual system should not provide a preference for a specific grasp orientation.

Method

Participants

The participants were students and staff from the psychology department of the University of Würzburg. Participants (16 women, 8 men; 21 right-handed, 3 left-handed) were

Fig. 1 In Experiments 1 and 2, the cup was used (second object from the *left, handle* at backside, without the *white* and *black* patch). In Experiment 3, the mug, cup, hairspray, shampoo, book, and wooden spoon (from *left* to *right*) were used. The view corresponds to the participants' view of the objects. The depicted object orientation was defined as "upright"

between 20- and 52 years old ($m = 25$ years). They were offered a chocolate bar for compensation.

Stimulus and procedure

After a participant gave informed consent, he was seated in front of a table. On the table were two gray circles (diameter 10 cm and distance of centers 12 cm), located horizontally before the midline of the participant. A cylindrical cup was used to make movements with different initial cup orientation as comparable as possible. The cup was red with a white inside (Fig. 1, see Online Resource 1 for dimensions).

The task of the participant was to first close the eyes. Then, the experimenter placed the cup on the left circle so that the handle pointed away from the participant. After the experimenter told the participant to place the cup either "upright" or "inverted", the participant opened the eyes, grasped the cup with the right-hand, and placed it on the right circle. The experimenter observed and noted the grasp of the participant when he was first grasping the cup. Grasps were categorized as thumb-up grasp, thumb-down grasp, top grasp (fingers enclose cup from top), or handle grasp (see Online Resource 2 for examples). After that, the participant closed the eyes again and the next trial started.

There was no time pressure, and the participants were not instructed to use a specific grasp for moving the cup.

Each experiment consisted of four trials, which resulted from the combinations of the two different initial cup orientations (upright or inverted) and the two target orientations (upright or inverted). We refer to trials in which the initial and target orientations were identical as *transport trials* and to trials in which the initial and target orientation differed as *rotation trials*. The order of the trial was balanced over the 24 participants used for the data analysis.

Participants spontaneously grasped the cup at the handle in 13% of all trials. As the handle grasp may be used for the instructed task as well as for drinking, the handle grasp cannot be associated exclusively with the habitual or the goal-directed system. Thus, we replaced the five participants who grasped the cup at the handle at least once before rotation.[2] Except for the trials in which the handle was grasped, these participants showed a pattern of results comparable to the remaining participants.

Results

Table 1 displays the frequency of the participants' grasp selections for the four different trial types. Grasp selection depended on the initial cup orientation in rotation trials, two-sided exact McNemar test, $P = .01$. If the cup had to be rotated and was initially inverted, only 1 out of 24 participants selected a thumb-up grasp. However, if the cup was initially oriented upright, 9 out of 24 participants selected a thumb-up grasp. If the cup had to be transported without rotation, most participants selected a thumb-up grasp or grasped the cup from the top, independent of the orientation of the cup, two-sided McNemar-Bowker test, $\chi^2(2) = 1$, $P = .61$.

Finally, grasp selections between rotation and transportation trials with similar initial cup orientation differed significantly for the 18 participants, who used only thumb-up and thumb-down grasps throughout the experiment, two-sided exact McNemar test, upright–upright versus upright—inverted: $P = .008$; inverted—inverted versus inverted—upright: $P < .001$.

Discussion

Experiment 1 revealed that both goal-directed and habitual factors play a role in grasp orientation selection. On the one hand, participants adjusted the grasp orientation to the

intention of rotating or transporting the cup. On the other hand, if participants intended to rotate the cup, the initial orientation of the cup played a role in grasp orientation selection. Thus, if the goal-directed system and the habitual systems were in conflict, participants selected both thumb-up and thumb-down grasps with relatively high frequencies. However, if both systems were not in conflict, participants selected the predicted grasp in almost all cases.

The strong discrepancy between grasps selected for transportation and grasps selected for rotation shows that the goal-directed system is a major determinant of grasp orientation selection in object handling tasks, which is in accordance with the literature (e.g., Herbort and Butz 2010, 2011; Rosenbaum et al. 1990, 1996). Participants selected an awkward thumb-down grasp in 79% of all rotation trials but only in 8% of all transportation trials, thus mostly finishing the movement in a neutral posture. However, a closer look at the rotation trials revealed that the participants were 33% more likely to select a thumb-down grasp if the cup was initially inverted than when it was presented upright. Thus, although participants intended to rotate the upright cup, they selected that grasp orientation more frequently that is habitually used to grasp an upright cup. This shows that, besides intentional factors, also habitual stimulus–response associations influence grasp orientation selection.

Five participants were replaced because they grasped the cup by the handle at least once, even if the handle faced away from them. Interestingly, the executed handle grasps frequently would have appeared awkward or even non-functional when used for drinking.[3] This suggests that the habitual system may have selected the to-be-grasped part of the cup rather than a specific grasp orientation selection in the trials, in which the handle was grasped. In sum, Experiment 1 reveals considerable influence of both the goal-directed and the habitual systems in grasp selection.

Experiment 2

Experiment 2 was conducted for two reasons. First, we wanted to replicate the findings of Experiment 1 with another sample and a more rigorous data recording technique. Second, recent studies have shown that the end-state comfort effect is smaller for grasps with the left-hand than grasps with the right-hand in both, left- and right-handed participants (Janssen et al. 2009, 2011). This difference has been attributed to the involvement of left-hemispheric networks in planning and execution of object manipulation

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[2] The excluded participants used the following grasps: upright–upright: 2× handle, 3×thumb-up; upright-inverted: 1× thumb-up, 2× thumb-down, 2× handle; inverted-upright: 1× thumb-down, 4× handle; inverted–inverted: 3× thumb-up, 1× handle, 1× error (participant did not rotate cup).

[3] As no videos were recorded in Experiment 1, we analyzed handle grasps in Experiment 2. In Experiment 2, 6 out of 16 handle grasps were non-functional with respect to drinking.

and tool use (c.f. Frey 2008). Thus, if the ability to plan future actions according to intended object manipulations was reduced for left-handed actions, one could expect two findings in a cup rotation experiment. First, the frequency of end-state comfort compatible grasps should be smaller for the left-hand than for the right-hand. Second, as the influence of advance motor planning, and thus the influence of the goal-directed system, is smaller for left-handed than for right-handed actions, the habitual system should consequently contribute stronger to grasp orientation selections in left-handed than in right-handed actions. Hence, one would expect that the initial cup orientation had a stronger influence on grasp orientation selection in left-handed than in right-handed actions. To analyze the effect of initial object orientation and the hand used for grasping, we asked participants to rotate an upright or inverted cup with either the left- or right-hand.

Method

Participants

The participants were recruited from the citizens of Würzburg. Participants (21 women, 13 men; all right-handed) were between 17- and 49 years old ($m = 27$ years). Half of them participated in one of several "button-press" experiments that were unrelated to the current studies before they participated in Experiment 2. They were offered a chocolate bar for compensation.

Stimulus and procedure

After a participant gave informed consent, he was seated in front of a table. As in experiment 1, two gray circles (diameter 10 cm and distance of centers 12 cm) were located on the table—however, now on the frontal axis before the participant. A trial began with the participant closing the eyes. Then, the experimenter placed the cup, which was already used in Experiment 1, on the far circle, with the handle facing away from the participant, and told the participant to open the eyes. After that, the experimenter instructed the participant to rotate and place the cup on the near circle, by instructing either an "upright" or "inverted" target orientation, depending on the initial cup orientation. This instruction was used to conceal that the cup had to be rotated in every trial and so to encourage participants to replan the grasp orientation in every trial. After moving and rotating the cup, the participant closed the eyes again and the next trial began. There was no time pressure, and the participants were not instructed to use a specific grasp for moving the cup. The movements were videotaped for later analysis.

Each session of Experiment 2 consisted of four trials, resulting from the combinations of hand (left or right) and initial cup orientation (upright or inverted). The first two and the second two trials were always executed with the same hand but the trial order was otherwise randomized. Before the first and third trial, the experimenter told the participant which hand to use from now on. As we were mostly interested in the decision between thumb-up grasp and thumb-down grasp, the data of 24 participants, who exclusively used thumb-up or -down grasps, were collected. This required recording data of 34 participants altogether. The different possible trial orders were randomized and counterbalanced among these 24 participants.

Data analysis

The videotapes were rated by one of the authors (OH) and one independent rater. The raters scored each grasp to be a thumb-up grasp, a thumb-down grasp, a handle grasp or a top-grasp (Online Resource 1) and agreed on all but one trial (99%).[4]

Results

Table 2 displays the frequencies of the different grasp selections for all participants (AP) and, in parentheses, for the subgroup (SG) that only used thumb-up and thumb-down grasps. We used two-sided McNemar-Bowker tests (AP) and exact two-sided McNemar tests (SG) to compare grasp frequencies.

The initial cup orientation significantly affected grasp selection in both samples and for both hands, AP/right: $\chi^2(4) = 16$, $P = .003$, AP/left: $\chi^2(4) = 15$, $P = .005$, SG/right: $P = .002$, SG/left: $P = .004$. However, the hand used for the movement had neither a significant effect on grasp selection for upright, nor for inverted cups, AP/upright: $\chi^2(2) = .66$, $P = .72$, AP/inverted: $\chi^2(3) = 3$, $P = .39$, SG/upright: $P = .69$, SG/inverted: $P = 1.00$.

Discussion

Experiment 2 replicated the finding that the initial orientation of the cup had a considerable influence on grasp selection. On average, the inverted cup was grasped about 10 times as frequent with a thump-down grasp than with a thump-up grasp. In contrast, upright cups were grasped 1.3 times as frequent with a thumb-up grasp than with a thumb-down grasp. This provides further support for the involvement of the habitual system in grasp orientation selection.

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[4] In one trial, the participant rotated the cup using a thumb-down grasp but placed it on the far circle. After additional instruction, he moved the cup to the near circle without rotating it, using a thumb-up grasp. This trial was included in the analysis as thumb-down trial.

Table 2 Frequency of grasp selections dependent on trial type in Experiment 2

Hand	Initial cup orientation	Grasp selection			
		Thumb-down grasp	Thumb-up grasp	Top grasp	Handle grasp
Right	Upright	12 (11)	18 (13)	1	3
	Inverted	23 (21)	3 (3)	3	5
Left	Upright	14 (13)	16 (11)	1	3
	Inverted	26 (22)	2 (2)	1	5

Numbers in parentheses are frequencies of those participants who exclusively used thumb-up and thumb-down grasps throughout the experiment

No differences between actions executed with the left and with the right-hand were found. Even more so, numerically the end-state comfort effect was slightly larger in left-handed actions than in right-handed actions. Thus, we could not replicate an advantage for right-handed actions in motor planning (Janssen et al. 2009, 2011). Several differences between our experiment and the reports of Janssen et al. could account for this discrepancy. First, Janssen et al.'s task was more difficult than ours, because it required bimanual actions and had a more complex stimulus-to-response mapping. Second, our experiment required to solve a rather common everyday task, for which already stereotypic solutions may preexist and which thus may have required little online planning (McCarty et al. 1999). In contrast, the participants of Janssen et al. had to grasp and rotate CD-casings, using somewhat uncommon grasps, which might have required more elaborate motor planning.

In sum, Experiment 2 showed again that the habitual system contributes considerably in grasp selection for object interaction. Previously reported advantages for motor planning for right-handed actions could not be replicated.

Experiment 3

The previous experiments revealed that the initial orientation of a to-be-rotated cup affected grasp orientation selection. This suggests that the habitual system contributes to grasp orientation selection. In particular, we argued that the tendency to use a thumb-down grasp for rotating a cup was reduced if the cup was upright rather than inverted, because the thumb-up grasp is more strongly associated with the upright than with the inverted cup. If the object-orientation-dependent grasp selection resulted from the different strength with which specific grasps are associated with common and uncommon object orientations, then this effect should be absent in objects that are never presented in their common orientation or that simply do not have a common orientation.

Thus, in Experiment 3, we created situations in which the goal-directed and the habitual systems are either in con-flict or not as in Experiment 1. Additionally, we required participants to rotate six different, vertically oriented everyday objects (Fig. 1). Three of the objects—a cup, a mug, and a hairspray container—were selected because we assumed that they afford a thumb-up grasp if presented upright but no specific grasp when presented inverted. These objects have a vertical canonical orientation. The other three objects—a book, a spoon, and a shampoo—were selected because they are usually not oriented vertically before they are grasped and are often not oriented upright. For example, the book and spoon are usually aligned to the transverse plane (e.g., lying on a desk or in a kitchen drawer) before being grasped. The shampoo may be placed with the opening facing up or down. These objects do not have a vertical canonical orientation. If the habitual system biases grasp orientation selection, we expected that object-orientation-dependent grasp selections should only be found in vertically oriented objects that have a vertical canonical orientation. On the other hand, objects that were never presented in their canonical orientation or simply do not have a canonical orientation should not be subject to such a bias.

Method

Participants

Altogether, 27 women and 9 men participated in Experiment 3, aged between 18 and 43 years (*m* = 25 years). According to the handedness scale of Coren's (1993) Lateral Preference Inventory, 33 were right-handed and 3 were left-handed. They received 5€ or course credit for participation.

Stimuli and procedure

Six different objects had to be handled throughout the experiment (Fig. 1, see Online Resource 1 for weight and dimensions): a cup, a plastic mug, a hairspray container, a book (Butz 2006), a shampoo bottle, which could be placed with the opening facing up or down, and a wooden spoon, which was fixed between two plastic disks and could thus

be placed vertically on the table. The assumption that cup, mug, and hairspray had a vertical canonical orientation but the book, the shampoo, and the spoon had not was largely confirmed by asking participants to place each object "as they would usually find it in their environments" (Online Resource 1). A black and a white marking were attached at the top and the bottom of each object.

The participants were seated at a desk, on which again two gray circles were located in front of the participant—this time horizontally aligned (diameter: 10 cm and distance of the centers: 12 cm). A trial began with the participant closing the eyes. Then, the experimenter placed an object on one of the circles and pressed a button. After a randomly chosen interval of 200–800 ms, the word "white" or "black", followed by a beep (440 Hz for 100 ms) after 1,000 ms, was played into the participant's headphones. The participant was instructed to open his eyes once he heard the word, but to delay grasping and moving the object until the beep was played. The participants had to place the object on the other circle so that the marking of the announced shade (white or black) was on top. After that, the participant closed the eyes again and the next trial began. There was no time pressure, and the participants were not instructed to use a specific grasp for transporting the object. The experimental session was videotaped for later analysis.

Four factors were varied in the experiment. First, six different objects were used. Second, as the object could have to be moved from the left to the right circle or vice versa, there were two movement directions (left-to-right and right-to-left). Third, the object orientation could initially be upright or inverted. Figure 1 shows all objects in their assigned upright position. Fourth, the object had either to be rotated by 180° (rotation trials) or not to be rotated (transport trials). In every block, each combination of object, movement direction, object orientation, and movement type was presented once and in random order. A single session consisted of three blocks, separated by short breaks, except for the first participant, who only performed two blocks. The entire experiment lasted for approximately 45 min.

Data processing

Two raters rated each video according to the grasp (prone, neutral, and supine), the movement executed (hand rotation, no hand rotation), the hand used (left or right), and the object. A trial was discarded if raters did not agree on the object, hand, movement, or if one rater rated the grasp as supine and the other as prone Raters agreed on 97% of all trials on all four criteria. If the movement was performed with the left-hand, if the wrong movement type was executed (rotation instead of transport movement), if the object

was rotated without rotating the wrist (e.g., letting object swing around by holding it with thumb and index finger), or if the experimenter used the wrong object, a trial was also discarded (4.5%). Finally, only participants who provided at least one trial in which the object was rotated for each object, object orientation, and movement direction were included in the analysis (26 participants, all right-handed). The grasp orientation in each trial was coded with 1 for prone (thumb-down) grasps, 0 for neutral grasps, and −1 for supine (thumb-up) grasps. If one rater rated the grasp orientation to be neutral and the other rater rated the grasp orientation to be either supine or prone, the ratings were averaged.

Results

Grasp orientations were averaged for each combination of subject, object, object orientation, movement direction, and movement type. Figure 2a shows the average grasp orientation selection split by movement type and object. A repeated measures ANOVA with within-subject factor object (book, cup, hairspray, mug, shampoo, and spoon) and movement type (transport, rotation) revealed that grasp
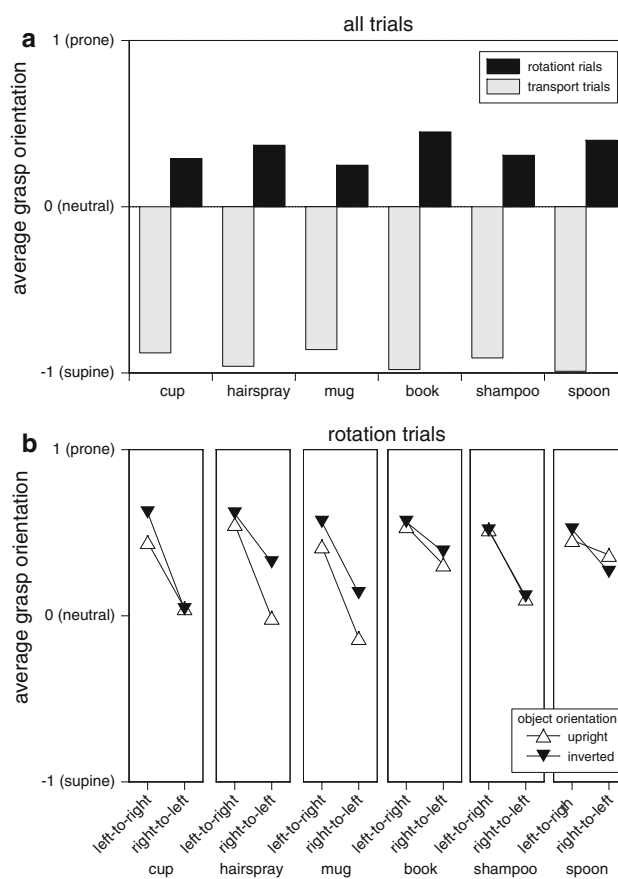
Fig. 2 The figures show the average grasp orientation selection for rotation and transport trials (**a**) and for rotation trials split up by object orientation and movement direction (**b**) for each object

Table 3 *F*-values and *P*-values of the ANOVAs with with-subject factors object orientation and movement direction for each object

Objects	Object orientation		Movement direction		Interaction	
	$F(1,25)$	P	$F(1,25)$	P	$F(1,25)$	P
Mug	7.14	.01	20.4	.001	1.18	.29
Cup	1.31	.26	11.8	.002	2.23	.15
Hairspray	11.3	.003	16.7	.001	5.43	.03
Shampoo	0.007	.93	9.38	.005	0.045	.83
Book	1.15	.29	3.84	.06	0.216	.65
Spoon	0.102	.75	4.15	.05	3.50	.07

orientation selection depended on the intended movement, $F(1,25) = 89.2$, $P < .001$.[5] Furthermore, movement type interacted with object, $F(5,125) = 5.82$, $P = .001$. There was no significant main effect of object, $F(5,125) = .209$, $P = .96$. Thus, participants' grasp orientation selection depended strongly on the intended interaction with the object as well as on the object itself.

To further investigate the influence of the object on grasp orientation selection, we now turn to the rotation trials in more detail. Figure 2b shows the grasp orientation selection in the rotation trials split by object, movement direction, and object orientation. To statistically test the results, a repeated measures ANOVA with within-subject factors object (book, cup, hairspray, mug, shampoo, and spoon), object orientation (upright, inverted), and movement direction (right-to-left and left-to-right) was conducted. Grasp orientation selection depended significantly on object orientation and movement direction, $F(1,25) = 8.00$, $P = .009$, and $F(1,25) = 14.4$, $P = .001$, respectively. The factor object did not reach significance, $F(5,125) = 2.20$, $P = .09$. The main effects were modulated by the interaction between object and movement direction, object and object orientation, and the three-way interaction, $F(5,125) = 4.30$, $P = .005$, $F(5,125) = 2.79$, $P = .02$, and $F(5,25) = 2.74$, $P = .03$.

Table 3 lists the results of separate two-way repeated measures ANOVAS with the within-subject factors movement direction and object orientation. The object orientation affected the grasp orientation selection significantly for the hairspray and the mug but not for the other objects. The movement direction affected grasp orientation selection (at least marginally) for all objects.

A contrast analysis confirmed that object orientation affected grasp orientation stronger for objects with vertical canonical orientation (cup, hairspray, and mug) than for objects without a vertical canonical orientation (book, shampoo, and spoon), $F(1,25) = 10.2$, $P = .004$. Furthermore, movement direction affected grasp orientation stronger for objects with a vertical canonical orientation than for

objects without a vertical canonical orientation, $F(1,25) = 23.3$, $P < .001$.

Discussion

Experiment 3 replicated and extended Experiments 1 and 2 in several ways. First, as in Experiment 1, the grasp orientation selection depended strongly on the intended object interaction. In most cases, grasps were selected that avoided awkward postures at the end of the movement. Second, in rotation trials also the direction, in which the object had to be moved, affected grasp orientation selection. Third, the object orientation affected grasp orientation selection only if the used object orientations were differently associated with different grasps. This confirms once again that the habitual and goal-directed systems both contribute to grasp orientation selection.

Interestingly, in Experiment 3, the influence of the cup's orientation could not be replicated, even though the difference in grasp orientation selections between upright cup trials and inverted cup trials points generally in the same direction as in Experiment 1. On the other hand, there were significant effects of the object orientation for the mug and the hairspray can. Possible reasons for the reduction of the effect of the initial object orientation compared to Experiments 1 and 2 are discussed in the "General discussion".

The horizontal direction of the object transportation movement affected grasp orientation selection.[6] Thus, when the grasp orientation was planned, also the direction of the movement was taken into account. This extends previous research on anticipatory components in prehension movements. On the one side, it has been previously shown that the hand transport and finger-shaping components of prehension movements depend on specific features of the intended object transportation movements, such as amplitude or direction (e.g., Gentilucci et al. 1997). Experiment 3

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[5] We report Greenhouse-Geisser corrected *P*-values but uncorrected *F*-values.

[6] Please note that left-to-right movement and right-to-left movements differed not only in the direction of the movement but also with respect to the location of the start- and end-point. As start point and end-point were only 12 cm apart, we believe that the direction of the movement is the main source of the observed effects.

now reveals that also grasp orientation selection depends on the direction of the intended object transportation movement. On the other side, the posture after the movement has been frequently discussed as being the primary determinant of grasp orientation selection (e.g., Johnson 2000; Short and Cauraugh 1999; Rosenbaum et al. 1996). Our data show that also specific features of the movement are reflected in grasp orientation selection.

We see two possible reasons for this effect. First, it is possible that muscle-synergies make it preferable to start a right-to-left movement in which the hand is rotated by 180° with a supine hand orientation and a left-to-right movement with a prone hand orientation. At least subjectively, the further movement seems less awkward than the latter one. Second, a bias toward generating continuous movements may have caused the effect. Consider that if the hand approaches the object from the right, a supine hand orientation is necessary to enable grasping. Likewise, an approach from the left requires a prone hand orientation for grasping. To generate a continuous overall movement trajectory, participants might have tended to approach the object in the same direction as the required transport movement and thereby had to orient the hand according to the movement direction to enable grasping.

General discussion

We conducted three experiments on the influence of the habitual and goal-directed system on grasp orientation selection for object handling. We created experimental conditions in which the habitual and the goal-directed systems favor either the same or different grasping actions. For example, different grasps were favored when an upright cup is supposed to be turned over, because, in this case, the habitual system suggested a thumb-up grasp while the goal-directed system preferred a thumb-down grasp. These conditions were compared with conditions in which both systems can be assumed to favor the same grasp selection.

Experiment 1 showed that grasp orientation is strongly determined by the anticipated interaction and thus by the intentional system. This observation adds to the broad body of research on anticipatory action selection (e.g., Cohen and Rosenbaum 2004; Gentilucci et al. 1997; Haggard 1998; Herbort and Butz 2010; Janssen et al. 2009, 2011; Johnson-Frey et al. 2004; Rosenbaum et al. 1990, 1992, 1996). Additionally, though, Experiment 1 extends this literature by showing that the habitual system biased grasp orientation selection toward a habitual thumb-up grasps when the cup was upright.

Experiment 2 replicated Experiment 1 by revealing an effect of the habitual system on grasp orientation selection in both left-handed and right-handed actions of right-handers. In Experiment 3, six different objects had to be grasped for transport. Only if different vertical orientations of an object could be assumed to be habitually associated with different grasps, the initial orientation of the object affected grasp selection. Besides the object-dependent grasp orientation selection, Experiment 3 revealed that also the horizontal direction of a rotation movement affected grasp orientation selection.

Influencing variables in the goal-directed system

Experiments 1 and 3 revealed that the goal-directed system plays a major role in grasp orientation selection. Several variables, however, did influence the grasp selection from the goal-directed system side. Experiments 1 and 3, as well as many other studies before, identified the required rotation as a key element of movement planning. Indeed, in the present experiments, participants grasped to-be-rotated objects in about 70–80% of all trials with an awkward thumb-down grasp and thus ended in a more comfortable thumb-up posture.

Additionally, we also found that the *direction* of a transport and rotation movement had considerable impact on grasp orientation selection. This extends previous research by showing that also specific properties of the object movement are anticipated and included into the plan for the grasp orientation, besides the final posture. It is likely that the influence of movement direction was rooted in muscular synergies and the necessary grasp orientation adjustments in order to smoothly blend the grasping and transportation movement.

Finally, one could speculate whether the goal-directed system mediates the influence of the habitual system on grasp orientation selection. For example, it might be possible that looking at an inverted cup elicits the goal to rotate the cup, causing the observed effects of initial object orientation on grasp orientation selection. However, at least when observed from the perspective of the task level, it is unlikely that external stimuli triggered the intention to manipulate the object in a specific way because in this case, participants would have carried out wrong object manipulations. However, participants hardly made any errors when moving the object. Thus, from the task level perspective, the effect of the habitual system was unlikely to be mediated by the goal-directed system.

Habitual system

All experiments provided support for the involvement of the habitual system in grasp selection. If an object was presented in its canonical position, a tendency to grasp the object as it is usually grasped was observable. Interestingly, the participants were about 13–14 times as likely to use a

thumb-up grasp rather than a thumb-down grasp if the cup was initially upright rather than inverted in Experiments 1 and 2, but this odds ratio fell to only about 1.4 in Experiment 3. Two findings may help to understand this discrepancy. Weigelt et al. (2009) showed that a repetitive motor task that involved grasp selections interfered with a memory task. If participants are engaged in a memory task, objects are less frequently grasped according to their normal use (Creem and Proffitt 2001). The differences in object-orientation-dependent grasp selection between the experiments may have emerged because accessing the habitual grasp and executing repetitive motor tasks both recruit limited memory processes, and Experiment 3 was more demanding in that respect than Experiments 1 and 2. In Experiments 1 and 2, the same cup was presented repeatedly and was visible before the onset of the experiment. Thus, participants had time to classify the object beforehand and only needed to evaluate its orientation to access the habitual action. Additionally, the task consisted of only four trials, which largely reduced the impact of the motor task on memory and may have facilitated retrieval of habitual grasps. In contrast, in Experiment 3, different objects were presented in random order, possibly requiring the reaccess of object semantics in every trial. The repetitive nature of the task may have caused a considerable memory load, which may have hampered access to the habitual grasps in Experiment 3 and may thus have caused the reduction of object-orientation-dependent grasp selection. Thus, the present experiments provide additional support for the notion that cognitive and motor processes are largely overlapping (e.g., Cruse 2003).

Theoretical implications

The observation that intentional factors and habitual factors affect motor behavior has implications for models on motor planning and control. Interestingly, recent models of motor planning and control emphasized either the premises of habitual associations (e.g., Oztop et al. 2004) or (immediate) goal-directed planning (e.g., Butz et al. 2007; Herbort et al. 2010, Rosenbaum et al. 2001). The current data show that the integration of habitual and goal-directed processes is necessary to understand human motor behavior. Moreover, both kinds of models focus on the transformation of object *locations* into motor commands but the present data suggest that also the object *identity* and the requirements of intended future actions need to be reflected in the models to be able to account for human grasp selection.

A promising avenue to merge habitual and goal-directed processing in models of motor control is the affordance competition hypothesis (Cisek 2007). According to this hypothesis, during processing of sensory information potential rewarding, stimuli or actions are specified and compete for execution. Concurrently, intentional and habitual processes bias the competition, leading to the selection of the most suitable action, given the current environment and internal state of the actor. Thus, the affordance competition hypothesis integrates the concepts of habitual processing by means of specification of potential actions from visual stimuli (affordances) and the concept of goal-directed processing by means of selection among the possible actions, based on current plans or needs.

Thus, future versions of motor planning models should consider this approach to account for the influence of habitual as well as intentional factors in object interaction. Such integration seems well possible. For example, to extent the posture-based motion planning theory (Rosenbaum et al. 2001), the set of postures that bootstraps motor planning (posture base) could be modulated by the identities of different objects. In our SURE_REACH model (Butz et al. 2007; Herbort et al. 2010), habitual factors could be introduced by object-specific modulations of the neural goal-representation maps.

An additional challenge of future models is the integration of the anticipated requirements of future actions in the motor planning process. The current and previous results show that the goal-directed system integrates a number of variables—such as the intended object rotation or the intended object transportation direction—when planning the grasp orientation. Moreover, these variables seem to be flexibly integrated according to the requirements of the task. Recent models of anticipatory grasp orientation selection for object manipulation, such as the *weighted integration of multiple biases* model (Herbort and Butz 2011), might be considered a step in this direction.

Summary

In conclusion, the presented experiments provide evidence for the interactions between the habitual system and the goal-directed system during grasp selection for object manipulation. The intentional system anticipated the demands of the intended rotation and translation of the object. The habitual system biased grasp selection toward the grasp usually applied during a particular object interaction. The strength of the latter bias depended on object type and object orientation. Moreover, the quantitative discrepancy between habitual effects in Experiments 1 and 2 as compared to Experiment 3 suggests that the habitual system's effect on grasp orientation selection may be mediated by working memory. Future models of motor planning should aim at integrating aspects of both systems to account for everyday motor acts.

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