Journal of Motor Behavior

ISSN: 0022-2895 (Print) 1940-1027 (Online) Journal homepage: http://www.tandfonline.com/loi/vjmb20

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To cite this article: Yuzuko C. Nakamura, Carol A. O'Sullivan & Nancy S. Pollard (2018): Effect of Object and Task Properties on Bimanual Transport, Journal of Motor Behavior, DOI: 10.1080/00222895.2018.1465391

To link to this article: https://doi.org/10.1080/00222895.2018.1465391

Published online: 09 May 2018.

Journal of Motor Behavior, Vol. 0, No. 0, 2018

RESEARCH ARTICLE

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Effect of Object and Task Properties on Bimanual Transport

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ABSTRACT. 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 starting and ending position (configuration) as well as the need to balance the object on the use of these three strategies in a bowl-moving task. We find that configuration and balance have a strong effect on choice of strategy, and size and weight have a weaker effect. Hand-offs are most often used when the task requires moving an object from left to right and vice versa, while the unimanual strategy was frequently used when passing front to back. The bimanual strategy is only weakly affected by configuration. The need to balance an object causes subjects to favor unimanual and bimanual strategies over the hand-off. In addition, an analysis of transport duration and body rotation suggests that strategy choice may be driven by the desire to minimize body rotation.

Keywords: arm movements, bimanual performance, grasping, motion planning

Introduction

Because the redundancy of the human motor system allows for alternative movement strategies for completing the same task, a key question in studying motor behavior is understanding what criteria determine the selected motor plan. It is possible that these complicated choices are determined by an underlying minimum principle such as time or energy minimization (Engelbrecht, 2001), which allows people to select a single motion plan that is responsive to arbitrary starting and ending positions of the transport task; size, weight, and shape of object to be transported, etc.

In the area of one-handed grasping, this question has been studied in the context of how people select approach trajectories (e.g., Paulignan, Frak, Toni, & Jeannerod, 1997), contact points (e.g., Gilster, Hesse, & Deubel, 2012; Voudouris, Smeets, & Brenner, 2012), and the pose of the hand when grasping (e.g. Park, Seo, Son, Kim, & Cheong, 2014) based on object or task characteristics. However, a less understood part of motion planning is how people decide to use one hand or two when transporting objects. In the case of transporting objects, multiple strategies capable of accomplishing the task are available: a person can use one hand exclusively to transport the object, can grab the object with two hands, or pick an object up with one hand and transfer it to the other hand. Researchers have previously shown that size and weight of an object affects whether people grasp it with one hand or two hands (Cesari & Newell, 2000). In addition, they found that hand length can be used to fairly accurately predict the transition point when an object starts to be handled with two hands. The weight of the subject's hand also has some ability to predict the weight at which that subject will transition from one to two hands, but there is a greater amount of unexplained variation in the weight case than in the size case. Researchers have also shown that the end goal affects the usage of the left and right hand for grasping in a Tupperware-stacking task (Rosenbaum, Coelho, Rhode, & Santamaria, 2010). When the end goal is to the right, people walk from left to right stacking containers along the way, using mainly their left hand to grab and place. The opposite is true when the end goal is toward the left. Alternatively, some people use both hands simultaneously (symmetric bimanual strategy) to grab and place, although this strategy was used less frequently and was less responsive to end goal location.

None of these studies, however, fully consider the task of object transport. The task of transporting an object opens up new strategies including one where the object is grabbed with one hand but then handed off to the other hand, which places it (hand-off strategy). Cesari and Newell (2000) only consider the act of grasping (apprehending) an object, briefly lifting it, and replacing it. As such, handing off between hands is not a strategy under consideration. While Rosenbaum et al. (2010) consider the whole process of transporting objects to a final destination, they consider grasping actions independently from placing actions, meaning that it is unfeasible to identify instances where an object might have been handed off between hands. In order to fully understand the choice of using one vs. two hands in the task of object transport, handing-off actions must be explicitly considered. An open question not answered by these studies is how object and task properties affect entire transport strategy, including not just usage of the pure unimanual and symmetric bimanual strategies but usage of the hand-off strategy as well.

The present study investigates two questions: the first is what effect object and task factors have on the use of

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unimanual, bimanual, and hand-off transport strategies, and the second is what is the underlying reason those strategies are chosen. We expect that the same effects of object size and weight that affected use of one- and two-handed grasping would manifest in transport as well. Two hands can function as a large manipulator (Bullock, Ma, & Dollar, 2013) and using two hands can spread the weight of an object to a more comfortable load at each hand. While there is no theoretical or empirical work on the effect of size or weight on hand-offs in adults, an infant study researching the development of manipulation skills over time (Palmer, 1989) recorded when infants handed objects off hand-to-hand (switching), finding that heavier objects were handed off less frequently, although no explanation was offered for why this might be.

We also expected that transporting an object that requires its balance to be carefully maintained would push people to use the symmetric bimanual strategy. It has been found that manipulating an object that must be carefully balanced has the effect of increasing task difficulty, which in turn influences selection of (pre-)grasp strategy (Chang, Klatzky, & Pollard, 2009). In particular, this study found that the difficulty of the object-balancing task had the effect of increasing the amount of pregrasp rotation people performed. The pregrasp rotation of the object put the hand configuration into a region that was shown to have greater lifting capabilities. This range of angles may be related to the "comfortable" mid-range of movement where more precision of hand motion can be applied (see Rosenbaum, van Heugten, & Caldwell, 1996 and the middle-is-faster effect). It is possible that the use of two hands simultaneously might have a similar effect of increasing precision of control. An infant study by Palmer (1989) indicates that when surfaces are stable (hard rather than foam), infants spend more time holding an object in a single hand, which may be because unstable surfaces make the unimanual strategy more difficult. However, there has not been work specifically investigating whether the need to carefully maintain an object's balance has an effect on people's choice of one vs. two hands.

Hand-offs have not been studied much in previous literature. Studies have shown that object location influences the choice of left and right hands when grasping. In particular, studies on handedness find people prefer to not cross the midline when reaching. For example, Gonzalez, Flindall, and Stone (2014) found that for right-handed participants, over 95% of objects located to the right of the participant's midline were reached for with the right hand, while 65–90% of objects located to the left of the participant's midline were reached for with the left hand. Hand-offs from one hand to the other may be used as a way to avoid crossing the midline when grabbing and placing, so would be used when the start and goal location are on different sides of the body.

The second question we sought to answer was what explains the choice between the unimanual, bimanual, and hand-off strategies. In particular, we wanted to investigate whether minimum principles are a plausible explanation for choice of transport strategy. The time it takes to execute an action and the metabolic energy consumption in executing it are common minimum principles used in biology to explain behavior, and may be useful for understanding motor behavior as well (Engelbrecht, 2001). In this study, we considered the explanatory ability of two possible costs: the quickness with which the movement could be executed, and the amount of rotation each strategy requires in order to execute. In these experiments, we wanted to test if either of these measures—movement duration and body rotation—had the ability to explain people's transport strategy choices.

The following set of experiments seeks to answer these questions related to the use of one and two hands in transport. The first experiment focuses on a larger set of start and goal positions, while the second experiment focuses on a larger set of object sizes and weights.

Experiment 1

Measures and Hypotheses

The first 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 the bowl's balance was important) and configuration (the start and goal position of the bowl relative to the subject). We collected which hand(s) subjects used to pick and place the bowl. Our expectations 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 use their left hand to pick/place when the bowl/goal was in the left hemispace and use their right hand to pick/place when the bowl/goal was in the right hemispace.

The second goal was to investigate the reason underlying strategy selection. In order to answer this question, we collected movement time and amount of hip rotation. We then compared how the choice of strategy and experimental conditions affected the movement time and rotation. We expected that strategies that people favor and use frequently would be quicker or involve less body rotation.

Method

Participants

We ran an experiment with 16 participants (4F, 12M; 14 right-handed, 2 mixed-handed (self-reported handedness, with a prompt "The dominant hand is the one typically used for writing, brushing teeth, throwing, using a spoon, opening a box (the one on the lid, etc.)"); mean age = 27.8

(SD = 6.8)). In addition, a left-handed participant was recruited and data collected. However, the pattern of this 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 were discarded and are not represented in the following results. 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 trial consisted of the participant moving a bowl from one table to another. The experiment varied bowl size (two conditions) and weight (two conditions), the presence within the bowl of a tube with a ball balanced on top (two conditions), and the subject's starting location and facing direction. There were seven different standing place-facing direction combinations (hereafter called "configurations") in which the subject could stand (Figure 1). There was one trial per condition, resulting in 56 trials overall per participant (2 size × 2 weight × 2 balance × 7 configurations).

The bowls moved were metal 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 "small" bowl was 12.2 cm × 6.1 cm (diameter, height), while the "medium" 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.

There were seven possible configurations (Figure 1b). The experiment consisted of seven blocks of eight trials. Within a block, all trials shared the same starting configuration. This clustering of trials by starting configuration was done to avoid making the subject move around after each trial. The presentation of these blocks was randomized, and the presentation of trials within each block was randomized.

At the start of the experiment, the participant was instructed to not knock over the styrofoam ball used in the "balance" condition. 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. Participants were only required to start

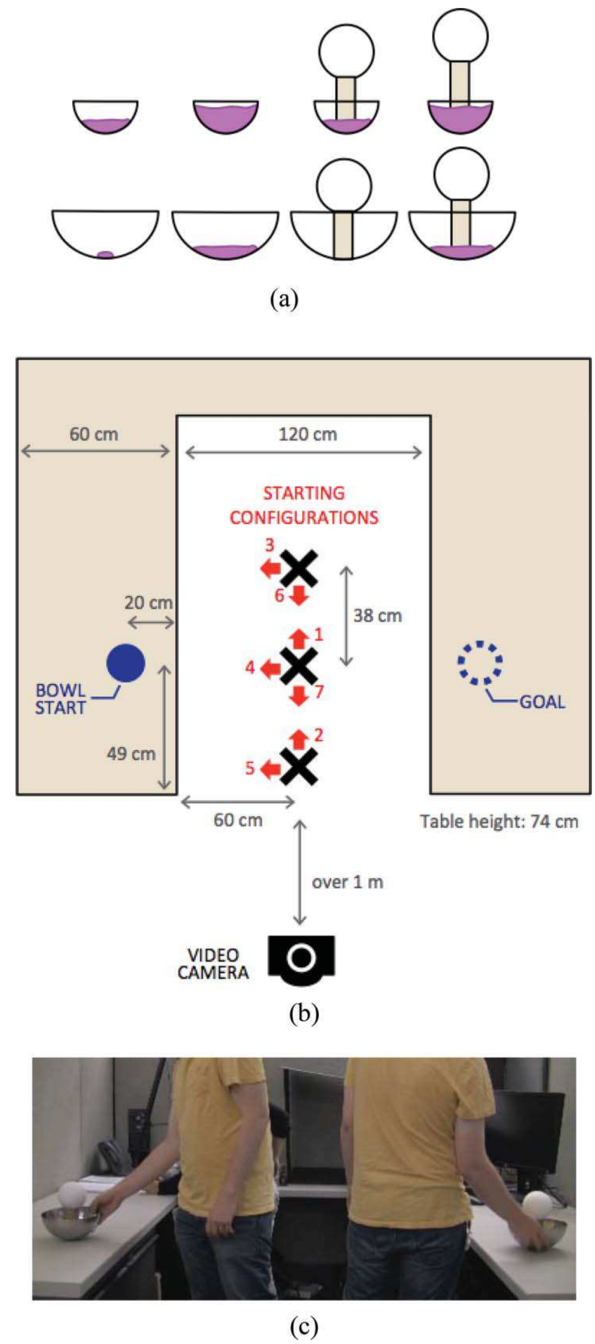

FIGURE 1. Experimental setup. (a) Bowls can be small or medium; light or heavy; and with or without a balance tube. (b) The seven arrows in this diagram indicate the seven possible starting configurations of the participant, which consist of a standing location and a facing direction. There are three standing locations with either two or three facing directions, yielding a total of seven possible start configurations. (c) Screenshots of video collected as part of the experiment. These screenshots feature the start and end of object transport within a trial.

the trial at a particular spot and facing a particular way; once the trial started, they were allowed to walk around the experimental space freely while transporting the bowl.

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 min.

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 (left, right, or both hands). Using this way of distinguishing transport strategies, there are nine possible strategies. These strategies 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.

To calculate rotation, first, facing directions of the hip at transport start and end were visually estimated by a researcher from the video, rounded to the nearest 45° (octant). For example, in Figure 1c, the participant's hips at the start of transport faced forward-left while at the end, the participant was facing a direction between straight backward and backward-right. This was determined to be closer to the backward direction. The facing direction of the hip (as opposed to the shoulder or chest) was chosen because its orientation was easiest to estimate visually. The angles of the hip's facing direction at trial start, transport start, and transport end were recorded. Rotation was then defined as the octants rotated between trial start and transport start, plus the octants rotated between transport start and transport end. For the trial depicted in Figure 1c, this participant started the trial facing the bowl, rotated roughly one octant at the time of grasping, and then rotated counterclockwise roughly five octants to place.

Data Analysis

First, we analyzed the effect of the experimental factors (size, weight, balance, and configuration) on the response of choice of transport strategy using a mixed-effects generalized linear model with a logistic link function (a generalized linear mixed model or GLMM). This model was fit to the data using the glmer function of R's lme4 package (Bates, Mächler, Bolker, & Walker, 2015). This analysis method was chosen because it was capable of handling both binary response data and the repeated measures experimental design. The response variables analyzed were usage of bimanual, hand-off, and unimanual strategy (three separate analyses with binary outcomes). Size, weight, balance, configuration, 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 nonsignificant variables until no more could be removed (a significance level of .01 was used to determine which factors to keep). For effects remaining in the model, plots showing the mean probability of a strategy being used under each condition and an estimation of the standard error of that mean were generated using the effect function of R's effects package (Fox, 2003; Fox and Hong 2009).

In order to understand the reason behind people's preference of certain strategies over others, a second analysis investigated the effect of strategy (bimanual, hand-off, and unimanual) on transport duration and body rotation using linear models with duration or rotation as the response; strategy and the four experimental variables as fixed effects; and participant as a random intercept. A final model was selected by removing nonsignificant effects using likelihood ratios.

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

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

Experiment 1 Results

Strategy Frequency Overview

All nine possible strategies from Table 1 were observed at least once. However, the strategies we were mainly interested in—the symmetric bimanual strategy (BI), the two hand-off strategies (LR, RL), and the two unimanual strategies (L, R)—were much more common than the four "mixed" strategies (LB, RB, BL, BR) that involved changing the number of hands grasping the bowl during transport. These four mixed strategies were used in less than 5% of trials. We therefore focus on the bimanual, hand-off, and unimanual strategies in our analysis.

Effect of Experimental Variables on Grasp Strategy

For all three strategies—bimanual, hand-off, and unimanual—balance and configuration remained in the model. In addition, the balance $\times$ configuration 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. In configurations where the unimanual strategy was frequently used (C3, C4, and C5 configurations involving moving the bowl from front to back; see Figure 3), the balance requirement cut down unimanual usage. In the other four configurations (ones 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 configuration (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 C1, C2, C6, and C7, which involved moving the bowl from left to right or vice versa. The unimanual strategy was used most at C3, C4, and C5, which are the three configurations where the bowl is moved from front to back. Figure 2 summarizes these balance and configuration effects.

Figure 3 provides a useful way of visualizing configuration and balance effects. It arranges the raw strategy usage data[2] at each configuration to be at the angles where the bowl starts and ends relative to the participant. For example, at C1, the bowl starts out directly to the left of the participant and is moved to the participant's right. In this configuration, 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 was significant in any of the models. Size and all related interaction effects were able to removed from the full model (unimanual: $\chi^2(28) = 18.3$, $p = .92$), 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

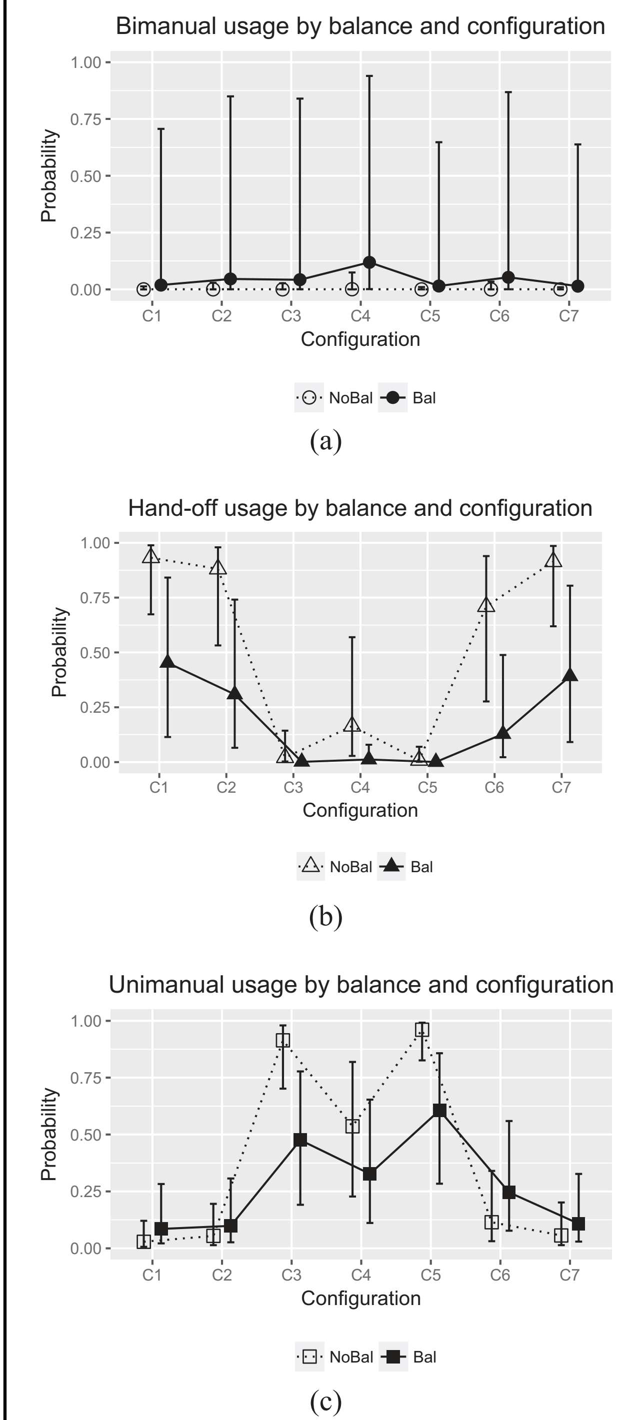

FIGURE 2. Effects of balance and configuration on the usage of the three strategies: the main effects for the bimanual and hand-off strategies, and the significant interaction effect for the unimanual strategy. The bars signify estimated standard error of the mean in log-odds space.

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

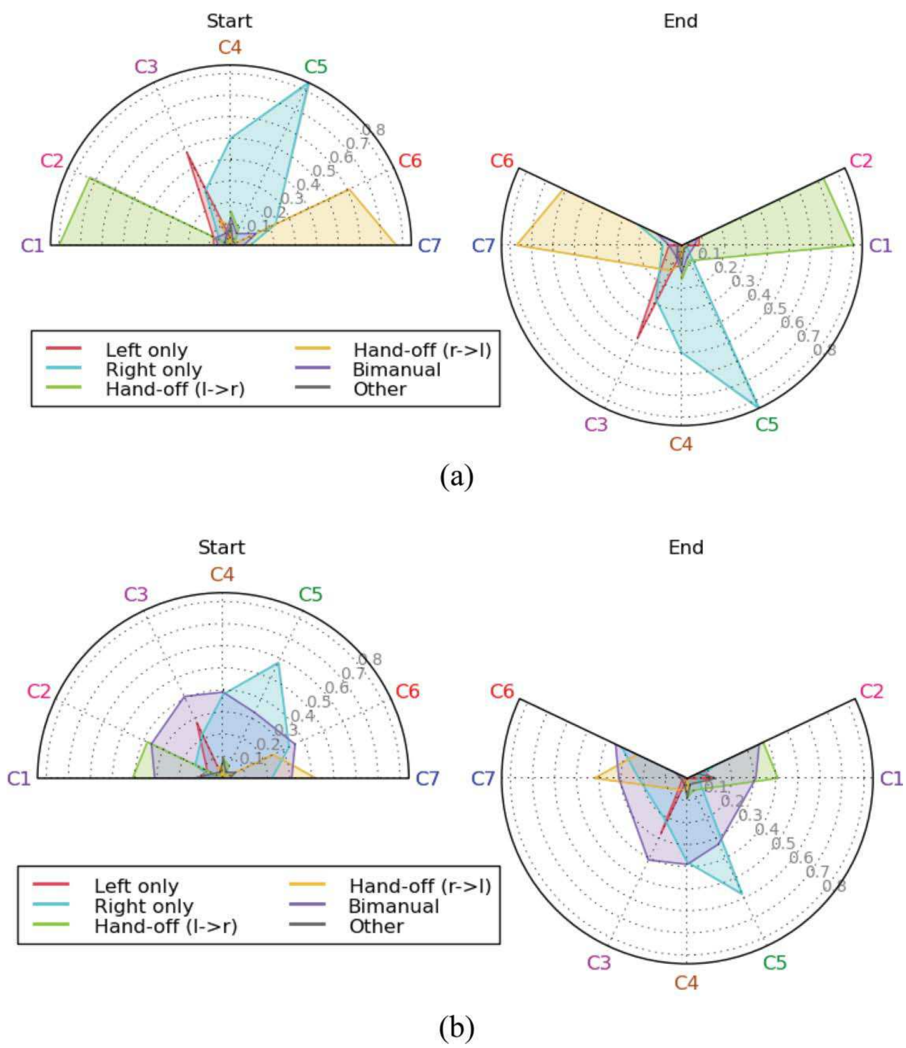

FIGURE 3. Angle plots showing strategy usage at all configurations. Data are plotted at starting and ending angles, from the perspective of someone facing up. (Down indicates the goal is behind the subject; left and right indicate toward the left and right hands.) Strategy usage is shown for (a) no balance cases only and (b) balance cases only.

(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

First, we investigated the possibility that minimizing movement time might be underlying people's strategy choices. Using the generalized linear model that had duration as a response variable, both strategy ($\chi^2(2) = 18.9$, $p < .0001$) and the strategy × balance interaction ($\chi^2(2) = 40.2$, $p < .0001$) were significant. Examining the significant strategy × balance interaction effect (Figure 4) reveals that the bimanual strategy is slower than the other two strategies in the no-balance case, while the hand-off strategy is slower in the balance case, which potentially explains the lower hand-off selection and higher bimanual selection in the

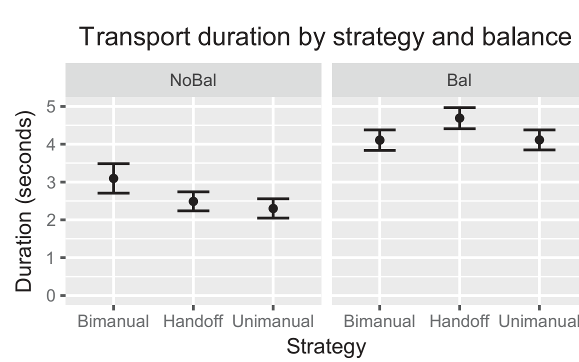

FIGURE 4. Transport duration by strategy and balance.

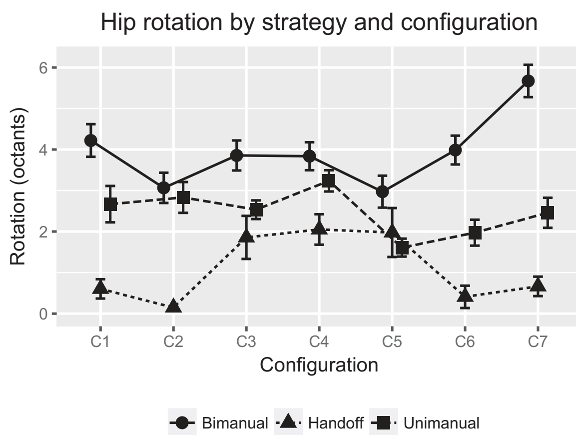

FIGURE 5. Total rotation by strategy and configuration. The y-axis is the average number of octants rotated for each strategy at each configuration.

balance case found in the first analysis. However, duration does not explain why people often decline to use the bimanual strategy in the balance case, or why the unimanual and hand-off strategies are so dominant in certain configurations.

The second possibility we investigated was that the desire to minimize rotation might be underlying strategy choice. Strategy ($\chi^2(2) = 475$, $p < .0001$) and the strategy × configuration interaction ($\chi^2(2) = 196$, $p < .0001$) remained in the rotation model. As Figure 5 illustrates, (1) bimanual strategies require more rotation than unimanual strategies, which generally (except at C7) require more rotation than hand-off strategies; and (2) configuration affects the rotation needed at each strategy by different amounts. In particular, the hand-off strategy needs more rotation at C3, C4, and C5, which could be responsible for the low popularity of hand-offs in those configurations.

Experiment 2

The previous experiment did not yield an effect of size or weight, as expected from previous work. It is possible that the bowl weights and sizes used did not span a sufficiently broad range to include the transition point where individuals switch from one-handed to two-handed grasping, as found in Cesari and Newell (2000). The focus of this experiment was to test if weights and sizes larger than the ones previously investigated could elicit a size/weight effect on bimanual usage. Four bowl sizes and three weights were used. In addition, we replaced the method of collecting movement time and rotation through visual inspection of video with a more accurate motion capture system. Finally, we collected information on step counts and head and chest rotation for analysis and comparison with the hip rotation measure used in Experiment 1.

Measures and Hypotheses

We hypothesized a greater range of sizes and weights would elicit a switch from unimanual strategy to bimanual strategy as the dominant transport strategy as observed in previous work. In addition, we hypothesized the balance and configuration effects on strategy and the strategy effects on movement time and rotation found in the first study to appear in this study as well.

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 trial consisted of moving a bowl from one table to another. There were 11 size/weight combinations for the bowls and three possible starting configurations (Figure 6). There were two balance/no balance conditions as in Experiment 1. There was one trial per condition, resulting in 66 trials overall per participant (11 bowls × 3 configurations × 2 balance).

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)

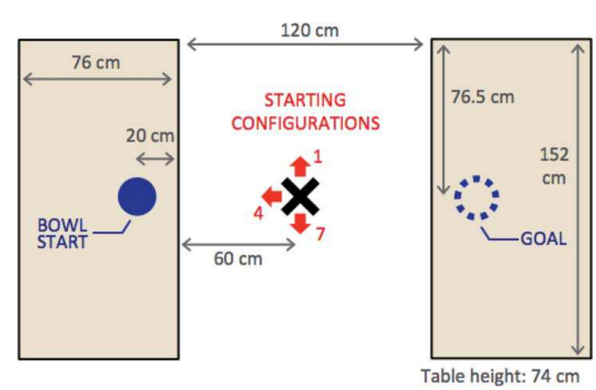

FIGURE 6. Experiment 2 setup with only one starting location (with three facing directions).

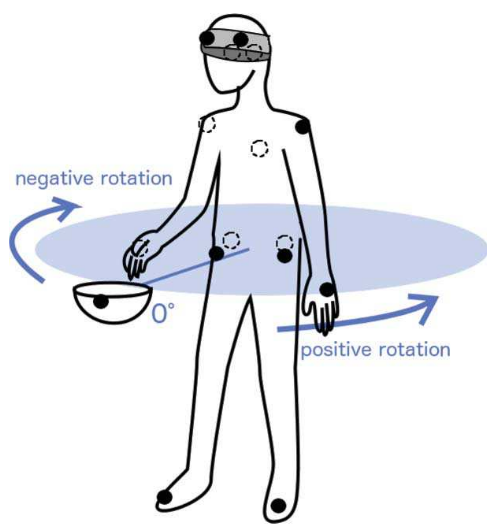

FIGURE 7. Motion capture setup for Experiment 2. The black and dotted circles represent the placement of 16 reflective markers on the front and back of the participant. The direction of the bowl is defined as zero degrees (the direction of the goal is ±180°) and counterclockwise rotations are positive angles.

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 temporal resolution) to more accurately determine transport times and facing angles. Reflective markers were placed on various parts of the participants (Figure 7), 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 clustering trials with the same starting configurations together. The procedure was otherwise identical to the first experiment. The entire procedure including instruction, obtaining consent, and using motion capture markers took 30–35 min.

Data Processing

Motion capture data were 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 which direction the participant rotated between the two time points. Hip orientation at the start and end were then used to calculate rotation as in Experiment 1.

For head orientation, a similar procedure was used to calculate the head facing direction from four markers. Chest orientation was calculated by finding the direction normal to the line connecting the shoulder markers and choosing the facing direction to be the one further (greater than 90°) from the back marker. For the head, torso, and hip, transport rotation was defined as the rotation from the moment of picking the bowl up to the moment of placing it; total rotation was defined as transport rotation plus the amount of rotation from the starting configuration to bowl picking.

Data Analysis

Analysis was identical to Experiment 1. Grasp strategy usage was analyzed using three generalized linear mixed models (GLMM). The effect of strategy on duration, rotation, and step count was analyzed using a linear mixed model that included the experimental factors, grasp strategy, and their interactions. Inclusion of a factor in a final model 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. To calculate group means for effects involving both size and weight, the lsmeans package of R was used (Lenth, 2016).

To explore the effect of hysteresis, we tested whether the number of bimanual uses in directly preceding trials affected whether participants used the bimanual strategy again. All trials under conditions shared between Experiments 1 and 2 (small or medium bowls of the heavy weight, in configurations C1, C4, and C7) were analyzed regardless of whether their preceding trials were also shared. Participants who either never or always used bimanual strategy affected the results of this analysis and so were removed. The remaining trials were analyzed using a GLMM to compare if using the bimanual strategy in none or all of the trials in the preceding set had a significant effect on the outcome. This analysis was done for one, two, and three previous trials.

Experiment 2 Results

Basic Strategy Frequencies and Comparison to Experiment 1

Similar to Experiment 1, the four mixed strategies (LB, RB, BL, and BR) were used in a small proportion of the trials (3.4%). Unlike in Experiment 1, the

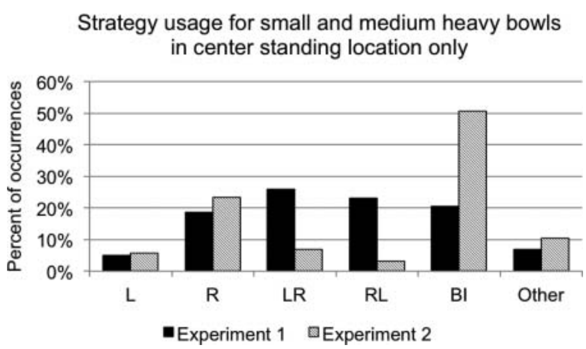

FIGURE 8. Comparison between Experiments 1 and 2 on identical trials.

bimanual strategy (BI) was the most popular strategy, while hand-off usage was cut down. We can limit the examination to only trials featured in both experiments. These are all three configurations 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 (Figure 8), 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. In addition, the model for bimanual strategy also had a main effect of weight. These effects are summarized visually in Figure 9.

In the model for bimanual usage, the effects remaining were size ($\chi^2(3) = 14.1$, $p = .003$), weight ($\chi^2(2) = 21.4$, $p < .0001$), balance ($\chi^2(1) = 251$, $p < .0001$), and the size × balance interaction effect ($\chi^2(3) = 14.6$, $p = .002$). Figure 9 indicates that heavier weights increase bimanual usage slightly. It also indicates that bimanual usage is nearly maxed out in the balance condition, while, 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 configuration ($\chi^2(2) = 84.9$, $p < .0001$; Figure 10) main effects. The hand-off strategy is less often used at the smallest bowl size (Figure 9). The balance and configuration effects

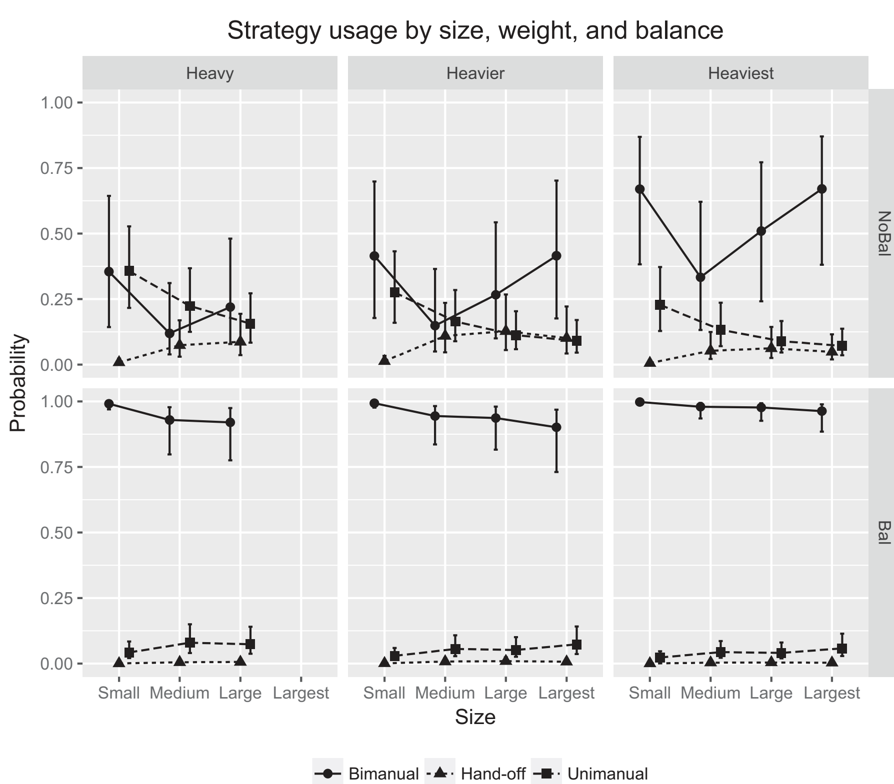

FIGURE 9. Effects of size, weight, and balance on the usage of the three strategies. Size, weight, balance, and the size × balance interaction effect are significant for bimanual usage; size and balance main effects are significant for hand-off usage, and the balance main effect and size × balance interaction effect are significant for unimanual usage.

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 configuration ($\chi^2(2) = 29.2$, $p < .0001$) as well as the size × balance interaction ($\chi^2(3) = 17.9$, $p = .0005$). 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 starting configuration, in Experiment 2 the balance condition cut down unimanual usage in all configurations. The configuration effect (Figure 10) was similar to Experiment 1, with most unimanual usage when moving the bowl front to back (C4). The size × balance interaction (Figure 9) 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 ($\chi^2(42) = 41.4$, $p = .50$) and unimanual ($\chi^2(42) = 42.3$, $p = .46$) models. Unlike the other two strategies, configuration was able to removed from the bimanual model ($\chi^2(44) = 59.5$, $p = .059$).

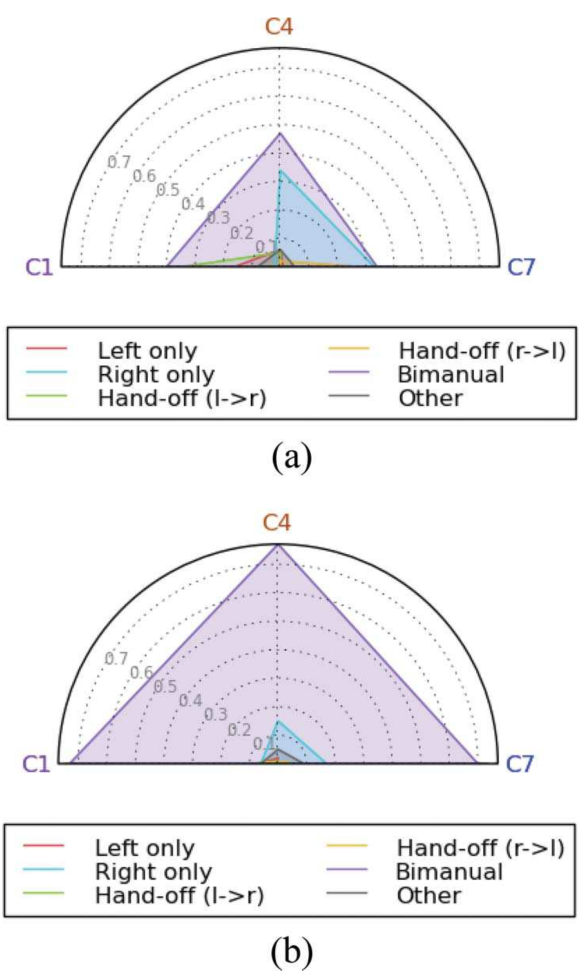

FIGURE 10. Angle plot showing strategy usage at all configurations for (a) no-balance cases and (b) balance cases.

Effect of Strategy on Duration, Rotation, and Step Count

For duration, the results in Experiment 2 match the first experiment closely. Both strategy ($\chi^2(2) = 24.1$, $p < .0001$) and strategy × balance ($\chi^2(2) = 66.0$, $p < .0001$) were significant, with the bimanual strategy taking longer in the no-balance case but competitive in the balance case (Figure 11).

For rotation, similar to Experiment 1, both strategy ($\chi^2(2) = 474$, $p < .0001$), and the strategy × configuration interaction ($\chi^2(2) = 66.0$, $p < .0001$, Figure 12a) were significant. In addition, the strategy × size ($\chi^2(6) = 21.5$; $p = .002$) and strategy × balance ($\chi^2(2) = 16.0$; $p < .001$) interactions were also significant. Although the mean rotations for unimanual and hand-off strategies were slightly higher using the motion capture in Experiment 2, the interaction effect is similar to the first experiment (compare with C1, C4, and C7 in Figure 5). The main exception is that at C4, the unimanual strategy requires more rotation than the bimanual strategy.

For step count, the strategy ($\chi^2(2) = 222$, $p < .001$), strategy × size ($\chi^2(6) = 21.1$; $p = .002$), and strategy × balance × configuration interaction ($\chi^2(4) = 18.3$, $p = .001$, Figure 12b) were significant. The configuration pattern is similar to the rotation results (Figure 12a), except for unimanual at C1.

Correlations Between Measures

Figure 13 contains information on the correlation between hip rotation and other measures—duration, step count, and other rotation measures. Because duration and the rotation measures were continuous, they were compared using the Pearson's R correlation coefficient. Because steps

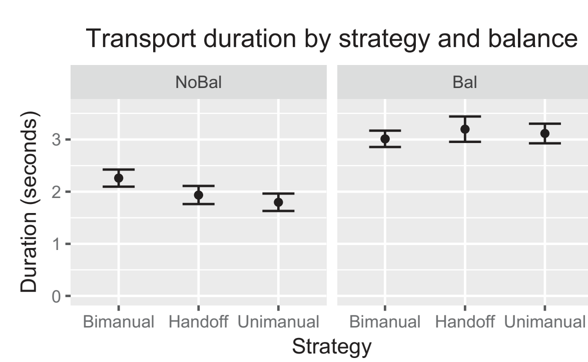

FIGURE 11. Transport duration by strategy and balance.

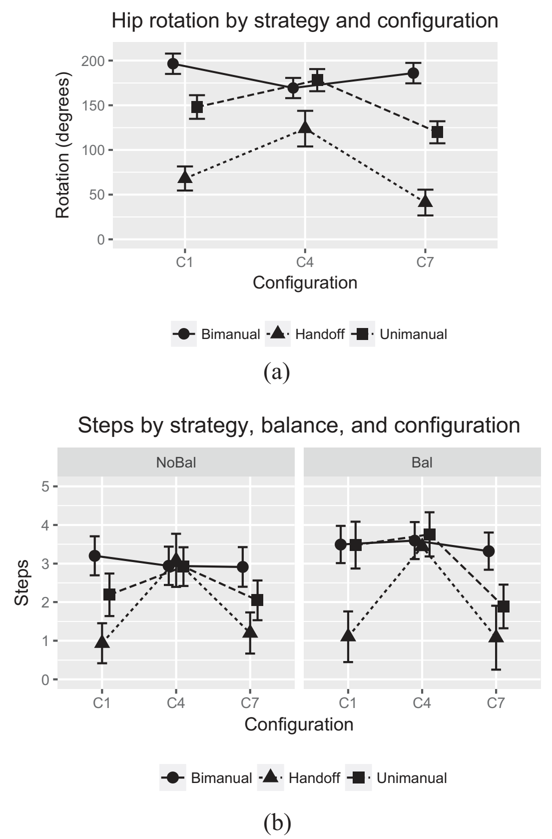

FIGURE 12. Total hip rotation by strategy and configuration compared to step count by strategy, balance, and configuration.

were discrete, we use a boxplot to compare rotation and steps. Hip rotation and duration have low correlation ($R^2 =$ .280). By contrast, there is a moderately strong relationship between hip rotation and step count (Figure 13, right). The correlation between hip rotation and other rotation measures is high indicating hip rotation is acceptable to use as a proxy for other kinds of rotation.

Hysteresis Analysis

The results of the analysis of the previous trials was that whether the k previous trials had zero or k bimanual uses (for $k = 1, 2, 3$) did not have a significant effect on whether the current trial would be bimanual in Experiment 1 ($k = 1$: $\chi^2(1) = 2.46$, $p = .117$; $k = 2$: $\chi^2(1) = 1.86$, $p = .172$; $k = 3$: $\chi^2(1) = 3.48$, $p = .062$), but was significant in Experiment 2 for three previous trials ($k = 1$: $\chi^2(1) = 0.594$, $p = .441$; $k = 2$: $\chi^2(1) = 4.45$, $p = .035$; $k = 3$: $\chi^2(1) = 9.00$, $p = .0027$). This difference is mostly likely due to the lower bimanual usage in Experiment 1, which makes the dataset analyzed smaller, as Experiments 1 and 2 have similar trends (Figure 14).

Discussion

The factors that affect the use of one or two hands in object transport, especially the strategy of handing off between hands, are not well understood. In these experiments, we wanted to investigate the effect of object and task properties on the selection of bimanual, hand-off, and unimanual strategy, and to identify principles that might be underlying this selection.

Previous work examining grasping (Cesari & Newell, 2000) has found that increasing the size of an object will

Correlation with total hip rotation	R^2
Duration	.280
Transport hip rotation	.932
Total torso rotation	.910
Transport torso rotation	.891
Total head rotation	.567
Transport head rotation	.741

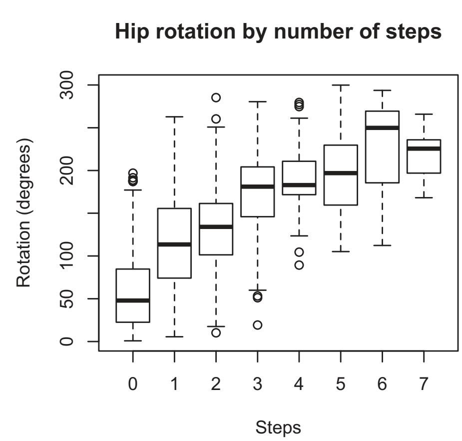

FIGURE 13. The relationship between (left) hip rotation and duration, and hip rotation and other rotation measures (Pearson's R) and (right) hip rotation and step count.

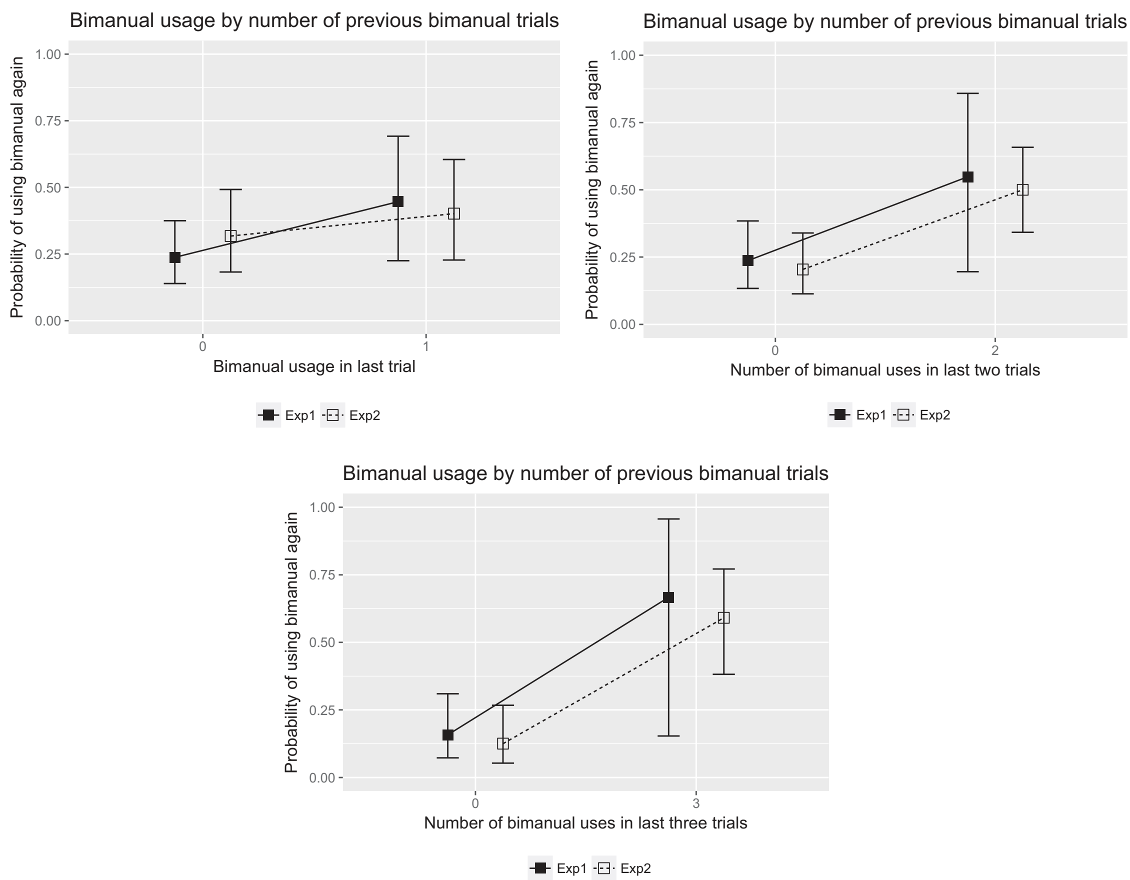

FIGURE 14. Effect of previous bimanual usage on current trial's bimanual usage for Experiments 1 and 2.

cause people to transition from one-handed to two-handed grasping. In our work examining transport, we found similar effects of size. However, these effects were weaker than we had expected based on the Cesari and Newell results. One possible explanation for a weak size effect is that the typical grasping location of a bowl does not increase as the bowl gets bigger. Specifically, subjects typically pinched the rim of the bowl, which is similarly thin across bowl sizes. By contrast, in previous studies, the objects manipulated were cubes or toys, where all graspable dimensions increase in width simultaneously. Previous work (Feix, Bullock, & Dollar, 2014) has shown that grasps are overwhelmingly formed around an object's thinnest dimension, so the consistently thin bowl lip may explain the relatively weak effect of size on bimanual usage. Further investigation could clarify the effect of an object's thinnest dimension on choice of transport strategy.

Another unexpected effect of size on strategy is that 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. The fullness of the bowl appeared to make unimanual grasps more difficult: most, but not all, unimanual grasps were formed by pinching the rim of the bowl. These grasps required placing the thumb inside the bowl, which is more difficult to do when the bowl is full. By contrast, most bimanual grasps involved forming multiple contacts around the outside surface of the bowl and thus were not affected by the bowl's fullness. In the future, using fillers of higher density could be used to test whether bowl fullness was influencing choice of strategy.

The Cesari and Newell (2000) study also found a similar effect of weight on causing people to transition from one-handed to two-handed grasping. The effect of weight on transport strategy in our experiments was also weaker than we expected. The absence of a weight effect in Experiment 1 may be because the heavy bowl was not sufficiently heavy to affect people's strategy choices. However, Experiment 2 also contained a weak effect of weight found only in the bimanual strategy. This weak effect may be due to high usage of the bimanual strategy in general (discussed below).

Palmer (1989) found an effect of weight on hand-offs. However, we did not find an effect of greater weight on discouraging hand-offs. It is possible this effect only applies to handing-off as an idle action (as opposed to a transport strategy) or to infant development. Using a finer step size in weights may help to clarify how weight causes people to transition between bimanual, hand-off, and unimanual strategies.

In these experiments, we expected that the use of two hands is a strategy that decreases the difficulty of a balancing task, similar to the effect of pregrasp rotation found by Chang et al. (2009). Our data strongly support this possibility in two ways. First, use of the bimanual strategy increases when balance is necessary (Figures 2 and 9). Second, although the bimanual strategy is slowest when balance is not required, it becomes faster than hand-offs and as fast as the unimanual strategy in the balance case (Figures 4 and 11), making it the strategy with the smallest increase in movement time going from no-balance to balance cases.

Previous work (Rosenbaum et al., 2010) has investigated the effect of start and goal location on the use of left, right, and both hands. Similar to their work and other handedness studies (e.g., Gonzalez et al., 2014), we observed that the left hand is more often used to pick and place on the left side of the body and the right hand on the right side (see Figure 3). Matching Rosenbaum and colleagues' work, we also found that two-handed picking and placing were much less responsive to object start/goal position than one-handed picking and placing.

We also wished to extend Rosenbaum et al.'s work to distinguish between pure unimanual transport and hand-offs. Our findings indicate that hand-offs function as an alternative to the unimanual strategy. Hand-offs and unimanual strategies each dominate at disjoint sets of configurations. We expected that hand-offs would be used when the start and goal are located in different left/right hemispaces. Our findings support this guess, with configurations with this property being dominated by hand-off usage, while hand-off usage is dramatically cut down when this property does not hold (Figure 3). Although we found that hand-offs function as an alternative to the unimanual strategy, we also found that hand-offs seem to be less stable than the unimanual strategy. This is indicated by relatively longer movement times in balance cases (Figures 4 and 11) and being disfavored compared to the unimanual strategy in balance cases (Figure 2).

The second major question we investigated was the underlying reason behind choices of transport strategy. Minimization has been a guiding principle when trying to explain motion choices (Engelbrecht, 2001), and our results support that minimal principles may be useful for explaining selection of transport strategy. Specifically, our results indicate that the desire to minimize body rotation is likely underlying people's choices of transport strategy. First, the large amount of body rotation necessary for bimanual transport could explain why the seemingly less stable hand-off and unimanual strategies were widely used even in the balance cases of Experiment 1 (see Figure 3b). Second, the usage of hand-offs corresponds closely to configurations where less rotation is performed. Our results also indicate that other measures of rotation and step count are strongly tied to hip rotation.

Although we did not investigate it in this study, it is also worth asking why these different strategies entail different amounts of body rotation. One possible reason why people rotate different amounts is that the reach of the arms changes with reaching angle, so rotation may be used to change reaching length, including equalizing the reaching length of both hands for a bimanual grasp. Factors such as different comfort and lifting ability at different points within a joint's range of motion (Chang et al., 2009) may also be important. More work is needed to determine in detail the biomechanical considerations underlying the different amount rotated for each strategy in each configuration.

Comparing the two experiments, we see that the less precise methodology of the first experiment nevertheless yielded similar results to the motion capture technology used in the second. We also found that 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). Our hysteresis analysis indicates it is possible that previous trials affect the strategy choice in the next trial, meaning that the different bowl sizes and weights used in Experiment 2 could have affected strategy usage on the shared bowl sizes and weights. Another possibility is that the act of wearing motion capture markers could make people more self-conscious about their motions and affect their strategy choices. A third possibility is that changing the starting configuration frequently as in Experiment 2 and not in Experiment 1 may have encouraged people to use a single transport strategy (the bimanual strategy) by default rather than adapting their strategy to the starting configuration. Further investigation is needed.

This is a preliminary study with a small number of participants. Therefore, the results should be interpreted conservatively. However, overall, our work indicates that the choice of hands in transport is highly responsive to task demands. In this work, we focused on the hand-off strategy, finding that it is similar to the unimanual strategy, but is less stable. It is mainly used in configurations that involve transporting an object between left and right hemispaces, where it reduces the amount of body rotation needed to complete the transport task. For bimanual transport, we found that using two hands is a strategy that can be employed to reduce the difficulty of maintaining an object's balance, similar to pregrasp rotation. However, it requires more body rotation and effort. The selection of bimanual, hand-off, and unimanual transport strategy appears to balance these considerations of stability and effort.

FUNDING

National Science Foundation10.13039/501100008982 [1218182]; Disney Research.

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Received June 15, 2017
Revised March 2, 2018
Accepted April 3, 2018