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## Selection criteria for preparatory object rotation in manual lifting actions

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## **Abstract**

Participants lifted a canister by its handle while balancing a ball on the lid. Experiment 1 allowed object rotation prior to lifting. A lifting comfort zone was measured by the variability in object orientation at lift; its size depended on the object mass and required task precision. The amount of pre-lift rotation correlated with the resulting change in lifting capability, as measured for different object orientations. Experiment 2 required direct grasping, without preparatory rotation. Task completion time and success rate decreased, and initial object orientation affected pre-lift time. Results suggest that lifting from the comfort zone produces more robust performance at a cost of slower completion; moreover, physical rotation could be replaced by mental planning when direct grasping is enforced.

## **1 Introduction**

In many scenarios, there are multiple actions which can achieve the specified task goal. The redundancy of the human motor system allows for alternative movement strategies for completing the same task, and a key question is to understand what criteria determine the selected motor plan. This study examines criteria which could explain how people choose between alternative movements of either a single direct action or a sequence of sub-actions to complete a manual lifting task.

Previous research (Chang et al., 2008) has shown that people sometimes choose to use an extra sub-action of preparatory object rotation to complete a lifting task even though a direct reach-to-grasp action would succeed. The preparatory object rotation was used to first physically re-orient the object handle without supporting the entire gravitational load of the object. Then, the final grasp was formed to lift the object for the instructed object transport task. The strategy using the two sub-actions of a physical rotation and a lift resulted in more convergent body postures and grasp choices at the object lift-off point compared to the strategy of using a single direct lift. An open question not answered by the previous study is what criteria determine when and how much object rotation is incorporated into the motor plan as an alternative to a direct lifting plan.

A principal question investigated by the present study is whether posture-dependent strength capabilities can explain the preference for the preparatory object rotation strategy. According to the posture-based planning model (Rosenbaum et al., 1993a,b, 1995), motor plans are based on goal postures rather than the movements between postures. The choice of using preparatory object rotation instead of a single direct action may be driven by the preference for a particular posture for the primary lifting action that achieves the task

goal. The body of work on the end-state comfort effect (Rosenbaum et al., 1992; Short & Cauraugh, 1997; Fischman, 1998; Zhang & Rosenbaum, 2008, e.g.), has provided evidence that the comfort of a final goal posture determines the manual action, even if it requires awkward postures at the beginning of an action. In the previous work, end-state comfort has been evaluated by awkwardness ratings (Rosenbaum et al., 1990, 1993b; Short & Cauraugh, 1997) or distance from neutral joint positions (Zhang & Rosenbaum, 2008). In this work, we examine whether the choice of the object lift-off posture in a manual task is determined by the lifting capability of the posture. This is theoretically important because it contributes further understanding of the biomechanical aspects that may be associated with psychophysical assessment of postural comfort. Individual strength has been investigated previously for predicting choices between alternative movement strategies of stooping versus squatting bimanual lifting tasks (Burgess-Limerick & Abernethy, 1997), but the focus was on strength capabilities between individuals rather than the differences between postures for one individual.

A second question investigated in this study is whether preparatory object rotation is used to achieve an object lift-off posture which is optimal versus satisfactory for the task. If individuals maximize the efficiency of the lift, they would tend to select postures with the maximum lifting capability even for different levels of task precision or object mass. However, if only a minimum efficiency threshold has to be satisfied, then there may be a larger range of selected lift-off postures when the task is less difficult. In this investigation, we examine whether the preference for selected lifting postures is sensitive to two task difficulty factors: object mass and task precision. Previous work by Latash & Jaric (2002) studied how postural movements in drinking tasks were strongly correlated with the task precision, as defined by a geometric task difficulty index related to the critical angle for spilling. Results from Rosenbaum and associates also showed that the end-state comfort effect is diminished for tasks requiring less precision. We believe that in addition to task precision, object mass is also a factor which affects posture selection, especially for more demanding manual tasks. Manipulation requires not only meeting specific kinematic constraints specified by the task, but also applying or resisting forces due to the interaction with the object. The ability to meet the load requirements for a task are posture dependent, since muscle strength varies for different operating postures. Thus tasks involving heavier objects may result in the selection of a posture with greater lifting capability in order to satisfy a minimum efficiency or strength margin constraint. Our study expands on the previous literature by examining how posture selection may be sensitive to both task precision and object load.

Experiment 1 in this study investigates the questions of (1) whether the preparatory rotation is correlated with the change in lifting capability, and (2) whether the selected lifting postures are relatively constant or

vary with task difficulty. First, we hypothesized that people would choose to use the preparatory rotation to avoid lift-off angles with lower lifting capability in favor of selected lift-off angles with higher lifting capability. This predicts that the amount of object rotation would be correlated with the difference in lifting capability between the initial orientation and the lift-off orientation. Second, we examine the effects of task precision and object mass on the task performance. The contribution of these two factors to the task difficulty factors was evaluated by the effect on total time for task completion. It was expected that the selection of lift-off postures would be more constrained for increased task difficulty, due to more stringent satisfaction requirements. This effect could be observed in the lift-off object configuration in two ways. The amount of object rotation prior to lifting could increase with increased object mass or increased angular precision. In addition, the variability in the object lift-off angles could decrease with increased object mass or increased angular precision.

It is possible that lifting capability represents a “hard”, or immutable, constraint on the movement strategy selection rather than a “soft” constraint or preference. Preparatory object rotation may be selected because the task is not feasible using the alternative strategy of direct reach-to-grasp lifting, where the object is not rotated before lift-off. In Experiment 2, we examined whether the manual task was feasible using only direct grasping without object rotation. We found that for most of the task conditions, participants could successfully complete the task using only direct grasping even though preparatory rotation was spontaneously used in Experiment 1 for the same conditions. Moreover, the dependence of physical rotation on the initial object orientation, as found in Experiment 1, was echoed in Experiment 2 by a similar trend in pre-lift preparation time, suggesting that the physical action was replaced by mental planning. The comparison of Experiment 1 results with the constrained condition in Experiment 2 also allows us to investigate how the posture selection for the lifting action affects other aspects of the movement, such as timing and robustness of task performance. Our results show that direct lifting (when successful) requires less time for task completion, but lifting after preparatory rotation is more robust for completing the task trials successfully.

## **2 Experiment 1**

The purpose of Experiment 1 was to examine what factors affected the selected lift-off postures when participants used preparatory object rotation. The experiment consisted of two parts. In Part I, participants had to lift a canister, selected from a set of 4, to uncover a token on the table surface. The canister was presented at multiple initial orientations, and it was expected that participants would use preparatory object rotation

before lifting the canister. The dependent variable of interest from Part I was the selected object orientations at the lift-off time. The distribution of lift-off postures was measured for different levels of object mass and task precision. In Part II, participants performed similar grasping actions on a weighted canister. Lifting capability was measured for different object orientations to investigate whether increase in lifting capability was correlated with the amount of preparatory object rotation in Part I.

## 2.1 Participants

Twelve adults (6 male, 6 female) volunteered for the study (age =  $26.4 \pm 4.9$  years [mean  $\pm$  standard deviation], height =  $1.70 \pm .007$  m, mass =  $64.1 \pm 12.4$  kg). All participants were right-handed by self-report. All participants signed informed consent forms approved by the Institutional Review Board.

## 2.2 Apparatus

The object for the manipulation task was a plastic cylindrical canister (Fig. 1). Two indentations in the side of the canister formed a handle which could be grasped by inserting the thumb in one indentation and the fingers in the other indentation (Fig. 1a). A lightweight plastic ball (diameter 3.8 cm) was balanced on a cylindrical ring which was affixed to the canister lid. The diameter  $D$  of the ring determined the required angular precision in the object's vertical orientation for keeping the ball balanced (Fig. 1b).

The canister was presented to the participant on a flat platform at a height of 0.9m from the ground (Fig. 2). A screen was placed between the subject and the platform (Fig. 2a). Participants stood facing the screen with their hands relaxed at the side. Before a trial, the screen started in the lowered position so that the participant could not see the object placed on the platform. When a trial commenced, the screen was completely raised to show the object on the platform.

A T-shaped marking on the floor indicated the standing position (Fig. 2b). Participants stood in place with their feet centered around the vertical line of the T and their toes just behind the horizontal line of the T. The T marking was offset from the table such that the canister position was 0.1m to the right and 0.2m in front of the T intersection. The offset position was chosen for comfortable lifting of the canister using the right hand (Fig. 2b).

Passive reflective markers were used for tracking the object motion in Part I. The screen was tracked by 5 markers and each canister object was tracked by 6 markers. The 3D positions of the markers were recorded at 120 Hz using a Vicon camera system (Vicon Motion Systems, Los Angeles, California, USA). The 3D

marker trajectories were reconstructed using ViconIQ software and were not filtered or processed in any way before the data analysis described in Section 3.1.

Underneath the platform was a uni-directional measuring scale (0.02kg resolution) for digitally recording the lifting capability measurement in Part II (Fig. 2a). The scale data were recorded separately from the kinematic data using MATLAB software (Mathworks, Inc.; Natick, MA). The scale output was queried repeatedly via the serial port interface such that the time periods between data samples were approximately 0.2-0.3 seconds.

### **2.3 Part I: Lifting motion**

In Part I of the experiment, a flat disc (diameter 2.5cm) was placed on the platform underneath the canister. The token retrieval task was to lift the canister in order to uncover the disc, while keeping the ball balanced on the cylindrical ring. Participants were instructed to use only the right hand to contact the canister and were restricted to contacting the canister at the handle area (Fig. 1a). Only the left hand could be used to contact the token. Participants were free to move either the canister and/or the token from the original position, as long as at the end of the trial, both the canister and the token were placed on the platform and the canister did not cover the token. Participants were instructed to perform the task as quickly as possible while keeping the ball balanced.

There were 4 versions of the canister to test 2 levels of object mass and 2 levels of angular precision. For the object mass factor, the canister was filled with material to achieve a total mass of either 0.40kg (light) or 1.20kg (heavy). The canisters were covered by two different colors of tape to provide visual labels corresponding to the light canister (grey) and heavy canister (blue). For the angular precision, the cylindrical balance ring had diameter  $D$  of either 3.6cm (wide) or 0.8cm (thin). The diameter of the ring was visible to the participants when the object was presented on the platform.

The canister was presented on the platform in one of 8 orientations, as denoted by the handle direction (Fig. 2c). It was expected that the participant would slide or rotate the canister before lifting to adjust the orientation when the handle faced away from the participant. In the verbal instructions for the token retrieval task, there was no suggestion of preparatory rotation or sliding.

## 2.4 Part II: Lifting capability

In Part II of the experiment, the maximum lifting capability was measured for different handle orientations in order to investigate whether lifting capability was a criterion for the preparatory object rotation observed in Part I. The canister object was placed on the platform and the participants stood at the T-marking as before. The task was to repeat the lifting grasp on the object in order to measure the lifting capability for a specific handle orientation. Participants were instructed to attempt to reach the presented configuration of the canister handle using the right hand and apply as much upward lifting force as was comfortable. Unlike Part I, participants were instructed not to move or re-orient the canister from its presented configuration. Participants were allowed to skip or abort the trial at any time if they could not reach the handle or apply upward force comfortably.

The filled canister had a total mass of 13.7kg, which was beyond the unimanual lifting capability of any participant. The lifting capability was measured as the difference between the initial scale output and the minimum scale output during the grasp. To mimic the perception of the canister as experienced in the Part I lifting trials, a ball was balanced on the canister lid as in Part I. As before, the cylindrical balance ring had diameter  $D$  of either 3.6cm (wide) or 0.8cm (thin). There was no token to retrieve with the left hand.

The canister was presented in one of 10 handle orientations: the 8 orientations from Part I (Fig. 2c) and 2 additional orientations at the midpoint between angle 7 and 8 (denoted 7.5) and the midpoint between angle 8 and 1 (denoted 8.5). The additional orientations were sampled because it was hypothesized that the maximum lifting capability would occur within the region of selected lift-off angles. The lift-off angles were expected to be in the region between handle orientations 1 and 7, where the handle faced toward the participant's right hand.

## 2.5 Procedure

Before the trials recorded in Part I, the participants were first introduced to the canisters to become familiar with the mass levels and angular precision levels. Each of the 4 canisters was held, one at a time, with the ball balanced on the ring. There were no other practice trials for task training before the main experiment. The experimenter drew attention to the color coding of the object mass levels at this time.

There were a total of 32 trials for Part I, with one trial for each possible combination of the 2 mass levels, 2 angular precision levels, and 8 initial handle orientations. The 32 conditions were presented in a randomized sequence. If the ball was dropped before the canister was returned to the platform, the trial was aborted. A

new randomized sequence was generated for the remaining conditions, including the failed condition. Thus the participant could not anticipate the trial conditions before the screen was raised at the beginning of each trial. After every 8 trials, participants were given a break where they were seated for approximately 1 minute. During the break, the experimenter asked the participant to report any fatigue from prolonged standing or repeated lifting.

In Part II for the measurement of the lifting capability, there were 10 trials for each of the 2 angular precision levels, as given by the balance ring diameter. The first set of 10 trials tested the lifting capability for one angular precision level, followed by a second set of 10 trials for the other angular precision level. The order of angular precision levels alternated based on the order of participation. Thus, 6 participants were presented with the wide diameter ring first, and 6 participants were presented with the thin diameter ring first. Within each set, the 10 possible handle orientations were presented in a randomized sequence. It was not expected that the ball would drop due to the canister weight and the restriction to leave the canister configuration unchanged from its presented condition. However, if the ball was dropped, the failed condition would be repeated within a newly randomized sequence of the remaining conditions. A break was given between the two sets of 10 trials.

In addition to the scheduled breaks, the protocol included immediate rest if the participant reported fatigue at any time during the study. The entire experiment required approximately 90 minutes for a single participant.

## **3 Data analysis**

### **3.1 Lift-off angle and timing**

The selected object orientation at the lift-off time was the variable of interest from the lifting trials in Part I. In addition, the timing of the task completion was measured to characterize the difference in task difficulty for the tested conditions. The lift-off angle and timing measures were computed from segmentation of the motion data for the canister and the screen. To obtain this motion data, the recorded 3D marker trajectories were first manually labeled and then registered to a rigid-body model of each object to find the object position and orientation at each time frame. To reduce noise in the tracking estimates, the model registration used all available markers (up to 5 markers for the screen and 6 markers for each canister) per time frame. The object configuration data was always computed from at least 4 markers.



For each trial, three time intervals comprise the total time ( $T_0$ ) for task completion (Table 1). First, pre-interaction ( $T_1$ ) consists of perception and reaching for the object.  $T_1$  starts when the screen is raised and ends at the initial canister movement. Then, object interaction ( $T_2$ ) occurs if there is optional adjustment of the canister configuration on the surface.  $T_2$  starts at the initial canister movement and ends at the object lift-off from the surface. Finally, object lifting and token retrieval ( $T_3$ ) starts after the object lift-off and ends when the object is returned to the surface.

The four key time points defining the time intervals were estimated automatically from the kinematic data based on manually-selected thresholds. (1) The start of the trial was determined as the time frame when the lower edge of the screen was raised above the canister to reveal the task conditions of mass level, angular precision level, and handle orientation. (2) Initial canister movement was detected when the average object marker difference from the starting configuration exceeded 5mm. (3) Object lift-off from the surface was detected when the upward vertical displacement of the canister position exceeded 5mm change from the initial vertical position. (4) Task completion when the object is set down was detected when the vertical displacement of the canister fell within 5mm of the ending vertical position.

The third key time point, the object lift-off from the surface, was used to analyze the amount of preparatory object rotation. The object lift-off angle is the orientation of the object in the horizontal plane at the lift-off time frame. Object rotation was measured as the change in orientation between the initial handle angle and the lift-off handle angle. We computed the absolute amount of rotation so that there was no distinction between clockwise or counterclockwise rotation.

We also measured the variability of the selected lift-off angles over the set of 8 initial handle orientations for each of the 4 canisters. The average absolute deviation (AAD) is computed as the mean deviation of a lift-off angle from the mean of the set of 8 lift-off angles. It was hypothesized that for tasks which are more difficult, the AAD of the lift-angle would be smaller because participants would respond to task constraints with more preparatory rotation, in order to grasp the handle from a preferred orientation.

We analyzed the object orientation and timing metrics with linear mixed-effects (LME) models (Verbeke & Molenberghs, 2000) using the NLME package (Pinheiro & Bates, 2000) for R 2.6.2 (R Development Core Team, 2008). Similar to ANOVA tests for repeated measures, LME models account for the correlated errors between the dependent, repeated observations from an individual participant. The advantage of LME models is the greater statistical power in estimating the significance of the fixed effects compared to a repeated measures ANOVA, which is due to the LME models' simplified parameterization of the random effects' correlation structure. In our study, the data were grouped by participant such that the LME model accounts for

the correlation between the repeated observations by fitting an individual intercept value for each participant. LME models can also handle missing observations without discarding all observations for one participant. This allowed us to include data from participants even if the lifting task were not completed for all handle orientations.

The *t*-test results in an LME model indicated which explanatory variables were statistically significant as fixed effects. In addition, the significance of each random effect in the final LME model was checked using a likelihood *L* ratio test comparing the selected LME to the linear ANOVA model without the random effect (Pinheiro & Bates, 2000).

The explanatory variables that were tested as fixed effects in the LME models included the object mass, angular precision as determined by balance ring diameter, the initial handle orientation, and the square of the initial handle orientation. The square of the initial handle orientation was included because it was expected that the time and amount of preparatory rotation would increase for initial angles further from some central preferred lift-off angle. It was also expected that the preferred lift-off angle would be around orientation 8, where the handle faced toward the participants' right side. Thus, the scale for the handle orientation variable was centered at orientation 8 for all LME models. The centering was achieved by re-coding orientations 1 through 8 as values -1, -2, -3, 4, 3, 2, 1, 0.

Task difficulty was measured by the total time for task completion. It was expected that the token retrieval task would be more difficult for increased object mass and/or for increased task precision. That is, even for the central orientation 8, the time duration would be longer for lifting the heavier canister and/or balancing the ball on the thin diameter ring. Thus the LME models for timing tested the task difficulty factors of object mass and angular precision as additive main effects.

For preparatory rotation prior to lift-off, we hypothesized that the amount of rotation would increase with task difficulty more for the initial handle orientations which are further from the central orientation. That is, for the central orientation, the object rotation would be small regardless of the canister mass and the balance ring diameter, because the handle was already in the preferred lifting configuration. For initial orientations outside the preferred region, there would be more rotation for increased task difficulty, because the requirement for the handle to be within the preferred region would be stronger. Thus the LME model for object rotation included the interaction effects of the object mass with the squared orientation factor and the angular precision level with the squared orientation factor.

A corresponding hypothesis for object lift-off configuration was that the participants would select the lift-off angle of the handle with more consistency for more demanding tasks. That is, with increased task

difficulty, the variability of the lift-off angle would be smaller. The AAD measure was used for this test of lift-off angle variability. Since a single AAD measure was computed over the set of 8 initial handle angles for each of 4 canisters, only object mass and angular precision were tested as additive fixed effects in the LME model.

### **3.2 Lifting capability**

The purpose of measuring the canister lifting capability in Part II was to investigate whether the amount of rotation in Part I was correlated with the change in the lifting capability for a given handle orientation.

The lifting capability for a given handle orientation was computed as the difference between the initial scale measurement (when only the object mass contributed to the scale reading) and the minimum scale measurement (when the participant applied the most upward force on the canister). A lifting capability profile for the entire 360-degree orientation range was computed by linear interpolation of the 10 samples measured in Part II. There were two profiles for each participant because the lifting capability was measured for the two levels of balance ring diameter. The maximum lifting capability was the largest measurement over the 10 samples, and it was used to normalize the profile magnitude. Thus, all lifting capability measures were expressed as a percentage of the maximum capability.

The lifting capability at the 8 initial handle angles was directly measured as part of the 10 samples. In contrast, the selected lift-off angles were different for each individual, and the lifting capability was not measured directly. For one level of balance ring diameter, there were 8 actual lifts in Part I for each of two object mass levels. The lifting capability associated with each actual lift-angle was estimated from the linearly-interpolated lifting capability profile with the matching task precision level.

We hypothesized that the preparatory rotation action in Part I changed the orientation to improve the lifting capability for the primary lifting action. Thus, a larger amount of rotation would correspond to a larger increase in the lifting capability. For each individual trial, we computed the difference in the lifting capability at the selected lift-off angle relative to the lifting capability at the initial object angle. The data tested by the correlation computation were the mean values averaged over the 12 participants. For each of the 32 task conditions, the mean amount of rotation was paired with the mean difference in lifting capability.

In addition, for each of the 4 combinations of object mass and task precision, we computed the minimum and the AAD variability of the capability measures at the lift-off angles for the 8 trials. We expected that increased task difficulty would result in greater restrictions on the preferred lifting capability at the selected lift-off angles. Thus, similar to our hypothesis that the lift-angle variability from Part I would decrease with

increased task difficulty, we hypothesized that the variability in the lifting capability measures for the lift-off angles would also decrease with increased task difficulty. This was tested by a LME model with object mass and angular precision as additive fixed effects.

## 4 Results

For both parts of the experiment, no participant reported fatigue or requested immediate rest in addition to the scheduled breaks.

For the lifting task in Part I, participants sometimes failed to maintain the angular precision constraint such that the balanced ball was dropped during the trial. Out of the 12 participants, 4 participants failed for 1-3 trials, 6 participants failed for 6-8 trials, and 2 participants failed for 10-12 trials. The conditions for the failed trials were repeated in a random order as described in the procedure. For two participants, there was no recording of successful task completion for 1 of the 32 conditions, due to experimenter error. For one participant, the recording of a successful lift was incomplete for 1 condition due to equipment error. These unavailable conditions were omitted in the LME model such that there are a total of 382 (instead of 384) data points for the object rotation, time  $T_1$ , and time  $T_2$ . There are a total of 381 data points for time intervals  $T_0$  and  $T_3$ , due to the incomplete trial recording.

### 4.1 Timing

The total time  $T_0$  for task completion (Fig. 3) was 3.46 seconds on average for the baseline light object with wide diameter ring at initial orientation 8 (Table 2). Increasing the object mass increased  $T_0$  by 0.73 seconds ( $t(365) = 4.00$ ,  $p < 0.001$ ) and increasing the angular precision increased  $T_0$  by 2.96 seconds ( $t(365) = 16.22$ ,  $p < 0.001$ ). The task also took longer when the handle orientation started further from the central orientation 8, as indicated by the positive coefficient for the squared orientation term ( $t(365) = 17.60$ ,  $p < 0.001$ ). The significant effect on the linear orientation term ( $t(365) = -5.66$ ,  $p < 0.001$ ) indicates that the quadratic trend is not symmetric around orientation 8. From the linear orientation and squared orientation coefficients, we computed that the minimum of the quadratic trend occurs at about 20 degrees counterclockwise from orientation 8 (Fig. 3).

## 4.2 Object rotation and lift-off angle selection

The amount of preparatory object rotation (Fig. 4) increased by 7.7 degrees for the increased angular precision corresponding to the thin diameter balance ring ( $t(364) = 2.21, p = 0.0276$ ) (Table 3). The positive coefficient for the squared orientation ( $t(364) = 16.62, p < 0.001$ ) indicates that the amount of rotation increased as the initial object orientation was further from the central orientation 8. The positive coefficient for the interaction effect of angular precision with squared orientation ( $t(364) = 2.33, p = 0.0206$ ) indicates that there was an increase in the trend's quadratic curvature for the thin diameter balance ring compared to the wide diameter balance ring.

The average angular deviation (AAD) from the mean lift-angle (Fig. 5) was 43.0 degrees for the baseline light object with wide diameter balance ring. The lift-off angle variability decreased by 4.6 degrees for increased object mass ( $t(34) = -2.12, p = 0.0414$ ) and decreased 12.9 degrees for increased angular precision ( $t(34) = -5.90, p < 0.001$ ) (Table 4).

We also performed the test on lift-angle variability on a subset of the data, excluding the two participants who failed and repeated the most trials (10 and 12 trials) in Part I. For the subset of the remaining 10 participants' lift-angle AAD measures, the lift-angle variability decreased by 7.1 degrees for increased object mass ( $t(28) = -5.62, p < 0.001$ ) and decreased by 11.0 degrees for increased angular precision ( $t(28) = -3.29, p = 0.0027$ ).

## 4.3 Lifting capability

The maximum lifting capability (Fig. 6a) ranged from 1.5kg to 8.2kg. The maximum lifting capability for the wide diameter ring was greater than that for the thin diameter ring for 10 of the 12 participants. The maximum measurement occurred in the region between orientations 1 and 7.5 for all participants for the wide diameter angular precision level. For the thin diameter angular precision level, the maximum capability measurement occurred between orientations 1 and 7.5 for 10 of the 12 participants. In the two exception cases, the second largest measurement occurred between orientations 1 and 7.5, and it was at most 0.18kg less than the maximum measurement. Figure 6b shows that the average lifting capability profile is asymmetric around the region of maximum capability, since the lifting capability decreases more steeply for orientations to the left of the central region.

Figure 7 shows the correlation between the amount of object rotation and the normalized lifting capability. The data are divided into two groups due to the asymmetry of the left region (initial orientations 1-3) and right

region (initial orientations 4-8) of the object orientation scale . For the left region, where the object rotation was counter-clockwise, the Pearson correlation coefficient was  $r(10) = 0.9319$  ( $p < 0.001$ ). For the right region, where the object rotation was clockwise, the Pearson correlation coefficient was  $r(18) = 0.9678$  ( $p < 0.001$ ). The positive correlation value indicates that a larger amount of rotation before lifting corresponded to a larger change in the lifting capability at the selected lift-off angle relative to the initial handle angle.

For all participants, the minimum lifting capability measure for a set of 8 selected lift-angles was greater than 50% of the individual's maximum lifting capability. The mean of the minimum lifting capability measure varied from 70% to 74% for the 4 combinations of object masses and angular precision levels (Table 5). The variability of the lifting capability (Fig. 8) measured by the AAD decreased by 1.5% for the increased angular precision ( $t(34) = -2.39$ ,  $p = 0.0225$ ) (Table 6).

## 5 Experiment 2

The purpose of the second experiment was to investigate the alternative strategy of direct grasping, for comparison with the preparatory object rotation strategy. In a direct grasping strategy, an object is grasped from its presented configuration without any prior adjustment in the environment.

First, Experiment 2 tested whether the canister lifting task in Experiment 1 Part I was still achievable without preparatory object rotation. That is, was preparatory rotation necessary to complete the task successfully, or was it possible to perform the task using direct grasping without rotation? Second, Experiment 2 provides additional insight into the trade-offs in task performance between the two movement strategies. Was one strategy more robust for repeated task success? If the task was possible to complete by direct grasping, did it require more time than the spontaneously selected preparatory rotation strategy? If so, what time-period of the action would be lengthened?

### 5.1 Apparatus and procedure

The procedure for Experiment 2 was the same as for Experiment 1 Part I, except for an additional task constraint for the lifting trials. The experimental setting and set of canisters remained the same.

As in Experiment 1, there were a total of 32 trials, testing each possible combination of the 2 mass levels, 2 angular precision levels, and 8 initial handle orientations. The 32 conditions were presented in a randomized sequence, and a new randomized sequence was generated for the remaining conditions if there were any failed trials where the ball dropped. It was expected that it might not be feasible to lift the canister

from all of the presented handle configurations. Thus, a condition was not repeated in the sequence once there were 3 failures for that specific condition.

The participant was instructed to retrieve the token under the canister as quickly as possible, without disturbing the balanced ball and without sliding the canister on the platform surface prior to lifting. The participant was informed that there would be a maximum of 3 attempts for any one set of task conditions.

Five participants (4 male, 1 female) who participated in Experiment 1 volunteered for Experiment 2 as a follow-up study.

## 5.2 Data analysis

Because the task timing would be compared between the constrained condition in Experiment 2 and the unconstrained condition in Experiment 1, we first verified that the 5 follow-up participants were a representative subset of the 12 original participants with respect to the task completion time for Experiment 1. An LME model tested the total task completion time for the preparatory rotation trials in Experiment 1 for the  $N = 5$  subset of data.

The number of unsuccessful trials were compared between the two movement strategies for the 5 participants in Experiment 2. The total number of unsuccessful attempts included trials of any repeated task conditions. It was expected that there would be fewer unsuccessful attempts with the unconstrained preparatory rotation strategy in Experiment 1, because direct-reach-to-grasp actions would be less robust to the variety of task conditions.

The task timing for the direct grasping trials in Experiment 2 was determined using the same time segmentation procedure from Experiment 1 (see Section 3.1). The time courses of the natural preparatory rotation strategy and the direct grasping strategy were compared using LME models. The input data were the time intervals for the trials from Experiment 1 Part I and Experiment 2. Only the data from the 5 follow-up participants were considered, so that the strategies were compared trial-by-trial for corresponding task conditions and participant.

We hypothesized that the unconstrained preparatory rotation strategy of Experiment 1 could result in less total time for task completion relative to Experiment 2 due to the advantage of lifting the canister from a preferred object orientation. It was expected that the additional time required for the optional rotation action would be offset by decreased time for the pre-interaction and lifting action intervals. The LME model tested the fixed effect of the strategy on the time interval duration in a model which also included a random effect for the participant and fixed effects for the object mass, angular precision, the initial handle orientation, and

the square of the initial handle orientation.

In addition, separate LME models tested the fixed effects on timing intervals for each strategy. In this case, the model for preparatory rotation tested the entire set of data from the 12 participants in Experiment 1. Another model for direct grasping tested the set of data from the 5 participants in Experiment 2.

### 5.3 Results

No participant reported fatigue or requested immediate rest in addition to the scheduled breaks.

Three participants failed to complete the token retrieval task for 6-8 trials (including repeated task condition attempts), 1 participant failed for 11 trials, and 1 participant failed for 22 trials. For all five participants, there were more failed attempts with the direct grasping strategy in Experiment 2 than with the natural preparatory rotation strategy in Experiment 1 (Fig. 9a).

The token retrieval task was feasible for all five participants if it involved the lower angular precision requirement corresponding to the wide diameter balance ring (Fig. 9b). Failures to complete the task within 3 attempts were otherwise observed for all participants (two failing at 1 condition, two at 2 conditions, and one at 5 conditions). One participant was not able to directly lift the light canister with the thin diameter balance ring at handle orientation 4. Four of the five participants were not able to directly lift the heavy canister with the thin ring at handle orientation 4. The other infeasible tasks occurred at handle orientations 3, 5, and 7 for the heavy canister with the thin ring.

The first LME model tested whether the 5 follow-up participants were representative of the original 12 participants. It was based on the total task time for the preparatory rotation trials in Experiment 1. The fixed effects which were significant for the complete set (Table 2) were also significant for the subset of 5 follow-up participants. The average total time was 3.96 seconds, which was higher than the average for all 12 participants (3.46 seconds).

The next LME model compared the timing between the two strategies for the successfully completed trials (Table 7). The total time for task completion  $T_0$  was on average 1.49 seconds shorter using direct grasping instead of preparatory rotation ( $t(298) = -6.00, p < 0.001$ ). The pre-interaction time  $T_1$  of perception and reaching before initial object movement was 0.75 seconds longer for direct grasping over preparatory rotation ( $t(298) = 5.41, p < 0.001$ ). The second time interval  $T_2$  for object interaction between initial object movement and object lift-off was 2.30 seconds shorter for direct grasping without preparatory rotation ( $t(298) = -11.43, p < 0.001$ ). The difference in the object lifting time  $T_3$  between the two strategies was not significant.



For the direct grasping trials in Experiment 2, the total time  $T_0$  for task completion was 3.51 seconds on average for the baseline light object with wide diameter ring at initial orientation 8 (Table 8). Increasing the angular precision increased  $T_0$  by 2.58 seconds ( $t(140) = 7.92, p < 0.001$ ). Similar to the Experiment 1 trials, the task took longer for initial handle orientations further from the central orientation 8 (Fig. 10), as indicated by the positive coefficient for the squared orientation term ( $t(140) = 9.88, p < 0.001$ ).

The main difference in timing between the two strategies (Fig. 11) is the quadratic trend with respect to initial handle orientation (Table 9). For the natural preparatory rotation strategy in Experiment 1, the object interaction time  $T_2$  had the largest coefficient (0.33) for the squared orientation effect ( $t(366) = 21.35, p < 0.001$ ). The squared orientation coefficients were 0.04 ( $t(366) = 4.17, p < 0.001$ ) for the pre-interaction time  $T_1$  and -0.02 ( $t(366) = -2.13, p = 0.0335$ ) for the object lifting time  $T_3$ . However, for the direct grasping strategy in Experiment 2, the pre-interaction time  $T_1$  had the largest coefficient (0.22) for the squared orientation effect ( $t(140) = 6.32, p < 0.001$ ). The squared orientation coefficients were 0.05 ( $t(140) = 5.06, p < 0.001$ ) for the object interaction time  $T_2$  and 0.09 ( $t(140) = 5.02, p < 0.001$ ) for the object lifting time  $T_3$ . In other words, the response to initial handle orientation occurred primarily in the object interaction time for the preparatory rotation strategy but occurred primarily in the pre-interaction time for the direct grasping strategy.

## 6 Discussion

Preparatory object rotation, as opposed to direct-reach-to-grasp, was investigated as a movement strategy. Of particular concern were the conditions that lead to preparatory rotation and its utility. Selecting preparatory rotation over the alternative of direct grasping requires a choice in the amount of object rotation, which determines the object angle at the lift-off time. The experimental results suggest that the lifting capability associated with a particular object orientation is one criterion which underlies the selected movement strategy. The choice of lift-off angles, in turn, is sensitive to difficulty factors of object mass and task precision. In almost all of the task conditions, preparatory rotation is optional, because it is possible to use direct grasping even for object lift-off angles associated with lower lifting capability. One potential advantage of selecting a posture with higher capability is the improved robustness of completing the task successfully, at the cost of longer time for task completion.

## 6.1 Selection criteria for object rotation and lift-angle

This study replicated previous observations that preparatory rotation shows a quadratic trend with respect to the initial handle orientation of the lifted object (Chang et al., 2008). That is, people tend to rotate the object in the shorter direction toward a desired lift-off orientation. More importantly, this investigation extends beyond the previous work by examining posture-dependent lifting capability as a criteria for the lift-off angle selection.

The results of Experiment 1 showed that the maximum lifting capability occurred around the central object orientation number 8, in the same region of initial handle angles where participants performed the least amount of rotation. The lifting capability might be considered a biomechanical measure of the comfort associated with a lifting posture, especially for a somewhat demanding task as the token retrieval task presented here. Accordingly, the set of selected lift-angles with high lifting capability could be described as a “comfort zone” for the lifting grasps.

In particular, there was a strong correlation between the amount of object rotation and the change in the lifting capability that rotation would produce. This correlation suggests that the sub-action of preparatory rotation acts to increase the posture-dependent capability for the primary lifting task. The object reconfiguration, which anticipates the strength capability for the final action, may be an externalization of the end-state comfort effect first observed by Rosenbaum et al. (1990). Instead of only choosing a body posture in response to a task condition, the participant also adjusts the object in the environment to obtain task conditions which afford preferable postures.

The correlation curves (Fig. 7) contained points where there was a small negative difference in the lifting capability for a small amount of rotation. These corresponded to trials for initial handle orientations 1, 7, and 8, where the lifting capability is already near the maximum. The change in handle orientation may be due to the local adjustment resulting from the grasping interaction at lift-off time. The small decrease in lifting capability may be acceptable because the handle angle remains within the preferred comfort zone and does not need to be at the optimum posture. The values of negative change in lifting capability could also be due to limitations in the measurement technique of lifting capability, which depended on participants to perform the lifting interaction with a consistent amount of maximum effort for all samples.

The selection criteria for the lift-off angle may be a combination of both costs associated with goal postures at the lift-off states and costs associated with the rotation sub-action. For example, the variability of lift-off angles over different initial angles may be due to a trade-off between the pushing effort required

for the amount of rotation and the lifting capability at the final selected lift-off angle. Future investigation is required to determine whether goal postures alone are sufficient for predicting the selection of preparatory movements, as in a posture-based planning model (Rosenbaum et al., 1993a,b, 1995). It is possible that for complex manipulation involving preparatory object adjustment, action costs are required to model the dynamic object interaction in addition to the goal grasping postures.

## **6.2 Sensitivity to task difficulty factors**

Experiment 1 also investigated how the task difficulty affects the specific strategy of preparatory object manipulation. Our intent was to examine whether the lift-off angle selected by the preparatory rotation was invariant across task conditions, which might be the case if individuals had a fundamental preference for a particular set of geometric task conditions. We expected, however, that the selection of object lift-off angles would vary in response to the task demands, such that more demanding tasks would result in a narrower range of angles which resulted in successful task completion.

Object mass and required angular precision, as manipulated by object diameter, were tested as two specific task difficulty factors which could affect task performance in Experiment 1 Part I. The angular precision is similar to the geometric task difficulty index proposed by Latash & Jaric (2002) as a parameter for describing postural coordination for a drinking task. We additionally investigated object mass as a strength requirement for the manual lifting task in our experiments, which may be more physically demanding than a drinking task. The differences in total time of task completion confirmed that it was more difficult to lift the heavier object and/or balance with the thinner diameter ring. Both factors contributed to longer time for the token retrieval task, even for the same initial handle orientation.

We first examined the effect of the task difficulty factors on the amount of object rotation. Only angular precision, and not object mass, was a significant factor for the amount of rotation. When greater angular precision was required for the lifting task, the canister was rotated more from the initial orientation.

We also examined the effect of the two task difficulty factors on the variability of the object orientation at the lift-off time. Increased object mass and increased angular precision resulted in decreased lift-angle variability. This indicates that although object mass did not affect the amount of object rotation for a specific starting angle, mass did affect the selection of the preferred angles prior to lifting. The variability of the lift-angles represents the size of the comfort zone for a particular combination of object mass and task precision. Increased variability indicates a less restrictive selection of the preferred lifting postures. The lower levels of object mass and/or task precision resulted in a relaxation of the constraint on the region of selected lift-angles.

For the task precision factor (but not the object mass factor), the increased variability in the lift-angles also corresponded to increased variability in the lifting capability within the selected comfort zone. This result suggests that the externalization of the lifting capability criterion is diminished for less precise tasks, which adds to the previous finding by Rosenbaum et al. (1996) that the end-state comfort effect is decreased for less precise dowel wielding tasks.

The difference in the effect of object mass on the specific amount of rotation and the lift-angle variability could be due to the specific two levels of object mass tested in the experiment. The canister mass for the “heavy” level was specifically chosen to be light enough to avoid fatigue from repeated lifting. Given the trend in the predicted direction, we hypothesize that the object mass would reach significance as a factor for the amount of object rotation if a heavier canister could be reasonably tested in a future experiment.

### **6.3 Preparatory rotation as an alternative to direct grasping**

The strategy of preparatory rotation is an example of movement planning for a sequence of sub-actions to complete a task. In particular, preparatory rotation involves not only the anticipation of body posture but also the selection of intermediate object configurations which is an adjustable task condition. If the intermediate object configuration is similar for different task conditions, then a well-practiced or comfortable lifting action can be reused. Achieving similar intermediate task conditions for reuse of the lifting action requires adaptation of the rotation action for different initial object orientations. The rotation of the object handle to a particular region suggests that for some tasks there may be a preference for adapting only the preparatory action component for reuse of the lifting posture, compared to planning an entirely new direct grasping action. The present findings indicate that the choice to adapt the rotation motion instead of the lifting action may be influenced by the posture-dependent lifting capability as well as the difficulty factors of object mass and task precision.

In some cases, the task conditions may be sufficiently difficult that preparatory rotation may be required to complete the task because direct grasping is infeasible. The results of Experiment 2 suggest this might be the case for the lifting a heavy object with a strict angular precision requirement when the handle is opposite the preferred lift-angle region. In less demanding tasks involving a lighter object or less angular precision, direct grasping may be a feasible strategy for successful completion. The participants’ choice in Experiment 1 to use preparatory rotation even for these task conditions indicate there are advantages to reconfiguring the object to a new orientation with higher lifting capability. The results from Experiment 2 suggest that lifting from the preferred comfort zone improves the robustness of the lifting action such that the task can be

completed successfully in fewer attempts. The increase in robustness may be due to the increased efficiency or safety margin of the higher lifting capability relative to the minimal lifting capability required to complete the task.

Preparatory rotation did not result in a clear timing advantage over direct grasping, because the total time was shorter for direct grasping. The largest difference between the two strategies is the relative contribution of the different time intervals for pre-interaction, object interaction, and object lifting. The time  $T_3$  for object lifting was not significantly different between the two strategies. The results from Experiment 2 suggest preparatory rotation may be selected over direct grasping due to the shorter planning and reaching time  $T_1$  before initial object movement, even if the increase in the object interaction time  $T_2$  results in an overall longer time for task completion.

We further note differences in how the component times were affected by the object orientation. For the unconstrained preparatory rotation strategy, the pre-interaction time was relatively constant across different initial handle orientations (Fig. 11). That is because the goal posture for initial object movement must only contact the canister handle for the adjustment motion. The main contribution to the quadratic effect of initial orientation is from the object interaction time  $T_2$  where the preparatory rotation occurs.

However, when preparatory rotation is not permitted in the direct grasping trials, the main contribution to the quadratic orientation trend arises in the pre-interaction time,  $T_1$ . The increase in the pre-interaction time for direct grasping suggests that the restriction for no preparatory adjustment is compensated for by longer planning and reaching times before object contact. The planned posture for initial contact with the object must be capable of lifting the canister to complete the token retrieval task. This difference in the pre-interaction time may be partially due to a mental rotation of the object for posture planning, to compensate for the lack of physical rotation. The average increase of 0.75 s for time  $T_1$  is on the order of the delay times for mental rotation (0.4-1.1 s) reported by Cooper & Shepard (1973), for example. Although the preparatory rotation strategy requires longer absolute time for task completion, the longer pre-interaction time for direct grasping may affect the participants' perceived task time due to the complexity of initial planning phase.

Overall, preparatory object rotation involves several components which may be studied to understand how humans choose between alternative movement strategies. We investigated the changes in object configuration prior to lifting, which represented the selection of the preferred task-space conditions for the manual lifting action. Further investigation of posture and grasp differences may lead to greater insight into the factors determining an individual's choice between a direct grasping strategy and a preparatory rotation strategy. Factors such as initial and final object locations may also play a role in the selection of a manipulation

strategy. In addition, we observe the preparatory rotation is just one of many strategies that people use for object interaction prior to grasping. Other preparatory manipulation actions include sliding, pivoting, and complex tumbling maneuvers to reconfigure the the object before the final grasp. Additional research of preparatory manipulation strategies beyond preparatory rotation can complement the existing literature which has often focused on direct reaching and grasping tasks.

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## References

- Burgess-Limerick, R., & Abernethy, B. (1997). Qualitatively different modes of lifting. *International Journal of Industrial Ergonomics*, *19*, 413–417.
- Chang, L. Y., Zeglin, G. J., & Pollard, N. S. (2008). Preparatory object rotation as a human-inspired grasping strategy. In *IEEE International Conference on Humanoid Robots (Humanoids 2008)*.
- Cooper, L. A., & Shepard, R. N. (1973). The time required to prepare for a rotated stimulus. *Memory & Cognition*, *1*, 246–250.
- Fischman, M. G. (1998). Constraints on grip-selection: minimizing awkwardness. *Perceptual and Motor Skills*, *86*(1), 328–330.
- Latash, M. L., & Jaric, S. (2002). Organization of drinking: postural characteristics of arm-head coordination. *J Mot Behav*, *34*(2), 139–150.
- Pinheiro, J. C., & Bates, D. M. (2000). *Mixed-effects models in S and S-PLUS*. New York: Springer.
- R Development Core Team (2008). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org>.
- Rosenbaum, D. A., Engelbrecht, S. E., Bushe, M. M., & Loukopoulos, L. D. (1993a). A model for reaching control. *Acta Psychol (Amst)*, *82*(1-3), 237–250.
- Rosenbaum, D. A., Loukopoulos, L. D., Meulenbroek, R. G., Vaughan, J., & Engelbrecht, S. E. (1995). Planning reaches by evaluating stored postures. *Psychological Review*, *102*(1), 28–67.
- Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J. D., & Jorgensen, M. J. (1990). *Attention and Performance XIII: Motor Representation and Control*, chap. Constraints for Action Selection: Overhand Versus Underhand Grips, (pp. 321–342). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Rosenbaum, D. A., van Heugten, C. M., & Caldwell, G. E. (1996). From cognition to biomechanics and back: the end-state comfort effect and the middle-is-faster effect. *Acta Psychol (Amst)*, *94*(1), 59–85.
- Rosenbaum, D. A., Vaughan, J., Barnes, H. J., & Jorgensen, M. J. (1992). Time course of movement planning: selection of handgrips for object manipulation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(5), 1058–1073.

- Rosenbaum, D. A., Vaughan, J., Jorgensen, M. J., Barnes, H. J., & Stewart, E. (1993b). *Attention and performance XIV - A silver jubilee: Synergies in experimental psychology, artificial intelligence and cognitive neuroscience*, chap. Plans for object manipulation, (pp. 803–820). Cambridge: MIT Press, Bradford Books.
- Short, M. W., & Cauraugh, J. H. (1997). Planning macroscopic aspects of manual control: end-state comfort and point-of-change effects. *Acta Psychologica*, *96*(1-2), 133–147.
- Verbeke, G., & Molenberghs, G. (2000). *Linear mixed models for longitudinal data*. New York: Springer.
- Zhang, W., & Rosenbaum, D. A. (2008). Planning for manual positioning: the end-state comfort effect for manual abduction-adduction. *Experimental Brain Research*, *184*(3), 383–389.



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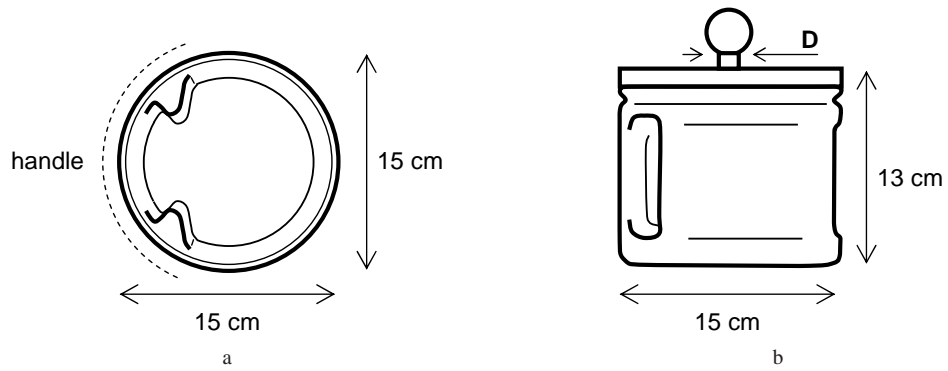


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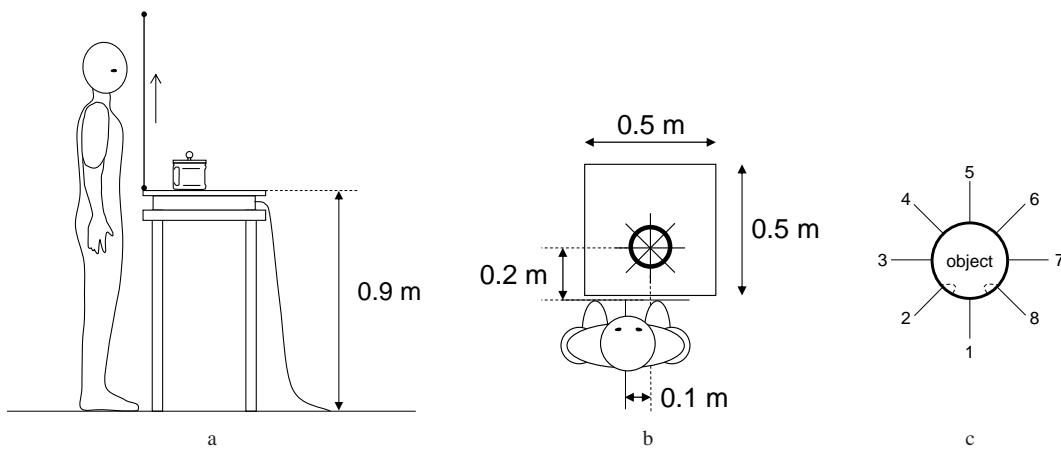


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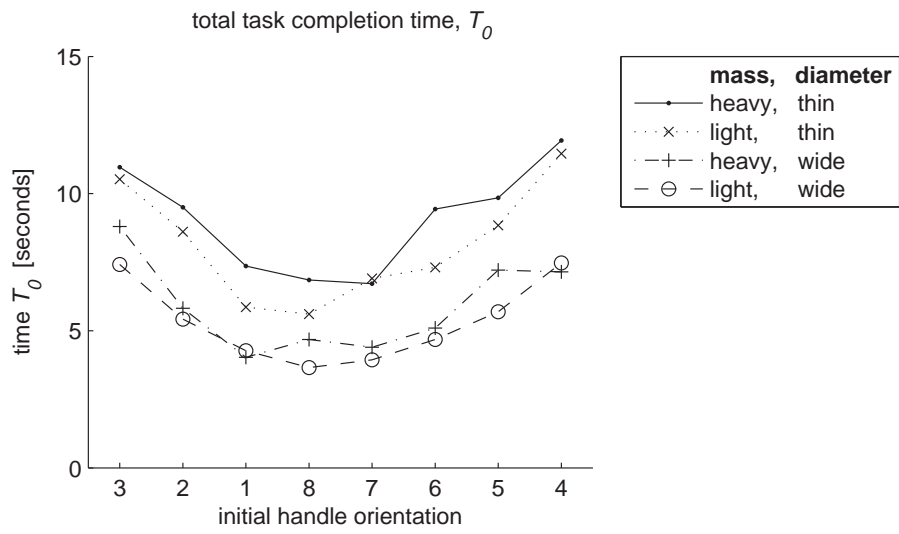


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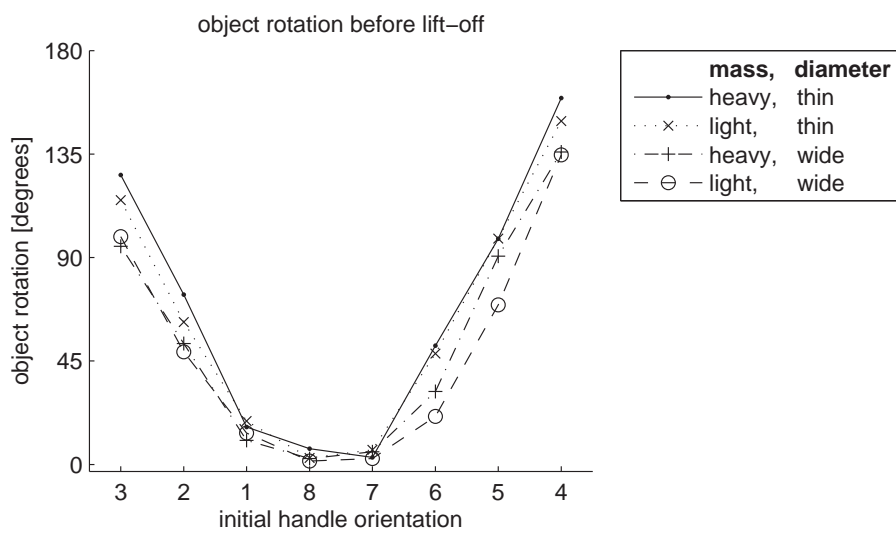


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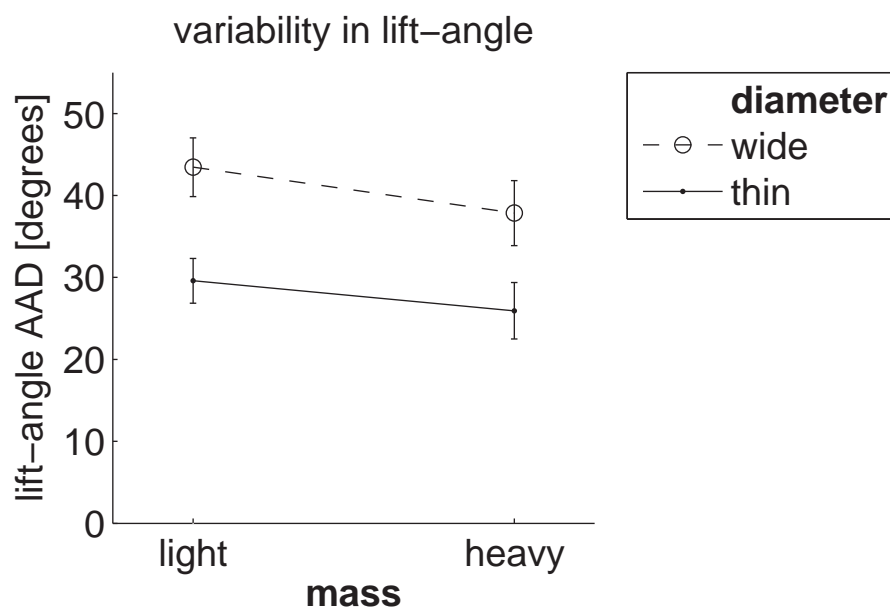


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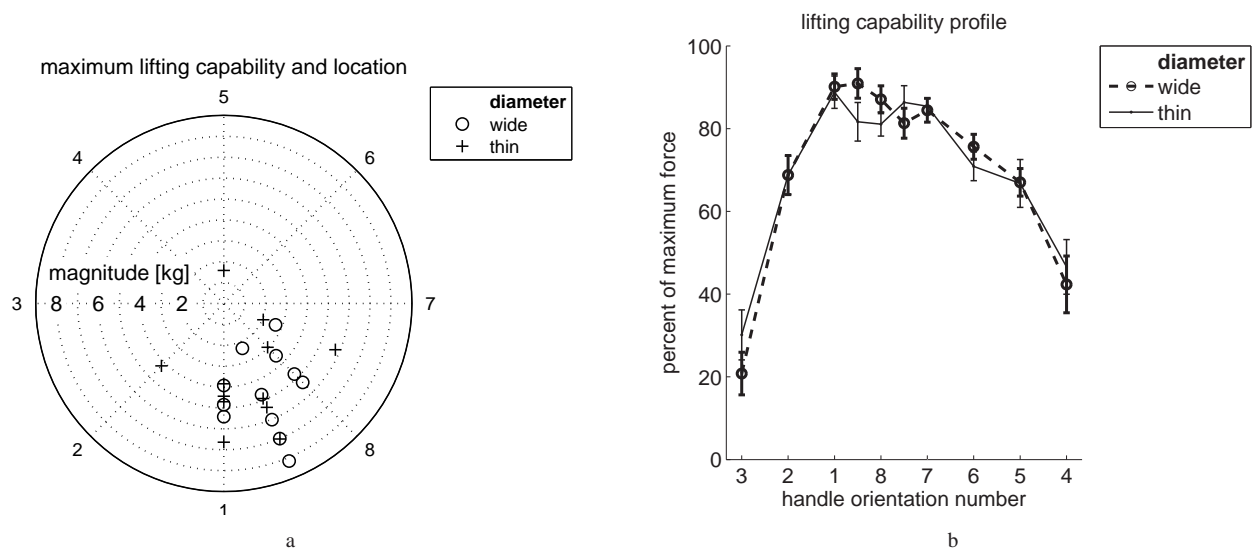


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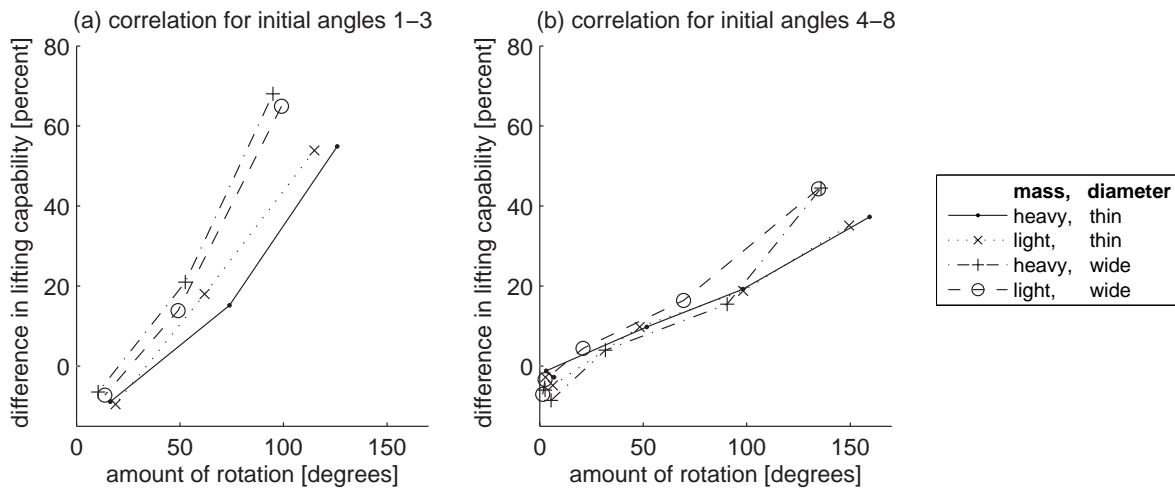


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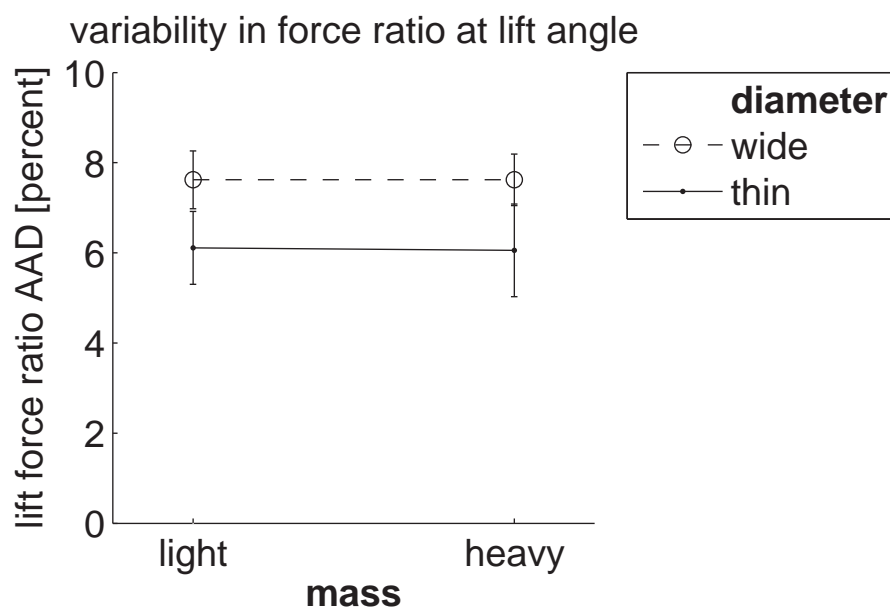
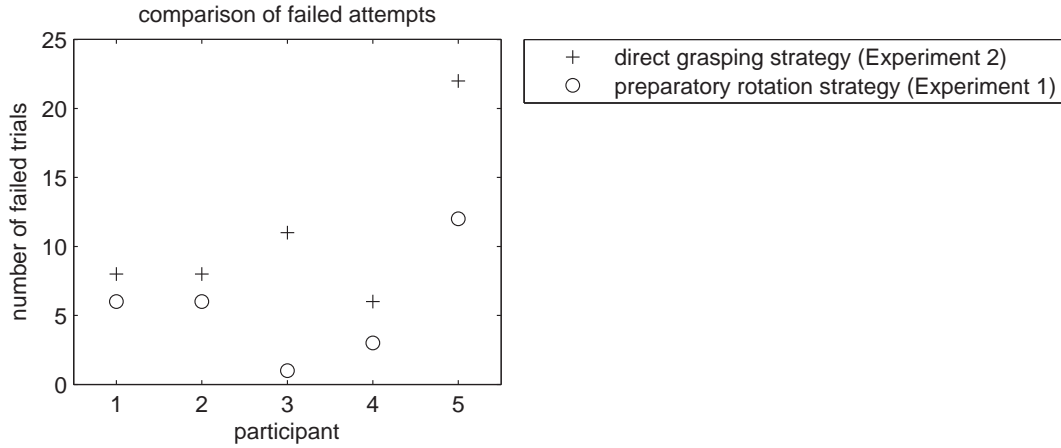
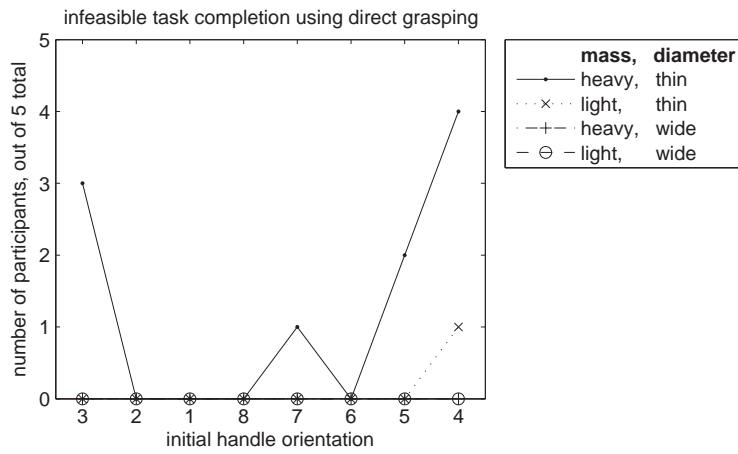


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a



b

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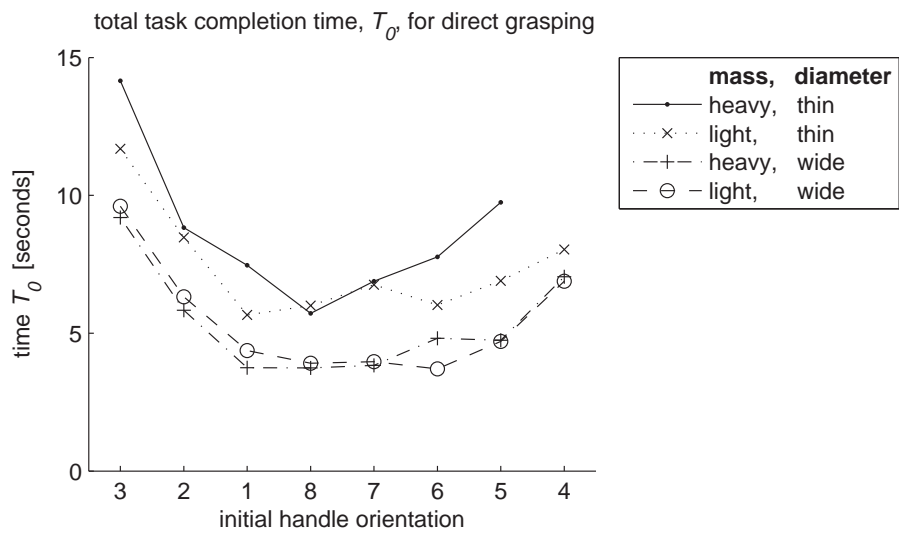


Figure 10: Mean data for the total time  $T_0$  for task completion when constrained to direct grasping. The point at initial orientation 4 for the heavy canister with the thin ring is not shown because only 1 of the 5 participants completed this task condition. The LME model results (Table 8) indicate that task completion time was longer for increased angular precision corresponding to the thin diameter balance ring. The task also took longer if the handle orientation started farther from the central orientation 8, as indicated by the quadratic trend with respect to the initial handle orientation.

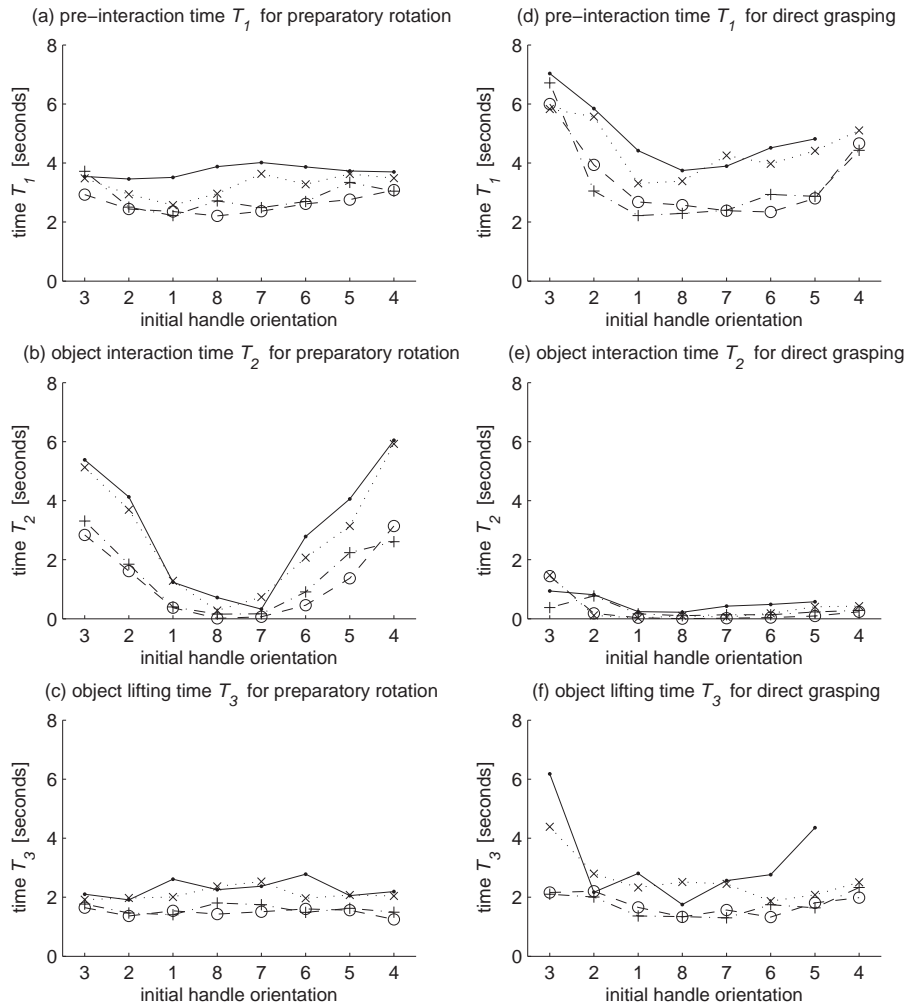


Figure 11: Mean data for the task components for both (a, b, c) the natural strategy observed for 12 participants in Experiment 1 and (d, e, f) the direct grasping strategy observed for 5 follow-up participants in Experiment 2. For the direct grasping condition, the point at initial orientation 4 for the heavy canister with the thin ring is not shown because only 1 of the 5 participants completed this task condition. (Table 9) presents LME results of the fixed effects for each time interval.

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Table 1: Response metrics observed for each trial of the token retrieval task in Experiment 1 Part I, where the participant lifted the canister from a presented object start orientation. Two groups of response metrics examined the object configuration choices for the preparatory rotation strategy and the timing of the task completion.

Response metric	Computation notes
Object configuration	
Lift-off angle	Handle angle in horizontal plane at lift-off frame
Preparatory rotation	Angle change between starting angle and lift-off angle
Timing	
Pre-interaction (perception and reaching), $T_1$	Raising of screen to initiation of object movement
Object interaction (preparatory adjustment), $T_2$	Initiation of object movement to object lift-off from surface
Object lifting and token retrieval, $T_3$	Object lift off to object return to surface
Total time, $T_0 = T_1 + T_2 + T_3$	Raising of screen to object return to surface

Table 2: Effects on task completion time (seconds) resulting from the linear mixed-effects (LME) analysis. The  $t$ -test and  $L$  ratio test results indicate the significance of the fixed effects and random effects, respectively. Significant effects ( $p < 0.05$ ) are denoted by asterisks (\*). In the model, the baseline mass level was light (L) and the baseline diameter for angular precision was wide (W). Thus the mean value for the mass and angular precision are the additive effects for the heavy (H) level and the thin (T) ring diameter.

Main effects	Mean Value (s)	Std. Error (s)	$t$ (DF)	$p$
$T_0$ : total task completion time			$t(365)$	
Baseline (L=0, W=0)	3.46	0.61		
Object mass (H=1)	0.73	0.18	4.00	<0.001 *
Angular precision (T=1)	2.96	0.18	16.22	<0.001 *
Orientation <sup>2</sup> coefficient	0.35	0.02	17.60	<0.001 *
Orientation coefficient	-0.25	0.04	-5.66	<0.001 *
Random effects	Baseline value (s)	Residual error (s)	$L$ ratio	$p$
$T_0$	2.00	1.78	248.85	<0.001 *



Table 3: Interaction effects on amount of preparatory object rotation (degrees) from the LME analysis. The  $t$ -test and  $L$  ratio test results indicate the significance of the fixed effects and random effects, respectively. Significant effects ( $p < 0.05$ ) are denoted by asterisks (\*). In the model, the baseline mass level was light (L) and the baseline diameter for angular precision was wide (W). Thus the mean value for the mass and angular precision are the additive effects for the heavy (H) level and the thin (T) ring diameter.

Fixed effects	Mean Value (deg)	Std. Error (deg)	$t(DF)$	$p$	
Main effects			$t(364)$		
Baseline (L=0, W=0)	-1.3	3.1	-0.41	0.6818	
Object mass (H=1)	2.1	3.5	0.61	0.5427	
Angular precision (T=1)	7.7	3.5	2.21	0.0276 *	
Orientation <sup>2</sup> coefficient	9.6	0.6	16.62	<0.001 *	
Orientation coefficient	-4.6	0.6	-7.94	<0.001 *	
Interaction effects					
Object mass * Orientation <sup>2</sup>	0.4	0.5	0.76	0.4503	
Angular precision * Orientation <sup>2</sup>	1.1	0.5	2.33	0.0206*	
Random effects		Orientation <sup>2</sup> coefficient (deg)	Residual error (deg)	$L$ ratio	$p$
		1.3	23.3	38.28	<0.001 *

Table 4: Main effects on lift-angle variability resulting from the LME analysis. Lift-angle variability is measured by the average absolute deviation (AAD) of lift-angles over the set of 8 initial handle orientations. The  $t$ -test and  $L$  ratio test results indicate the significance of the fixed effects and random effects, respectively. Significant effects ( $p < 0.05$ ) are denoted by asterisks (\*). In the model, the baseline mass level was light (L) and the baseline diameter for angular precision was wide (W). Thus the mean value for the mass and angular precision are the additive effects for the heavy (H) level and the thin (T) ring diameter. The negative values for the additive effects indicate the lift-angle variability decreases for increased object mass and increased angular precision.

Main effects	Mean Value (deg)	Std. Error (deg)	$t(DF)$	$p$
Lift-angle variability			$t(34)$	
Baseline (L=0, W=0)	43.0	3.3		
Object mass (H=1)	-4.6	2.2	-2.12	0.0414 *
Angular precision (T=1)	-12.9	2.2	-5.90	<0.001 *
Random effects	Baseline value (deg)	Residual error (deg)	$L$ ratio	$p$
	9.3	7.6	19.16	<0.001 *

Table 5: Mean and standard error for the minimum capability ratios (percent) associated with the selected lift-angles of the four tested task conditions.

Mean $\pm$ standard error (percent)	Object mass	
	Light canister	Heavy canister
Angular precision level		
Wide diameter ring	70.3 $\pm$ 2.4	71.4 $\pm$ 2.6
Thin diameter ring	72.3 $\pm$ 3.0	73.7 $\pm$ 3.2

Table 6: Main effects on lifting capability variability from the LME analysis. Lifting capability variability is measured by the average absolute deviation (AAD) of lifting capability ratios (in percent) corresponding to the set of 8 initial handle orientations. The negative values for the additive effects indicate the variability decreases for increased object mass and increased angular precision.

Main effects	Mean Value (percent)	Std. Error (percent)	$t(DF)$	$p$
Lifting capability variability			$t(34)$	
Baseline (L=0, W=0)	7.6	0.7		
Object mass (H=1)	0.03	0.6	-0.04	0.9671
Angular precision (T=1)	-1.5	0.6	-2.39	0.0225 *
Random effects	Baseline value (percent)	Residual error (percent)	$L$ ratio	$p$
	1.5	2.2	5.10	0.024 *

Table 7: Fixed effect of manipulation strategy on movement time (seconds) from the LME analysis. Significant effects ( $p < 0.05$ ) are denoted by asterisks (\*). In the model, the baseline strategy was the natural preparatory rotation strategy observed in Experiment 1. Thus the mean value for the strategy factor is the additive effect for the direct rotation strategy observed in Experiment 2.

Main effect of direct grasping strategy	Mean Value (s)	Std. Error (s)	$t(298)$	$p$
$T_0$ : total task completion time	-1.49	0.25	-6.00	<0.001 *
$T_1$ : perception and reaching	0.75	0.14	5.41	<0.001 *
$T_2$ : manipulation and grasping	-2.30	0.20	-11.43	<0.001 *
$T_3$ : object lift and token retrieval	0.06	0.11	0.54	0.5863

Table 8: Effects on task completion time (seconds) from the LME analysis of the direct grasping trials in Experiment 2. Significant effects ( $p < 0.05$ ) are denoted by asterisks (\*). Except for object mass, the fixed effects which are significant are the same as those for the preparatory rotation trials (Table 2).

Main effects	Mean Value (s)	Std. Error (s)	$t(DF)$	$p$
$T_0$ : total task completion time			$t(140)$	
Baseline (L=0, W=0)	3.51	0.92		
Object mass (H=1)	0.44	0.32	1.35	0.1807
Angular precision (T=1)	2.58	0.33	7.92	<0.001 *
Orientation <sup>2</sup> coefficient	0.36	0.04	9.88	<0.001 *
Orientation coefficient	-0.64	0.08	-7.94	<0.001 *
Random effects	Baseline value (s)	Residual error (s)	$L$ ratio	$p$
$T_0$	1.92	1.96	70.44	<0.001 *

Table 9: Fixed effects on movement time (seconds) resulting from the LME analysis. Significant effects ( $p < 0.05$ ) are denoted by asterisks (\*). In the model, the baseline mass level was light (L) and the baseline diameter for angular precision was wide (W). Thus the mean value for the mass and angular precision are the additive effects for the heavy (H) level and the thin (T) ring diameter.

Main effects	Natural strategy with preparatory rotation (Experiment 1, $N = 12$ )				Direct strategy without preparatory rotation (Experiment 2, $N = 5$ )			
	Mean Value (s)	Std. Error (s)	$t(DF)$	$p$	Mean Value (s)	Std. Error (s)	$t(DF)$	$p$
$T_1$ : pre-interaction			$t(366)$				$t(140)$	
Baseline (L=0, W=0)	2.35	0.21	11.36	<0.001 *	2.26	0.64	3.55	<0.001 *
Object mass (H=1)	0.35	0.08	4.51	<0.001 *	0.21	0.07	0.97	0.3314
Angular precision (T=1)	0.76	0.08	9.76	<0.001 *	1.37	0.22	6.32	<0.001 *
Orientation <sup>2</sup> coefficient	0.04	0.01	4.17	<0.001 *	0.22	0.02	9.06	<0.001 *
Orientation coefficient	0.01	0.02	0.48	0.6344	-0.37	0.05	-6.85	<0.001 *
$T_2$ : object interaction			$t(366)$					
Baseline (L=0, W=0)	-0.45	0.36	-1.26	0.2072	-0.01	0.10	-0.07	0.9472
Object mass (H=1)	0.25	0.14	1.73	0.0837	0.10	0.09	1.06	0.2930
Angular precision (T=1)	1.57	0.14	11.00	<0.001 *	0.17	0.10	1.87	0.0640
Orientation <sup>2</sup> coefficient	0.33	0.02	21.35	<0.001 *	0.05	0.01	5.06	<0.001 *
Orientation coefficient	-0.29	0.03	-8.23	<0.001 *	-0.12	0.02	-5.23	<0.001 *
$T_3$ : object lifting			$t(365)$					
Baseline (L=0, W=0)	1.55	0.19	8.26	<0.001 *	1.26	0.35	3.59	<0.001 *
Object mass (H=1)	0.14	0.07	2.18	0.0296 *	0.13	0.16	0.82	0.4142
Angular precision (T=1)	0.64	0.07	9.81	<0.001 *	1.04	0.16	6.56	<0.001 *
Orientation <sup>2</sup> coefficient	-0.02	0.01	-2.13	0.0335 *	0.09	0.02	5.02	<0.001 *
Orientation coefficient	0.02	0.02	1.22	0.2214	-0.15	0.04	-3.94	<0.001 *