

Action observation facilitates anticipatory control of grasp for object mass but not weight distribution

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ABSTRACT

Action observation has been shown to facilitate the performance of the observer and is being increasingly used as a rehabilitation tool following neurological damage. During object manipulation, visual observation of performance is suggested to enable the updating of the sensorimotor representations of object properties. Here, through 3 experiments, we examine the effect of action observation of a novel object on the updating of object mass and weight distribution for bimanual manipulation. For each experiment, naïve participants were allocated into pairs and assigned as the “performer” or “observer”. For experiments 1 and 2, observers sat opposite the performers. For experiment 3, observers stood behind the performer. The pairs observed and lifted either i) a light or heavy box in experiment 1, or ii) a box with a left or right uneven center of mass in experiments 2 and 3. Our results showed that action observation facilitated the updating of object mass information but not information about weight distribution. Specifically, observers of the heavy box subsequently applied larger forces and force rates in accord with the mass of the box. In contrast, both performers and observers of the uneven box had large peak rolls. We suggest that this shows the robustness of observation in facilitating an understanding of object mass while highlighting the complexity of manipulating an object with uneven weight distribution.

1. Introduction

Action observation facilitates motor learning, in several tasks, even in the absence of actual performance (for review see: [5,33]). This has been suggested to involve mechanisms where visual information is transformed into sensorimotor representations, of the observer, for future action (for review see: [28,32]). Action observation has also been increasingly used as a rehabilitation technique for patients with neurological damage such as adults with stroke (for review see: [3]) and children with cerebral palsy (for review see: [2]). Successful object manipulation involves obtaining information about object properties such as its mass, and weight distribution [11,21]. Prior to any physical experience with the object, this information can be obtained through visual cues of these properties [8,12,16]. Aside from visual cues of the object itself, observation of the manipulation provides other useful information about object properties [1,4,6]. Information about an object's mass can be obtained through observation of a single lift [25]. This is analogous to sensorimotor updating that occurs after a few experiential trials with an object [12].

During action observation, the visual system receives considerable

information that requires processing to extract aspects important for the task (see: [19]). Most studies examining action observation of object manipulation involved observing and lifting an object with a unimanual, often two-digit precision grip. For bimanual lifts, observation has been shown to enable the accurate judgment of object mass [30]. Whether observation of a single lift can facilitate bimanual object manipulation with regards to object mass and weight distribution is unknown.

In the present study, 3 experiments were conducted, to determine if observation of a single bimanual lift facilitates performance of an observer by updating representations of object mass and weight distribution. We used naïve participants instead of actors to minimize actor expectations that may cause stereotypical or exaggerated motions. Observations were thus of novel performance. Experiment 1 involved observing the lift, and then lifting, a light or heavy box. We hypothesized that observation would facilitate performance by enabling the application of appropriate forces to object mass to regulate the load phase time. In experiments 2 and 3, observers observed lifts of a visually symmetrical box with an asymmetrical weight distribution that shifted the object's center of mass to the left or right. Because of this, the frame of reference of the observer might affect the transformation of sensory

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information [22,36]. Thus, experiments 2 and 3 were identical in all aspects aside from the point of view of the observer. We hypothesized that when the frame of reference is the same, observation would result in facilitated performance through the reduction of object roll.

2. Materials and methods

2.1. Participants

120 right-handed healthy adults with normal or corrected-to-normal vision participated in the study after providing informed consent. Participants were paired by gender. Each experiment had 40 unique participants (mean $\pm$ SD age: Experiment 1–27.00 $\pm$ 5.46 yrs., 22 females; Experiment 2–27.03 $\pm$ 3.74 yrs., 26 females; Experiment 3–27.33 $\pm$ 4.45 yrs., 24 females). The study was approved by the Teachers College, Columbia University Institutional Review Board.

2.2. Apparatus

All experiments used a custom-made device that resembled a solid box (height $\times$ width $\times$ depth: 30 $\times$ 42 $\times$ 15 cm) identical to one used in a previous study [20]. Force sensors on the grasp surfaces (Mini 40 Force/Torque sensor; ATI Industrial Automation), measured grip and load force, and torque sampled at 500 Hz (resolution = 0.02 N, 0.01 N, and 0.025 Ncm, respectively). An electromagnetic sensor (Polhemus Fast-track, 0.005 mm of range, and 0.025 resolution), mounted on top of the device, measured the vertical position and roll (i.e., tilting in the frontal plane) sampled at 120 Hz. Data were filtered using a second-order Butterworth filter with a cutoff frequency of 6 Hz. Lead weights were placed in various compartments in the device to alter the mass or center of mass depending on the experiment.

2.3. Experimental setup and procedure

Across all experiments, within each pair, one participant was randomly assigned the role of “performer” and another “observer.”

Fig. 1 shows the setup for the experiments. The task goal was to bimanually lift the box 10 cm using a smooth, self-directed pace, avoiding any roll. An audio tone signaled the start and end, of the trial. Observers were informed that they were to watch the performers lift the box once, then lift the box themselves. To minimize auditory cues, the observers wore a headset that played a background noise during the observation. In each experiment, 20 pairs were pseudo-randomly assigned to one of two conditions (light or heavy box for experiment 1, left or right COM for experiments 2 and 3).

2.3.1. Experiment 1 – Mass front observer

The empty box weighed 1.55 kg (light box) while a lead block weighing 2.45 kg was added to the center of the box to change its mass to 4 kg (heavy box). The observer sat opposite the performer to observe the lift (Fig. 1A, B).

2.3.2. Experiment 2 – Weight distribution front observer

The observer sat opposite the performer (Fig. 1C, D). However, the lead block was now placed either on the left or right side to shift the center of mass (COM). The external torque was $\pm$ 200 Ncm, shifting the center of mass by $\pm$ 9 cm from the object's center.

2.3.3. Experiment 3 – Weight distribution back observer

Experiment 3 used the same box configuration as experiment 2, however, the observer now stood on a step stool behind the performer (Fig. 1E, F). Thus, both subjects had the same frame of reference.

2.4. Data processing and analysis

Outcome measures used to determine the effect of observation for all experiments include:

- Initial peak load force (tangential, LF) rate and grip force (normal, GF) rate (determined as the first maximum value of the first derivative of LF or GF prior to lift onset that subsequently decreases $>30\%$). For experiment 1, LF was the combined LF, while GF was the

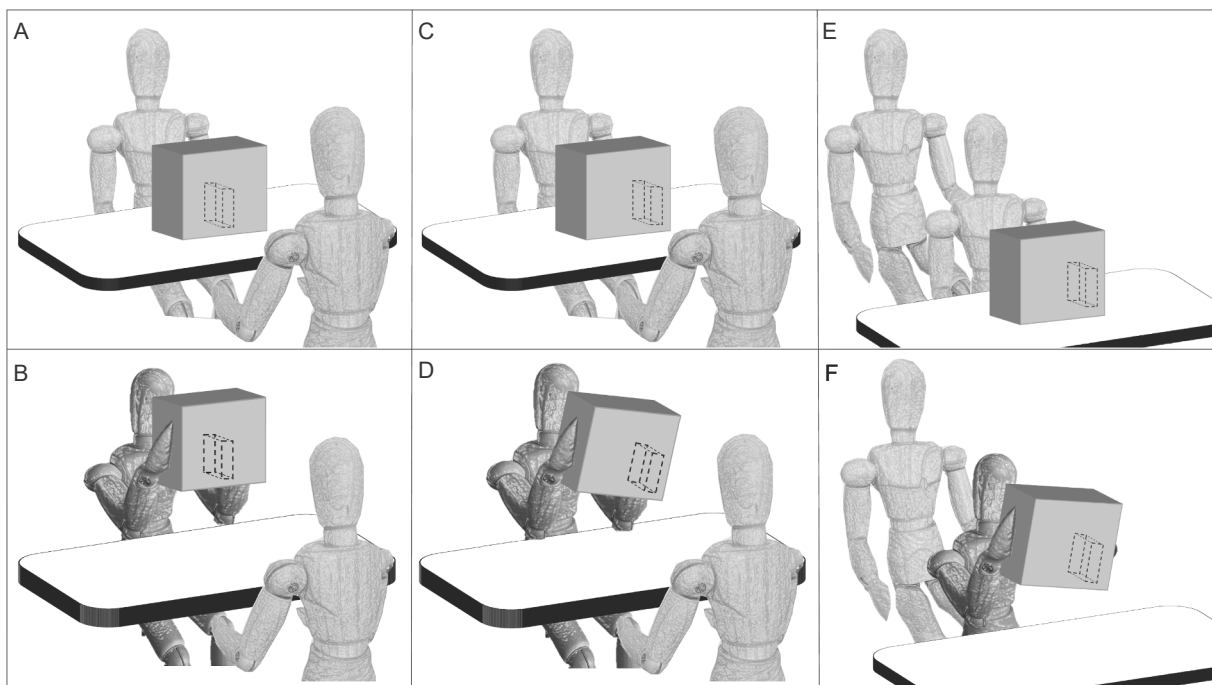


Fig. 1. Experimental setup and schematic of performers' lift. The dotted box represents the lead block that was placed inside the box out of view of the participants. A, B: Experiment 1. Heavy box depicted. C, D: Experiment 2. The lead block was either in the left (depicted) or right side of the box, performer reference, resulting in rolls. E, F: Experiment 3. Same box configuration as experiment 2. Observer now stood behind performer.

average GF of both hands. For experiment 2 and 3, the initial peak force rate applied to the heavier and lighter sides were calculated separately.

b) Load phase duration represents the time when load forces exceed 0.2 N and increased consistently thereafter to lift onset (point where the

vertical position of the box went above 0.1 cm and continued increasing).

c) Maximum velocity of the box

To determine the effect of observation on torque generation, exper-

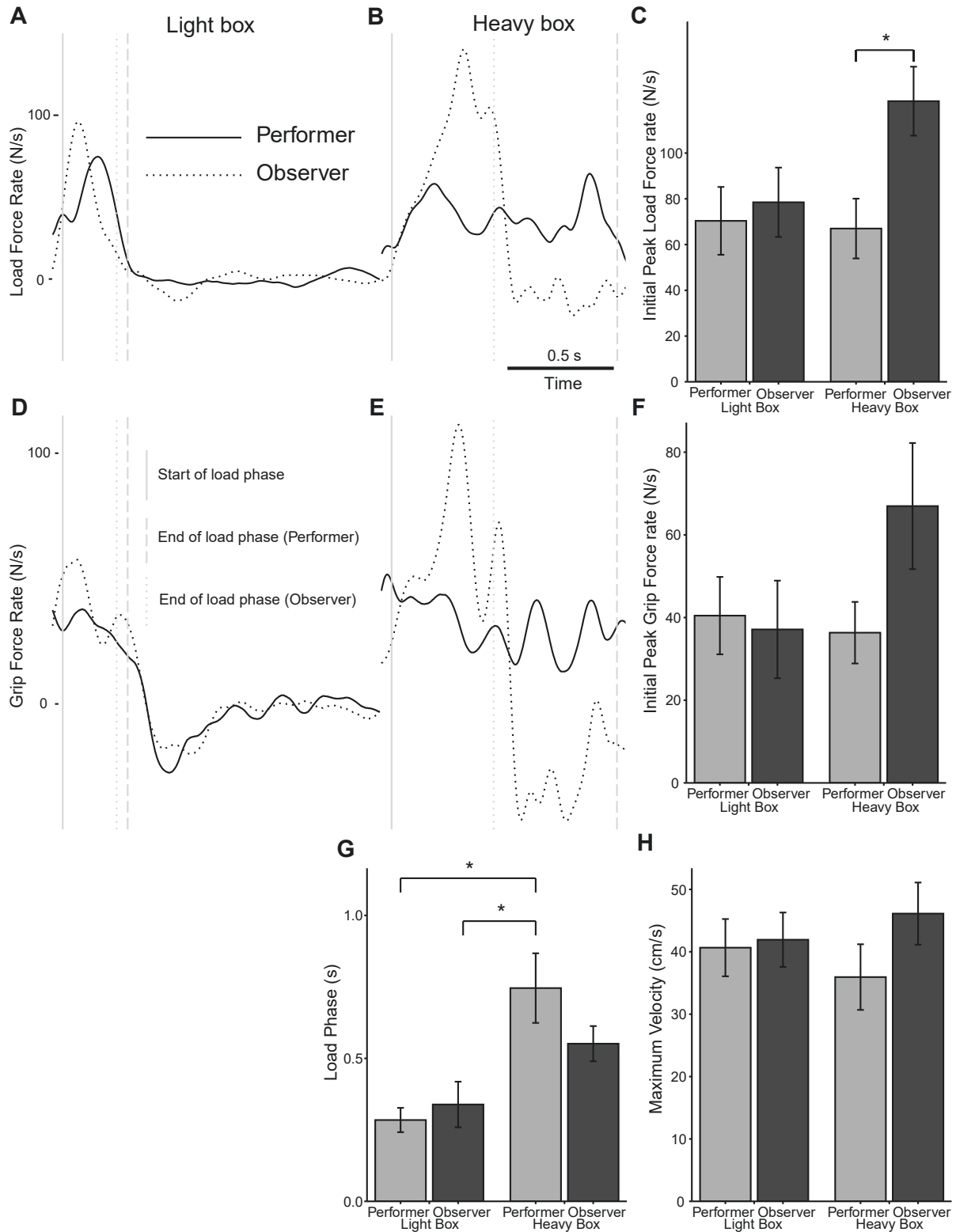


Fig. 2. Representative participant traces from each group for load force rate, grip force rate, and group averages (mean $\pm$ S.E.) in Experiment 1. **A-C.** Load force rate measurements. **D-F.** Grip force rate measurements. The vertical lines indicate load phase; first vertical line indicates the start of load phase, second vertical line indicates the end of load phase or lift onset. **G.** Load phase duration. **H.** Maximum velocity. * $p < .05$.

iment 2 and 3 included these additional outcome measures [13]:

- d) Peak roll: The angle of the device in the frontal plane. Positive values represent counterclockwise rotations. Peak roll is the maximum roll recorded within 250 ms after lift onset.
- e) Load force difference (LF_{diff}) is defined as the LF of the hand on the heavier side (side of the COM) minus the hand on the lighter side. COP difference (COP_{diff}) is measured by the COP of the hand on the heavier side minus the COP of the other hand. Center of pressure (COP) represents the vertical location of the point at which hand forces are applied on the individual grip surfaces.

- f) Compensatory torque (T_{com}) represents the torque generated by the participant's hands measured in Ncm. Positive values indicate a clockwise moment.

$$a. T_{com} = \left(LF_{diff} * \frac{d}{2} \right) + (GF_{mean} * COP_{diff}) \text{ where } d \text{ denotes the width between the two grasp surfaces.}$$

Aside from peak roll, values were recorded at lift onset, before feedback-driven motor commands could be made.

We performed one-way ANOVAs on the outcome measures. For experiments 2 and 3, because peak load and grip force rates were obtained for each hand, we performed a mixed ANOVA with repeated measures

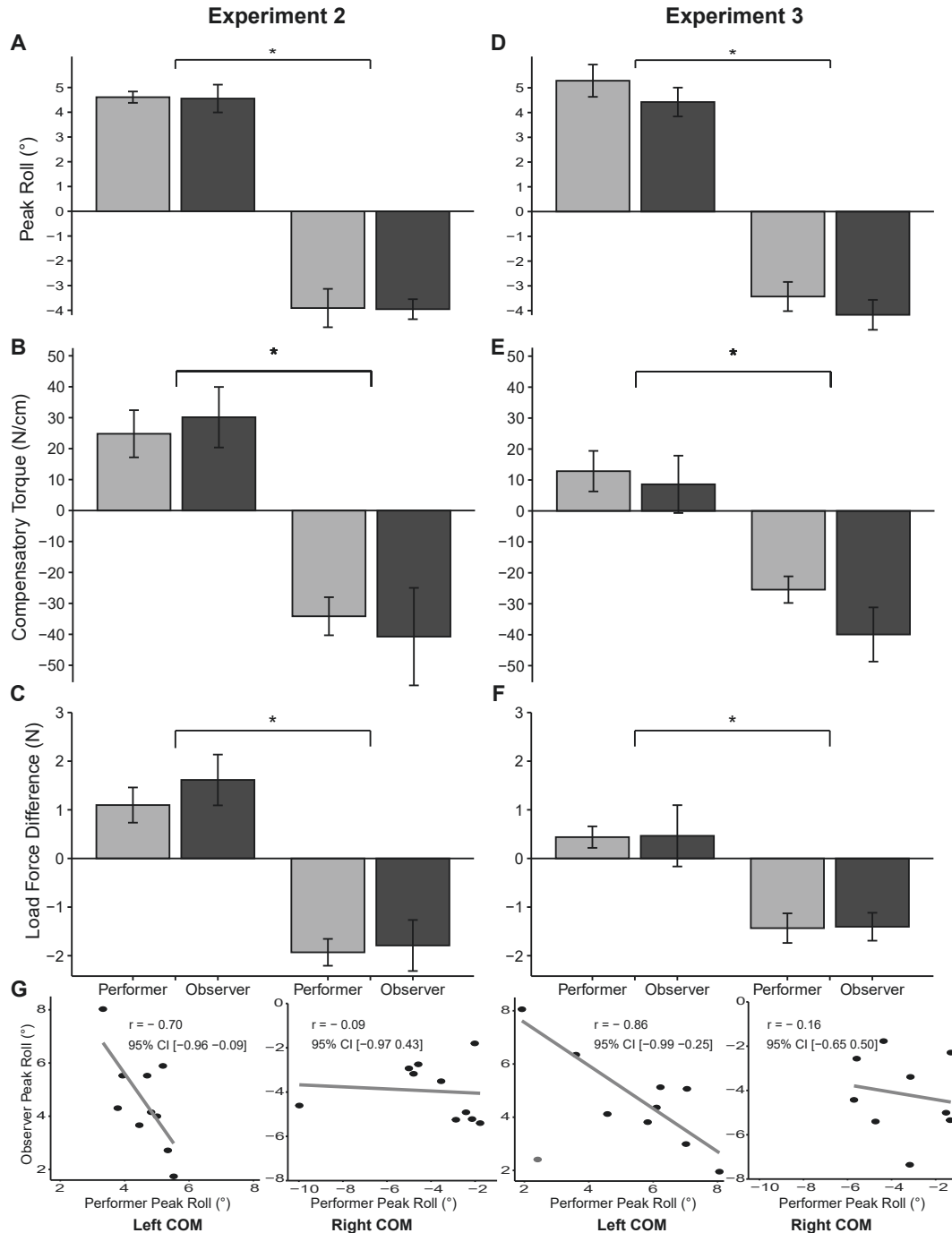


Fig. 3. A-F. Average results of the main variables of torque generation for all the participants in experiments 2 and 3 (mean $\pm$ S.E.). * $p < .05$. G. Scatter plot of peak rolls for performer (x-axis) and observer (y-axis) pairs across experiments 2 and 3.

on hand. Post-hoc tests were performed on significant effects with Bonferroni corrections. Analysis on gender did not reveal any effect and thus was not considered further. Additionally, we examined the correlation between the performers and observers on torque generation. To prevent spurious correlations, we used a toolbox that allowed us to perform more robust correlation analyses [24,29,34].

3. Results

3.1. Experiment 1 – Mass

Observation of one lift was enough to facilitate the performance of the observer on the heavy box. Fig. 2 shows the trajectories and analyses of the various measures for representative participants from each group. During the load phase (between vertical lines), peak load and grip force rates were similar between the light box performer and observer (Fig. 2A, D). For the heavy box performer, the load phase was characterized by multiple load and grip force peaks (Fig. 2B, E solid line). The heavy box observer, however, had fewer peaks with a shorter load phase (Fig. 2B, E dotted line). Further analysis indicated that initial peak load force rate (Fig. 2C) and load phase duration (Fig. 2G) differed between the groups (Initial peak load force rate: $F(3,36) = 3.15$, $p = .04$, $\eta^2 = 0.21$; load phase: $F(3,36) = 6.67$, $p = .001$, $\eta^2 = 0.36$). Post-hoc tests revealed that the initial peak load force rate was higher and load phase shorter for the observer of the heavy box compared to the performer (p 's < 0.05).

3.2. Experiment 2 – Center of mass front observer

Analysis revealed no main effects between groups for initial peak load and grip force rate, load phase, or maximum velocity (Supplementary Fig. S1, S2). There were differences between lifts of the left and right COM but not between performers and observers (Fig. 3A-C). The measures peak roll, Tcom, and LF_{diff} showed significant differences between groups (peak roll $F(3,36) = 85.45$, $p < .001$, $\eta^2 = 0.88$; Tcom $F(3,36) = 12.89$, $p < .001$, $\eta^2 = 0.52$; LF_{diff} $F(3,36) = 18.51$, $p < .001$, $\eta^2 = 0.61$). Post-hoc tests revealed that for these measures, for both the performer and observer, left COM values were more positive than the right COM (p 's < 0.05).

3.3. Experiment 3 – Center of mass back observer

Results from experiment 3 were the same as experiment 2 (Fig. 3D-F). Development of peak load and grip force rates, and load phase appeared similar across the groups and COM measures were the same as experiment 2 (Supplementary Fig. S3, S4 show the trajectories of a representative participant).

3.4. Correlation between peak roll of performers and observers

Across experiments 2 and 3, the peak roll between performers and observers was negatively correlated (Fig. 3G). For both experiments, when the object had a left COM, as the peak roll of the performer increased, that of the observer decreased. No other measures were significantly correlated.

4. Discussion

Across three experiments, we sought to determine if action observation of a single lift of a novel performer would facilitate the bimanual lifting performance of an object. Our results show that action observation facilitated performance through the updating of mass information, but failed to show any effect of weight distribution. We discuss these findings and their implications.

4.1. Observation confirms or updates current mass information

Successful object manipulation is characterized by lifting movements that are smooth with the application of grip and load forces appropriate to the object's mass (for review see: [15]). In experiment 1, performers and observers of the light box and observers of the heavy box showed smooth lifting movements, as characterized by the single peaks of load and grip force rates. On the other hand, the performers of the heavy box had multiple smaller force rate peaks and longer load phase durations, resulting in jerky lifting movements (Fig. 2). By observing smooth lifts, the light box observers continued to rely on the same estimation of object mass. For the heavy box, since it was visually identical to the light box, the performers lifted it as though it weighed closer to the light box. Thus, their force application was too small, resulting in jerky movements [10,12] and a longer load phase for the heavy box performers. The longer performers' duration before lift-off led to observers increasing their estimation of the box's mass. Thus, when the heavy box observers lifted it, the updated mass information led to smoother lifts through the application of larger force rates that also resulted in shorter load phases compared to the performer (Fig. 3).

4.2. Observation of object roll is insufficient to facilitate performance

Experiments 2 and 3 examined action observation of an object with asymmetrical weight distribution. Our results did not support our hypothesis, instead showing similar behaviors regardless of frame of reference. In both instances, lifts resulted in object rolls and minimal generation of compensatory torques (Fig. 3). However, closer examination of the results revealed that the peak roll of the performers may have affected the rolls of the observers. Specifically, the negative correlation implies that larger performer peak rolls led to smaller observer rolls (better performance). This occurred regardless of the frame of reference but only when the center of mass was on the left. Taken together, these results indicate that 1) observation of weight distribution does not facilitate performance as well as that of mass, 2) error size possibly influenced post-observation performance.

To pick up an object with an unequal weight distribution, the external torque of the object needs to be taken into consideration. Unlike the zero-torque required for symmetrically weighted objects, this involves added internal processes where estimation and anticipation of the external torque influences behavior [14,31,35]. Lifting an asymmetrically weighted box additionally involves anticipating object roll to update the internal representation of torque control [9,20,23]. This added complexity could be a reason why single lift observations lead to facilitated performance on a symmetrically weighted box but not for an asymmetrically weighted box. Additionally, when performer rolls are variable, such as the current study with naïve performers, the ability of the observers to notice the rolls depends on the magnitude of the performer rolls. As such, the larger the error (roll) observed, the more information it provides about weight distribution that can be used to facilitate performance. This is in line with other studies showing the effect of error on observation [4,26]. An important point to note is that even though roll was negatively correlated between the performer and observer, no other measure achieved significance. This indicates that something other than compensatory torque influenced the facilitation of observer performance. We suggest that the observation of object roll led observers to infer that the object had unexpected properties. Without actual experience with the object, the observers chose a strategy whereby they stiffened their end effectors in anticipation of the roll [7,17]. The lack of correlations for right COM rolls could indicate a directional effect. However, we remain cautious in interpreting these correlations due to the small sample size. Further studies could examine this effect in detail.

A previous study showed that error observation facilitated torque generation but did not lead to reduced rolls using a two-digit unimanual grasp [27]. However, participants had prior experience with the object.

As such, on observing rolls, the observers could rely on the retrieval of their previous sensorimotor memory during practice to update their representations of torque control. This updating through sensorimotor memory has already been shown to be an important aspect of behavior [11,13,18]. This could mean that either observation of a single object roll is not enough to provide the necessary information for torque control, and/or actual sensorimotor experience is required to confirm any understanding obtained through the observation. Subsequent studies could attempt to dissociate and determine which of these is true, or if a separate explanation is required.

Action observation involves the mirror neuron system [35]. The regions of the brain where mirror neurons have been found, has been suggested to represent the kinematic features of observed actions [1,2]. Specifically, the inferior parietal lobule (IPL) has been assumed to provide a 'goal-description' of the observed action whereas the inferior frontal gyrus is suggested to represent the kinematic features of observed actions. Our study has shown that although information about object weight can be obtained through observation of kinematic motion, information about weight distribution cannot. This might be due to the kinematic-kinetic continuum required for torque control [41]. These findings could affect future neurorehabilitation tools.

5. Limitations

Observing single lifts possibly limit observations especially for the weight distribution experiments. However, observing multiple lifts might not be feasible in this paradigm since improvement is seen within 2–3 lifts [20]. We did not use experienced performers, and thus do not know whether cues other than errors may have influenced observational learning. However, the shifts in hand position are typically small (<1 cm) and the forces are not observable, whereas the rolls were large, so we do not expect other cues to be helpful. Future studies could examine this in detail.

6. Conclusion

The present study examined if action observation would enable the updating of object mass and weight distribution information for successful performance in a bimanual lifting task. We have shown facilitated performance after observation of a heavier than expected box led to kinematic changes that more closely aligned with the box's mass. However, no overall performance improvement was seen after observation of an error associated with object torque. This highlights the robustness of observation in generating mass information but also underscores the complexity of weight distribution.

Author contributions

T.L.-M., J.G., J.C., and A.M.G., conceived and designed research; T.L.-M., J.G., and J.C. performed experiments; T.L.-M., and J.G. analyzed data; T.L.-M. prepared figures, and drafted manuscript; T.L.-M., J.G., and A.M.G. interpreted results of experiments; T.L.-M., J.G., J.C., and A.M.G., edited, revised manuscript, and approved final version of manuscript.

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All authors have contributed to the manuscript. Andrew Gordon and Trevor Lee designed the study and wrote the manuscript. Jennifer Guterman and Jaymin Chang collected and analyzed data and contributed to the statistics, figures and editing text.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.neulet.2022.136549>.

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