Effect of object and task properties on bimanual manipulation

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The use of both hands simultaneously when manipulating objects is fairly commonplace, but it is not known what factors encourage people to use two hands as opposed to one during simple tasks such as transport. In particular, we are interested in three possible transport strategies: unimanual transport, handing off between hands, and symmetric bimanual transport. In this study, we investigate the effect of object size, weight, and position as well as the presence of a balance requirement on the use of these three strategies in a bowl-moving task. We find that position and balance have a strong effect on choice of strategy, and weight has a weaker effect. Position affects unimanual and hand-off strategies, while balance affects all three. Our results suggest that the bimanual strategy is the most desirable strategy for balancing while hand-offs are the least desirable. In addition, an analysis of transport duration and rotation suggests that strategy choice is also driven by the desire to minimize body rotation and reaching into contralateral space.

Keywords: bimanual performance; grasping; arm movements; motor planning; handedness

Introduction

While it is difficult to assess how much of daily human manipulation involves both hands simultaneously (bimanual manipulation), various people surmise that bimanual manipulation is the predominant form of manipulation. For example, Kimmerle et al. (2003) claim, “The majority of activities of daily living are typically executed bimanually, for example, getting dressed, cooking, eating, and the majority of tool uses,” while Guiard (1987) reviews various handedness inventories and finds that slightly more than half of the tasks listed are bimanual.

Bimanual manipulation can appear in different forms, such as independent (each hand performing its own task), symmetric (the hands have similar roles on one task), or role-differentiated (each hand having a specialized role) (Guiard 1987). In the case of object transport (a task where an object is grabbed and moved), we observe that there are actually two two-handed strategies possible (in addition to a one-handed strategy). The first two-handed strategy is handing off, which is when the object is grasped with one hand, but then transferred to the other hand to be placed. The second is symmetric bimanual grasping, which is when both hands are used to form a single grasp of the object.

The existence of multiple ways of accomplishing the same task – unimanual, hand-off, and symmetric bimanual – raises the questions of how often various strategies are used and how people pick between them. This work examines four criteria that could potentially explain how people choose between these possible strategies: size, weight, balance, and location.

For large object sizes, two hands/arms can function similarly to a large manipulator (Bullock et al 2013), allowing people to grasp large objects. For heavy object weights, using both arms can spread the load to a more comfortable level at each arm and can also reduce the torque/moment by supporting the object at two places. Previous work by Cesari and Newell (2000) indicates a transition point where people switch from using one hand to using two hands as the length or density of cubes increases. However, this study was interested in grasping, not transport. The task of transport adds considerations like goal location that can change people's decisions and open up new strategies such as the hand-off strategy we are interested in.

For tasks requiring attention to balance, what is needed is very fine motor control, such as small adjustments when an object is in danger of toppling. The presence of a fine control requirement might encourage the use of two-handed strategies. As in the case of using two hands on the handlebars of a bike, it may be easier to make small adjustments by controlling the difference between two forces than to modulate the magnitude of a single force.

Finally, there are various studies that show how start and goal position of an object affect hand choice for unimanual grasping (e.g. Gonzalez et al 2014). There is also work on how start and goal position affect choice of one hand vs. two for the actions of picking and placing (Rosenbaum et al 2010). However, the study analyzes picking actions and placing actions independently and so does not explore when hand-off strategies are used.

In order to understand how these four factors possibly influence unimanual, hand-off, and bimanual strategies, we performed an experiment using different sizes and weights of bowls, difficulty of balancing, and starting positions for the subject. Our results indicate that balance and position strongly affect transport strategy. For balance, the symmetric bimanual strategy seems to be good for balancing objects while transporting them, while the hand-off strategy is avoided when balance is needed. For position, the hand-off and unimanual strategies were preferred at different positions, and this preference seems related to how much rotation is involved with each strategy at each position. We also find a weak weight effect and a size effect mostly centered around the smallest bowl size tested.

Related work

Studies on infant grasping

There is extensive investigation on when bimanual manipulation skills emerge in infants. Greaves and colleagues (2012) review a body of literature investigating what sorts of toy properties can encourage various kinds of bimanual manipulation (bimanual reaching, holding, handing off, turning, symmetric, and asymmetric) in developing children. Compared to studies of adult bimanual manipulation, infant studies on bimanual manipulation investigate a broader set of object features and are concerned with more types of bimanual manipulation – for example, Palmer (1989) looks at not only toy size and weight, but also toy texture, rigidity, and sound production, and table surface hardness. She also notes occurrences where an object is switched between hands (handed off). While we are interested in the use of bimanual manipulation skills in adults, not the development, the results of infant studies can inform adult studies. For example, the previously-mentioned work (Palmer 1989) found that switching was less frequent on heavy objects and that unimanual strategies were more frequent for hard tables than foam tables, possibly because objects on the hard table were more stable. These results related to handing off and object stability are the only ones we have found in the literature related to our interest in hand-off strategies and in balance as a factor.

Observations of bimanual manipulation

Several studies note the frequency or type of bimanual manipulation observed during the completion of everyday tasks. These studies do not vary experimental variables in a controlled setting, but rather record the usage of different types of manipulation in a natural setting. Kousaka et al. (2013) are mostly interested in one-handed actions, but note how much time is spent in bimanual manipulation (here defined as both hands doing the same action) in the areas of cooking, eating, shopping, driving, and using a computer. For the task of object transport, which we are interested in, they found that transport is roughly 15% bimanual for the cooking and eating cases, and 0% for shopping. Although this study doesn't analyze hand-offs, it provides an idea of how often people use symmetric bimanual grasping when transporting. Terrenghi et al. (2007) observe how people use unimanual and bimanual manipulation in a photo-sorting task. In this study, subjects spent over 90% of their time engaged in bimanual manipulation (here defined as both hands active at the same moment in time). Eight of twelve participants used one hand to hold a stack of photos and singulate the top and the other hand to transport photos, while three participants picked up photos with one hand, held them in both hands while examining them, and placed with one hand. Another bimanual strategy observed was holding in standby (one hand keeping photos between fingers while the other hand continues picking and placing).

Effect of object/task properties on grasping strategy

Similar to our study, several experimental studies investigate the effect of object or task properties on hand usage when grasping. For example, an experiment by Rosenbaum (2008) investigates how the choice to walk to the left or right of a table is influenced by goal position and object position. Participants were asked to grab a bucket from a table before continuing on to one of seven goal locations. Depending on which side of the table the bucket is closer to and how far left or right the final goal position is, the participant can be forced to trade off between reaching across the table for the bucket or taking a less efficient route to the goal. Rosenbaum and colleagues (2010) investigate how goal location affects the usage of left, right, or both hands when grasping or placing for a Tupperware-stacking task, finding that the location of the goal (and thus direction of walking) influenced which hand people used to grab the containers. Our study is similarly interested in how position affects the usage of each hand, but we use a simpler pick-and-place task, are explicitly interested in the hand-off strategy (the method of coding in this Tupperware experiment doesn’t allow detection of hand-off strategies), and consider other factors like object size and weight simultaneously.

A study by Cesari and Newell (2000) investigates how object size and weight influence the number of fingers or hands used. By having participants grasp cubes of different sizes and densities, they fit a single equation that uses hand length or mass to predict the transition point (cube size or weight) between four- and five-finger grasps and one- and two-handed grasps. They find that transitions from one hand to two happen when cube length is roughly 64% the length of the participant's hand length (i.e. the transition from one- to two-handed grasping is centered around 9.9 cm to 12.8 cm for the range of adult human hands measured in the study (16.9 cm to 19.5 cm)). The weight at which transition from one to two hands happens has more variance, occurring when the cube weight is 2 to 2.5 times the mass of the hand. For the people tested, the center of the transition ranged from 500 g to 1500 g. Similar to this study, we are also interested in how size and weight affect the frequency of bimanual grasps, but we are also interested in hand-offs and the role of position and balance. Choi and Mark (2004) extend Cesari and Newell's cube study to investigate how object distance and weight affect reaching modes (using the arm and shoulder only, using the torso to reach, and standing to reach).

Experiment 1

Measures and hypotheses

The goal of this experiment was to determine how various object and task properties affect whether people use one or two hands to transport a bowl. The object properties varied were bowl size and weight. The task properties varied were balance (whether balance was important) and position (the position of the bowl relative to the subject). We collected which hand(s) subjects used to pick and place the bowl.

Our hypotheses were as follows: Larger object size, heavier object weight, and the presence of a balance requirement would encourage the use of the symmetric bimanual strategy. Start and goal position would affect the use of hand-offs, as people would make use of the range of both arms.

Method

Participants

We ran an experiment with 17 participants (5F, 12M; 1 left-handed, 14 right-handed, 2 mixed-handed (self-reported handedness); mean age = 27.5 (SD = 6.7)). The method was approved by the Disney Research Institutional Review Board, and the informed consent of all participants was obtained in accordance with the Declaration of Helsinki.

Procedure

Each participant performed 56 tasks that consisted of moving a bowl from one table to another, where the subject's starting location and facing direction varied. There were 8 different types of bowls and 7 different standing place-standing direction combinations (hereafter called "positions") that the subject could stand (Fig. 1).

The bowls moved were IKEA® BLANDA BLANK bowls of two different sizes. The BLANDA bowls were chosen due to their simple, symmetric geometry – in particular, their lack of a lip that could be used for grasping – and their similar shape across sizes. The smaller bowl was 12.2 cm × 6.1 cm (diameter, height), while the larger bowl was 20.2 cm × 9 cm.

The "light" bowls were filled with aquarium stones to the total weight of 290 g, while bowls in the "heavy" condition were filled to 640 g total.

In the "balance" condition, a toilet paper roll (4.1 cm diameter × 10.5 cm height) with a 4" (10 cm diameter) styrofoam ball balanced on top was used to add the difficulty of balancing to the moving task. The roll was inserted into and stabilized by the aquarium stones inside the bowl. For bowls without enough stones to stabilize the roll, the roll was attached to adhesive putty at the bottom of the bowl. The roll and ball were removed in the “no balance” condition, and a packet of stones added to maintain the above-listed weights.

There was one trial per condition, resulting in 56 trials overall per participant (2 size × 2 weight × 2 balance × 7 positions). Tasks sharing a facing position/direction were presented consecutively in a block to avoid making the subject move around after each trial. Otherwise, the presentation of the blocks and tasks within each block were randomized.

At the start of the experiment, the participant was instructed to not knock over the styrofoam ball used in the balance cases. If the ball fell from the tube, the trial was repeated. The error was recorded but the trials with errors were not included in the analysis – only successful trials were analyzed.

The trials were videotaped with an ordinary video camera that included the participant, start location, and goal location in the frame. The entire procedure including instruction and obtaining consent took under 30 minutes.

Data processing

Videos were reviewed by the researcher, and the following annotations were made: (1) grasp strategy, (2) approximate transport duration, and (3) approximate hip rotation.

Strategies were differentiated by which hand(s) were used for grasping and placing. The nine possibilities are shown in Table 1.

For duration, the start of transport was considered to be the second when a stable grasp was formed[1] and the end was the second when the bowl made contact with the goal table. Duration was calculated as the number of seconds in between.

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[1] When grasping, subjects would first move and adjust their fingers on the bowl; then their fingers would stop moving for a moment as the participant braced to take on the load of

To calculate rotation, first, facing directions of the hip at transport start and end were estimated from the video, rounded to the nearest 45° (octant). For clockwise turns, the end angle was annotated as negative while counter-clockwise turns were annotated as positive. Rotation was defined as the positive difference between the angle of the initial facing direction and the angle of the start of bowl transport, plus the positive difference between transport start and end angles.

Note that there was some ambiguity in categorizing grasp strategy: the second hand sometimes floated near the object, or briefly touched it before dropping away. Because contact was non-existent or brief, these cases were annotated as unimanual motions.

Data analysis

A mixed-effects linear model with a logistic link function was fit to the data using the `glmer` function of R's lme4 package (Bates et al. 2015). The response variables analyzed were usage of bimanual, hand-off, and unimanual strategy (three separate analyses with binary outcomes). Size, weight, balance, position, and their interactions were used as fixed effects in the model. Variation between participants was modeled as a random intercept. Because models had difficulty converging when random slopes were added, random slopes were not included in the model. A stepwise procedure comparing likelihood ratios (using ANOVA) was used to eliminate non-significant variables until no more could be removed (a significance level of .01 was used to determine which factors to keep). For significant effects, plots showing the mean probability of a strategy being used under each condition and an estimation of the

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the bowl. This solidifying of the grasp pose right before lifting was considered the moment a stable grasp is formed.

standard error of that mean were generated using the `effect` function of R's effects package (Fox 2013).

In addition, in order to understand the reason behind people's preference of certain strategies over others, the effect of strategy (bimanual, hand-off, and unimanual) on transport duration and body rotation were investigated using linear models with duration or rotation as the response, and strategy and the four experimental variables as fixed effects. Non-significant variables were removed using likelihood ratios.

The pattern of the left-handed participant's data differed noticeably from that of the other participants – for example, right-handed participants used their right hand unimanually more often than they did their left hand, and this was reversed for the left-handed individual. As such, this participant's data was discarded when performing analysis. Their data is not represented in the following results.

Experiment 1 results

Strategy frequency overview

Frequencies of grasp strategies are summarized in Fig. 2. All strategies were observed at least once, but strategies that involved switching from one to both hands or vice versa were rare.

Effect of experimental variables on grasp strategy

For all three strategies – bimanual, hand-off, and unimanual – balance and position remained in the model. In addition, the balance × position interaction effect remained in the unimanual model ($\chi^2(6)=48.8$, $p<.0001$).

Balance as a main effect was significant in bimanual ($\chi^2(1)=235$, $p<.0001$) and hand-off ($\chi^2(1)=127$, $p<.0001$) strategies, but not the unimanual ($\chi^2(1)=3.1$, $p=.080$).

When the balance requirement was in play, the bimanual strategy was more likely, the hand-off strategy less likely, and had a more complicated effect on the unimanual strategy. At positions where the unimanual strategy was popular (P1, P4, and P7 – positions involving moving the bowl from front to back), the balance requirement cut down unimanual usage. At the other four positions (positions involving moving the bowl left hemispace to right hemispace or vice versa), however, unimanual usage increased in the balance case.

The three strategies were also affected by position (bimanual: $\chi^2(6)=18.0$, $p=.006$; hand-off: $\chi^2(6)=371$, $p<.0001$; unimanual: $\chi^2(6)=257$, $p<.0001$). Hand-offs were the strategy people used most often at P2, P3, P5, and P6, which involved moving the bowl from left to right or vice versa. The unimanual strategy was used most at P1, P4, and P7, which are the three positions where the bowl is moved from front to back. Fig. 3 summarizes these balance and position effects.

Fig. 4 provides a useful way of visualizing position and balance effects. Rather than using the arbitrary numbering of the positions, Fig. 4 arranges the raw strategy usage data[2] at each position to be at the angles where the bowl starts and ends relative to the participant. For example, at P3, the bowl starts out directly to the left of the participant and is moved to the participant's right. At this position, the hand-off left-to-right (LR) strategy is the most common strategy (used about 60% of the time) followed by the bimanual strategy.

Neither size nor weight were significant in any of the models. Size and all related interaction effects were able to removed from the full model (unimanual:

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[2] This data separates out the two unimanual strategies (L and R) and the two hand-off strategies (LR and RL). It also shows raw frequency of each strategy averaged over participants, rather than the predicted probabilities of Fig. 3 that account for random variation between participants.

$\chi^2(28)=18.3$, $p=.92$), or from a partial model after the removal of weight (bimanual: $\chi^2(14)=13.3$, $p=.51$; hand-off: $\chi^2(14)=20.9$, $p=.10$). Weight and interaction effects involving weight were able to be removed from the full model (bimanual: $\chi^2(28)=24.2$, $p=.67$; hand-off: $\chi^2(28)=24.2$, $p=.67$) or from a partial model after the removal of size (unimanual: $\chi^2(14)=13.8$, $p=.47$).

Reason for strategy choice

Although some participants use the bimanual strategy as a dominant strategy, its total observed usage in the balance case only reached 33%. One possible explanation for this is that the other strategies have some other benefit and so can still be appealing even when balance is a factor.

The first hypothesis we tested was that hand-off and unimanual strategies were quicker. We used the generalized linear model with duration as a response to test this hypothesis. For the duration model, both strategy ($\chi^2(2)=18.9$, $p<.0001$) and the strategy × balance interaction ($\chi^2(2)=40.2$, $p<.0001$) were significant. However, examining the significant strategy × balance interaction effect (Fig. 5) reveals that the bimanual strategy is on par with the unimanual strategy and faster than the hand-off strategy in the balance case. Thus, duration does not explain why people often decline to use the bimanual strategy in the balance case.

The second hypothesis we tested was that hand-off and unimanual strategies require less rotation. Strategy ($\chi^2(2)=475$, $p<.0001$) and the strategy × position interaction ($\chi^2(2)=196$, $p<.0001$) remained in the rotation model. As Fig. 6 illustrates, (1) bimanual strategies require more rotation than unimanual strategies, which generally (except at P7) require more rotation than hand-off strategies; and (2) position affects the rotation needed at each strategy by different amounts. In particular, the hand-off strategy needs more rotation at P1, P4, and P7, which could be responsible for the low popularity of hand-offs at those positions.

Experiment 1 discussion

In Experiment 1, balance had a strong effect in line with our hypotheses. When balance was needed, hand-offs were used less often while the bimanual strategy was more likely to be used. Balance had a mixed effect on unimanual strategy: the strong positional variation in the no-balance case was “evened out” somewhat in the balance case. Together, these effects suggest that the unimanual strategy is between the other two strategies in terms of stability. During balance cases, it “steals” some uses from the hand-off strategy, but loses some to the bimanual strategy.

Position had a strong effect on hand-off and unimanual usage, and a weaker effect on bimanual strategy. The unimanual strategy was the most popular of the three strategies when moving the bowl from front to back, while hand-offs were most common when passing across left-right hemispaces. By contrast, usage of the bimanual strategy did not seem to vary as much with position, which is similar to results found by Rosenbaum et al. (2010).

The desire to minimize body rotation seems to be a part of strategy choice. Hand-offs are most popular at the four positions where minimal rotation is required, and unimanual is popular at the other three positions. The bimanual strategy requires the most rotation.

In this experiment, we found a strong effect of position and balance on grasp strategy. However, we didn’t find the effect we expected of greater size and weight on bimanual strategy. One possibility is that the bowls were not sufficiently large or heavy enough to encourage bimanual usage. We investigated this possibility in a second experiment.

Experiment 2

Measures and hypotheses

The focus of this experiment was to test if weights and sizes larger than the ones previously investigated can elicit a size/weight effect on bimanual usage. Four bowl sizes and three weights were used.

Method

Participants

We ran an experiment with 16 participants (6F, 10M; 15 right-handed, 1 mixed-handed (self-reported handedness); mean age = 26.2 (SD = 6.1)). The method was approved by the Carnegie Mellon University Institutional Review Board, and the informed consent of all participants was obtained in accordance with the Declaration of Helsinki.

Procedure

Each participant performed one trial for each of the 66 conditions tested in the experiment. Each trial consisted of moving a bowl from one table to another. There were 11 size/weight combinations for the bowls (Fig. 7) and 3 different places/directions that the subject could stand (Fig. 8). There were 2 balance/no balance conditions as in Experiment 1.

Two more IKEA® BLANDA BLANK bowls were added: a large bowl (28 cm × 13 cm (diameter, height), 600 g), and largest bowl (36 cm × 17.9 cm, 1110 g).

Three weight levels were used: the “heavy” condition of Experiment 1 (640 g), as well as a “heavier” condition (1140 g) and a “heaviest” condition (1640 g). There was no heavy condition for the largest bowl because it weighed more than 640 g when empty. Greater weights for the smallest bowl were achieved with sealed bags of lead at the bottom.

The main difference between this experiment and the previous one is the use of motion capture technology (Vicon system, 120 fps resolution) to more accurately determine transport times and facing angles. Reflective markers were placed on various parts of the participants (Fig. 9), including the middle of the back of their hand, and on each bowl. The bowl was oriented with the marker at the "12 o'clock" position from the participants' point of view to minimize interference during grasping.

Unlike the previous experiment, all 66 trials were fully randomized, with facing direction allowed to change from trial-to-trial rather than same starting positions clustered together.

The procedure was otherwise identical to the first experiment. The entire procedure including instruction, obtaining consent, and using motion capture markers took 30 to 35 minutes.

Data processing

Motion capture data was used as an alternate way to calculate transport duration and rotation. For determining both of these, transport start and end were determined by when the velocity of the marker on the bowl fell below a 0.1 m/s threshold in each direction starting from the peak velocity timestep. Duration was defined as the time between these two timesteps.

The orientation of the hip at transport start and end was calculated as the vector from the midpoint of the back hip markers to the midpoint of the front hip markers. The direction to the bowl was defined as zero degrees and samples taken between transport start and end were used to determine if the facing angle at a snapshot was positive (counter-clockwise from the bowl) or negative (clockwise from the bowl). Hip orientation at the start and end were then used to calculate rotation as in Experiment 1.

Data analysis

Analysis was identical to Experiment 1. Grasp strategy usage was analyzed using three generalized linear mixed models. The effect of strategy on duration and rotation was analyzed using a linear mixed model that included the experimental factors, grasp strategy, and their interactions. Significance of a factor was determined using likelihood ratios between the model with the factor included and one without it.

One benefit of using generalized linear mixed models is that they are capable of handling the unbalanced experimental design caused by the lack of a Heavy Largest bowl (Fig. 7, top-right corner).

Experiment 2 results

Basic strategy frequencies and comparison to Experiment 1

Strategy frequencies are summarized in Fig. 10. Unlike in Experiment 1, the bimanual strategy (BI) was the most popular strategy. Compared to Experiment 1 (Fig. 2), bimanual usage in Experiment 2 was much higher while hand-off usage was cut down. We can limit the examination to only trials featured in both experiments. These are all three positions of Experiment 2, the small and medium sizes at the "Heavy" weight only, and with both no-balance and balance cases included. Even so, the pattern of strategies is drastically different (Fig. 11), despite the task being the same.

Effect of experimental variables on grasp strategy

The models for all three strategies included significant effects of size and balance, as well as the size × balance interaction for the bimanual and unimanual strategies. These effects are summarized visually in Fig. 12.

In the model for bimanual usage, the effects remaining were size ($\chi^2(3)=14.1$, $p=.003$), weight ($\chi^2(2)=21.4$, $p<.0001$, Fig. 13), balance ($\chi^2(1)=251$, $p<.0001$), and the size × balance interaction effect ($\chi^2(3)=14.6$, $p=.002$, Fig. 12a). Fig. 13 indicates that heavier weights increase bimanual usage slightly. Fig. 12a indicates that bimanual usage is nearly maxed out in the balance condition. In the no-balance condition, small bowls are markedly likely to be handled with two hands, more so than larger bowls. However, beyond that point, increasing bowl size pushes people to use the bimanual strategy more often.

For the hand-off strategy, the three effects remaining in the model were size ($\chi^2(3)=49.5$, $p<.0001$), balance ($\chi^2(1)=104$, $p<.0001$), and position ($\chi^2(2)=84.9$, $p<.0001$) main effects. The hand-off strategy is less often used at the smallest bowl size. The balance and position effects are similar to those found in Experiment 1: balance cuts down hand-off usage, and hand-offs are used more frequently to transport left-to-right or vice versa than front-to-back.

For unimanual usage, the effects that remained in the model were the main effects of balance ($\chi^2(1)=44.5$, $p<.0001$) and position ($\chi^2(2)=29.2$, $p<.0001$) as well as the size × balance interaction ($\chi^2(3)=17.9$, $p=.0005$, Fig. 12c). The main effect of size was not significant ($\chi^2(3)=4.39$, $p=.22$). Unlike in Experiment 1 where the effect of balance depended on the position, in Experiment 2 the balance condition cut down unimanual usage at all positions. The position effect was similar to Experiment 1, with most unimanual usage when moving the bowl front to back (P4). The size × balance interaction (Fig. 12c) shows that unimanual usage declines as bowl size increases for the no-balance case only.

The bimanual strategy was the only strategy that had a weight effect. Weight and its interaction effects were removed from the full hand-off (χ^2(42)=41.4, p=.50) and unimanual (χ^2(42)=42.3, p=.46) models. Unlike the other two strategies, position was able to removed from the bimanual model (χ^2(44)=59.5, p=.059).

Effect of strategy on duration and rotation

For duration, the results in Experiment 2 match the first experiment closely. Both strategy (χ^2(2)=24.1, p<.0001) and strategy × balance (χ^2(2)=66.0, p<.0001) were significant, with the bimanual strategy taking longer in the no-balance case but competitive in the balance case (Fig. 14).

The rotation results were similar to Experiment 1. Both strategy (χ^2(2)=474, p<.0001), and the strategy × position interaction (χ^2(2)=66.0, p<.0001, Fig. 15) were significant. The interaction effect is similar to the first experiment – compare with the three middle columns of Fig. 6), except at P4 the unimanual strategy requires more rotation than the bimanual strategy.

Experiment 2 discussion

The goal of Experiment 2 was to see whether the addition of larger and heavier bowls could yield an effect of size and weight on bimanual usage.

Experiment 2 found an effect of higher weights increasing bimanual usage. Larger bowl sizes also seem to encourage bimanual usage, similar to findings by Cesari and Newell (2000) and in some infant grasping studies (Palmer 1989), but bimanual usage is actually highest for the smallest bowl. This may be due to how this bowl at all weights was nearly full, making it difficult for people to place their thumb deep inside the bowl, which may have pushed people to use two-handed grasps that could be used by contacting the exterior of the bowl only. In addition, the bowls in our study differed from objects used in previous studies. The typical grasping location of a bowl (the lip) does not increase as the bowl gets bigger. In previous studies, the objects manipulated were cubes or toys that increased in size in all three dimensions simultaneously. This property of the bowls may explain the relatively weak effect of size on bimanual usage compared to other studies.

Experiment 2 featured a much larger amount of bimanual grasps, even on trials identical to those in Experiment 1. Some of the differences between the experiments that could cause this include:

(1) A larger proportion of the bowls being heavier, larger, or (for the small bowls) full could cause more people to use a bimanual strategy by default, affecting even the small/medium bowls at the lightest weight.
(2) The act of wearing motion capture markers could make people more self-conscious about their motions and affect their strategy choices.

However, despite the different distribution of strategies, Experiment 2 duplicated the important position and balance effects of Experiment 1. In addition, the more accurate way of collecting duration and rotation information in Experiment 2 yielded results similar to the less precise methodology of Experiment 1.

General discussion

In this experiment we studied the task of moving bowls from one location to another. We varied (1) object size, (2) object weight, (3) balance, and (4) starting position, and analyzed these variables' effects on grasp strategy and pose.

Our results showed that strategies were strongly influenced by the position of the object/goal and the presence of a balance requirement and less strongly influenced by object weight.

Although bimanual strategy was slightly affected by object start/goal position, as seen by the significant effect found in Experiment 1, this effect of position was not as dramatic as it was for the unimanual and hand-off strategies. This relative position-invariance of bimanual strategy is in line with findings from an earlier study of grasp strategy on Tupperware containers (Rosenbaum et al 2010).

Our data contained left/right asymmetry in unimanual reaching (e.g. the difference between “left only” and “right only” spikes in Fig. 4a), indicating a preference to use the right hand, even if it requires reaching into contralateral space or rotating. This bias toward right-handed reaching matches that found in handedness studies (Gonzalez et al 2014).

Avoiding reaching across the body and minimizing rotation could be behind the different popularity of strategies by position. Thus, hand-offs become popular when the start and goal position are in different left-right hemispaces as this strategy minimizes contralateral reaching and rotation.

Bimanual usage for the small bowl was particularly high. Part of the strategy choice may be due to the fullness of the bowl, a factor not considered in this study. In the future, using fillers of higher density could be used to test whether bowl fullness was influencing choice of strategy.

Finally, the second of our experiments had a significantly larger amount of bimanual strategy usage than the first experiment, even when comparing identical trials (unchanged bowl size and weight). This could possibly suggest that the wider set of tasks is capable of influencing people’s default strategy, or it is possible that the changes to the experimental method are responsible. Even within the first possibility, it’s not clear whether greater weights, sizes, fullness, or uncertainty is what is behind the greater bimanual usage. Further investigation is needed.

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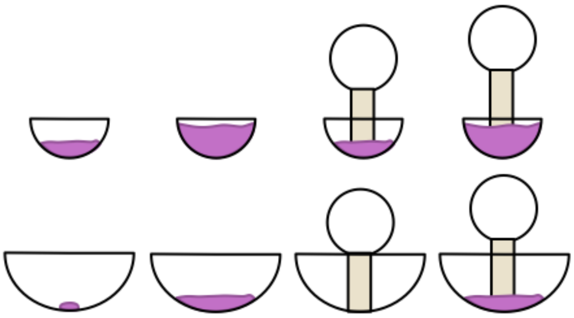
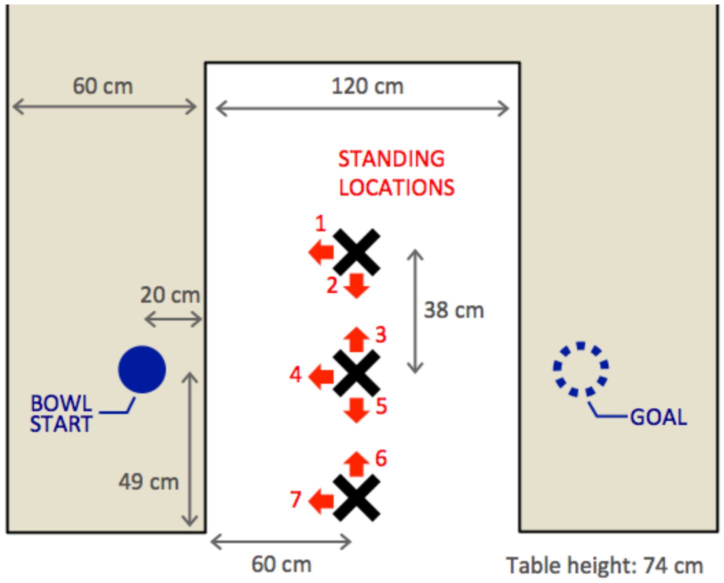
Table 1. The nine transport strategies and their codes.

L	Left only	One-handed pick up, transport, and place with left hand
R	Right only	One-handed transport with right hand
LR	Hand-off (l→r)	Hand-off from left hand to right (pick up with left, place with right)
RL	Hand-off (r→l)	Hand-off from right to left
LB	Left→bi	Pick with left hand, add right to place bimanually
RB	Right→bi	Pick with right hand, add left to place bimanually
BI	Bimanual	Pick up, transport, and place with both hands
BL	Bi→left	Grab bimanually, place with left hand only
BR	Bi→right	Grab bimanually, place with right hand only

Figure 1. Experimental setup. (a) Bowls can be small or medium; light or heavy; and with or without a balance tube. (b) The seven arrows in this diagram indicate the seven possible starting configurations of the participant, which consist of a standing location and a facing direction. There are three standing locations with either two or three facing directions, yielding a total of seven possible start configurations (referred to as "positions").



(a)



(b)

Figure 2. Frequencies of each strategy.

	Strategy	Frequency	
L	Left only	79	9%
R	Right only	252	28%
LR	Hand-off (l→r)	174	19%
RL	Hand-off (r→l)	153	17%
LB	Left→bi	3	<1%
RB	Right→bi	5	<1%
BI	Bimanual	195	22%
BL	Bi→left	1	<1%
BR	Bi→right	34	4%

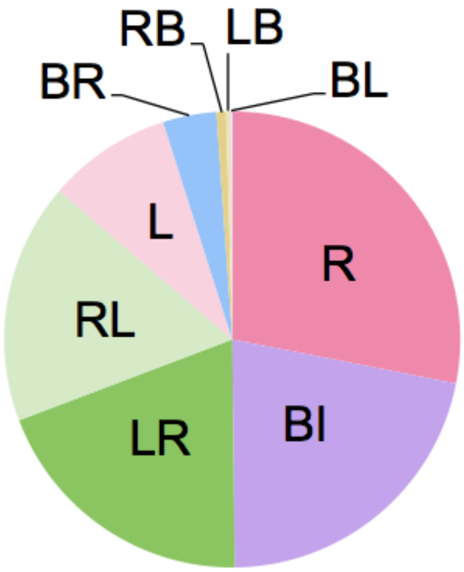
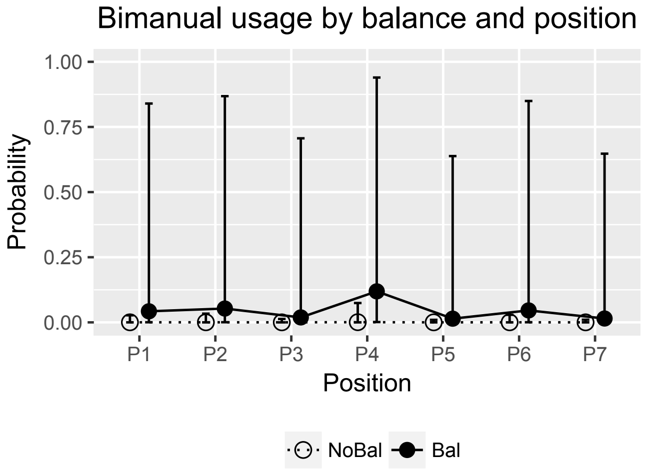
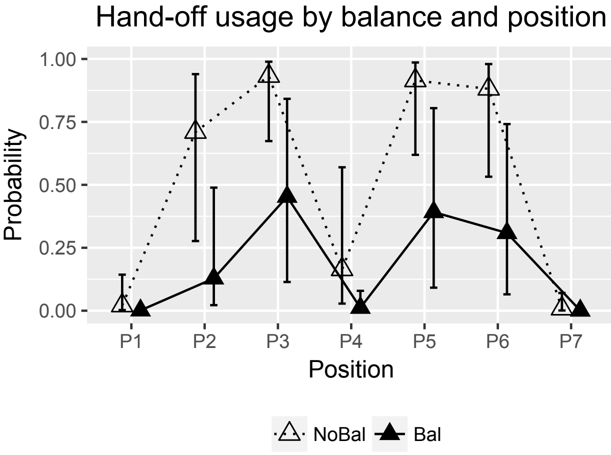


Figure 3. Effects of balance and position on the usage of the three strategies: the main effects for the bimanual and hand-off strategies, and the significant interaction effect for the unimanual strategy.



(a)



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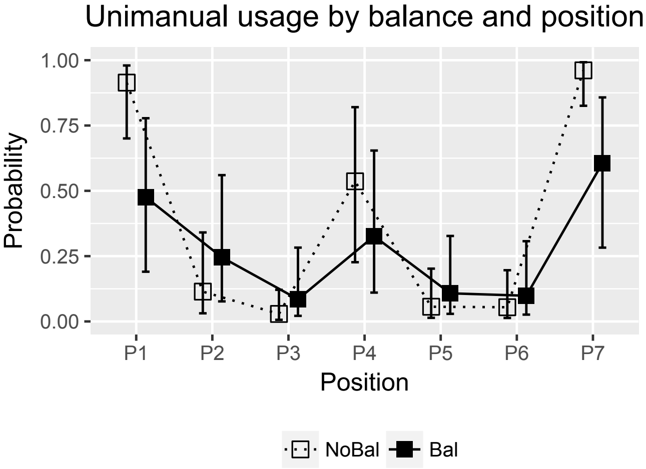
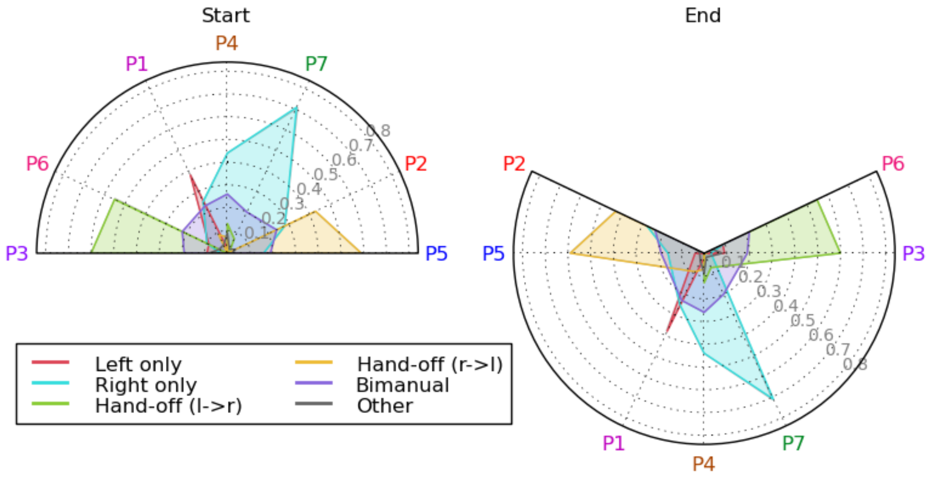
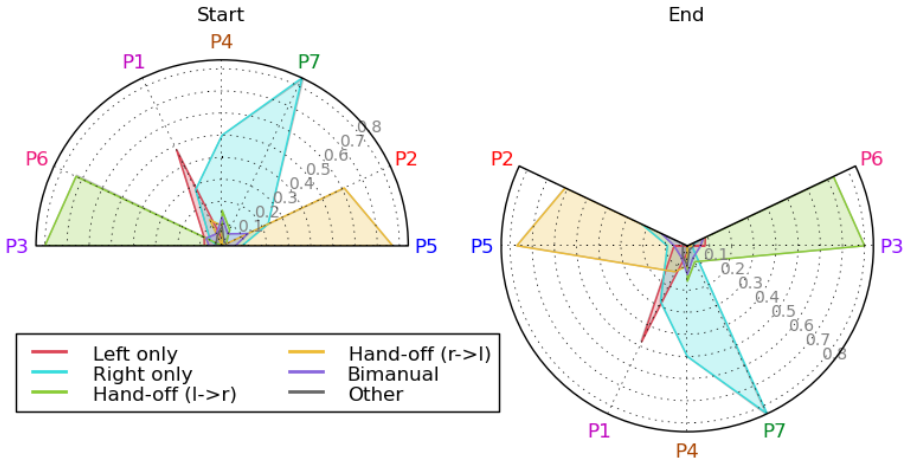


(c)

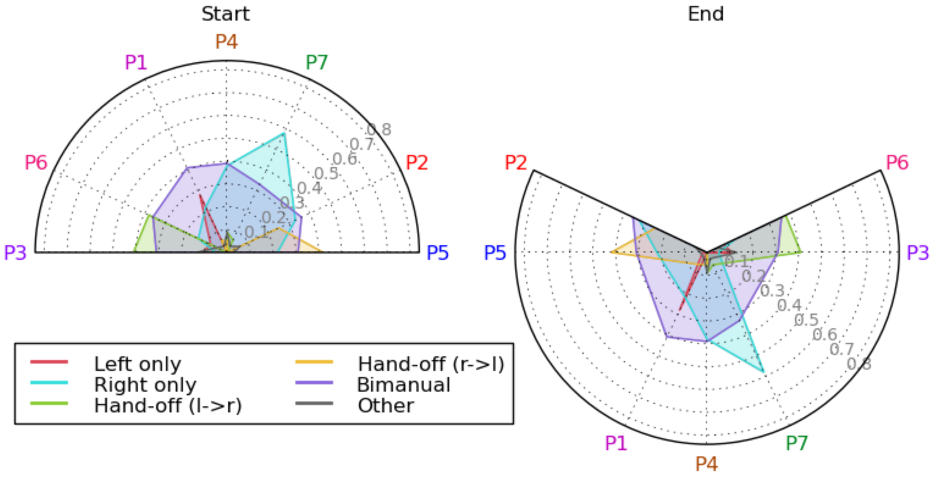
Figure 4. Angle plots showing popularity of strategies at each position. Data is plotted at starting and ending angles, from the perspective of someone facing up. (Down indicates the goal is behind the subject; left and right indicate toward the left and right hands.) Strategy popularity is shown for (a) all cases, (b) no balance cases, and (c) balance cases only.


Start
End
P1
P4
P7
P6
P2
P3
P5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Left only
Right only
Hand-off (l->r)
Hand-off (r->l)
Bimanual
Other

(a)


Start
End
P1
P4
P7
P6
P2
P3
P5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Left only
Right only
Hand-off (l->r)
Hand-off (r->l)
Bimanual
Other

(b)


Start
End
P1
P4
P7
P6
P2
P3
P5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Left only
Right only
Hand-off (l->r)
Hand-off (r->l)
Bimanual
Other

(c)

Figure 5. Transport duration by strategy and balance

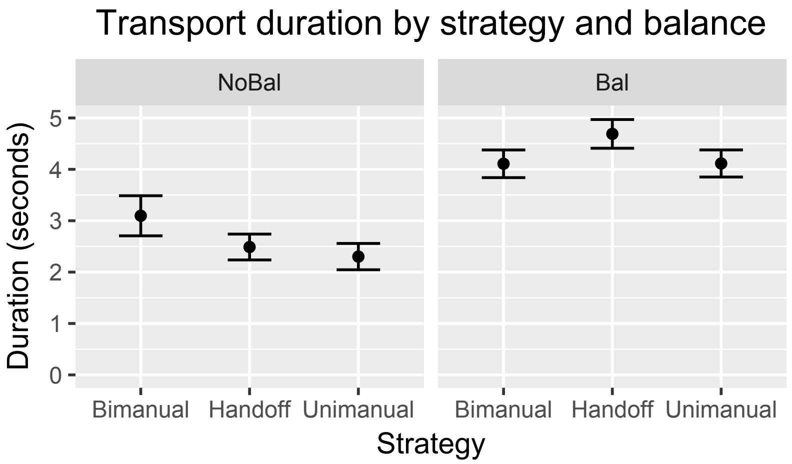


Figure 6. Total rotation by strategy and position. The y-axis is the average number of octants rotated for each strategy at each position.

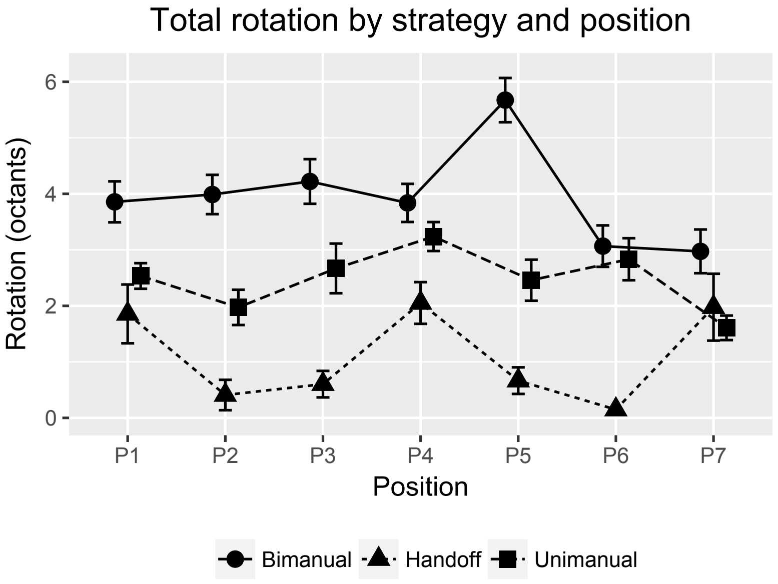


Figure 7. The eleven different size/weight combinations for the bowls. The heavier small bowls were padded with lead to increase density. The two bowls marked with an asterisk are repeated from Experiment 1.

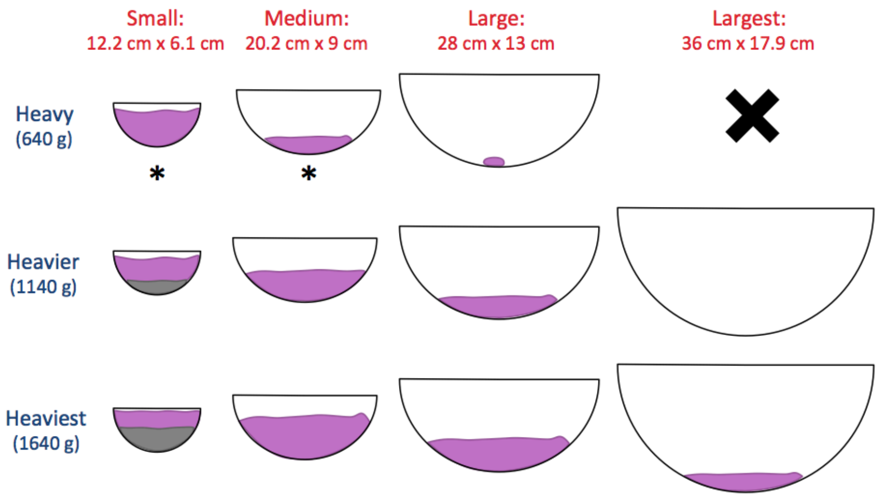


Figure 8. Experiment 2 setup with only one starting location (with three facing directions).

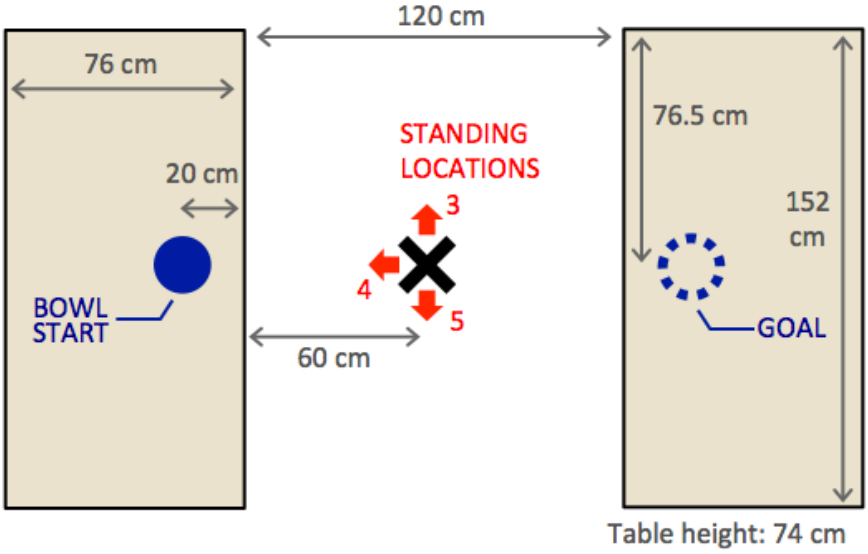


Figure 9. Motion capture setup for Experiment 2. The black and dotted circles represent the placement of 16 reflective markers on the front and back of the participant. As in Experiment 1, the direction of the bowl is defined as zero degrees (the direction of the goal is ±180°) and counter-clockwise rotations are positive angles.

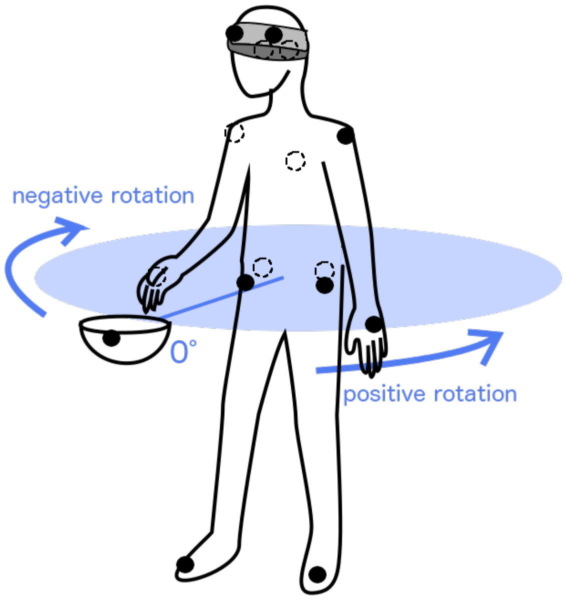


Figure 10. Frequencies of each strategy.

	Strategy	Frequency	
L	Left only	55	5%
R	Right only	189	18%
LR	Hand-off (l→r)	84	8%
RL	Hand-off (r→l)	58	5%
LB	Left→bi	20	2%
RB	Right→bi	25	2%
BI	Bimanual	600	57%
BL	Bi→left	18	2%
BR	Bi→right	7	<1%

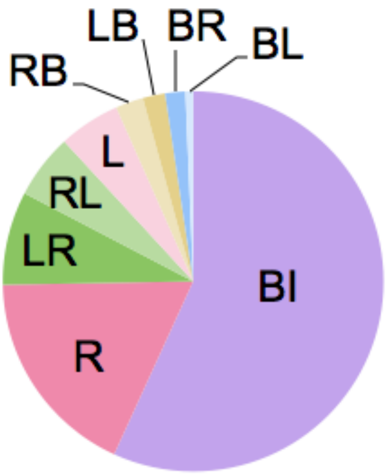


Figure 11. Comparison between Experiment 1 and 2 on identical trials.

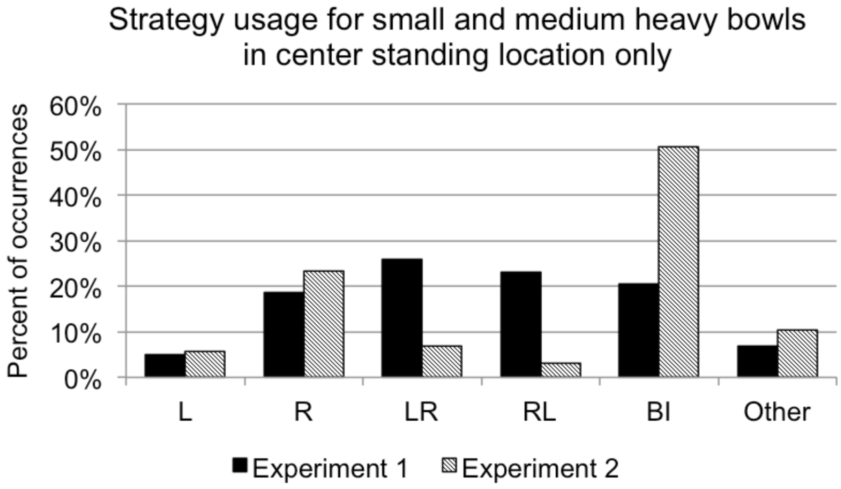
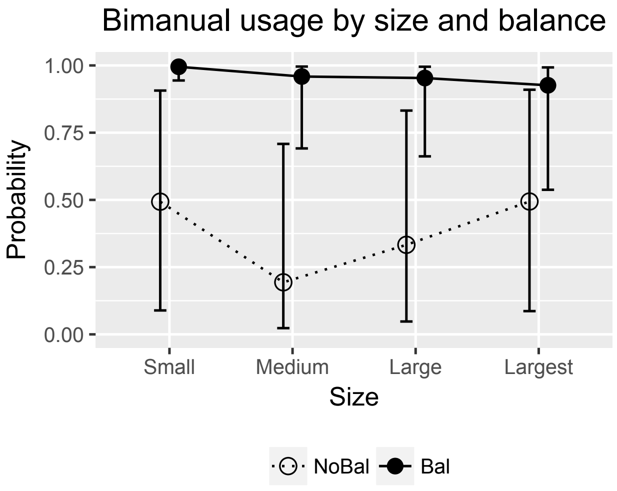
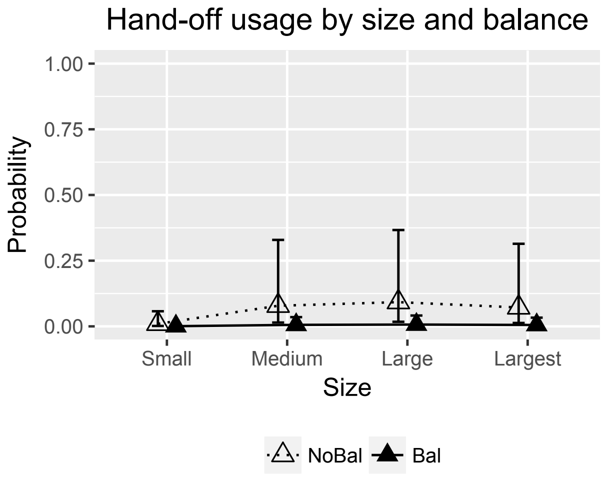


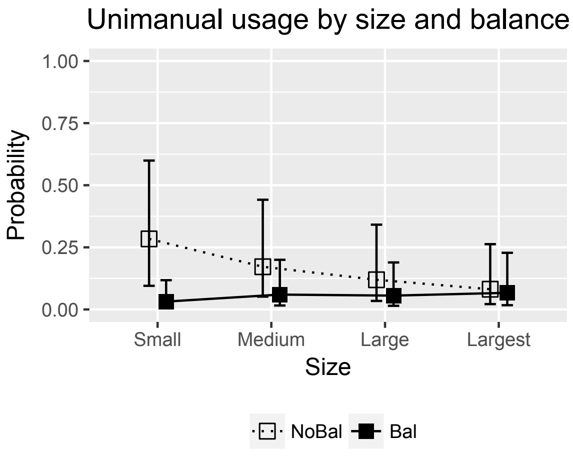
Figure 12. Effects of size and balance on the usage of the three strategies: the significant interaction effects for the bimanual and unimanual strategies, and the significant main effects for the hand-off strategy.


Bimanual usage by size and balance
Probability
1.00
0.75
0.50
0.25
0.00
Small
Medium
Large
Largest
Size
NoBal
Bal

(a)


Hand-off usage by size and balance
Probability
1.00
0.75
0.50
0.25
0.00
Small
Medium
Large
Largest
Size
NoBal
Bal

(b)


Unimanual usage by size and balance
Probability
1.00
0.75
0.50
0.25
0.00
Small
Medium
Large
Largest
Size
NoBal
Bal

(c)

Figure 13. Weight effect for bimanual strategy usage.

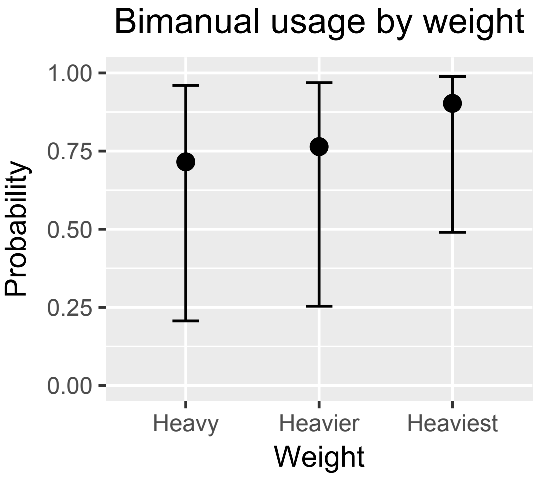


Figure 14. Transport duration by strategy and balance.

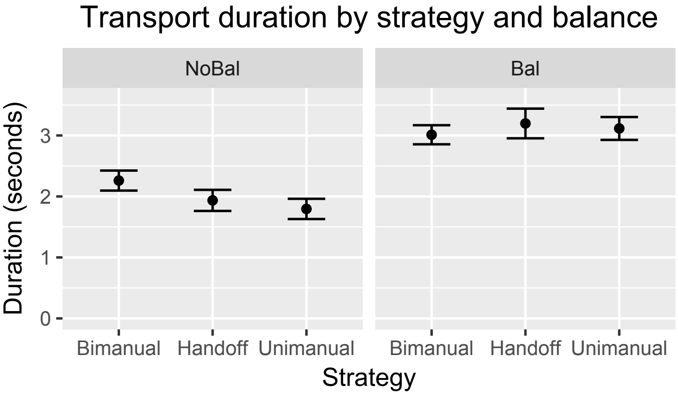
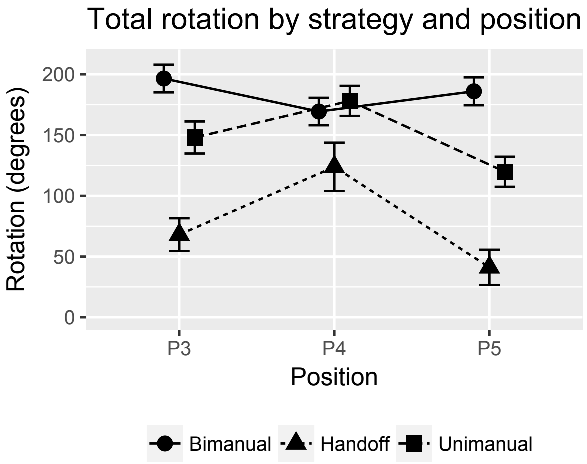


Figure 15. Start-to-pick-to-place rotation by strategy and position.


Total rotation by strategy and position
Rotation (degrees)
200
150
100
50
0
P3
P4
P5
Position
Bimanual
Handoff
Unimanual