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Second-order grasp planning reflects sensitivity to inertial factors

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ABSTRACT

Previous studies have shown that people's grasps of objects are tuned to the objects' inertial properties. In most of those studies, information obtained about the attunement of the grasps to the objects' inertial properties was limited to *first-order* grasp planning (i.e., planning of grasps based on immediate task demands). We investigated attunement of grasps to an object's inertial properties in the context of *second-order* grasp planning (i.e., planning of grasps based on subsequent task demands). In Experiment 1, participants grasped a horizontal rod whose right or left end would be brought down onto a target. Consistent with previous findings, participants grasped the rod so as to complete the movement with a thumb-up posture, using an overhand grasp when the right end of the rod was to be brought to the target and an underhand grasp when the left end was to be brought to the target. They also grasped the rod to the right of center, but more so when doing this with an underhand than when with an overhand grasp. In Experiment 2, participants performed the same task with an asymmetrically weighted rod. Changes in subjects' grasps in Experiment 2 compared to Experiment 1 suggested that participants grasped the rod based on the inertial properties of the rod in a way that took advantage of the pendular properties of the hand-plus-object.

1. Introduction

Consider someone grasping a hammer to pound a nail. The person will likely pick up the hammer by its handle with the radial (thumb) side of the hand toward the head, and s/he will grasp the handle closer to the bottom than the top. But if the same person picks up the same hammer not to pound a nail but instead to pull a nail out of a board with the hammer's claw, then s/he will pick up the hammer with the ulnar (little-finger) side of the hand toward the head and grasp it closer to the claw. If the hammer's appearance is identical in the two cases, the difference in behavior indicates that the manipulation does not just depend on how the hammer looks – an example of *first-order* grasp planning – but also on the actor's plan for what s/he intends to do with the hammer *after* it is picked up – an example of *second-order* grasp planning (Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012; see Wagman & Carello, 2003).

The choice of how and where to grasp an object affects how the mass of the object is distributed relative to the wrist and thus alters the mass distribution of the hand-object system. Such choices alter how easily the object can be controlled, and depend on the sensitivity of the actor to the inertial properties of the object and body (see Carello & Turvey, 2017). Insofar as grasping an object is an act that transforms a detached object into a hand-held tool (Gibson, 2014/1979), choosing how and where to grasp an object reflects sensitivity to the functionality of the ensemble of elements involved in the act (Wagman & Carello, 2003; Wagman & Taylor, 2004).

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Here, we investigated the extent to which participants are sensitive to the way grasp types and grasp locations alter the functionality of a hand-held object for a task in which the act of grasping the object had implications for the final position of the body well after initial contact with the object. We asked how grasp type and grasp location depended not just on the immediate lift of an object but also on the final position to which the object would be brought. Previous studies have looked at this question (Cohen & Rosenbaum, 2004; Rosenbaum, Marchak, Barnes, Vaughan, Slotta, & Jorgensen, 1990; Rosenbaum et al., 2012), but they have paid scant attention to the inertial properties of the object being grasped. What work has been done on the influence of inertial properties on grasps have concerned first-order grasp planning in relatively simple, "single-act" maneuvers like lifting an object with as little rotation as possible and putting the object back down again. Under such circumstances, participants show sensitivity to the inertial properties of the grasped object and the associated controllability of the hand-object system. For example, when attempting to minimize object rotations, people grasp objects with appropriate force and in appropriate locations on the object (Bingham & Muchisky, 1993; Bingham & Muchisky, 1995; Lederman & Wing, 2003; Wing & Lederman, 1998). Under similar task instructions, participants tend to grasp objects with greater variability of finger placement when they are more uncertain about the mass distribution of the object (Lukos, Ansuini, & Santello, 2007). Finally, people prospectively adjust fingertip forces based on experience lifting the objects or based on expectations about the objects' inertial properties (Gordon, Westling, Cole, & Johansson, 1993).

One study that did investigate the effect of inertial properties on second order grasp planning was by Wagman and Carello (2003). They found that participants chose to grasp an object closer to its center of mass when the participants were to perform a precision task (e.g., striking a small nail) than when the same participants were to perform a power task (e.g., pounding a large spike). Carrying forward the same general approach, in the two experiments reported here, rather than varying the nature of the grasp that was required (precision versus power), we focused only on the power grasp, asking how it would be oriented where it would be applied to a horizontal dowel that was lifted, rotated, and displaced so either its left or its right end would be brought down onto a target. We hypothesized that our university-student participants would be sensitive to how grasp choices (in terms of both grasp orientations and grasp location) would influence the mass distribution of the hand-object system and the subsequent functionality for completing the manipulation task.

In the first experiment, we investigated grasp choices for an object rotation and placement task when the object being lifted, rotated, and placed had an internally symmetric load (i.e., was of uniform density). In the second experiment, we investigated grasp choices for the same object rotation task when the object being lifted and turned had an internally asymmetric load, the side of which was externally (visibly) marked. We analyzed grasp type (overhand versus underhand grasps) and grasp locations in both experiments to quantify subjects' sensitivity to task constraints and the object's inertial properties.

We also analyzed grasp locations along the length of the rod to test an additional hypothesis about the grasps, namely, that our participants (all of whom used the right hand), would grasp the horizontal rod farther to the right when they used an underhand grasp than when they used an overhand grasp. The basis for this prediction was our expectation that our participants would grasp the rod so as to exploit its pendular properties. That is, they would grasp the rod so as to take advantage of the gravitational forces acting on it, thereby decreasing the muscular forces required to perform the rotation (cf. Bernstein, 1967; Rosenbaum, Chapman, Coelho, Gong, & Studenka, 2013). Grasping the rod more to the right when the rod was picked up with an underhand grasp meant that more of the rod's length (and therefore in this case, more of its mass) would fall below the axis of rotation at the grasp location. Similarly, grasping the rod more to the left (or less far to the right) when the rod was picked up with an *overhand* grasp meant again that more of the rod's length (and therefore in this case more of its mass) would fall below the axis of rotation at the grasp location. In short, grasping the rod to place more of the rods' length (and subsequently, mass) below the axis of rotation while the rod was being turned would make it easier to turn the rod. À la Bernstein (1967), who emphasized exploitation of, rather than opposition to, physical mechanics our participants would leverage gravitational forces during the rotation.

2. Experiment 1

In Experiment 1, our participants reached out and grasped a horizontal wooden rod (Fig. 1), rotated it 90°, and placed an end, specified before the reach, end down onto a target. The rod had a white end and a black end and was internally weighted such that the mass distribution was symmetric about the rod's center. Across trials, we varied the rod's initial orientation (i.e., which end was either to the participant's right or left at the start of the trial) and final orientation (i.e., which end of the rod was to be placed down onto the target at the end of the trial). The four possible pairs of initial and final object orientations were tested in a random order per participant.

We had four predictions. First, participants would show a strong preference for grasping the rod in such a way that they would exhibit a thumb-up orientation (Fig. 1A) rather than a thumb-down orientation (Fig. 1B) upon the completion of the rod transport. So we expected our participants to exhibit the so-called *end state* comfort effect (see Rosenbaum et al., 2012, for a review). This meant that when the right end of the rod would be placed down, the rod would be grasped with an overhand (palm facing down) grasp (assuming use of the right hand), but when the left end of the rod would be placed down, the rod would be grasped with an underhand (palm facing up) grasp (again assuming use of the right hand).

Our second prediction was that because the rod's center of mass was always at the rod's geometric center (30 cm from either end), the initial object orientation (i.e., which end was to the participant's right or left at the beginning of the trial) would not systematically influence the final grasp orientation. Therefore, participants would show strong preferences for the grasp choices described above regardless of how the rod was oriented in the cradle (i.e., which end was either to the participant's right or left at the start of the trial).

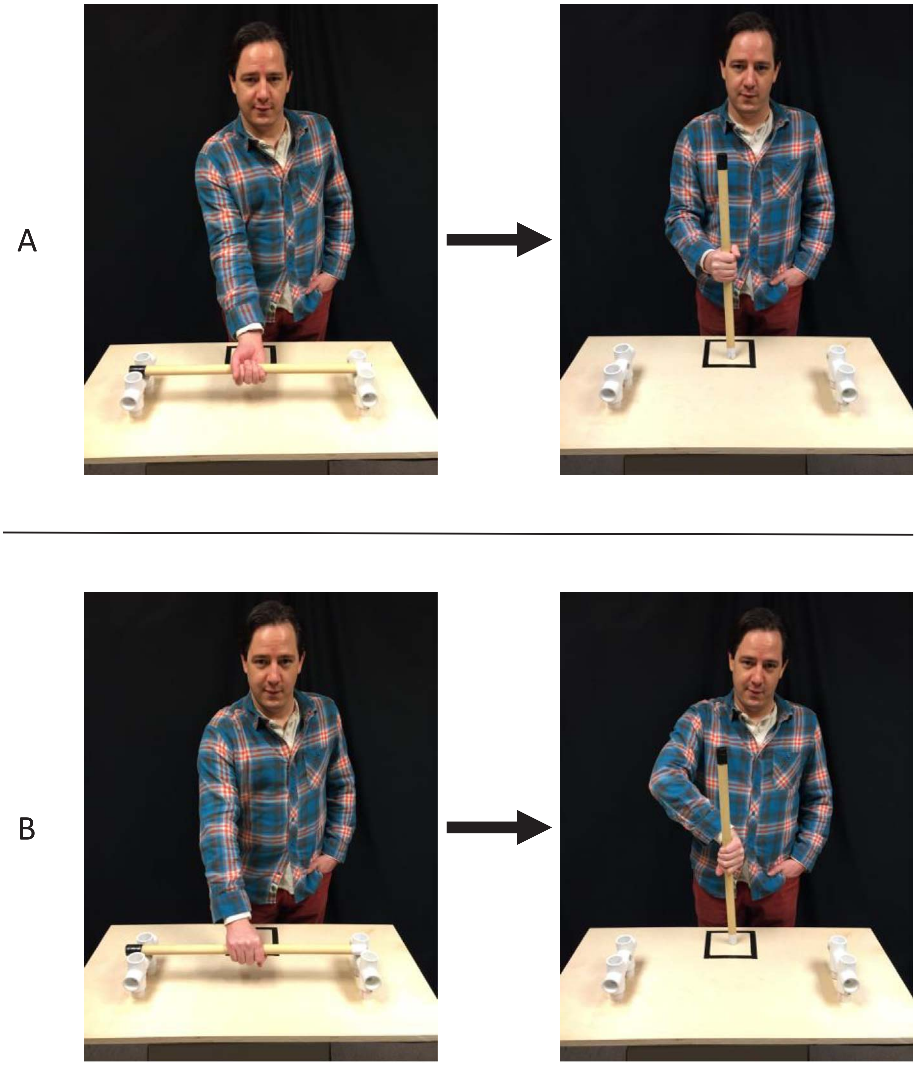

Fig. 1. The experimental apparatus and task. (A) A participant grasping the rod with an underhand grasp to complete the rotation with a thumb up (TU) grasp orientation. (B) The same participant grasping the rod with an overhand grasp to complete the rotation with a thumb down (TD) grasp orientation. Note: only one of the four conditions (black end to the participant's right; white end to be placed on the table) is shown here. The participant gave permission to have his face shown in these published photographs.

Our third prediction was about grasp location. Because the rod's center of mass was always at the rod's geometric center (30 cm from either end), the dynamics of rotating the rod would not change across changes in initial orientation. Therefore, we expected the average grasp location to remain constant but to become more stereotyped (less variable) across trials. In other words, participants would choose a grasp location that they found comfortable and continue grasping the rod at that location across trials.

Our fourth prediction was that participants would grasp the rod at a location that enabled them to exploit the pendular qualities of the rod. That is, participants (all of whom used the right hand), would grasp the horizontal rod farther to the right when they used an underhand grasp than when they used an overhand grasp.

2.1. Method

2.1.1. Participants

Twenty undergraduate students (4 men, 16 women) participated for extra credit in psychology courses at Illinois State University. Nineteen participants were right-handed, and one was left-handed, as judged by the Lateral Preference Inventory of Coren (1993). Given that our hypotheses were based on the assumption that participants would grasp and rotate the object with the right hand, data from the one left handed participant were excluded from the data analysis.

2.1.2. Materials and apparatus

Fig. 1 shows the rod that was used in Experiment 1. It was 60 cm long with a 1.27 cm radius, and was made of wood that was hollowed out (0.64 inner radius) and filled with metal pellets, then capped at both ends with two inserted dowels (each 22.5 cm long), leaving room for a 15 cm long column of pellets in the rod's interior (cf. Wagman & Carello, 2003). Critically for comparison with the next experiment, the center of mass of the rod coincided with the rod's geometric center (30 cm from either end of the object). The total mass of the rod was 344 g. One end was wrapped with black tape (5 cm wide). The other end was wrapped with white tape (also 5 cm wide).

The rod rested on two cradles that stood on a wooden table at which the subject stood As seen in Fig. 1, the cradles were constructed of PVC pipe and were secured to the table so they were parallel to each other, approximately 60 cm apart, and approximately at arm's length from the edge of the table where the participant stood. The target rectangle (15 cm × 15 cm) onto which the specified end of the rod was placed was framed with black duct tape near the edge of the table where the participant stood. The near edge of the target was approximately 2.5 cm from the edge of table closest to the participant. The target was centered with respect to the midpoint of the line joining the cradles.

A small piece of tape placed on the back of each participant's hand between the second and third knuckles was used to aid in measuring grasp location. Placement of the tape on the subject's hand was allowed by the subject. The procedure used in this experiment (and the subsequent experiment) was approved by the Illinois State University Institutional Review Board.

2.1.3. Procedure

The experimenter placed the rod on the cradle so the locations of the black and white ends of the object were appropriate for each forthcoming trial. The participant's task was to use his or her preferred hand (for all participants, the right hand, as said before) to pick up the rod from the cradle with a power grip (thumb wrapped around the object), turn the rod 90°, and place the specified end of the object (the black end or the white end) in the target such that the object was oriented vertically (see Fig. 1).

Before each trial, the experimenter instructed the participant to place either the black end or the white end down onto the target. Once the participant performed the task, he or she closed his or her eyes, as per instruction, and the experimenter recorded the final grasp orientation (a "thumb up" or "thumb down" grasp as described above) as well as the distance of the mark on the subject's hand from the table, which was defined as the grasp location. To measure grasp location, the experimenter placed one end of a meter stick on the table so it was parallel with the rod and recorded the vertical distance between the table and the tape mark on the participant's hand. Because the participant took hold of the rod and maintained his or her grasp until setting the rod back down on the target, we assumed that the grasp on the rod upon setting it down on the target was the same as the grasp upon lifting it from the cradles. While the experimenter placed the rod on the cradle for the next trial, the participant kept his or her eyes closed to minimize the chance that the experimenter's grasp and manipulation of the rod might bias the participant's behavior. Once the rod was placed on the cradles and the experimenter moved away from the apparatus, the participant was invited to re-open his or her eyes. Each participant experienced each combination of initial orientation and final object orientation six times in a random order (a total of 24 trials).

2.2. Results

2.2.1. Grasp orientation

Given our hypotheses about grasp orientation, we analyzed the grasp orientations in terms of the orientation of the hand after the specified end had been placed on the table. Final grasp orientations were coded as either thumb up (TU) or thumb down (TD).

Consistent with our predictions and the large body of previous research cited above, participants achieved a final TU orientation on a majority of trials. Final TU orientations were observed on 427 of 456 trials (93.64% of trials). Per participant, TU final grasps were observed, on average, in 22.5 of 24 trials. All twenty participants chose TU grasps more often than they did TD grasps. In fact, a majority of the participants chose a TU grasp on every trial.

We used the per-participant final-TU proportions to test two other hypotheses. One was that the proportion of final thumb-up orientations, henceforth p(TU), was at the chance level of 0.5. This hypothesis could be strongly rejected, $t(18) = 19.11$, $p < .001$, Cohen's $d = 4.38$. The other hypothesis was that p(TU) was perfect, or exactly 1. This hypothesis could also be rejected, $t(18) = 2.79$, $p < .05$, Cohen's $d = 0.64$.

We analyzed whether the likelihood of a final thumb up orientation depended on the initial or final orientation of the rod—-specifically, whether the left or right end had to be brought down onto the target. The null hypothesis was that there would be no difference when the *right* end had to be brought down onto the target or when the *left* end had to be brought down onto the target. Given that our primary dependent measure was dichotomous (TU vs. TD final grasp orientation), we conducted a linear mixed effects binomial regression with participant as a random effect. Coefficients are reported as odds ratios (ORs). The dependent variable measures the grasp position as equal to 1 for a final TU grasp orientation and equal to 0 for a final TU grasp orientation. Neither the main effect of Initial Object Orientation ($OR = 1.07$, ± 95% CI = [0.44, 2.60], $p = .88$) nor the main effect of Final Object Orientation was significant, $OR = 0.94$, ± 95% CI = [0.38, 2.28], $p = .88$. However, the interaction between Initial Object Orientation and Final Object Orientation interaction was significant ($OR = 7.70$, ± 95% CI = [1.29, 46.11], $p = .025$). These results show that (1) when the black end of the object was to the right of the participant, a final TU grasp orientation occurred more often when the black end was to be placed on the table than when the white end was to be placed on the table, and (2) when the white end was to the right of the participant, a final TU grasp orientation occurred more often when the white end was to be placed on to the target than when the black end was to be placed on to the target (see Fig. 2). Described another way, these results show that when the rod had to be picked up with an *overhand* grasp in order to bring the designated end of the rod (the right end) down onto the target,

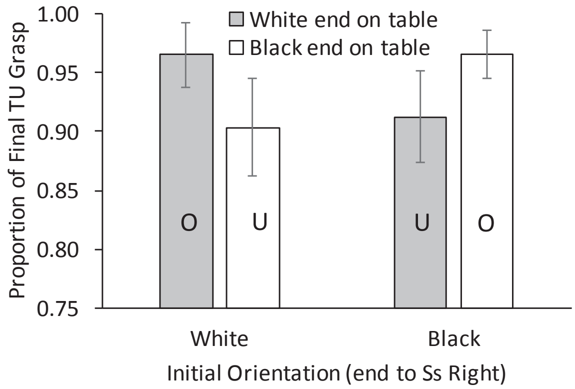

Fig. 2. Proportion of thumb-up grasp orientation as a function of initial and final object orientation. O indicates that the combination of initial and final orientation dictated an overhand grasp in Experiment 1. U indicates that the combination of initial and final orientation dictated an underhand grasp (assuming a right-handed participant). Error bars indicate standard error of the mean.

this action was completed nearly 100% of the time. By contrast, when the rod had to be picked up with an *underhand* grasp in order to bring the designated end of the bar (the left end) down onto the target, this action was completed somewhat less often (see Fig. 2).

2.2.2. Grasp location

We also analyzed the subjects' grasp locations on the rod (Fig. 3). Although we recorded the grasp locations when the rod was upright, we recoded these distances to reflect the distance between the tape mark placed on the hand and the left end of the rod at the time of lifting the rod, assuming, as stated above, that the grasp location on the rod remained constant between the time it was picked up and the time it was set on the target. Averaged across participants, conditions, and trials, the mean grasp location was 31.3 cm (SEM = 0.24 cm) from the left end of the 60 cm long rod, or 52.10% of the way toward the rod's right end.

To find out whether the grasp location depended on the initial and final orientation of the rod, we conducted a 2 (Initial Object Orientation: black end to right vs. white end to right) × 2 (Final Object Orientation: black end on table vs. white end table) analysis of variance (ANOVA) of the mean grasp location. The main effect of initial orientation was not significant, $F(1,18) = 0.637$, $p = .435$, $\eta_p^2 = 0.03$, but there was a marginally significant main effect of Final Object Orientation $F(1,18) = 3.83$, $p = .07$, $\eta_p^2 = 0.18$, and a marginally significant interaction of Final Object Orientation and Initial Orientation $F(1,18) = 2.89$, $p = .1$, $\eta_p^2 = 0.14$. As seen in Fig. 3, participants tended to grasp the object farther to the right when they grasped the rod with an underhand grasp than when they grasped the rod with an overhand grasp.

We calculated the mean grasp locations for the first half of the trials (trials 1–12) and the second half of the trials (trials 13–24) for each participant. A *t*-test revealed no difference between the grasp location in the first (M = 30.78 cm, SEM = 0.42) and second half of the trials (M = 30.63 cm, SEM = 0.43), $t(18) = 0.42$, $p = 0.68$, Cohen's $d = 0.10$. However, the variability (SD) of the grasp locations decreased from the first ($M = 2.40$ cm, SEM = 0.29) to the second half ($M = 1.71$ cm, SEM = 0.17), $t(18) = 2.37$, $p < .05$, Cohen's $d = 0.59$ (see Fig. 4). At the level of the individual participants, seventeen participants (85%) showed a decrease in variability in grasp position from the first half of the trials to the second half of trials; three of the participants did not.

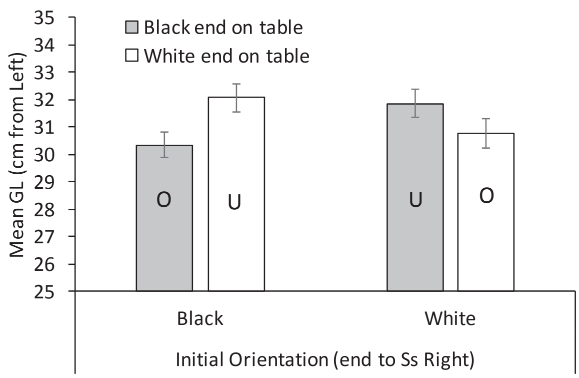

Fig. 3. Mean grasp location (measured from the participant's left) as a function of initial and final orientation. O indicates that the combination of initial and final orientation dictated an overhand grasp in Experiment 1. U indicates that the combination of initial and final orientation dictated an underhand grasp (assuming a right-handed participant). Error bars indicate standard error of the mean.

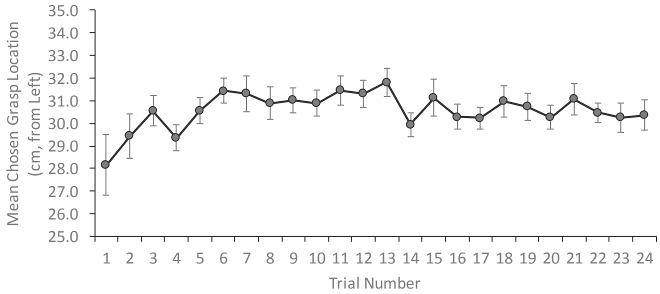

Fig. 4. Proportion of thumb-up grasps at time of task completion as a function of trial number in Experiment 1. Error bars indicate standard error of the mean.

2.3. Discussion

Consistent with our expectations and with previous research, we found in Experiment 1 that participants grasped the horizontal rod in a way that afforded a thumb-up final grasp orientation when the rod was lifted, rotated, and had its end placed on a horizontal surface (Rosenbaum et al., 2012). Our participants, all of whom used the right hand to perform the task, grasped the rod with an *overhand* grasp when the *right* end of the rod would be placed down onto the target and used an *underhand* grasp when the *left* end of the rod would be placed down onto the target.

Grasp *locations* became less variable over trials, as predicted. In addition, we obtained some evidence that participants grasped the rod farther to the right when they used an underhand grasp and brought the left end of the rod to the target than when they used an overhand grasp and brought the right end of the rod to the target. Although the *p* values of some of the relevant tests did not fall below the conventional threshold ($p < .05$) for statistical significance, we were wary about accepting the null hypothesis in these cases, especially in light of evidence to be presented in the next experiment where, essentially the same pattern appeared again.

3. Experiment 2

In Experiment 2, we asked participants to perform the same task as in Experiment 1 but with a rod that had an asymmetric mass distribution such that the center of mass was closer to one end of the rod (the white end) than the other. In all other respects, including the visual appearance of the rod, the object to be manipulation was identical to the one used in Experiment 1. As in Experiment 1, across trials we varied both the initial and final orientation of the rod. Consequently, the mass distribution of the rod (relative to the participant) varied from trial to trial. On a given trial, the center of mass was located either closer to the left (if the white end of the rod was to the left) or closer to the right (if the white end of the rod was to the right).

We had four predictions. First as in Experiment 1 and previous research (see Rosenbaum et al., 2012, for a review), we predicted that participants would show a strong preference for grasping the object in a way that afforded a final thumb-up grasp orientation.

Second, given the changing location of the center of mass and the resulting change in the dynamics of the rotating rod from trial to trial, we expected that initial and final rod orientation (either individually or in combination) to influence final grasp orientation. That is, unlike Experiment 1, grasp orientation would reflect how the changing mass distribution affected the dynamics of rotating the rod.

Our third prediction was about grasp location. Again, given the changing location of the center of mass and the resulting change in the dynamics of the rotating rod from trial to trial, we expected grasp location to depend more strongly on the initial and/or final orientation than it did in Experiment 1, when the rod's mass distribution was centered and constant. By virtue of what we found in Experiment 1 with respect to grasp location, we expected grasp location to be farther to the right for (right-hand) underhand grasps than for overhand grasps, but we expected this effect to be modulated by whether the weighted end was to the participant's right or left.

Fourth and finally, given the changing location of the center of mass and the resulting change in the dynamics of the rotating rod from trial to trial, we expected grasp location not to change in location or precision over trials.

3.1. Method

3.1.1. Participants

Twenty new undergraduate students (6 men; 14 women) participated in fulfillment of an extra credit option in their psychology courses at Illinois State University. All participants were right-handed as judged by the Lateral Preference Inventory (Coren, 1993)

3.1.2. Materials and apparatus

The rod used in Experiment 2 was identical to the one used in Experiment 1 except that the 15 cm column of metal pellets within the rod was not centered with the geometric center of the rod. This was achieved by filling the hollowed out portion with the column of metal pellets, capping one end of the rod (the end wrapped in white tape) with a 9.5 cm dowel, and capping the other end (the end wrapped in black tape) with a 35.7 cm rod (cf. Wagman & Carello, 2003). This created a 15 cm long column of pellets the center of which about its long axis was located 16.8 cm from white end of the 60 cm-long rod. (In Experiment 1, the center of the pellets was at

30 cm.) The total mass of the object was 344 g, as in Experiment 1. All other materials were identical to those used in Experiment 1.

3.1.3. Procedure

The procedure was identical to that of Experiment 1.

3.2. Results

3.2.1. Grasp orientations

Grasp orientations were coded as in Experiment 1. Consistent with our predictions and the results of Experiment 1, participants grasped the rod in a way that afforded final thumb-up orientations on a majority of trials. This was the case in 451 (94.0%) of the 480 trials. Nineteen participants chose TU grasps more often than they did TD grasps. The remaining participants chose an equal number of TU grasps as TD grasps. Again, a large majority of participants always chose a TU grasp on every trial. On a per-subject basis, p(TU) was 0.937, a level that was significantly different from 0.5, $t(19) = 13.54$, $p < .001$, Cohen's $d = 3.03$, and marginally different from 1, $t(19) = 1.79$, $p = .09$, Cohen's $d = 0.40$.

As in Experiment 1, we analyzed whether the likelihood of a final thumb-up orientation depended on the initial or final orientation of the rod. We did so by conducting a linear mixed effects binomial regression with participant as a random effect. The lack of variance in one of the factor combinations (i.e., when Initial Object Orientation was 'white' and Final Object Orientation was 'white') due to observing thumb-up grasp for 100% of trials inflated the odds ratios, so rather than reporting those ratios, we report the odds themselves. The main effects of Initial Object Orientation (*odds* = 161.73, ± 95% CI = [8.58, 314.88], $p = .04$) and Final Object Orientation (*odds* = 162.65, ± 95% CI = [9.50, 315.80], $p = .04$) were significant. However, these main effects were superseded by a significant interaction between Initial Object Orientation and Final Object Orientation interaction (*odds* = 355.00, ± 95% CI = [28.65, 641.34], $p = .03$).

As in Experiment 1, these results show that (1) when the black end of the object was to the right of the participant, a final TU grasp orientation was more likely when the black end was to be placed on the table than when the white end was to be placed on the table, and (2) when the white end was to the right of the participant, a final TU grasp orientation was more likely when the white end was to be placed on to the target than when the black end was to be placed on to the target (see Fig. 5).

3.2.2. Grasp locations

As in Experiment 1, grasp locations were recoded to reflect the distance between the tape mark placed on the hand and the left end of the rod at the time of lifting the rod (again assuming that the grasp location on the rod remained constant between the time it was picked up and the time it was set on the target). Averaged across participants, conditions, and trials, the mean grasp location was 30.9 cm (SEM = 0.18) from the left end of the 60 cm long rod, or 51.5% toward the rod's right end. A 2 (Initial Object Orientation: weighted end to right vs. unweighted end to right) × 2 (Final Object Orientation: weighted end on table vs. unweighted end on table) ANOVA was conducted on the mean grasp location. There was a main effect of Initial Orientation $F(1,19) = 5.82$, $p < .05$, $\eta_p^2 = 0.24$. Participants tended to grasp the object farther to the right when the weighted end was on the right ($M = 32.0$ cm, SEM = 0.32) than when the weighted end was on the left ($M = 31.1$ cm, SEM = 0.34). Neither the main effect of Final Orientation, $F(1,19) = 0.54$, $p = .47$ $\eta_p^2 = 0.03$, nor the interaction of Initial × Final Orientation $F(1,19) = 1.35$, $p = .26$ $\eta_p^2 = 0.07$ was significant (see Fig. 6).

Regarding practice and grasp locations (Fig. 7), mean grasp locations were calculated for the first half of the trials (trials 1–12) and for the second half of the trials (trials 13–24) for each participant. A *t*-test yielded no difference between grasp location in the first ($M = 30.9$ cm, *SEM = 0.79*) versus second half (M = 30.9 cm, *SEM = 0.83*), $t(19) = 0.12$, $p = .99$ Cohen's $d = -0.02$. A *t*-test also failed to yield a difference between the variability (SD) of grasp locations in the first ($M = 3.0$ cm, *SEM = 0.30*) and second halves of

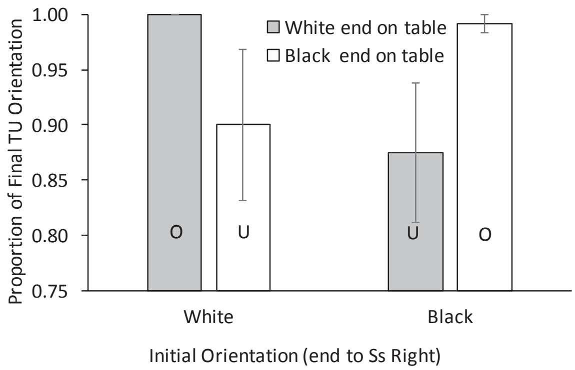

Fig. 5. Proportion of thumb-up grasps as a function of initial and final orientation. O indicates that the combination of initial and final orientation dictated an overhand grasp in Experiment 2. U indicates that the combination of initial and final orientation dictated an underhand grasp (assuming a right-handed participant). Error bars indicate standard error of the mean. The error bar was, necessarily, of length 0 when the proportion was 1.

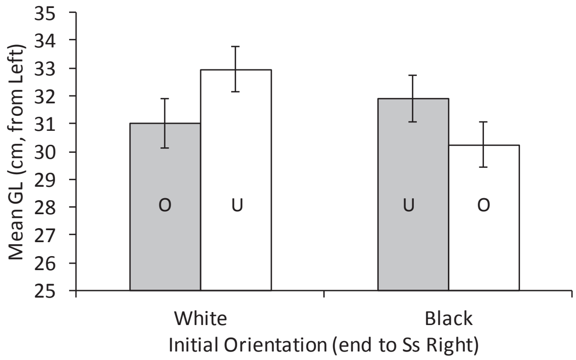

Fig. 6. Mean grasp location (measured from the participant's left) as a function of initial and final orientation. O indicates that the combination of initial and final orientation dictated an overhand grasp in Experiment 2. U indicates that the combination of initial and final orientation dictated an underhand grasp (assuming a right-handed participant). Error bars indicate standard error of the mean.

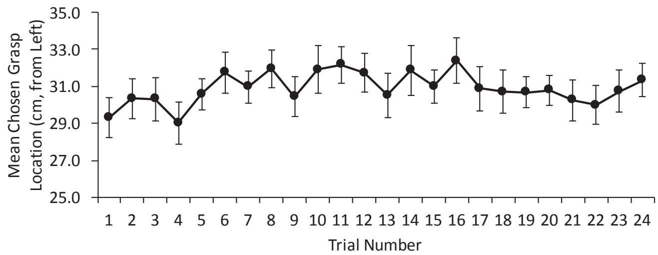

Fig. 7. Proportion of thumb-up grasps at time of task completion as a function of trial number in Experiment 2. Error bars indicate standard error of the mean.

the trials ($M = 2.8$ cm, $SEM = 0.36$) $t(19) = 0.69$, $p = 0.5$, Cohen's $d = 0.69$. At the level of the individual participants, eleven participants (58%) showed a decrease in variability in grasp position from the first half of the trials to the second half of trials; eight of the participants did not.

3.3. Discussion

The results of the second experiment were consistent with all of our expectations. Consistent with our expectations about grasp orientation, participants showed a strong preference for a thumb-up final grasp orientation. The planned final object orientation influenced this preference. Comparing the results of the two experiments, there was more inter-participant variability in picking up the rod with an overhand grasp when the rod was asymmetrically loaded (Experiment 2) than when the rod was symmetrically loaded (Experiment 1).

Consistent with our expectations concerning grasp location, the initial object orientation (how the weight was distributed) systematically influenced grasp location. Moreover, grasp locations changed neither in location nor precision. In this respect, the results concerning grasp locations differed from those of Experiment 1, where grasp locations became less variable in trials 13–24 than in trials 1–12. Having an asymmetric load apparently made it harder for subjects to settle on a particular grasp location that they would use for all of the necessary object transfers. Consistent with this interpretation and notwithstanding the possibility that there were inherent differences in the ability or willingness of subjects in Experiments 1 and 2 to limit the variability of their grasp locations, the larger standard deviations of the grasp locations in Experiment 2 than in Experiment 1 suggests that subjects in the second experiment were less certain about where to take hold of the rod than were subjects in the first experiment. That they were, given that the extra load inside the rod often switched positions, is consistent with the finding of Lukos et al. (2007), mentioned earlier, that lower uncertainty about loads leads to lower variability in grasps.

A final difference between the grasp location results of Experiments 1 and 2 was that subjects grasped the rod farther to the right when they picked up the rod with an underhand grasp (on about 90% of relevant trials) to bring the left end of the rod down onto the target if the right end was more heavily loaded than the left end. In the General Discussion section, we speculate on why this behavior may have appeared and what it might reveal more generally about the prospective control of behavior.

4. General discussion

Previous research has shown that when people grasp and rotate an object such as a dowel, they grasp the object in such a way that at the completion of the rotation, they exhibit a more comfortable "thumb up" posture rather than a less comfortable "thumb down" posture (see Rosenbaum et al., 2012, for a review). That is, people exhibit second order planning in how they grasp an object. Their grasp orientations are based in part on what they plan to do with the object after it is picked up—so called second-order planning.

In the two experiments reported here, we studied second-order planning in both grasp orientation and grasp location along the length of a horizontal rod when participants grasped, lifted, rotated, and lowered one or the other end of the rod onto a target. We were especially interested in the effects of inertial factors on the choice of grasp orientation and grasp location.

In Experiment 1, we found that participants grasped the rod in a way that afforded a thumb-up grasp orientation after the rotation. In addition, their grasp locations became less variable with practice performing the task (i.e., variability decreased from the first half to the second half of trials). Critically, relative to Experiment 2, the rod had a symmetric mass distribution. In Experiment 2, a new group of participants from the same general population grasped and rotated the same rod, but now the rod an *asymmetric* mass distribution. Again, participants tended to grasp the rod in a way that afforded a thumb-up grasp orientation after the rotation, especially when the weighted end was to be rotated downward. Participants grasped the object closer to the weighted end (i.e., closer to the center of mass), and their grasp locations did not change in either location or variability from the first half of the trials to the second half of trials.

Together, the two experiments show that participants were sensitive to how grasp type and grasp location altered the functionality of a hand-held object for a task in which the act of grasping the object was temporally removed from completion of the task to be performed. Our results show that participants were sensitive to how grasp type and grasp location altered the mass distribution of the hand-object system in second order grasping planning task. We say more about this in the following sections by focusing on grasp orientation and then by focusing on grasp location.

4.1. Grasp orientation

The main difference between the two experiments reported here was that in Experiment 1 participants performed the task with a *symmetrically* weighted wooden rod, whereas in Experiment 2 they did so with an *asymmetrically* weighted wooded rod. Despite this difference, participants tended to grasp the rod in a way that afforded a thumb-up grasp orientation, suggesting that the so-called end-state comfort generalizes across objects with different mass distributions and across manipulation tasks with changing rotation dynamics. In the context of each experiment, when the specified rotation was counterclockwise, participants grasped the rod with an overhand grasp (with the right hand), and when the specified rotation was counterclockwise, they grasped the rod with an underhand grasp (again, with the right hand). When data from the two experiments were combined—and here is a new statistic—participants grasped the rod in this manner on a total of 875 (93.5%) of the 936 trials (see Figs. 2 and 5).

Despite the overall tendency to grasp the rod in a way that afforded a thumb-up final grasp orientation (i.e., the tendency to exhibit second order planning) across both experiments, there were subtle differences in the grasp orientations chosen for the asymmetrically weighted rod (Experiment 2) depending on how it was to be rotated. Participants were (slightly) less likely to exhibit second order planning when the unweighted end was to be placed on the target than when the weighted end was to be placed on the target (see Fig. 6). This may have been a result of the increased challenge in leveraging gravitational forces when rotating the weighted end away from the table.

4.2. Grasp location

Across both experiments, participants tended to grasp the rod in similar locations —just to the right of center of the horizontal object (see Figs. 3 and 6). In addition, in Experiment 2, participants tended to grasp the object farther to the right when the weighted end was on the right than when the weighted end was on the left (see Fig. 6). That is, when the object was asymmetrically weighted, participants grasped closer to the center of mass of object, thereby decreasing the muscular forces required to rotate the object about the wrist (see Wagman & Carello, 2003).

The mass distribution of the rod also influenced whether (and how) grasp orientation changed with practice performing the task. In Experiment 1, when the task was performed with a symmetrically weighted rod, mean grasp location did not change with practice, but choice of grasp location became less variable. In Experiment 2, when the task was performed with an asymmetrically weighted rod, neither mean grasp location nor variability in choice of grasp location changed with practice. In neither experiment did practice change the overall tendency to grasp the rod just to the right of center. However, when the location of the center of mass (and the subsequent dynamics of the rotation task) remained constant from trial to trial, participants could fine tune their grasp location, resulting in reduced variability in grasp location and further reduction of such variability with practice. By contrast, when the location of the center of mass (and the subsequent dynamics of the rotation task) changed from trial to trial, participants were less able to fine tune their grasp location, resulting in higher variability in grasp location and no reduction in such variability with practice (compare error bars on Figs. 4 and 7).

4.3. Agency and skilled behavior in motor control

Can our results be said to bear on larger issues such agency and skilled behavior in motor control? We think so. In large part, scientists studying perception and action hope to understand agency — the autonomous goal-directedness of behavior (E. Gibson, 1994; Reed, 1996; Turvey 2013). Agency manifests in behavior in multiple ways. The results of the experiments reported here bear on three of these — prospectivity, retrospectivity, and flexibility.

Prospectivity is the 'forward-looking' character of behavior. It allows for the coordination of current behavior with impending circumstances. Successfully performing any behavior requires perceiving whether a given behavior is possible, and if so, when and how the movements of the body must be controlled in doing so. In both of the experiments reported here, the tendency to grasp the rod in a way that afforded a thumb-up grasp orientation (i.e., the 'end state comfort' effect) provided a demonstration of prospectivity. Such a finding is consistent with a large body of previous research (see Rosenbaum et al., 2012; Wagman & Carello, 2003).

Retrospectivity is the 'backward-looking' character of behavior. It allows for the coordination of current behavior with prior circumstances. In Experiment 2, the reduction in variability in grasp location with practice performing the task with a symmetrically weighted rod (when the required rotation dynamics remained constant across trials) provided a demonstration of retrospectivity. Under such circumstances, participants 'fine-tuned' their grasp location with practice performing the task.

Finally, flexibility is the interchangeability of means to achieve an intended end. It allows for changes in behavior as circumstances vary. The same movement goal can be achieved by means of different (coordination of) anatomical components. In both experiments, the different coordination of the anatomical components (i.e., overhand vs. underhand grasping) in different circumstances (depending on the initial and final object orientation) provided a demonstration of flexibility. The tendency to grasp the object closer to the weighted end in Experiment 2 comprised an additional demonstration of flexibility.

4.4. Exploiting mechanics

Why did our participants vary the grasp location in this way? We think they did so to exploit the pendular qualities of the rod. They grasped the rod so as to take advantage of the gravitational forces acting on it, thereby decreasing the muscular forces required to perform the rotation task (cf. Bernstein, 1967). Grasping the rod more to the right when the rod would be picked up with an underhand grasp meant that more of the rod's length could fall below the axis of rotation where the index finger contacted the rod. Letting more of the rod's length lie below the axis of rotation while the rod was being lifted made it easier to let the rod drop due to gravity and to have greater control of the rod due to the greater power of the index finger, middle finger, and thumb behind them in the power grip that was used. Similarly, grasping the rod more to the left (or less far to the right) when the rod would be picked up with an *overhand* grasp meant again that more of the rod's length could fall below the axis of rotation and made it easier to let the rod drop due to gravity. Such subtle behavioral strategies reflected remarkable tuning to the functionality of the hand-object ensemble comprising the core elements of the acts to performed (Carello & Turvey, 2017; Wagman & Carello, 2003) and highly sophisticated prospective control (Rosenbaum, 2017; Rosenbaum, Herbort, Van der Wel, & Weiss, 2014; Wagman, 2014).

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