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RESEARCH ARTICLE

Adaptation of lift forces in object manipulation through action observation

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Abstract The ability to predict accurately the weights of objects is essential for skilled and dexterous manipulation. A potentially important source of information about object weight is through the observation of other people lifting objects. Here, we tested the hypothesis that when watching an actor lift an object, people naturally learn the object's weight and use this information to scale forces when they subsequently lift the object themselves. Participants repeatedly lifted an object in turn with an actor. Object weight unpredictably changed between 2 and 7 N every 5th to 9th of the actor's lifts, and the weight lifted by the participant always matched that previously lifted by the actor. Even though the participants were uninformed about the structure of the experiment, they appropriately adapted their lifting force in the first trial after a weight change. Thus, participants updated their internal representation about the object's weight, for use in action, when watching a single lift performed by the actor. This ability presumably involves the comparison of predicted and actual sensory information related to actor's actions, a comparison process that is also fundamental in action.

Keywords Action observation · Object manipulation · Motor learning · Human

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Introduction

Skilled object manipulation, including tool-use, requires learning object dynamics, which specify the relation between object motion and applied force. Such learning is considered to involve two components: learning the structure of the dynamics, captured by the form of the equations of motion, and learning the parameters for a given structure (Braun et al. 2009, 2010). Many studies of motor learning have examined point-to-point movements of a grasped object with novel and unusual equations of motion, often imposed by a robot (Lackner and DiZio 2005; Shadmehr et al. 2010; Wolpert and Flanagan 2010). In such cases, in which the actor must discover the structure of the dynamics, learning typically requires tens to hundreds of movements. However, most of our skill learning involves learning parameters of familiar dynamics, such as the weight of a book or the stiffness of an elastic band, and typically occurs over one or a few trials (Johansson and Westling 1988; Flanagan and Wing 1997; Ingram et al. 2010).

Although the adage *practice makes perfect* certainly applies to skill learning, the observation of others' actions constitutes an important source of information for such learning. It is well established that high-level task information, such as the sequence of required movements, can be learned through action observation (Heyes and Foster 2002; Torriero et al. 2007). However, recent findings indicate that action observation can implicitly facilitate learning of the structure of dynamics of novel loads (Mattar and Gribble 2005; Brown et al. 2010). Specifically, watching a video of an actor learning to move an unusual handheld load that initially perturbs hand motion leads to some improvement of skill acquisition when the observer subsequently performs the same skill-learning task.

In the current study, we examined whether people also acquire knowledge about the parameters of familiar loads through action observation. Using an object-lifting task, we tested the hypothesis that people naturally update knowledge related to object weight, used to adapt force output when subsequently lifting the object, based on watching an actor lifting the object. Previous studies have examined the effect of action observation on judgements of heaviness (e.g., Hamilton et al. 2007) and how heavy something looks (Runeson and Frykholm 1981; Bingham 1987; Shim and Carlton 1997). To our knowledge, only one study has examined the effect that action observation has on lifting behavior (Meulenbroek et al. 2007). In the latter study, in each trial, one participant lifted and then placed an object in a shared workspace and a second participant then lifted and retrieved it. The authors examined trials in which object weight unexpectedly changed and compared the change in lift height, relative to the previous trial, in placers and retrievers. As expected, in trials in which object weight decreased, lift height increased in placers. A slightly smaller increase in lift height was seen in retrievers, indicating a weak effect of action observation. Similarly, when object weight increased, a decrease in lift height was observed in both groups, but this decrease was slightly smaller in retrievers than placers. However, the latter result is less clear-cut because placers and retrievers exhibited different lift heights in the trial prior to the weight increase.

Here, we assessed, in addition to lift height, the forces applied to the object prior to lift-off, which, in trials in which weight increases, provide an earlier and clearer estimate of expected weight that is not affected by corrective mechanisms. Participants repeatedly lifted an object in alternation with an actor. The weight changed, unpredictably, every 5th to 9th of the actor's lifts so that participants (and the actor) could not reliably predict when the change in weight would occur. However, because the weight lifted by the participant always matched that of the actor, the participant could potentially gain information about the weight of the object in their forthcoming lift by observing the actor's current lift. We found that even though participants were naïve about the structure of the experiment, they effectively adapted the lifting force when lifting the new weight. Thus, participants exhibited rapid, single trial parametric learning through action observation.

Methods

Participants and general procedure

Nine participants, including 6 women and 3 men, were recruited from the population of undergraduate and graduate students at Queen's University. Participants provided written informed consent and received monetary compensation for their time. The ethics committee of Queen's University approved the study. For the analysis of lift height (see below), one participant was excluded because of missing object position information.

Seated participants repeatedly lifted an object located on a tabletop in front of them either by themselves or in turn with an actor seated on the other side of the table (Fig. 1a). Each lift was initiated by a tone that instructed the participant or actor to grasp the object by the handle using a precision grip and lift it. A second tone delivered 750 ms after lift-off instructed the lifter to replace the object on the table in the same location. Participants, and the actor, were encouraged to lift the object smoothly to a height of approximately 2 cm and to keep the duration and height of the lift consistent throughout the experiment. Participants and actor used the whole arm when lifting (i.e., they did not just lift via wrist movement) and rested their hand and forearm on the table between lifts. The time between successive lifts was approximately 5 s.

One of the authors (A. Reichelt) served as the actor throughout the experiment. Importantly, because we randomly changed the sequence of object weights for each experimental session (i.e., participant), the actor could not predict when changes in object weight would occur. Moreover, as will be described in the "Results," analysis of the actor's lift forces confirmed that the actor did not predict weight changes. The actor was instructed to maintain the same expression throughout each session and not to express surprise, either verbally or facially, during lifts when the weight changed.

Apparatus

The object consisted of a 5-cm^3 hollow cube made from the opaque black polyoxymethylene plastic Delrin® (Fig. 1b). A handle mounted on the top of the cube included two force–torque sensors (Nano 17 F/T, ATI Industrial Automation, Garner, North Carolina) that measured the forces applied by the tips of the thumb and index finger. A flat circular disk, covered by medium-grain sandpaper, capped each sensor. The two disks, and hence the surfaces contacted by the thumb and index finger, were oriented in parallel vertical planes, separated by a distance of 4 cm. A miniature electromagnetic position sensor (Polhemus Liberty, Burlington, Vermont), attached to the side of the object, measured the height of the lift.

The weight of the object was set to either 2 or 7 N (0.196 or 0.687 kg) on a given lift and could be changed between lifts without the knowledge of the participant or the actor. The change in weight was implemented by a linear motor programmed to position a trolley along a rotating rod attached, via a string, to the center of the object (Fig. 1b).

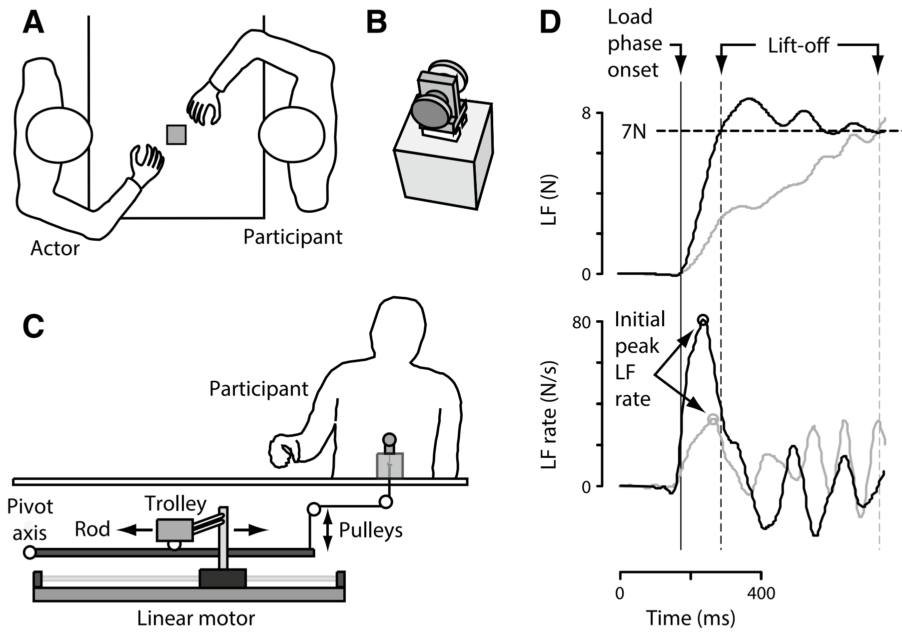

Fig. 1 Experimental setup and data analysis. **a** Top view schematic showing the positions of the actor and participant in conditions in which they lifted the object in alternation. **b** Object with handle instrumented with force sensors. **c** Diagram of the linear motor system used to programmatically specify object weight. **d** Load force (LF) and LF rate functions from two lifts of the 7 N weight. In one lift (*gray curves*), the initial increase in load force undershot object weight and, in the other lift (*black curves*), the initial increase in LF were close to the mark. Note that the initial peak in LF rate scaled with the initial increase in LF, which depends on expected object weight

The string passed through pulleys and through a small hole in the tabletop, to a hook located in the center of the cube, the bottom of which was open. The trolley moved between every trial to guard against the lifter using the sound of the linear motor system as a cue signaling a weight change.

Experimental conditions

Solo condition

In this condition, participants repeatedly lifted the object themselves. Without changes of the visual appearance of the object, its weight switched between 2 and 7 N across blocks of lifts, starting with the 2 N weight in the first block. The number of lifts per block was randomly varied between 5 and 9. Thus, the participants could not reliably predict when the weight would change based on the number of lifts. The participant completed 12 blocks of lifts. This provided 6 transitions from the 2 N weight to the 7 N weight. The solo condition provided a baseline with which to compare with the other conditions.

Coupled condition

In this condition, the actor and participant performed alternating lifts of the object with the actor going first. For the actor, the weight switched between 2 and 7 N across 12 blocks of 5–9 lifts, starting with the 2 N weight, and the participant experienced the same sequence of weights. Thus, neither the participants nor the actor could reliably predict when the weight would change based on the number of lifts.

Informed condition

This condition was the same as the solo condition, except that before each weight change, the experimenter verbally informed the participant about the change and indicated whether the new weight was light or heavy. Specifically, the participant was told either “the weight has changed and is now light” or “the weight has changed and is now heavy.” The informed condition allowed us to compare scaling of load forces on transition lifts in the coupled condition with that occurring when participants were explicitly informed about weight changes.

Each participant first completed the solo condition (solo1), followed by the coupled and informed conditions in counterbalanced order. They then completed a second solo condition (solo2). Because the solo1 condition was performed first, participants had experienced both weights and had learned that object weight could change when performing the coupled and informed conditions. The solo2 condition allowed us to evaluate the consistency of the participant’s behavior during the experimental session by comparing the lifting performance before and after the coupled and informed conditions.

Data analysis

Position and force signals were sampled at 1 kHz and smoothed using a fourth-order, zero-phase lag, low-pass Butterworth filter with a cutoff frequency of 14 Hz. Note that the position signal was updated at 240 Hz, and therefore, this signal was oversampled. The vertical load force (LF) applied to lift the object was computed as the sum of the vertical forces applied to the opposing contact surfaces of the handle, and the grip force was computed as the average of the normal forces applied to the surfaces. The rate of change of LF with respect to time, or LF rate, was computed using a first-order central difference equation. Our analysis focused on initial lifts of the 2 N and 7 N weights that followed blocks of 7 N and 2 N lifts, respectively. However, for reasons outlined below, we used different measures to assess lift performance for the 2 and 7 N weights.

Analysis of 7 N lifts

Under conditions in which object weight is accurately predicted, people tend to lift objects of varying weight in about the same amount of time. To accomplish this, they scale the LF rate, prior to lift-off, to the expected weight of the object—increasing load force more rapidly for objects they expect to be heavy. In addition, people predict the LF required for lift-off, and after initially increasing the LF rate, they reduce LF rate so that it approaches zero at the expected lift-off time. In general, the peak rate of change of LF during the initial increase in load force, which we will refer to as the initial peak LF rate, provides an index of predicted weight (Johansson and Westling 1988; Flanagan and Beltzner 2000; Flanagan et al. 2008; Baugh et al. 2012). However, if the object is far lighter than expected, there may be an abrupt cessation in LF increase at the time of lift-off. If lift-off occurs before the time at which the initial peak LF rate would have occurred had the object been as heavy as expected, the measured peak LF rate may not provide an accurate index of the expected weight (for further details see Johansson and Westling 1988). For this reason, we used the initial peak LF rate to examine the first 7 N lifts (following each block of 2 N lifts), but did not use this measure to examine the first 2 N lifts (following each block of 7 N lifts). In addition to determining the initial peak LF rate, we quantified the duration of the load phase—during which LF increases before lift-off—as the time from when LF exceeded 0.05 N until the time LF reached the weight of the object (see Fig. 1d).

For comparison with the first 7 N lifts, we also analyzed the second and last 7 N lifts of each block of lifts of the 7 N weight as well as the last 2 N lifts that preceded the first 7 N lifts. Based on previous work showing rapid updating of load forces across lifts when a prediction error occurs (Johansson and Westling 1988; Gordon et al. 1993), we expected smaller prediction errors on the second 7 N lifts, in comparison with the first 7 N lifts, and the most accurate predictions of the current weight in the last 7 N lifts.

For completeness, we also measured the initial peak rate of change of grip force (GF), which we will refer to as the initial peak GF rate. Because required GF depends on LF and is generally modulated in synchrony with LF (Johansson and Westling 1988; Johansson and Flanagan 2009), we expect the analyses of GF and LF to reveal similar results. However, because GF also depends on factors other than LF, including the frictional conditions between the digits and contact surface and the GF safety margin selected by the lifter, measures based on GF do not provide a direct measure of expected weight.

Analysis of 2 N lifts

When lifting objects that are lighter than expected to a small height (e.g., 2 cm as in the current study), people tend to overshoot the target height (Johansson and Westling 1988). Therefore, we used the maximum lift height to examine the first 2 N lifts (following each block of 7 N lifts). For comparison with the first 2 N lifts, we also analyzed the second and last 2 N lifts of each block of lifts of the 2 N weight as well as the last 7 N lifts that preceded the first 2 N lifts. We expected that lift height would decrease on the second and last 2 N lifts, in comparison with the first 2 N lifts, as participants update their prediction of object weight.

To assess the effects of condition and lift type (i.e., first, second, and last lifts), we used repeated measures ANOVA as well as planned within-subject comparisons. The Holm–Bonferroni test was used to correct for multiple comparisons. This test fully controls for family-wise error, but is more powerful than the stringent Bonferroni test. A p value of 0.05 was considered statistically significant.

Results

Single trial results

Figure 2 shows load force (LF), LF rate, and lift height (i.e., vertical positions) records from single trials, performed by a single participant, from the solo1, coupled and informed conditions. Very similar force and position records were observed, across conditions, for the last lifts in the blocks of lifts with the 2 N and 7 N weights. This result is expected because, in all three conditions, participants could rely on sensorimotor memory of the previous 4-8 lifts with the same weight in order to scale load force to the current weight. In fact, similar force and position records were also observed for the second 2 N and 7 N lifts, consistent with previous work showing that rapid, single trial updating of sensorimotor memory for weight (Johansson and Westling 1988; Johansson and Flanagan 2009).

The key trials are the first 7 N and the first 2 N lifts that followed blocks of 2 N and 7 N lifts. For the first 7 N lifts, the force records differed considerably across conditions

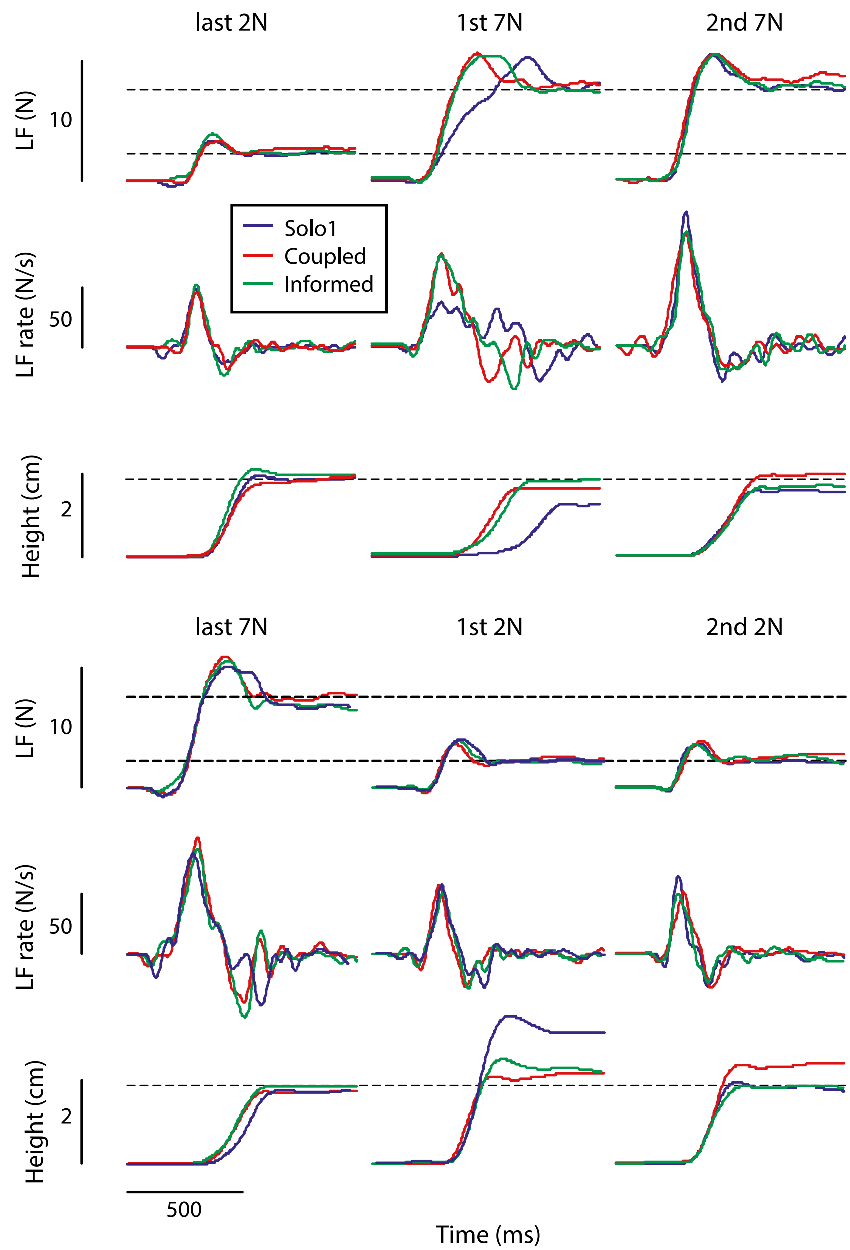

Fig. 2 Load force (LF), LF rate, and lift height records from a single participant. The *top row* shows examples of last lifts of a block of lifts of the 2 N weight and the first and second lifts of the subsequent block of lifts of the 7 N weight. The *bottom row* shows examples of last lifts of a block of lifts of the 7 N weight and the first and second lifts of the subsequent block of lifts of the 2 N weight. The records are color coded by condition (see *inset*)

for this participant. As expected, in the solo1 condition, the object did not lift off after the initial increase in LF, and an additional LF increase was required to achieve lift-off. However, in the coupled and informed conditions, the initial increase in LF was sharper and reached a greater force such that an addition LF increase was not required. Thus, this participant predicted the object weight quite well immediately after the weight transition in the coupled and informed conditions, but not in the solo1 condition. For the first 2 N lifts, the lift height records differed considerably across conditions. As expected, in the solo1 condition, a strong overshoot in lift height was observed, indicating that the participant was fooled by the decrease in weight. However, in the coupled and informed conditions, the maximum lift height was similar to that seen in the second and last lifts of both the 2 N and 7 N weights, indicating that participants predicted the weight quite well.

The left panels of Fig. 3 show, for each condition, cumulative distributions of initial peak LF rates across the six first 7 N lifts performed by each participant in each condition. The right panels of Fig. 3 show corresponding distributions of maximum lift height across the six first 2 N lifts. On average (see gray vertical lines), peak LF rates in 7 N lifts were greater and maximum lift heights in 2 N lifts smaller, in the coupled and informed conditions compared to the two solo conditions. Of particular interest is whether, in the coupled condition, the apparent benefits of observing the actor are sporadic (i.e., seen in some first 2

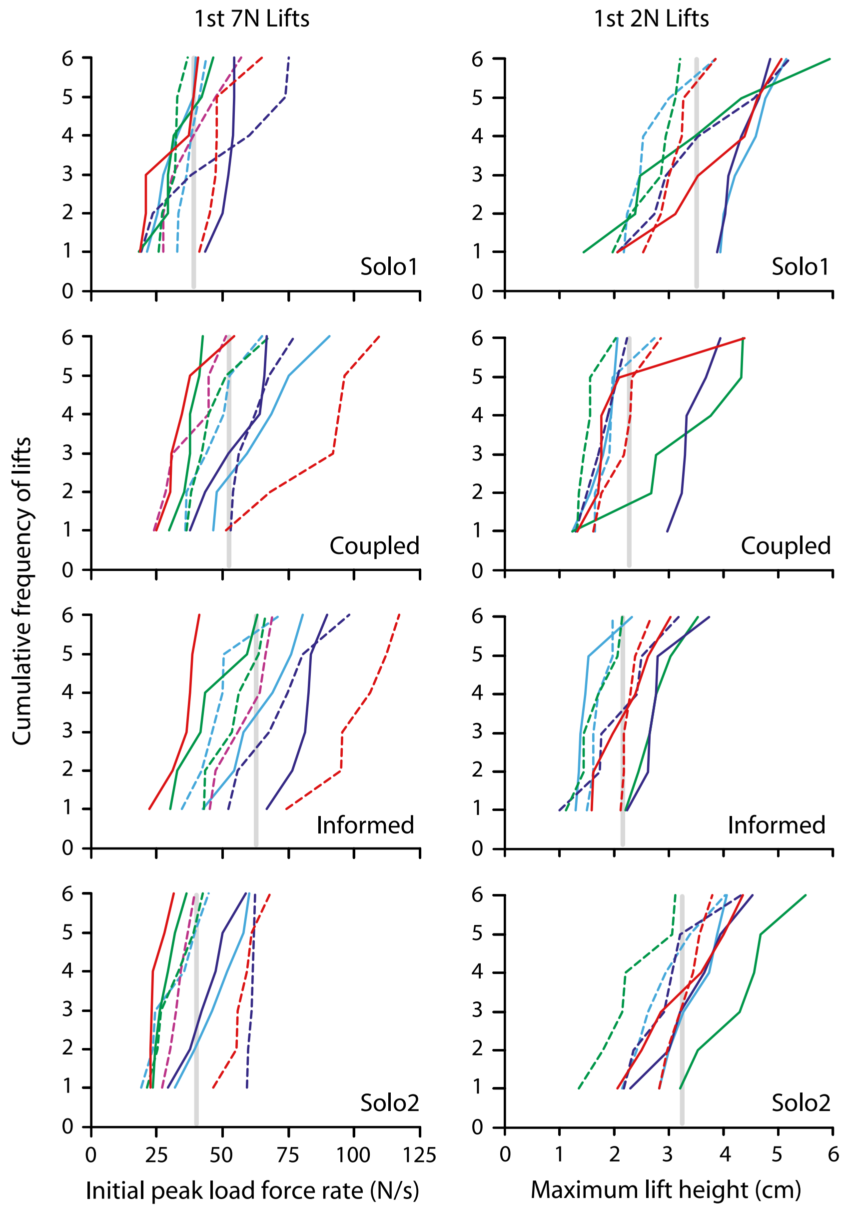

Fig. 3 Distributions of initial peak LF rates and maximum lift heights. The *left panels* show cumulative distributions of peak LF rate for the first 7 N lifts, and the *right panels* show cumulative distributions of maximum lift height for the first 2 N lifts. Separate distributions are shown for each participant in each condition. Each participant is represented by a consistent *line color* and type in all plots. The *gray vertical lines* indicate the mean value, average across all trials and participants, in each condition

and 7 N lifts, but not others). An example is provided by the participant represented by the solid red lines, who generated a relatively large lift height in one of the six first 2 N lifts. However, overall the spread of peak LF rates and maximum lift heights across blocks for a given participant appeared to be no greater in the coupled condition than in other conditions. To assess this issue quantitatively, we computed, for each participant and condition, the standard deviation of the peak LF rates and maximum lift height in first 7 N and first 2 N lifts, respectively. Repeated measures ANOVA failed to reveal significant differences in the SD of peak LF rates among the four conditions ($F_{3,24} = 2.05$; $p = 0.133$). In contrast, a significant effect of condition was observed for the SD of maximum lift heights ($F_{3,21} = 3.09$; $p = 0.049$). Corrected pairwise comparisons revealed a reliable difference in the SD of maximum lift heights between the informed and solo2 conditions ($p = 0.014$); however, no other differences between pairs of conditions were observed ($p > 0.018$ in all 5 cases).

Load force scaling when lifting the 7 N object

Figure 4a shows, for all four conditions, mean peak LF rate, averaged across participants, for the last 2 N lift and the first, second, and last 7 N lifts. For the last 2 N lifts, corrected pairwise comparisons failed to reveal any significant differences between conditions ($p \geq 0.32$ for all 6 comparisons). For the first 7 N lifts, corrected pairwise comparisons revealed significant differences between all four conditions with the exception of the solo1 and

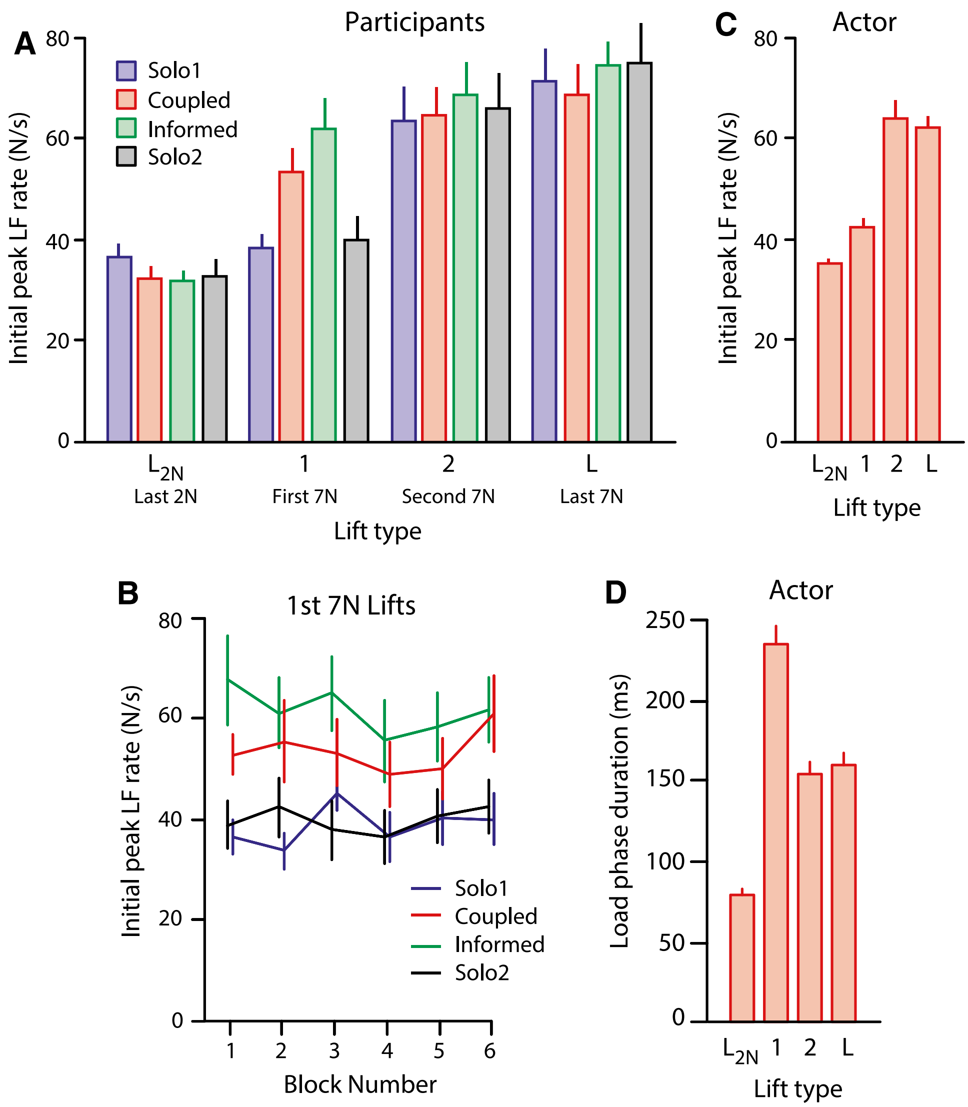

Fig. 4 Average LF results. **a** Mean initial peak LF rate, averaged across participants, for the last 2 N lifts (L_{2N}) and the first (1), second (2), and last (L) 7 N lifts in each condition. **b** Mean initial peak LF rate for the first 7 N lifts as a function of block number and condition. **c** Mean initial peak LF rates for the actor, averaged across sessions, for the four lift types in the coupled condition. **d** Mean load phase duration, averaged across sessions, for the four lift types performed by the actor in the coupled condition. **a**–**d** *Error bars* represent 1 SE based on participant means

solo2 conditions (solo1 vs. coupled, $p = 0.025$; solo1 vs. informed, $p = 0.004$; solo1 vs. solo2, $p = 0.73$; coupled vs. informed, $p = 0.020$; coupled vs. solo2, $p = 0.006$; informed vs. solo2, $p = 0.002$). This finding indicates that participants in the coupled condition used visual cues, obtained by watching the actor's first lift of the 7 N weight, to scale LF predictively when subsequently lifting the object. However, this scaling was not as strong as in the informed condition in which participants were told that the weight was heavy. Similar corrected pairwise comparisons performed for the second 7 N lifts and for the last 7 N lifts failed to show significant differences between conditions ($p \geq 0.71$ for all 12 comparisons).

We also examined differences in initial peak LF rate between the four different lift types for each condition. For the coupled condition, corrected pairwise comparisons revealed significant differences between all conditions ($p \leq 0.015$) with one exception; no difference between the second and last 7 N lifts was seen ($p = 0.20$). For the informed condition, significant differences were observed between all pairs of conditions ($p \leq 0.015$) with two exceptions; there was no difference between the first and second 7 N lifts ($p = 0.18$) or between the second and last 7 N lifts ($p = 0.19$). For the solo1 condition, there was no difference between the last 2 N lifts and the first 7 N lifts ($p = 0.22$), but all pairwise comparisons were significant ($p < 0.003$ in all 5 cases). For the solo2 condition, the peak LF rate was slightly but significantly greater in the first 7 N lifts than in the last 2 N lifts ($p = 0.007$) and all other pairwise comparisons were also significant ($p \leq 0.011$).

Note that an increase in peak LF rate from the last 2 N lift to the first 7 N lift was also seen in lifts performed by the actor in the coupled condition (Fig. 4c). It is important to appreciate that this increase does not imply that participants, or the actor, anticipated the increase in weight. Although the initial peak LF rate typically occurs before lift-off when the weight of the object can be well predicted from previous lifts, in some trials, the initial peak can occur around or just after the time of lift-off. Because lift-off leads to an abrupt cessation of LF increase (Johansson and Westling 1988), these later peaks will be smaller than they would be in trials in which the weight is unexpectedly heavy (such that lift-off does not occur). Importantly, lift-off does not lead to an abrupt cessation of grip force increase (Johansson and Westling 1988). Therefore, a key test of whether participants (in the solo conditions) or the actor (in the coupled condition) anticipated the increase in weight is whether peak GF rate increased from the last 2 N lift to the first 7 N lift. As we will show below, no such increase was observed, indicating that participants and the actor did not anticipate the switch from the 2 N to the 7 N weight.

Figure 4b shows, for each condition, mean peak LF rate, averaged across participants, for the first 7 N lifts in each of the six consecutive blocks of lifts performed with 7 N weight. Two-way repeated measures ANOVA revealed a significant effect of condition ($F_{3,\ 24} = 19.8$; $p < 0.001$), but no effect of block number ($F_{5,\ 40} = 1.34$; $p = 0.268$) and no interaction between condition and block number ($F_{15,\ 125} = 0.87$; $p = 0.599$). These results indicate that, within each condition, performance was stable across the session. Accordingly, the beneficial effect of action observation on force scaling in the coupled condition was present the first time the participant lifted the 7 N weight.

We also analyzed the behavior of the actor because we were interested in which cues the participants might have used to obtain information about the object weight from observing the actor. Figure 4c shows the actor's mean peak LF rate for the last 2 N lift and the first, second, and last 7 N lifts in the coupled condition based on the average of means computed for each experimental session (i.e., participant). As expected, the peak LF rate in the first 7 N lift was similar to that observed in the participants' solo conditions (Fig. 4a). Corrected pairwise comparisons indicated that, for both the first 7 N lift and the last 2 N lift, peak LF rate was smaller than for either the second or last 7 N lifts ($p \leq 0.001$ in all four cases), but did not differ significantly between the latter lift types. In addition, the peak LF rate was slightly but significantly greater in the first 7 N lift than in the last 2 N lift ($p = 0.004$). As noted above, this small increase in peak LF rate can arise because of biomechanical factors. These results indicate that the actor predicted a 2 N weight on the first 7 N lift but updated the weight prediction efficiently after a single lift.

One obvious cue about object weight that participants could have obtained by observing the actor is the duration of the load phase; that is, the period during which LF is increased prior to lift-off. Prolongation of the load phase typically occurs in trials when the lifter underestimates object weight because the increase in LF does not result in lift-off and additional increases in LF are required to achieve lift-off (Johansson and Westling 1988; c.f. gray curves in Fig. 1d). Figure 4d shows mean load phase duration, averaged across sessions, for the actor's last 2 N lifts and the first, second and last 7 N lifts in the coupled condition. Corrected pairwise comparisons between the four lift types failed to indicate significant difference in load phase duration between the second and last 7 N lifts. However, all other comparisons were significant ($p < 0.001$). The mean load phase duration for the first 7 N lifts was approximately 150 ms longer than for the last 2 N lifts. Likewise, the first 7 N lifts had longer load phase than the subsequent lifts in the 7 N blocks.

Grip force scaling when lifting the 7 N object

Although we were primarily interesting in adaptation of load forces through action observation, for completeness, we also examined the adaptation of grip forces. Figure 5 shows, for all four conditions, mean peak GF rate, averaged across participants, for the last 2 N lift and the first, second, and last 7 N lifts. For the first 7 N lifts, corrected pairwise comparisons revealed a marginally significant difference between the solo1 and coupled conditions ($p = 0.054$) and a significant difference between the solo2 and the coupled condition ($p = 0.023$). Significant differences between each of the solo conditions and the informed conditions were also observed (solo1 vs. informed, $p = 0.024$; solo2 vs. informed, $p = 0.017$). However, no differences were seen between the two solo conditions ($p = 0.18$) or between the coupled and informed conditions ($p = 0.10$). These findings are consistent with the idea that participants in the coupled condition used visual cues, obtained by watching the actor's first lift of the 7 N weight, to scale their fingertip force when subsequently lifting. Similar corrected pairwise comparisons performed separately for the last 2 N lifts, the second 7 N lifts, and for the last 7 N lifts failed to show significant effects between conditions ($p \geq 0.72$ for all 18 comparisons).

We also examined differences in peak GF rate between the four different lift types for each condition. For both the coupled and informed conditions, corrected pairwise comparisons revealed a significant difference between the last 2 N lifts and the three 7 N lifts ($p \leq 0.029$ in all six cases), but no differences between the three 7 N lifts ($p \geq 0.38$ in all six cases). For both of the solo conditions, corrected pairwise comparisons revealed that peak GF rate in both the last 2 N lifts and the first 7 N lifts were significantly smaller than in both the second and last 7 N lifts ($p \leq 0.002$ in all eight cases). However, in both the solo1 and solo2 conditions, there was no difference between the last 2 N lifts and the first 7 N lifts or between the second and last

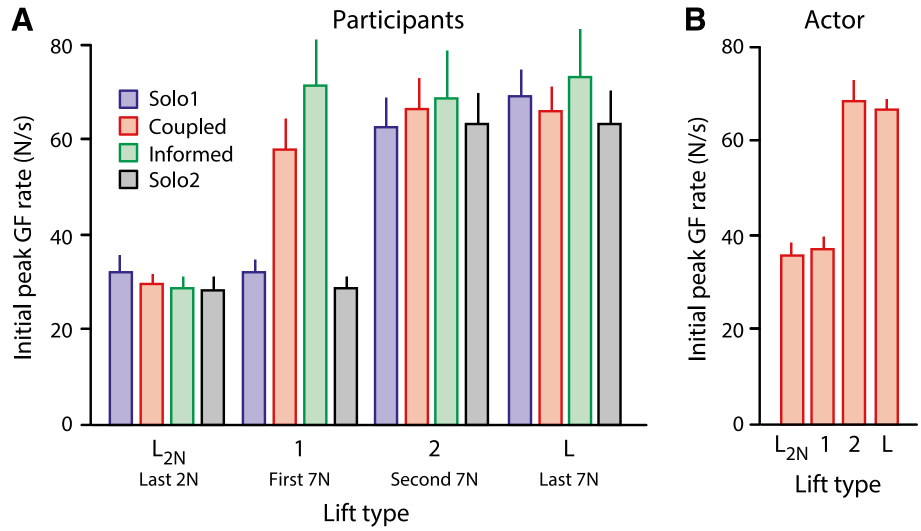

Fig. 5 Average GF results. **a** Mean initial peak GF rate, averaged across participants, for the last 2 N lifts (L_{2N}) and the first (1), second (2), and last (L) 7 N lifts in each condition. *Error bars* represent 1 SE based on participant means. **b** Mean initial peak GF rates for the actor, averaged across sessions, for the four lift types in the coupled condition

7 N lifts ($p \geq 0.17$ in all 4 cases). The fact that peak GF rate did not increase from the last 2 N lift to the first 7 N lift in the two solo conditions indicates that participants did not anticipate the change in weight. The finding that peak GF rate significantly increased from the last 2 N lift to the first 7 N lift in the coupled condition (as it did in the informed condition) further indicates that participants benefitted from observing the actor.

Figure 5b shows the actor's mean peak GF rate for the last 2 N lifts and the first, second, and last 7 N lifts in the coupled condition based on the average of means computed for each experimental session (i.e., participant). As expected, the peak GF rate in the first 7 N lifts was similar to that observed in the participants' solo conditions (Fig. 5a). Corrected pairwise comparisons indicated that, for both the first 7 N lifts and the last 2 N lifts, peak LF rate was smaller than for either the second or last 7 N lifts ($p \leq 0.001$ in all four cases). However, no significant differences were observed between the first 7 N lifts and the last 2 N lifts ($p = 0.90$) or between the second and last 7 N lifts ($p = 0.48$). These results indicate that the actor predicted a 2 N weight on the first 7 N lift but updated the weight prediction efficiently after a single lift.

Maximum lift height when lifting the 2 N object

As outlined above (see "Methods"), using peak LF rate to assess load force scaling on the first 2 N lifts following blocks of 7 N lifts is problematic. However, we can indirectly assess load force scaling by examining the height of the lift. Figure 6a shows, for all four conditions, mean maximum lift height, averaged across participants, for the last 7 N lift and the first, second, and last 2 N lifts. For the last 7 N lifts, corrected pairwise comparisons failed to reveal any significant differences between conditions ($p \geq 0.13$ for all 6 comparisons). For the first 2 N lifts, corrected pairwise comparisons revealed that each solo condition was significantly different than both the coupled and informed conditions (solo1 vs. coupled, $p = 0.011$; solo1 vs. informed, $p = 0.005$; solo2 vs. coupled, $p = 0.004$; solo2 vs. informed, $p = 0.001$). However, no differences were seen between the two solo conditions ($p > 2$, note that p values adjusted by the Holm–Bonferroni test can exceed 1) or between the coupled and informed conditions ($p = 0.53$). These finding indicates that participants in the coupled condition used visual cues, obtained by watching the actor's first lift of the 2 N weight, to scale LF predictively when subsequently lifting. This predictive scaling in the coupled condition appears to be as strong as in the informed condition in which participants were told that the weight was light. Similar corrected pairwise comparisons performed for the second 2 N lifts and for the last 2 N lifts failed to show significant effects between conditions ($p \geq 0.13$ for all 12 comparisons).

We also examined differences in maximum lift height between the last 7 N lift and the first, second, and last 2 N lifts for each condition. For the coupled condition, corrected pairwise comparisons failed to reveal any differences between lift types ($p \geq 0.064$ in all 6 cases). For the informed condition, the maximum lift height was greater for the first 2 N lifts than for the second 2 N lifts ($p = 0.020$), but no other differences were seen ($p \geq 0.22$ in all 5 cases). For both solo conditions, the maximum lift height was greater for the first 2 N lifts than for the three other lifts ($p < 0.001$ in all 6 cases), but no other significant differences were observed ($p \geq 0.08$ in all 6 cases).

Figure 6b shows, for each condition, maximum lift height, averaged across participants, for the first 2 N lifts in each of the six consecutive blocks of lifts performed with the 7 N weight. Two-way repeated measures ANOVA

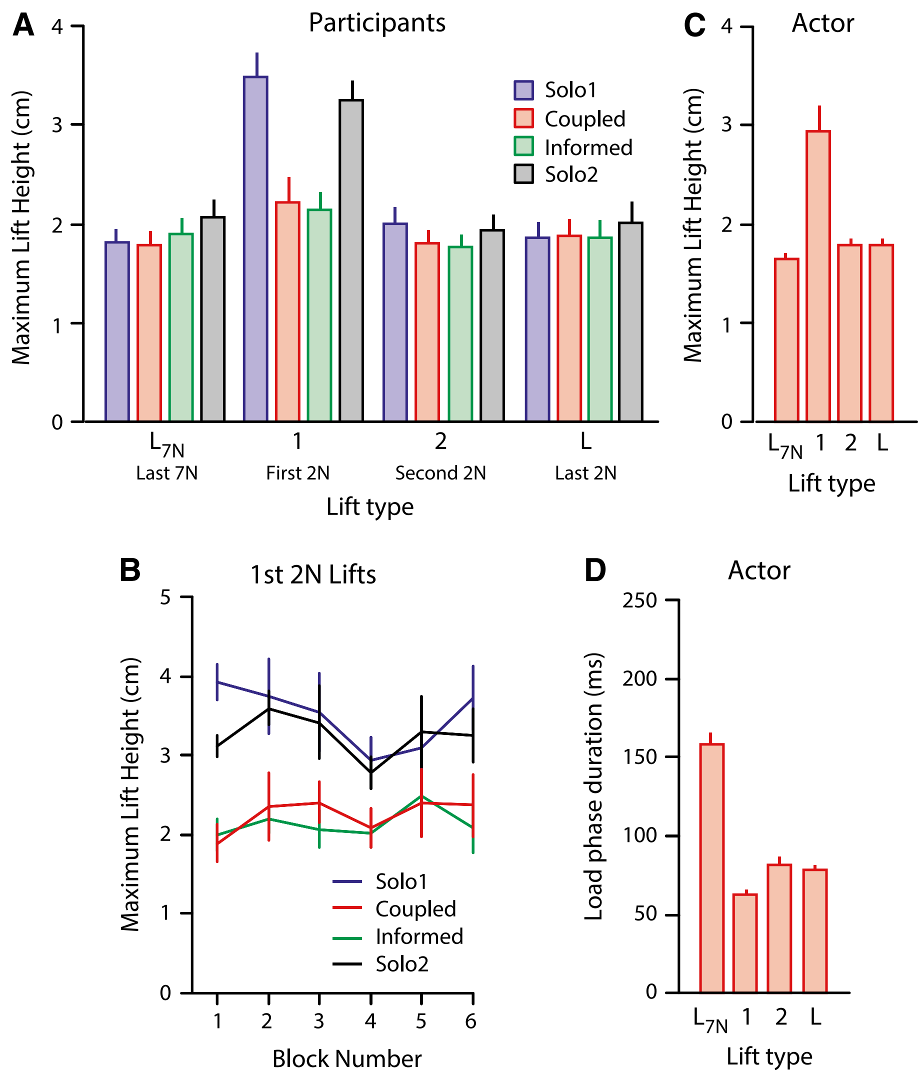

Fig. 6 Average lift height results. **a** Mean maximum lift height, averaged across participants, for the last 7 N lifts (L_{7N}) and the first (1), second (2), and last (L) 2 N lifts in each condition. **b** Mean maximum lift height for the first 2 N lifts as a function of block number and condition. **c** The actor's mean initial peak LF rates for the actor, averaged across sessions, for the four lift types in the coupled condition. **d** Mean load phase duration, averaged across sessions, for the four lift types performed by the actor in the coupled condition. **a**–**d** *Error bars* represent 1 SE based on participant means

revealed a significant effect of condition ($F_{3,\ 21} = 22.4$; $p < 0.001$), but no effect of block number ($F_{5,\ 35} = 1.68$; $p = 0.166$) and no interaction between condition and block number ($F_{15,\ 105} = 1.16$; $p = 0.311$). These results indicate that, within each condition, performance was stable across the session. Accordingly, the beneficial effect of action observation on force scaling in the coupled condition was present the first time the participant lifted the 2 N weight.

Figure 6c shows the actor's mean maximum lift height for the last 7 N lifts and for the first, second, and last 2 N lifts in the coupled condition based on the average of means computed for each experimental session (i.e., participant). Corrected pairwise comparisons indicated that maximum lift height was greater for the first 2 N lift than the last 7 N lift ($p = 0.001$), the second 2 N lift ($p = 0.002$), and the last 2 N lift ($p = 0.002$) but did not differ significantly between the latter lift types. These results indicate that the actor predicted a 7 N weight on the first 2 N lift but updated the weight prediction efficiently after a single lift.

The results shown in Fig. 6c indicate that participants could have obtained information about the weight of the object lifted by actor from the lift height, which was over 50 % larger on the actor's first 2 N lift than on the actor's previous 7 N lift. We would also expect the duration of the load phase of the actor's lift to decrease on first 2 N lifts since the object would lift off sooner than expected. Figure 6d shows the actor's mean load phase duration, averaged across sessions, for the last 7 N lift and for the first, second, and last 2 N lifts in the coupled condition. Corrected pairwise comparisons between the four lift types revealed that load phase duration was greater for the last 7 N lift than for all 2 N lifts ($p < 0.001$ in all 3 cases), that load phase duration was smaller for the first 2 N lift than the second ($p = 0.023$) and last ($p = 0.020$) 2 N lifts, and that there was not difference between the second and last 2 N lifts. The mean load phase duration for the first 2 N lifts was approximately 100 ms longer than for the last 7 N lifts, and therefore, load force duration may have been an effective cue indicating that the weight lifted by the actor had decreased.

In summary, our results indicate that in the coupled condition, participants gained information from observing the actor's lifts and used this information to adapt their motor output when the weight of the object changed. Overall, this adaptation was almost as strong as when participants were verbally informed about the weight change. The adaptation seen in the coupled condition was consistent throughout the experimental session, including the first lift of the 7 N weight following the initial block of lifts of the 2 N weight and the first lift of the 2 N weight following the initial block of lifts of the 7 N weight.

Discussion

Our results clearly support our hypothesis that participants extract information about object weight when observing another person lift an object and that they make use of this information when they subsequently interact with the object. Specifically, we demonstrate that when lifting weights previously lifted by another person, people naturally (i.e., without explicit instruction) extract information about weight. Moreover, they use this information effectively when scaling lifting forces. Therefore, this result extends previous work showing that people can make relative judgments about weights lifted by others (e.g., Runeson and Frykholm 1981; Bingham 1987; Shim and Carlton 1997; Hamilton et al. 2007).

Our results are broadly consistent with those reported by Meulenbroek et al. (2007) but show a stronger effect of action observation on lifting performance. These authors examined pairs of participants performing trials in which one participant (corresponding to the actor in our study) lifted an object and placed it into a shared workspace and the second participant then lifted and retrieved the object. They determined, for both placers and retrievers, the change in lift height, relative to the previous trial, in trials in which the weight was unexpectedly changed. When the weight was unexpectedly light, a marked increase in lift height was seen in both placers and retrievers, but the increase was slightly smaller in retrievers. In contrast, we found what appears to be a much stronger benefit of action observation. Specifically, in first 2 N lifts in the coupled condition, we found that whereas the actor's lift height increased substantially (as expected), participants' lift heights were not reliably greater than their lift heights in their previous lifts (i.e., the last 7 N lifts). Meulenbroek et al. (2007) also reported a modest benefit of action observation in trials in which the object was unexpectedly heavy. However, the latter result is somewhat unclear because, in the previous trial, lift height was greater in placers than retrievers. Moreover, lift height is not an ideal measure of expected weight in trials in which weight is unexpectedly increased because it will be affected by corrective actions taken when the object does not lift off at the expected time (Johansson and Westling 1988). In the current study, we used the initial peak rate of change of load force, which occurs prior to lift-off, to assess expected weight in trials in which weight was unexpectedly increased. Again, we found a very robust effect of action observation. Specifically, in first 7 N lifts in the coupled condition, participants (unlike the actor) exhibited a marked increase in peak load force rate that was almost as strong as when participants were verbally informed about the weight change. Several factors may have contributed to the stronger effects of action observation seen in the current study in comparison with the previous study by Meulenbroek et al. (2007). In the previous study, four different objects were used, which varied in both weight (230 or 835 g) and size (25 cm high cylinders with diameters of 2.5 or 6.5 cm), and the cylinder was changed every 3 trials. Thus, the participants presumably knew when a weight change might occur. Moreover, as the authors showed, size affected lift height independently of weight.

Our findings complement work by Mattar and Gribble (2005) demonstrating that adaptation of point-to-point movements of a handheld object that exerts a novel and unusual load on the hand can be enhanced (or impaired) by first observing an actor performing the task under the same (or opposite) load conditions. These authors found that action observation had a small but significant effect on initial performance, but that hundreds of trials were still required for full adaptation (as in the control condition without action observation). In contrast, we found that action observation had a dramatic effect on initial performance such that performance was close to being completely adapted on the first lift in the coupled condition. This difference can be expected from the two-component model of skill learning outlined in the Introduction. In the Mattar and Gribble (2005) study, full adaptation would have required observers to learn both the structure and parameters of the load because both the equations of motion of the load and the parameters of these equations were novel (Braun et al. 2009; Wolpert and Flanagan 2010). However, in the current study, only parametric learning was required because the participants were familiar with the structure (i.e., equations of motion) of the load. That is, our participants only had to adapt, via action observation, their force output to changes in object weight (or mass). Note that by using the term "parametric learning," we do not mean that observers learn the precise weight parameters. Rather, we are referring to the fact that they gain information about a parameter (i.e., weight) of an object with familiar dynamics.

When lifting objects, people scale their fingertip forces to the expected weight of the object and also generate a prediction about when they will receive sensory events signaling lift-off, including discrete tactile signals from mechanoreceptors in the hand that are sensitive to mechanical transient events (Westling and Johansson 1987). When an object is heavier or lighter than expected, sensory events signaling lift-off do not occur at the predicted time and the resulting mismatch between predicted and actual sensory events triggers task-protective corrective actions. For example, when the object is heavier than expected, the absence of the predicted sensory events signaling lift-off triggers a corrective action that involves probing increases in vertical load force (Johansson and Westling 1988; Wolpert and Flanagan 2001). This mismatch between predicted and actual sensory events also leads to an updating of memory related to object weight, which improves future motor output and sensory predictions (Flanagan et al. 2006; Johansson and Flanagan 2009).

It has been suggested that such error-based learning, which is a critical component of motor learning through practice (Wolpert et al. 2001; Shadmehr et al. 2010), may also underlie motor learning through observation (Wolpert et al. 2003; Mattar and Gribble 2005; Oztop et al. 2005; Brown et al. 2010). In a follow-up to the Mattar and Gribble (2005) study, Brown et al. (2010) showed that motor learning via observation is best when observers view movements with large errors. Based on the current results, we suggest that when watching another person lift an object, observers update information about the object's weight by predicting when the object will lift off and comparing this time to the viewed lift-off time. Of course, participants may also predict and evaluate other aspects of the actor's lift such as lift speed and height. For example, when an object is lighter than expected, the height of the lift will typically increase and the earlier-than-expected lift-off triggers a corrective action that brings the object back to the intended height (Johansson and Westling 1988). Moreover, observers can use other cues, such as hand shape, to estimate the weight of objects lifted by others (Alaerts et al. 2010b). In general, actors might also provide other facial or even verbal cues about unexpected weight changes when lifting objects. However, the actor used in the current study was instructed not to make any facial expressions and to act in a consistent manner throughout each experimental session. Moreover, previous work has shown that when watching another person perform an object manipulation task, observers direct their gaze at the objects as they are grasped and lifted and rarely look elsewhere (Flanagan and Johansson 2003; Falck-Ytter et al. 2006; Rotman et al. 2006; Webb et al. 2010).

One way in which observers may generate predictions about lift performance, including lift-off time, would be to covertly simulate the observed action in approximate synchrony with the actor (Iacoboni et al. 1999, 2001; Rizzolatti et al. 2001; Wolpert et al. 2003; Rizzolatti and Craighero 2004; Rizzolatti and Fabbri-Destro 2008). Behavioral evidence in support of this possibility comes from studies of observers' gaze behavior when watching object manipulation tasks. When watching an actor perform a block-stacking task, observers' gaze fixations closely resemble those of the actor in both space and time (Flanagan and Johansson 2003; Rotman et al. 2006). Specifically, observers, like actors, proactively fixate blocks that the actor is reaching for in order to grasp, and locations where the actor is reaching, with the block in hand, to place the block. It has been argued that, in action, task-specific eye movements are called by the motor plan such that they provide task critical visual (and proprioceptive) information at the appropriate times (Land and Furneaux 1997). If observers run a covert sensorimotor plan when watching action, then task-specific eye movements that are similar to the actor's would be expected.

Support for the idea that observers of action activate sensorimotor representations is also provided by neurophysiological studies showing that sensorimotor areas and circuits engaged when performing an action task are also recruited when observing the task (Rizzolatti et al. 2001; Rizzolatti and Craighero 2004; Malfait et al. 2010). Of particular relevance to the current work is recent results based on transcranial magnetic stimulation indicating that motor cortex facilitation in observers is specific to the muscles used by an actor lifting objects and scales with the force applied to the objects, that is, to object weight (Alaerts et al. 2010a, b). However, whether action simulation is used to generate predictions about observed action remains a matter of active debate (e.g., Brass et al. 2007; Aglioti et al. 2008; Hesse et al. 2009).

Because participants only lifted two weights (i.e., the 2 and 7 N weights), it seems likely that, in the informed condition, they learned to use the verbal information about the change in weight to access sensorimotor memory of these two weights. The fact that their lifting performance on the very first weight change in the informed condition was quite accurate suggests they may have assumed that the weights would be the same as in the prior conditions. In principle, in the coupled condition, participants could have also remembered the two weights, or the lift forces required to lift them, and then used visual information from the actor's lift in the coupled condition to select the appropriate memory. Alternatively, in the coupled condition, participants could have directly estimated object weight (or the change in object weight) by simulating the actor's lifts and comparing predicted and actual performance parameters (e.g., lift height and load phase duration). One argument against the former possibility is that, whereas participants anticipated weight changes in the coupled condition, they continued to adapt load force in subsequent lifts, indicating that they did not fully adapt load force on the first lift of the new weight. However, it is also possible that participants were simply being conservative in terms of changing their force output given uncertainly about the weight.

In summary, our results indicate that people naturally encode information related to object weight when watching another person lift objects. That is, in the coupled condition, participants exploited visual information from the actor's lifts to adapt their motor output to the weight of the object to be lifted despite the fact that they were not informed about the structure of the experiment (i.e., the fact that they would lift the same sequence of weights as the actor). Moreover, this adaptation occurred right from the start. That is, in the coupled condition, participants effectively adapted their force output the first time they watched the actor lift the 7 N weight after the initial block of lifts of the 2 N weight and the first time they watched the actor lift the 2 N weight after the first block of lifts of the 7 N weight. The efficacy of this predictive adaptation is presumably context-specific and may depend on the likelihood that the observer will be required to lift the object as well as on their level of engagement and attention. In our experiments, we used a single object and two weights, and this may have facilitated parameter learning through action observation. In future work, we plan to investigate such learning in situations with multiple weights and multiple objects.

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