Opposite Perceptual and Sensorimotor Responses to a Size-Weight Illusion

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Grandy, Mathew S. and David A. Westwood. Opposite perceptual and sensorimotor responses to a size-weight illusion. J Neurophysiol 95: 3887–3892, 2006; doi:10.1152/jn.00851.2005. The perceptual size-weight illusion (SWI) occurs when two different-sized objects with equal mass are lifted in sequence: the smaller object is consistently reported to feel heavier than the larger object even after repeated lifting attempts. Here we explored the relationship between sensorimotor and perceptual responses to a SWI in which the smaller of the two target objects in fact weighed slightly less (2.7 N) than the larger object (3.2 N). For 20 consecutive lifts, participants consistently reported that the small-light object felt heavier than the large-heavy object; however, concurrently measured lifting dynamics showed exactly the opposite pattern: peak grip force, peak grip force rate, peak load force, and peak load force rate were all significantly greater for the large-heavy object versus the small-light object. The difference in peak load rate between the two objects was greatest for the initial lift but decreased significantly beyond that point, suggesting that the sensorimotor system used sensory feedback to correct for initial over- and underestimations of object mass. Despite these adjustments to lifting dynamics over the early trials, the difference between the judged heaviness of the two objects did not change. The findings clearly demonstrate that the sensorimotor and perceptual systems utilize distinctly different mechanisms for determining object mass.

INTRODUCTION

Humans have a remarkable ability to interact with objects in a skillful manner. Although introspection suggests that one’s conscious perception of the objects in the environment guides one’s interactions with those objects (i.e., what we “see” determines the way that we act), considerable evidence suggests that the processing of object features for perception and action is quite different and indeed mediated by distinct cortical systems (Goodale and Milner 1992; for a recent review, see Goodale and Westwood 2004).

An intriguing—although controversial—line of inquiry has made use of perceptual illusions to study the relationship between perception and action in neurologically intact participants. Following the pioneering work of Bridgeman et al. (1979) and Aglioti et al. (1995), numerous studies have measured the sensitivity of perceptual and motor responses to various types of pictorial visual illusions—illusions that use carefully constructed geometric elements to influence the perceptual interpretation of a target object’s features. Despite some notable exceptions, these studies have been quite consistent in showing that actions are less sensitive to illusions than are perceptual reports or judgments about the target stimulus (for 2 reviews, see Carey 2001; Franz 2001). Most studies of perception-action relationships in object-directed behavior employ tasks for which the relevant object feature can be computed de novo from currently available visual information. For example, the preshaping of the grasp depends on the size and location of the target object (Jeannerod 1986). Both of these features can be computed through a combination of retinal (e.g., image size) and extraretinal cues (e.g., vergence) even if the actor has no prior experience with the specific target object. The mass of an object, however, cannot be computed solely on the basis of current visual information because there is no visual cue that provides direct information about this characteristic (Goodale 2000). Because the feedforward control of lifting dynamics (i.e., load force and grip force) requires a prediction of the target’s mass (Johansson and Cole 1992), this control must depend on sensorimotor mechanisms that either determine the volume of the target object, estimate its density through recognition of the object’s material composition, and multiply the two, or recognize the target object and remember its mass from previous interactions. In both cases, access to prior knowledge is required.

Because the perceptual system is thought to be the interface between current sensory input and prior knowledge (Goodale and Humphrey 1998), the control of lifting dynamics might depend on perceptual processing of the target object’s features—unlike the control of grasping kinematics. Consistent with this prediction, Brenner and Smeets (1996) and Jackson and Shaw (2000) found that lifting dynamics and perceptual judgments were both sensitive to pictorial size illusions, suggesting that the feedforward control of lifting depends on conscious perception of object size. Westwood et al. (2000) did not replicate this finding, reporting instead that lifting dynamics were unaffected by a pictorial size illusion. Unlike the other two studies, however, Westwood et al. (2000) held object mass constant for the different-sized target objects, which could have led to sensorimotor learning of actual object mass over repeated lifting attempts.

In a particularly intriguing study, Flanagan and Beltzner (2000) explored the relationship between perception and action in the well-known size-weight illusion (SWI). In a typical SWI paradigm, participants lift two objects with identical mass but different volumes. After lifting both objects participants invariably report that the smaller one feels heavier than the larger one; this is the perceptual SWI. In Flanagan and Beltzner’s (2000) study, lifting dynamics were measured while participants repeatedly lifted the small and large objects in alternating sequence. In a separate experiment with different participants, perceptual reports of object heaviness confirmed that the SWI was equally strong after 1 or 20 lifting trials as expected (i.e., the smaller object was consistently judged to be heavier than the larger object). In the early lifting trials, significantly smaller
grip and load forces were used for the smaller (vs. larger) object, consistent with the reasonable expectation that the smaller object would have less mass given the apparently similar material composition of the two objects. After only a few lifts, however, significant changes in the grip and load forces for the two objects were detected that rendered differences between the objects statistically indistinguishable. These results suggest that perception of object heaviness need not drive the control of lifting dynamics and that the control of lifting dynamics need not influence the perception of object heaviness. In other words, a dissociation between perception and action can occur even in a task that requires the retrieval of object information from memory.

Flanagan and Beltzner’s (2000) findings argue strongly against a leading account of the perceptual SWI that posits that the smaller object is judged to be heavier than the larger object because sensory feedback received during lifting indicates that the small object is heavier than it was expected to be (i.e., the sensory mismatch hypothesis) (Murray et al. 1999). However, the argument that perception and action utilize separate representations of object mass could be considerably strengthened by changing a characteristic of the standard SWI paradigm that creates problems for statistical interpretation.

The statistical problems arise from the fact that the two target objects have identical masses in the standard SWI paradigm. If the sensorimotor system can indeed learn the true mass of a target object after a few lifts, then one would expect to find similar lifting dynamics for the two objects in all but the first few lifting trials—a statistical null hypothesis. However, a finding like this could also be explained by a lack of statistical power. Although Flanagan and Beltzner’s data show significant changes in the lifting dynamics used for the individual objects during the first few lifting trials—suggesting a correction of initial errors in sensorimotor prediction of object mass—the fact that lifting dynamics for the two objects were not statistically different for the later trials cannot be taken as strong evidence that sensorimotor prediction errors were completely corrected. In other words, although the degree of sensory mismatch certainly decreased during the repeated lifts, it is difficult to conclude that it was eradicated.

The statistical phenomenon of regression to the mean—in which two sets of observations taken from the extreme ends of a single distribution are found to be more similar to each other when observed again—could also produce a pattern of findings similar to those observed by Flanagan and Beltzner; that is, lifting dynamics for the two objects were initially different but came to be statistically indistinguishable after a few repeated lifts.

Both of these concerns can be allayed by using a SWI paradigm in which the masses of the two objects are genuinely different. With a modification of the SWI paradigm that requires participants to lift a box with a handle and to adjust initial errors in mass prediction. The combination of these two positive statistical findings could not be attributed to a lack of statistical power or regression toward the mean and would therefore provide compelling support for the independence of sensorimotor and perceptual computations of object mass.

As an added benefit, one could use this modified SWI to determine whether or not the sensorimotor system can access distinct— and accurate—representations for more than one object in a set. In Flanagan and Beltzner’s (2000) study, this possibility could not be tested because the two objects shared the same mass. To use different lifting dynamics for each object in the modified SWI, separate and distinct object representations must be accessed that would presumably require a perceptual discrimination. On the one hand, this perceptual analysis could lead to an increased influence of the perceived rather than actual object mass on the lifting dynamics. On the other hand, once the perceptual discrimination between objects has been made, the control of lifting dynamics could be handed over to the sensorimotor system, which would then access a representation of the object’s actual mass.

For the purposes of the present investigation, we developed a modified version of the SWI paradigm in which the smaller of the two objects had slightly less mass than the larger object. Pilot testing confirmed that the perceptual SWI occurred with this modified stimulus set; that is, participants judged the smaller object to be heavier than the larger object. Based on the work of Flanagan and Beltzner (2000), we predicted that the sensorimotor system would quickly learn the true masses of the two target objects given repeated lifting attempts—leading to greater forces and force rates for the large-heavy versus small-light object—but that concurrent judgments of heaviness would remain consistently sensitive to the SWI. These predictions were borne out.

METHODS

Participants

Fifteen healthy participants (10 female, 5 male) 18–30 yr of age [mean = 21.3 ± 3.8 (SD) yr] participated in the study. Participants were recruited from the Dalhousie University Psychology Department and provided informed consent prior to participation: the experiment received approval from the local research ethics board. Participants were screened for neurological and visual impairments. Participants were asked to lift the target objects with their preferred writing hand (right hand, n = 13; left hand, n = 2).

Materials

The participants lifted two boxes, a large one (9.9 × 9.9 × 9.9 cm) and a small one (4.9 × 4.9 × 4.9 cm). The boxes were weighted with clay and metal beads. The loaded boxes differed in weight by 0.49 N, with the small box weighing 2.70 N (0.275 kg) and the large box weighing 3.19 N (0.325 kg). The density of the small box was 2.33 kg/l and the density of the large was 0.335 kg/l. These specifications were selected to be similar to the densities used by Flanagan and Beltzner (2000). The target box for a given trial rested on a platform with a microswitch embedded within to allow detection of object lift-off.

Participants lifted the boxes using a removable handle that was equipped with a six-axis force-torque sensor (Nano 17 E/F; ATI Industrial Automation, Garner, NC). Force-torque (FT) and microswitch data were collected using an analog/digital data acquisition board and custom LabView software.
Procedure

Participants were instructed to place their lifting hand in front of the platform, and on hearing the auditory cue, to grasp the handle with their index finger and thumb, and lift the object vertically to a marker 5 cm above the top of the platform. Once the object reached the designated height, the participant was instructed to hold the object stationary until a second auditory cue at which point the subject was asked to return the object to the platform. Participants were asked to lift the objects with the same velocity and to keep their hand in the same orientation over the course of the trials.

Each trial consisted of two lifts, one with the large object and one with the small object. The order of object lifting was counterbalanced among the participants so that half lifted the large object first. Each participant lifted each object a total of 20 times for a total of 40 lifts over the course of the experiment. After each lift, the participant was asked to assign the object a weight using a verbal scale from 1 to 10 (1 being light and 10 being heavy). This was repeated for each lift.

Data collection and analysis

The force-torque transducer sampled three orthogonal forces and three orthogonal torques at a rate of 200 Hz for a duration of 3 s starting from the auditory cue to begin lifting. The grip force (force normal to the grasping surface) and load force (resultant of the 2 forces tangential to the grasping surface) were calculated. Following the protocol of Flanagan and Beltzner (2000), the grip and load force rates were obtained by differentiating grip and load force data using a three-point central difference method (i.e., the 1st derivative of force with respect to time) after first filtering the force data with a fourth-order, zero-phase lag, low-pass Butterworth filter (cutoff frequency = 14 Hz). For each trial, the peak grip and load forces as well as peak grip and load force rates and the load phase duration (the time from when load force exceeded 0.2 N/s until lift-off as measured by release of the object contact switch; Flanagan and Beltzner 2000) were calculated and analyzed. Representative data for a single lifting trial are illustrated in Fig. 1.

RESULTS

Perceptual reports

Unlike traditional SWI experiments, the objects used in the present experiment did not have equal masses. Nevertheless, a robust perceptual SWI was observed. Verbal judgments of heaviness were analyzed using a 20 (trials) × 2 (objects; large-heavy versus small-light) repeated-measures ANOVA, alpha = 0.05. A significant main effect of object, \( F(1,14) = 47.5, P < 0.001 \), indicated that participants perceived the small object to be heavier than the large object throughout the entire experiment, despite the fact that the small object actually had less mass (Fig. 2). A significant main effect of trials, \( F(19,263) = 15.3, P < 0.001 \), indicated that the perceptual reports of heaviness increased significantly over the 20 lifting trials. Thus participants were not simply using the same heaviness ratings throughout the experiment but were instead responding to perceived changes in heaviness as requested. The gradual increase in perceived heaviness could indicate the increased effort required to lift the objects due to fatigue buildup. Importantly, no significant interaction was found between block and object, \( F(19,203) = 0.86, P > 0.05 \), indicating that the magnitude of the perceptual SWI was unchanged during the course of the experiment.

Lifting dynamics

To compare our results to those of Flanagan and Beltzner (2000), lifting dynamics were evaluated using five dependent measures: peak grip force (force normal to the grasping surface), peak grip force rate (1st derivative of grip force), peak load force (resultant force tangential to the grasping surface), peak load force rate (1st derivative of load force), and load phase duration. Representative data for a single lifting trial are illustrated in Fig. 1.
peak load force rate (1st derivative of load force), and load phase duration (time from when load force rate exceeded 0.2 N/s until lift-off). Each of these parameters is typically scaled to the anticipated mass of the object and thus serves as a good indicator of sensorimotor prediction of object mass (Gordon et al. 1991). Because peak force rates occur earlier in the lift than peak forces (Johansson and Cole 1992), these measures are less likely to be influenced by somatosensory feedback gained during the lift. Each of the five dependent measures was analyzed using a 20 (trials) × 2 (objects; large-heavy versus small-light) repeated-measures ANOVA, alpha = 0.05.

As expected, there was a significant main effect of object for all dependent measures (Fig. 3). Peak grip force, $F(1,14) = 95.1, P < 0.001$, peak grip rate, $F(1,14) = 19.1, P < 0.001$, peak load force, $F(1,14) = 147.8, P < 0.001$, and peak load rate, $F(1,14) = 14.9, P < 0.01$, were all higher for the large-heavy object. Load phase duration was longer for the large-heavy object, $F(1,14) = 70.8, P < 0.001$. It is important
to note, of course, that these effects are in the opposite direction to participants’ perceptions of the relative weights of the two objects; perceptual reports indicated the small-light object was believed to be heavier than the large-heavy object.

**PEAK GRIP FORCE AND PEAK GRIP RATE.** In addition to the main effect of object, there was a significant main effect of trials for peak grip force (PGF), \( F(19,261) = 3.20, P < 0.001 \), and peak grip rate (PGR), \( F(19,262) = 2.45, P < 0.001 \), indicating a rapid decrease in both parameters for the first few trials followed by a plateau. These rapid decreases in grip parameters likely reflect participant’s increasing confidence in their ability to grasp the target objects without slippage. No significant interaction was observed between object and trials for PGF or PGR.

**PEAK LOAD FORCE AND PEAK LOAD RATE.** No significant effect of trials was found for peak load force and rate (PLF and PLR), \( F(19,262) = 1.13, P > 0.05 \), indicating a gradual increase in load phase duration (LPD) over trials. A significant interaction between object and trials, \( F(19,205) = 1.67, P < 0.05 \), was pursued post hoc by comparing LPD for the two objects for the first five lifting trials. These post hoc analyses indicated no significant difference in LPD between the small-light and large-heavy objects for the first two trials, but significantly greater LPD for the large-heavy relative to small-light object for the next three trials. The changes in LPD over the early lifting trials are consistent with the decrease in peak load rate for the large-heavy object and the increase in peak load rate for the small-light object over the first five lifting trials.

In summary, whereas participants clearly indicated that the small-light object felt heavier than the large-heavy object throughout the experiment, the dynamics of their lifting responses indicated that the sensorimotor system was sensitive to the fact that the large-heavy object was in fact heavier than the small-light object. The changes in peak load rate and load phase duration during the first five lifting trials suggest that the sensorimotor system initially overestimated the mass of the large-heavy object and underestimated the mass of the small-light object but adjusted these estimates after receiving sensory feedback. Similar adjustments were not seen for judgments of object heaviness.

**DISCUSSION**

The results of the present study are unequivocal in showing a perception-action dissociation in response to a size-weight illusion. Participants reported that the small-light object (2.70 N) felt heavier than the large-heavy object (3.19 N) throughout the entire experiment, consistent with a classical SWI. In stark contrast, however, participants used smaller forces and force rates to lift the small-light as compared with large-heavy object, indicating that the sensorimotor system was sensitive to the true differences between the two objects. Thus the present results provide strong support for Flanagan and Beltzner’s (2000) contention that the control of lifting dynamics is driven by a system that is separate from that which supports the conscious perception of object heaviness. This conclusion flies in the face of the common intuition that one’s actions are guided by one’s perception of the target object’s features. The clear dissociation between perception and action provides important clues about the nature of the different sensory processes that underlie the control of lifting dynamics and the conscious perception of object heaviness.

The leading explanation for the existence of the perceptual SWI is a sensory mismatch (e.g., Murray et al., 1999). Because the two objects are constructed with the same surface material, participants expect the larger object to be much heavier than the smaller object because their densities should be the same. Consistent with this expectation, participants use greater forces and force rates to lift the larger as compared with smaller object during the first few lifts; this was observed in Flanagan and Beltzner’s (2000) study using a conventional SWI and also in the present study using a modified SWI. Because the actual masses of the two objects are quite different from their expected masses, however, the larger object accelerates upward more quickly than expected, and the smaller object more slowly than expected; in Flanagan and Beltzner’s study, this was reflected in greater load phase duration for the small as compared with large object despite their equivalent masses, and in the present study, it was reflected in the equivalent load phase durations for the two objects despite their different masses. The resulting somatosensory and visual feedback indicates to the actor that incorrect lifting dynamics were used because the masses of the two objects were incorrectly estimated. The larger object is less massive than expected, and the smaller object is more massive than expected; this is because, in contrast to the apparently similar material construction of the two objects, their densities are quite different.

Presumably, conscious perception of heaviness is highly sensitive to the initial feedback mismatch in the SWI paradigm. The large object is represented as “light” because it is lighter than expected, and the small object is represented as “heavy” because it is heavier than expected. This initial perception does not go away or even diminish after repeated lifting attempts despite the fact that the feedback mismatch diminishes quickly as the sensorimotor system adapts by decreasing the force or force rate used to lift the larger object and increasing the force or force rate used to lift the smaller object; this was seen in the present study and also Flanagan and Beltzner’s (2000) study. In other words, the instantiation of the perceptual SWI appears to depend on an initial feedback mismatch during lifting, but the persistence of the perceptual SWI does not.

Unlike the perceptual system, however, the sensorimotor system appears to use the feedback mismatch signals from early lifting trials to update the dynamics used to lift the two objects in subsequent attempts, presumably by changing a stored representation of the objects’ masses. This is clearly evidenced in the present study and Flanagan and Beltzner’s study by the changes in peak load rate and load phase duration seen during the early lifting trials, indicating a reduction of loading rate for the large object and an increase of loading rate...
for the small object. In other words, the sensorimotor system adapts to the initial errors that were made in predicting the weights of the two objects; this system is not held captive by its initial errors in the way that the perceptual system appears to be.

Because an accurate determination of the target object’s properties is central to the control of action, it is logical for the sensorimotor system to continuously adapt to feedback mismatch signals by updating a stored representation of the object. But why is this stored sensorimotor representation not “shared” with the perceptual system? In other words, what possible advantage could there be for the perceptual system to continue to represent the smaller object as “heavier” than the larger object?

As discussed earlier, perception is an inherently relative process: object features are perceived in relation to other objects (or standard points of reference) because absolute metrics are rarely useful for distinguishing between categories of objects (Goodale and Humphrey 1998). In the SWI paradigm, the most salient feature of the task is the unexpected difference in the relative densities of the two objects. Of course, the densities of the two objects have been deliberately manipulated to be inconsistent with their similar outward appearances. After the first lift, it becomes quite obvious to the actor that the densities of the two objects are different—different in relation to each other but also in relation to what their surface properties would normally predict. Because the relative density of the object is more salient for cognitive processing than its actual mass (at least in this task and probably more generally), participants’ reports of “heaviness” might be biased more strongly toward the object’s density than its absolute mass. Indeed, experiments by Kawai (2002) and Ross (Ross 1969; Ross and DiLollo 1970) have demonstrated that changes in density, independent of changes in actual mass, contribute to participants’ judgments of object heaviness. According to this line of reasoning, participants are not necessarily perceiving the heaviness of the object incorrectly but are rather responding to the object feature that is most salient for understanding its heaviness in the particular situation—in the case of the SWI paradigm, the relative density of the object.

With regard to the processing of object mass, the situation for the sensorimotor system is surely quite different. From the point of view of lifting an object, the sensorimotor system need only be concerned with those features that have a direct impact on the dynamics necessary to lift the object without dropping it; that is, the absolute—not relative—properties of the object such as its size, density, mass, or surface friction characteristics. In the context of the SWI paradigm, as with other situations involving repeated interactions with initially unfamiliar objects, the goal of the sensorimotor system is to use somatosensory and visual feedback to build and update a representation of each object’s actual heaviness (i.e., mass or density) to minimize future errors in lifting. When the decision has been made to lift a particular target object, it is of no consequence to the sensorimotor system that other objects in the surrounding environment have quite different densities and that the density of the object is quite different from the initial prediction that was made based on its visual appearance. In contrast to the perceptual system, then, the sensorimotor system has no reason to take into consideration the relative densities of the two objects when planning lifting dynamics, only the actual or absolute mass and density are relevant.

The present findings lend further support to the idea that perceptual and sensorimotor systems process object information in quite different ways, consistent with the different purposes that these systems have evolved to fulfill (Goodale and Humphrey 1998; Goodale and Milner 1992). The perception of object features is inherently relative and driven by those object features that are most useful for cognitive processing, whereas the sensorimotor processing of object features is absolute and driven by those object features that are most necessary for accurate control of action.

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REFERENCES


