Planning grasps for object manipulation: Integrating internal preferences and external constraints

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Abstract

Object interactions depend on a person's preferences (e.g. comfortable grasp) and the objects' shape (i.e. how an object can be grasped). Personal preferences have to be matched with the object's shape when planning to grasp an object. According to the simulation hypothesis, humans simulate the action outcome for each of the grasp options to select the best grasp. However, if an object offers many different grasp options, further processing is necessary to reduce the number of possibilities. According to the preference hypothesis, a preferred grasp is first computed and then adjusted to comply with the objects' shape, if necessary. To test the hypotheses, we asked participants to grasp knobs that could be grasped with two, four, or an unconstrained range of grasps. When participants chose among two or four options, planning time increased with the number of possible grasps which is in line with the simulation hypothesis. However, when grasps were unconstrained, planning times were as short as in the two-grasp condition, suggesting another – possibly preference-based – selection process in this case. In contrast to planning time, grasp choices were comparable regardless of the knob's shape. This suggest a common criterion most likely determined grasp selection in all conditions.

Keywords: Grasping, Planning, Affordance, End-state Comfort

In many situations, a person might prefer actions (e.g. have his cake and eat it) which are incommensurable with the options offered in the environment (either having the cake or eating it). In such situations, internal preferences need to be aligned to external constraints. Here we address the interplay between internal preferences and external constraints in the context of grasp planning for object manipulation.

When humans grasp objects, the grasps are largely determined by the intended use of the object and the grasp options offered by the object (Rosenbaum et al. 2012). Whereas the influence of the intended object use reflects an internal preference for certain grasps, the shape of the object provides external constraints on the grasp. In some situations, it might be easily possible to use the internally favored grasp. For example, Herbort and Butz (2012) observed how participants grasped to-be-rotated circular knobs, which could be grasped with arbitrary orientations of the forearm and the hand (for a review see Herbort, 2013). In other situations, the object may only allow for a few distinct grasps. For example, Rosenbaum et al. (1993) presented participants a bar in various orientations. As the bar could only be grasped in two ways, neither of which might correspond to the preferred grasp, internal preferences and external constraints needed to be integrated. Comparably constrained tasks have been studied in a wide range of settings (e.g. Coehlo et al. 2013; Herbort and Butz 2011; Meyer et al. 2013; Weigelt et al. 2006).

Interestingly, the theoretical models suggested for both tasks differ. In the context of grasp selection in externally rather unconstrained situations, Herbort and Butz (2012) proposed a computational model that directly computes a preferred grasp orientation. This model fits participant's grasp selections closely over a range of tasks (e.g. Olafsdottir, Tsandilas and Appert 2014). By contrast, it has been suggested selecting a specific grasp from a small number of alternatives involves the simulation of the action outcomes associated with the grasp possibilities (Johnson 2000).

Interestingly, the planning mechanisms considered for each task could be adapted for the other task. Here, we address whether one of the approaches is necessarily involved in externally constrained and unconstrained tasks. Two hypotheses can be distinguished.

First, according to the *preference hypothesis* grasp selections always involves the internal generation of a preferred grasp, irrespective of the possible grasps afforded by the object. If the object does not constrain the grasp, the preferred grasp could be used without further processing. If the preferred grasp is prohibited due to external constraints, additional processes needed to be invoked to align the preferred grasp with the external constraints (c.f. Herbort, 2013).

Second, according to the *simulation hypothesis* grasp selection is always based on the simulation of a few candidate grasps. If the object does not afford a few distinct grasp possibilities, additional processes, such as the generation of candidates needed to be involved (Johnson, 2000).

To distinguish between these hypotheses, we asked participants to grasp and rotate knobs that could be grasped with either two distinct (rectangular knob, Fig. 1a), four distinct (square-shaped knob), or an arbitrary grasp orientation (circular knob). As key dependent variables, we recorded the reaction time and the selected grasp orientation. If grasp selection was based on the generation of a preferred grasp (and matched to external constraints, if necessary) reaction times should be lowest if the object does not constrain the grasp (preference hypothesis). If the object allowed only for a few grasps, the selected grasp could be expected to be relatively close to the grasps selected without external constraints. If grasp selection was based on the evaluation of distinct grasp possibilities (and the generation of candidate grasps in unconstrained tasks), reaction times should be lowest if the knob afforded few distinct grasps (simulation hypothesis). Additionally, it could be expected that reaction times increase with the number of possible grasps.

Methods

Participants

Thirteen men and eleven women (mean age 31, sd = 12) participated for payment after giving informed consent. According to the Lateral Preference Inventory (Coren 1993), 22 were right handed and 2 were left handed.

Stimulus and Apparatus

Figure 1b,c show the layout of the experiment. A start button, a dial connected to a motor, and a LCD (17") were placed on a table. The distance between start button and dial was 30 cm. The dial consisted of one of various knobs in front of a disk (diameter 16 cm). A plastic pointer protruded 7 cm from the disk. The dial axis was elevated 16 cm over the table surface. Behind the pointer and the disk was a panel (32 x 32 cm), on which two targets were marked (1.7 cm x 1.7 cm, 120° clockwise and counterclockwise from the 12 o'clock position). A motor constantly pulled the pointer toward the 12 o'clock position with a light torque. Four different knobs were used in the experiment (Fig. 1a): a round knob (diameter 8 cm), a square-shaped knob (7 cm x 7 cm), and a rectangular knob (7 cm x 17 cm), which could be attached in a horizontal or vertical orientation.

Procedure

A trial began when the participants pressed the start button for one second. Then, a fixation cross (4 mm x 4 mm) was presented for 1000 ms, followed by "<" or ">" sign (14 mm x 15 mm), which cued a rotation to the clockwise (>) or counterclockwise (<) target. Participants then grasped the knob and rotated the pointer to the target. A trial was considered successful when the pointer was moved within 5° of the target within 3500ms an stayed there for another 500 ms. Participants were instructed to grasp the knob firmly with thumb and index finger of the right hand, complete the rotation as fast as possible, and release the knob once the target was acquired.

The experiment consisted of 12 blocks. In blocks 1-3 one of the four knobs was used (round, vertical rectangle, horizontal rectangle, square), in blocks 4-6 another knob was used, and so on. The order in which the knobs were used was counterbalanced over participants. Each block contained 18 clockwise and 18 counterclockwise in pseudo-random order.

Data recording and analysis

Movements of the dial and the tips of index finger and thumb were recorded at 100Hz (Ascension Trakstar). Data were resampled to 1000Hz and smoothed with a second-order low-pass Butterworth filter with a cut-off frequency of 10 Hz. The reaction time (RT) was defined as interval between stimulus onset (< or >) and the release of the start button. The grasp orientation (GO) was defined as the angle between thumb and index finger in the coronal plane. A GO of 0° was assumed when the index finger was directly above the thumb, negative orientations correspond to more supine orientations. GO was determined when the knob's rate of rotation first exceeded 25°/s.

The data of the first two trials in a block were considered warm-up trials and excluded from the analysis. Trials were further excluded from analysis if the data could not be segmented (3.8%), if the rotation was not finished in time (0.8%), if the pointer was rotated to the incorrect target (0.03%), or if RT or the duration from the onset of the grasp to the completion of the rotation deviated by more than 2.5 standard deviation from the respective conditions mean (3% of correctly executed rotations).

Results

Reaction times

Figure 2 shows mean RT by knobs and rotation angle. Mean RT were subjected to a within-subject ANOVA with factors knob shape (round; rectangular, pooled over horizontal and vertical; square) and rotation direction (clockwise, counterclockwise).[1] The ANOVA revealed a main effect of the knob shape, $F(2,46) = 3.4$, $p = .042$, $\eta^2_p = .129$. Moreover, RT were lower before counterclockwise rotations, $F(1,23) = 4.8$, $p = .038$, $\eta^2_p = .173$. The interaction did not reach significance, $F(2,46) = .2$, $p = .779$, $\eta^2_p = .010$. Follow-up ANOVAs with within-subject factors knob shape and rotation direction revealed no significant differences between the round and rectangular knob, $F(1,23) = 0.2$, $p = .632$, $\eta^2_p = .010$, a marginally significant difference between the round and square-shaped knob, $F(1,23) = 4.1$, $p = .054$, $\eta^2_p = .152$, and a significant difference between the rectangular and square-shaped knob, $F(1,23) = 6.3$, $p = .020$, $\eta^2_p = .215$.

Grasp selection

Figure 3 shows histograms of GO by knobs and rotation angle. An ANOVA with the same factors as above revealed that GO differed for clockwise and counterclockwise rotations, $F(1,23) = 177.8$, $p < .000$, $\eta^2_p = .885$. Neither a significant effect of the knob shape, $F(2,46) = 0.7$, $p = .470$, $\eta^2_p = .031$, nor a significant interaction were found, $F(1,23) = 0.7$, $p = .481$, $\eta^2_p = .030$.[2] Figure 4 shows that GOs for the round and square-shaped knob were highly correlated (for clockwise rotations: $r = .621$, $p = .001$; for counterclockwise rotations: $r = .649$, $p = .001$). Likewise, GOs for the vertical and horizontal rectangular knob were correlated with GO for the round knob (all rs ≥ . 465, all ps ≤ .022).

Discussion

We tested two hypotheses pertaining to grasp selection for object manipulation. According to the preference hypothesis, grasps are initially computed irrespective of the constraints imposed by the object and only adapted to those constraints if necessary. According to the simulation hypothesis, grasp selection is based on the evaluation of distinct grasp candidates, which may need to be generated if the objects does not impose any constraints.

The experiment provided mixed results. On the one side, reaction times were longer for the square-shaped knob than for the rectangular knob. This is in accordance with the simulation hypothesis. However, reaction times for grasping the circular knob were almost identical to reactions times for grasping the rectangular knob. This suggests that grasp selections for the circular knob were not based on the evaluation of distinct candidate grasps, because this would require additional, potentially time-consuming processes and thus result in higher reaction times. In this case, the grasp may have been directly computed, based on grasp preference. On the other side, grasp orientations when grasping the circular knob were highly correlated to those when grasping

[1] We report Greenhouse-Geisser corrected p values but uncorrected dfs. Comparable effects would have

[2] Please note that GO differ for the vertical and horizontal rectangular knob.

the rectangular or square-shaped knob. This suggests a common criterion for grasp selections in all tasks, even if different planning strategies might be employed in each task.

Grasp orientations differed considerably for rotations in different directions, regardless of the grasped object. This shows that the planned rotation played an important role in the selection of the grasp. It has been suggested that grasps are selected that enhance the control over the manipulated object in task comparable to that of the present experiment (Herbort, 2015; Rosenbaum et al., 2012).

The results have at least three implications. First, Johnson (2000) suggested that selecting among a few distinct grasp options involves the anticipation of the action outcomes associated with the options. However, evidence for this hypothesis is scarce. For example, it is supported by the finding that effective grasp planning requires a structured representation of hand states (Stöckel, Hughes and Schack 2012). The present data provide additional evidence by showing that planning time increases with the number of distinct grasp possibilities. Inline with the simulation hypothesis, this suggests that the distinct grasp options offered by an object may indeed be individually evaluated. However, when the object itself does not offer particular grasps – as was the case for the round knob – then it appears that no actual simulation takes place. Rather the grasp may be directly computed based on internal preferences.

Second, models for action planning often rely on intrinsic criteria, such as a preference for a comfortable arm posture at the end of an object manipulation. However, little direct evidence has been provided for this view and alternative explanations have been offered (Herbort 2013, Herbort and Butz 2012). The present experiment now revealed that grasp selections were very similar for knobs of different shapes, even though if the planning mechanisms might have differed. This suggest that a common, more abstract criterion might have determined the outcome of the planning process in both task.

Third, by now, grasp selection in discrete and continuous tasks have been mostly studied in isolation. Interestingly, different conclusion were drawn from both tasks. For example, in discrete tasks participants often consistently selected grasps that result in comfortable end postures (Rosenbaum et al., 2012). By contrast, this is rarely observed in continuous task spaces (Herbort, 2013, 2015). Despite these differences, the present result reveal that grasp selections in continuous and discrete tasks are highly correlated. This suggests that differences in the interpretation of experiments might rather be based on the specificities of the observed task than on differences in the underlying planning processes.

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Figure Legends

Fig. 1 a) The figure shows the knobs used in the experimental conditions. b) The figure shows the setup from a top down perspective. c) The figure shows the setup from the participant's view. The angles close to the square-shaped knob show the definition of grasp orientations. If the index finger would be on the knob's top edge and the thumb on the knobs lower edge, the grasp orientation would be 0° and so on

Fig. 2 The figure shows mean RT for the different knobs. For the rectangular knob, RT were pooled over the vertical and horizontal orientation of the knob. Error bars show standard errors of the mean

Fig. 3 The figure shows histograms of the GO used for the different knobs and rotation directions. GO were binned based on the possible grasps of each knobs. For comparison, grasps of the round knob were treated identical to grasps of the square-shaped knob. Error bars show standard errors of the mean

Fig. 4 The figure plots GOs for the round knob against GOs for each of the other knobs for individual participants and rotation directions

Fig. 1

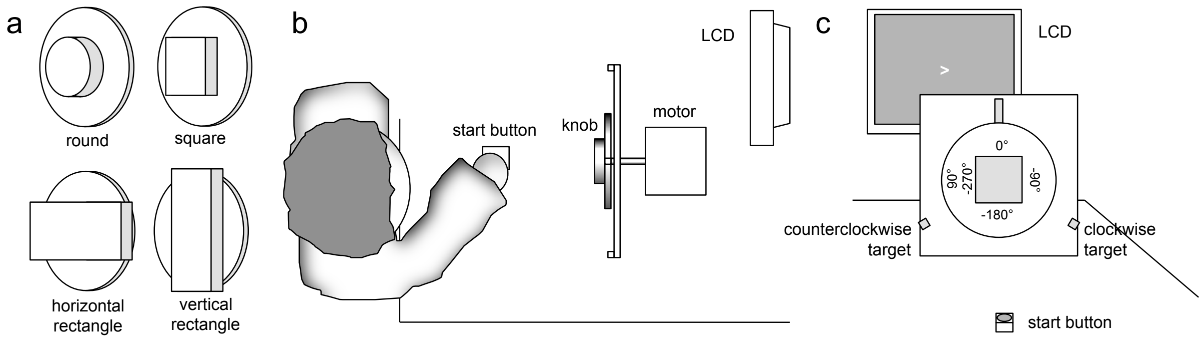
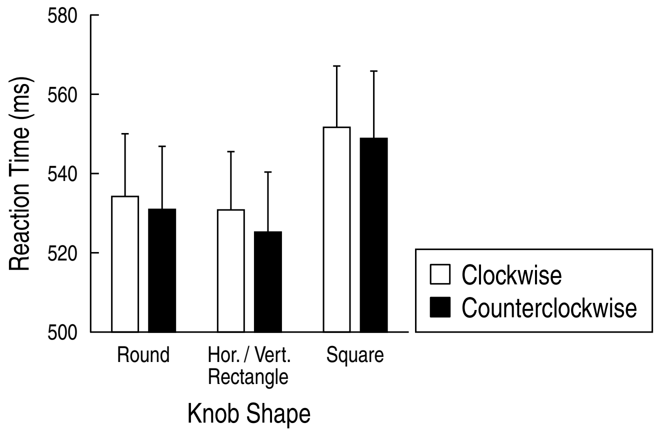
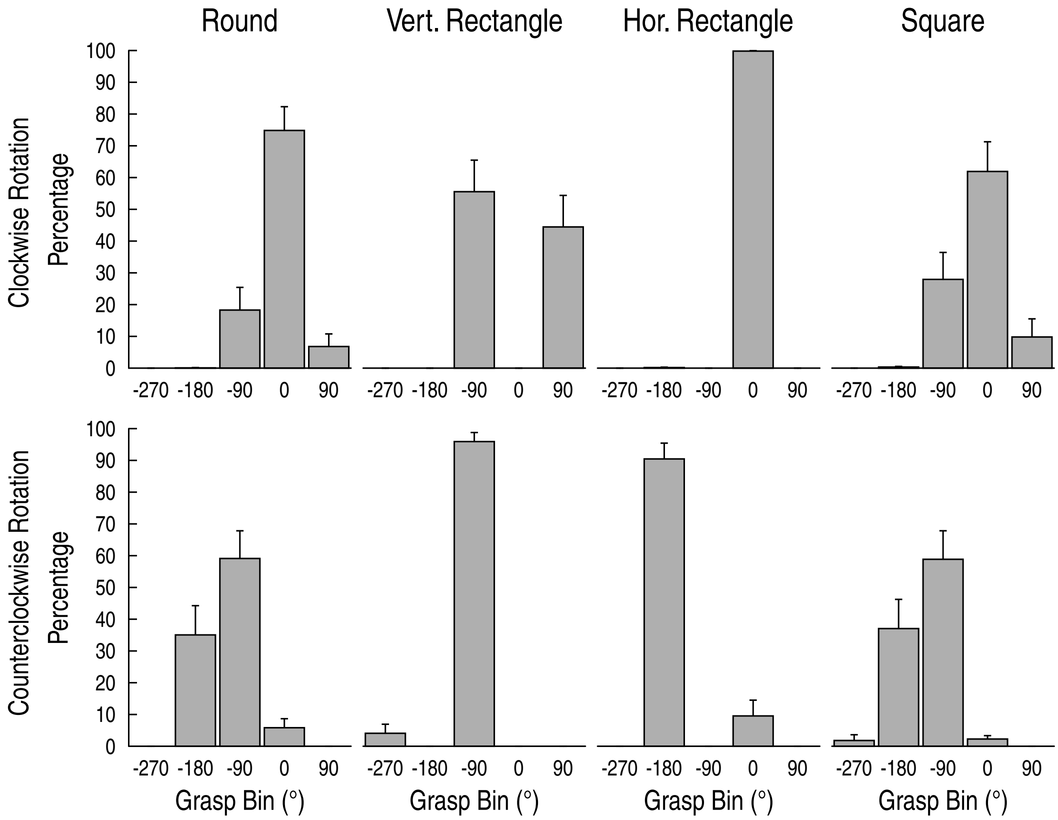

a
round
square
horizontal rectangle
vertical rectangle
b
start button
knob
motor
LCD
c
LCD
>
0°
90°
-270°
-90°
-180°
counterclockwise target
clockwise target
start button

Fig. 2



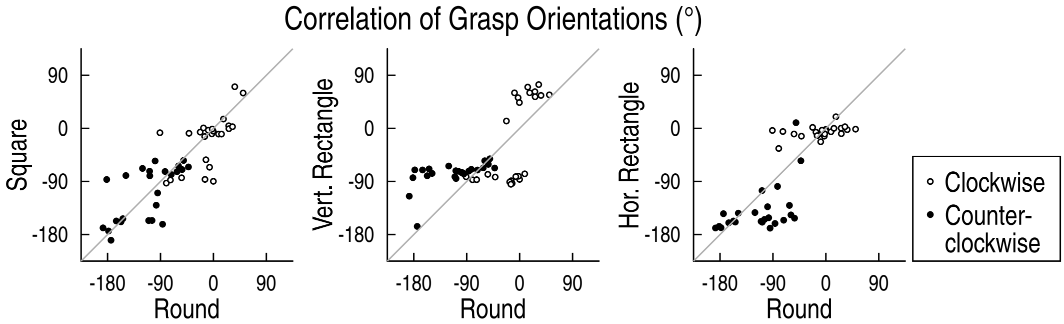
580
560
540
520
500
Reaction Time (ms)
Round
Hor. / Vert.
Rectangle
Square
Knob Shape
Clockwise
Counterclockwise

Fig. 3



Round
Vert. Rectangle
Hor. Rectangle
Square
Clockwise Rotation Percentage
Counterclockwise Rotation Percentage
0
10
20
30
40
50
60
70
80
90
100
-270
-180
-90
0
90
Grasp Bin (°)

Fig. 4



Correlation of Grasp Orientations (°)
Square
Vert. Rectangle
Hor. Rectangle
Round
90
0
-90
-180
Clockwise
Counter-clockwise