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Living in A Material World: How Visual Cues to Material Properties Affect the Way That We Lift Objects and Perceive Their Weight

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Buckingham G, Cant JS, Goodale MA. Living in a material world: how visual cues to material properties affect the way that we lift objects and perceive their weight. *J Neurophysiol* 102: 3111–3118, 2009. First published September 30, 2009; doi:10.1152/jn.00515.2009. The visual properties of an object provide many cues as to the tensile strength, compliance, and density of the material from which it is made. However, it is not well understood how these implicit associations affect our perceptions of these properties and how they determine the initial forces that are applied when an object is picked up. Here we examine the effects of these cues on such forces by using the classic "material-weight illusion" (MWI). Grip and load forces were measured in three experiments as participants lifted cubes made from metal, wood, and expanded polystyrene. These cubes were adjusted to have a different mass than would be expected for a particular material. For the initial lifts, the forces were scaled to the *expected* weight of each object, such that the metal block was gripped and lifted with more force than the polystyrene one. After a few lifts, however, participants scaled their forces to the *actual* weight of the blocks, implicitly disregarding the misleading visual cues to each block's composition (*experiments 1* and *2*). Despite this rapid rescaling, participants experienced a robust MWI throughout the duration of the experiments. In fact, the grip and load forces never matched the perception of weight until the differences in the visual surface properties between the blocks were removed (*experiment 3*). These findings are discussed in relation to recent debates about the underlying causes of weight-based illusions and the effect of top-down visual cues on perception and action.

INTRODUCTION

Surface cues, such as color, texture, and reflectance, provide information about the material properties of an object, such as its mass, compliance, and surface friction (Adelson 2001). These visual cues do not provide this information directly but instead invoke learned associations between the appearance of certain materials and their properties that have been built up over a lifetime of experience. It is these learned associations that often guide our interactions with a wide range of objects.

It is commonplace for individuals to have to lift items that they have never directly handled before. Johansson and Westling (1988) demonstrated that individuals are able to use anticipatory control strategies to lift objects. Individuals apply forces that directly mirror changes in object properties, such as size. Furthermore, Gordon and colleagues (1993) have shown that memory-driven expectations can be used to program the forces required for lifting a variety of everyday objects (e.g., a box of crackers or a telephone book). Thus when we reach out to pick up everyday objects that we have not necessarily had contact with before, the initial grip and lift forces that we apply are exquisitely tuned to differences in the surface properties of those objects. Moreover, we also categorize objects as relatively heavy or light on the basis of the material from which they appear to be made even before we pick them up. More than 100 years ago, Seashore (1899) described an interesting illusion that exploited this fact. This "material-weight illusion" (MWI) is elicited by constructing identically sized objects from different materials and adjusting them to have the same mass by hollowing out the heavy-looking objects and stuffing the light-looking objects with a high-density filler. The items made from lighter looking materials (e.g., expanded polystyrene) were reported as feeling heavier than items made from heavier looking materials (e.g., metal), despite their identical mass (Ellis and Lederman 1999; Harshfield and DeHardt 1970).

This illusion offers an opportunity to examine how our expectations influence our perception of material properties[1] and the forces we use to engage objects made of different materials before and after experience with individual objects. Here we show a clear disconnect between our perception of weight and the calibration of grip and load forces in the context of this illusion, similar to the one described in the size-weight illusion (SWI). An examination of the grip and load forces during the SWI was undertaken by Flanagan and Beltzner (2000), who gave participants differently sized cubes with identical masses to lift and judge their weights. Participants initially gripped the large cube with excessive force and the smaller cube with lower rates of force. After several lifts, however, the differences in the forces being applied to the blocks began to disappear. Despite this change in the pattern of force application across repeated lifts, the small cube was consistently reported to feel heavier than the large cube (the SWI).

In the present study, we examined the forces used when lifting blocks that induced the MWI. Participants were presented with three objects of the same size and weight that appeared to be made of expanded polystyrene, wood, and metal. The first time each participant picked up each object, the grip and load forces that were applied reflected the object's *expected* weight (i.e., more force was applied to the metal block than to the one that appeared to be made from expanded polystyrene). Afterward, consistent with the MWI, they reported that the expanded polystyrene block felt heavier than the metal one. Remarkably, however, after only a few trials, the peak fingertip grip and load forces, in addition to the force rates, were re-scaled to the *actual* mass of the blocks, despite continuing to experience the MWI. In other words, the participant's motor system was quickly tuned to the actual mass of objects even though his or her perception of heaviness appeared to rely on the mismatch between the expected density of the material from

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[1] Throughout this manuscript, mass is used in the literal scientific fashion, whereas weight and heaviness are used to refer to the individual's perception of the burden associated with lifting that object (i.e., a subjective measure).

which the object was made and its actual density. Follow-up experiments confirmed these findings, adapting paradigms from the SWI literature to confirm the dissociation between perception and action. These findings offer a unique insight into the role of "top-down" information triggered by visual cues in our perception of weight and in the calibration of grip and load forces.

METHODS

Experiment 1

Twenty-six students recruited from the undergraduate Psychology research participation pool from the University of Western Ontario took part in this experiment for course credit. Six participants were removed due to equipment malfunction, leaving a sample of 20 [12 male, 8 female; mean age = 23.3 ± (SD) 5.5 yr]. Two participants were left-handed, determined by self-report of writing hand. In all of the experiments, participants had normal or corrected-to-normal vision and were naïve to the experimental hypothesis. All testing procedures were approved by the ethics board at the University of Western Ontario, and participants gave informed consent prior to testing.

The three identically sized cubes (with a length, breadth, and width of 10 cm) made from different materials (metal, wood, and expanded polystyrene) were used to elicit the illusion (Fig. 1*A*). The metal block, made from solid aluminum (unaltered density: 2,700 kg/m^3), was hollowed out so it weighed exactly 700 g. The sides that would be visible to the participant (i.e., not the bottom) were left unaltered. The polystyrene block (unaltered density: 100 kg/m^3) was constructed around a smaller hollow wooden box filled with lead shot to increase its weight to 700 g. A clear adhesive was used to seal the polystyrene to the wooden box, so it appeared to be completely made from the surface material. Care was taken to ensure that the lead shot was tightly packed (i.e., no auditory cues of a filling) and that the center of mass coincided with the geometric center of the object. Finally, a solid cube of oak weighing 700 g was fashioned, and was not subjected to any alteration other than a coating with a walnut stain (density: 700 kg/m^3). All the blocks had identical small plastic "mounts" attached to the center of their top surface so that subjects would use the same grasping configurations for each lift. To clarify, all the task objects were the same size and weight and therefore had the same overall density (700 kg/m^3); they differed only in their surface material. Prior to the experiment, participants were given no indication that the stimuli were weighted inappropriately for their surface material (i.e., the experimenter did not handle the blocks).

Two six-axis force-torque sensors (Nano17 F/T; ATI Industrial Automation, Garner, NC) were attached to a custom-built aluminum and plastic handle with opposing grip pads to facilitate a precision grip with the thumb and forefinger (Fig. 1*B*) The surface of these grip pads were made from a rough sandpaper painted black, which provided enough friction to minimize the possibility of slippage during a lift. The handle allowed the force transducers to be mounted to each block and removed easily by the experimenter between lifts, adding 50 g to the total weight of the block. Custom-built light sensors, which projected a small beam of light 3 mm above and parallel to the surface of the table, were used to provide a time stamp for object lift-off (i.e., when the beam of light was broken, the object was on the table, and when the beam of light was unbroken, the object had been lifted off the table). Data from the force transducers and light sensors were sampled at 1,000 Hz to provide the relevant dependent measures (detailed in the following text).

Prior to each lift, participants sat with their eyes closed, and their dominant hand resting on a table in front of them. While their eyes were closed, the experimenter attached the appropriate object to the force transducer handle and placed it on the light sensor pad ~20 cm in front of the participant (Fig. 1*C*). Following a computer-generated auditory tone, participants opened their eyes and reached out to grasp the handle with the thumb and forefinger of their dominant hand. Then in a smooth controlled motion (i.e., with no artificial delay between the grasp and the lift), participants were required to lift the task object several centimeters off the table and hold it steady at the peak of the lift. It was made clear that the lift should be straight upward with no unnecessary "hefting" of the object. Three seconds after the start of the trial, a second tone signaled to participants that they could gently return the object to the light sensor pad on the table. After they had replaced the block, participants were asked to give the numerical value that they felt best represented the weight of the object they had just lifted. No constraints were placed on this value or its range other than larger numbers representing heavier weights (i.e., absolute magnitude estimation) (see Zwislocki and Goodman 1980). Participants lifted each block 15 times (45 lifts in total). A trial consisted of three lifts (1 with each material) with the order of presentation within each triplet being pseudorandomized. Three different pseudorandom orders were used and were counterbalanced across participants. Thus the forces used to lift the three different blocks (and the estimates of their heaviness) could be directly compared at different stages during the experiment. Participants were given several practice trials with (nonillusory) plastic cylindrical objects before starting the experimental trials. Prior to actually touching the blocks in the material-weight task, participants were requested to rate their expected heaviness based on visual appearance alone.

The perceptual heaviness judgments were normalized to a *z*-score distribution (based on the mean and SD of each participant's scores), and were examined in a 3 (material: metal, wood, polystyrene) × 15 (trial: lift 1, lift 2, etc) repeated-measures ANOVA. Data from the force transducers yielded grip force, which was defined as the vector orthogonal to the grip surface, and load force, which was defined as the resultant vector of the forces tangential to the grip surface. The data from each transducer (i.e., finger) were summed and passed through a dual pass fourth-order Butterworth filter, with a low-pass cutoff of 14 Hz. These data were plotted, and the value of the first peak was taken to provide the first dependent variables: *maximum grip force* (GF_{max}) and *maximum load force* (LF_{max}). The grip and load force data were differentiated with a three-point central difference equation to determine their rates of change, and the maximum values of these streams yielded two further dependent variables: *maximum grip force rate* (GFR_{max}) and *maximum load force rate* (LFR_{max}). These measures of force rates are likely to reflect preprogrammed forces, and hence expectation of heaviness, to a greater extent than the peak forces themselves (which may be influenced by somatosensory feedback. Additionally, *load phase duration* (LP_{dur}) was calculated by subtracting the lift-off time from the time point when load force increased >0.5 N (i.e., the "strain" of starting the lift). These measures were examined in separate analyses of variance with the same repeated-measures as above. Partial η^2 was reported to indicate the size of any

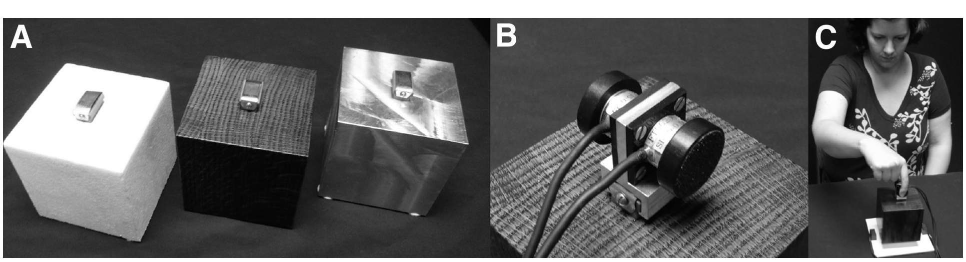

FIG. 1. *A*: the blocks made from expanded polystyrene, wood, and metal that were used to elicit the material weight illusion. *B*: the handle containing the force transducers from which the kinetic measures were derived. *C*: the experimental set up during a lift.

experimental effects across all measures. In addition, Tukey HSD tests (which corrected for inflated family-wise error rate) were used to examine the differences between the forces applied to the metal and polystyrene blocks at the first, second, and final lifts of the experiment.

Experiment 2

Twenty-nine right-handed students from the University of Western Ontario took part in this experiment. One participant was removed due to errors in data collection, leaving a sample of 28 (20 male, 8 female; mean age = 18.9 ± 1.2 yr). None of the participants had taken part in *experiment 1.*

The apparatus and testing procedures were identical to *experiment 1* in all aspects except for the adjustment to the mass of the metal and polystyrene blocks. The metal block had a 20-g weight inserted into its center, while the polystyrene block had 20 g removed from the lead filling. This proportionally small change in weight selected to balance maintaining the relatively small effect of the MWI, while allowing for differences in forces to be detected with a reasonable sample size. Therefore the metal block now weighed 720 g—20 g more than the wooden block, which in turn weighed 20 g more than the polystyrene block (680 g). Despite these slight changes in weight from the first experiment (and from 1 another), their external appearance remained unaltered. We predicted that this manipulation would require participants to apply slightly different forces to successfully lift each type of block, despite continuing to elicit an illusory difference in weight *in the opposite direction.*

Experiment 3

Nine right-handed students from the University of Western Ontario took part in this experiment (5 male, 4 female; mean age = 20.7 ± 3.4 yr). None of the participants had taken part in the previous experiments of this series.

The apparatus and testing procedures were identical to *experiment 2* except for the adjustment to the surface material of the (still differently weighted) blocks. Identical homogenous green covers were created out of cardboard to fit over the top of each block (Fig. 2). This cover completely obscured the surface material, giving participants no indication that each block may have different properties (the experimenter was aided by a small character on the edge of the block facing away from the participant to indicate the material beneath the green cover). The color of the cardboard covers was chosen to minimize expectations of heaviness based on prior experience with similar materials. The experimenter was careful to minimize auditory cues associated with placing the object in front of the participant. Despite these precautions, two participants claimed to know what material that they were lifting. However, no participants realized that they were lifting *different* materials from one trial to the next.

RESULTS

Experiment 1

There was a general increase in the perceived weight of the blocks as the experiment progressed [a main effect of trial: $F(14,266) = 15.86$, $P < 0.001$, partial $\eta^2 = 0.45$]. This is likely due to the fatigue of continued lifting, as similar findings have been described in earlier object-lifting research (e.g., Flanagan and Beltzner 2000). Crucially, participants judged the blocks to be of different weights [a main effect of material: $F(2,38) = 11.22$, $P < 0.001$, partial $\eta^2 = 0.37$]. The polystyrene block was consistently judged as feeling the heaviest (normalized mean score of 0.26), while the metal block was judged to be the lightest (normalized mean score of −0.30), with the wood block falling between the other two (normalized mean score of 0.06). This pattern was consistent across all lifts because there was no interaction between the material and trial variables [$F(28,532) = 0.61$, $P = 0.94$]. None of the individual post hoc tests between each material's heaviness rating at the relevant trials reached significance after corrections for multiple comparisons. However, the substantial main effect of material suggests that the MWI was robust and did not lessen with repeated lifting (Fig. 4*A, left*). It is worth noting that this finding directly contrasts with the results of Ellis and Lederman (1999), who reported no MWI with their objects in the heavy condition (where the objects had a mass that was >58.5 g). However, their task required participants to grasp the objects directly (taking care not to deform the surface) or lift them with a tray (presumably requiring some careful balancing). Both of these lifting styles appear to be more challenging than our task, especially with heavy objects where dropping or damaging them is a realistic possibility. Therefore we suggest that the participants in the Ellis and Lederman study may have just failed to notice the illusory differences in weight due to competition for attentional resources between the lifting and the judgment tasks.

The data from the force transducers yielded a different pattern of results (Fig. 3). In terms of GF_{max}, there was a main effect of trial [$F(14,266) = 15.76$, $P < 0.001$; partial $\eta^2 = 0.45$] and a main effect of material [$F(2,38) = 3.68$, $P < 0.05$; partial $\eta^2 = 0.16$]. Although there was no interaction between the variables [$F(28,532) = 1.46$, $P = 0.06$], there was a clear trend for different levels of force to be applied to the blocks at the start of the experiment than at the end of the task (Fig. 4). Post hoc analysis showed that participants used a higher level of force to grasp the metal block than they did the polystyrene block on the first trial, whereas similar forces were applied to both blocks on the later trials (Fig. 4*B*). The LF_{max} measure also showed a main effect of trial [$F(14,266) = 9.76$, $P < 0.001$; partial $\eta^2 = 0.30$] and a main effect of material [$F(2,38) = 4.99$, $P < 0.05$; partial $\eta^2 = 0.21$].

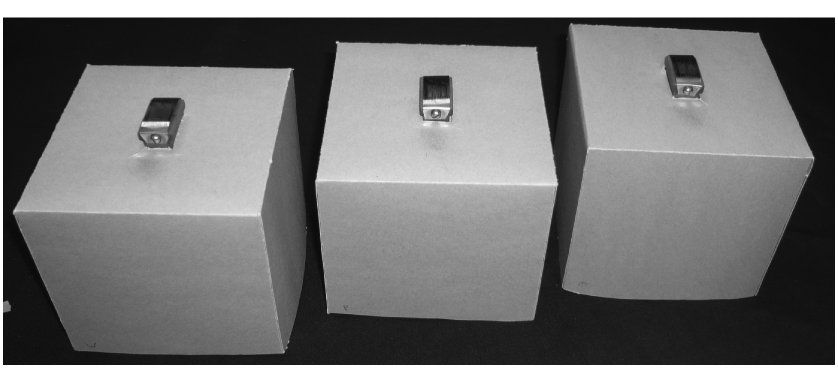

FIG. 2. The material-weight illusion (MWI)-eliciting blocks covered in green cardboard to remove any visual cues to material properties and differences in expectations of heaviness. For consistency, the blocks are still labeled as wood (700 g), polystyrene (680 g), and metal (720 g) in RESULTS.

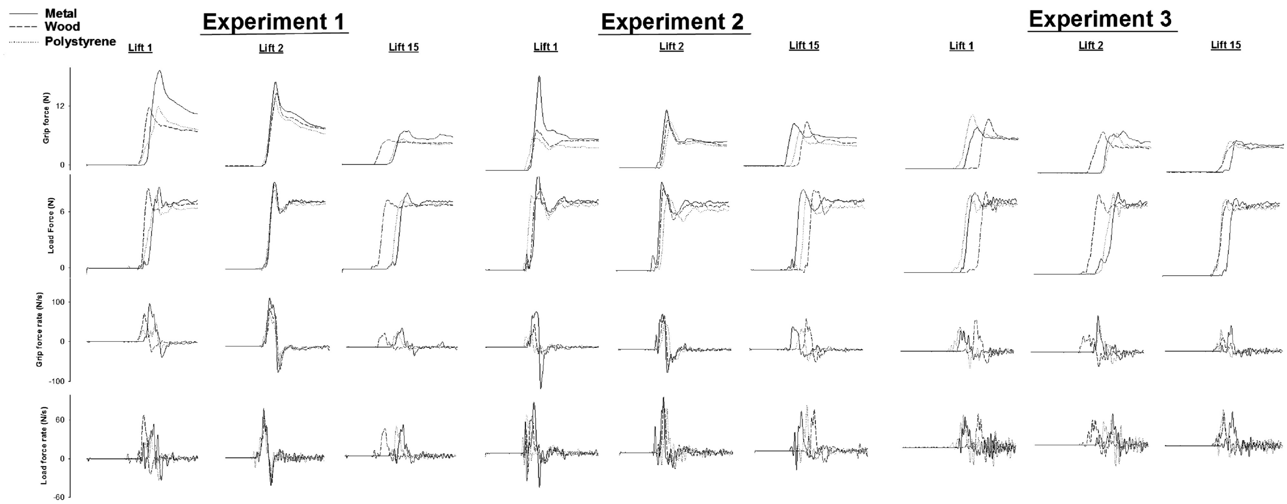

FIG. 3. Individual grip and load force and force rate plots from representative participants on *trials 1, 2,* and *15* for each different material in *experiments 1–3.* Each plot is aligned to the go cue, which signaled participants to open their eyes and then grip and lift the block.

Although these variables did not interact with one another [$F(28,532) = 0.80$, $P = 0.73$], a similar trend to the GF_{max} measure data can be seen in Fig. 4*C*. The GFR_{max} measure showed a main effect of material [$F(2,38) = 8.44$, $P < 0.005$] and a main effect of trial [$F(14,266) = 3.80$, $P < 0.001$, partial $\eta^2 = 0.17$]. Additionally, this measure also yielded a significant interaction between material and trial [$F(28,532) = 2.01$, $P < 0.005$, partial $\eta^2 = 0.10$]. Post hoc testing showed that lower rates of force were applied to the polystyrene block than the metal block on the initial trials, but similar rates of force were applied to both blocks during later lifts. This dramatic change in the lifting data across the task is in stark contrast to the consistent, unchanging perception of the MWI across all lifts of the experiment. The LFR_{max} showed a similar pattern of results to the GFR_{max} measure. While there was no main effect of trial [$F(14,266) = 1.44$, $P = 0.13$], there was a significant main effect of material [$F(2,38) = 7.93$, $P < 0.005$] as well as an interaction between the variables [$F(28,532) = 1.70$, $P < 0.05$; partial $\eta^2 = 0.08$]. The pattern of this interaction was consistent with the other measures, with polystyrene block being lifted at a substantially lower rate than the metal block for the first trial (Fig. 4*E*). Once again, nearly identical levels of force were applied to all the blocks in later lifts. The final measure, LP_{dur}, yielded no significant main effects or interactions (Fig. 4*F*).

The results of this experiment are consistent with the findings of researchers who have examined grip and load forces in the SWI (Flanagan and Beltzner 2000)—the perception of weight is not influenced by the level of forces applied to each object and vice versa. Prior to having picked up any of the blocks, participants indicated that they expected the metal block to be the heaviest (median heaviness rating = 8), the polystyrene block to be the lightest (median heaviness rating = 2), and the wood block to be somewhere in between (median heaviness rating = 5). Correspondingly, the application of forces for the first lift reflected the ordinal rankings of how much participants were expecting a particular block to weigh (i.e., the most force for metal and the least force for polystyrene). An interesting aspect of these data is the apparent lack of difference in the application of grip and load forces, and their rates of change, during the initial lift for wood and aluminum blocks. The similarity in rates of force application for these trials may be due to a combination of biomechanical limitations on how much force rates can be overestimated (due to the muscular properties of the arm and hand, which have limitations in how quickly the relevant muscles can be contracted), and participants' relative inexperience with solid blocks of the relevant materials of that size. In other words, participants may have expected both the wood and metal blocks to have been sufficiently heavy to require their maximum rates of force. After this initial lift, however, participants began to implicitly scale their forces to reflect the actual identical masses of each of the blocks. Thus from the second trial onward, the grip and load forces no longer differed across the three blocks, reflecting the fact that the blocks had the same weight. Crucially, however, the production of these forces bore no relationship to the perceived heaviness of the blocks. For example, participants always reported that the polystyrene block felt heavier than the metal one, but at no point in the experiment did participants grip or lift it with more force than the metal one. Thus perception of weight did not inform action, which had privileged access to more accurate mass information.

Flanagan and Beltzner's (2000) SWI study was only able to demonstrate that participants did not apply different levels of force to SWI inducing cubes. Classical hypothesis testing does not allow strong claims to be made based on the acceptance of the null hypothesis (i.e., that there will be no differences between conditions), reducing the impact of the crucial lack of differences force application at trial 15 in both their study and the current work. That is, the lack of differences in load force on later trials may merely have been due to a lack of power—the forces may just have been becoming more similar rather than scaling to the true mass of each object. This criticism of Flanagan and Beltzner's (2000) SWI experiment has been elegantly addressed by Grandy and Westwood (2006), who made small adjustments of the mass of each block in the opposite direction to the illusion. This manipulation resulted in the small, heavier-feeling block having slightly less mass (requiring significantly less force to lift) than the (still) lighter-feeling large block—a full dissociation between the perceived weight and forces applied to each block. To strengthen the findings of our first experiment, we replicated the Grandy and Westwood (2006) method in our MWI-inducing stimuli. To this end, the (heavy feeling) polystyrene block was adjusted to have slightly

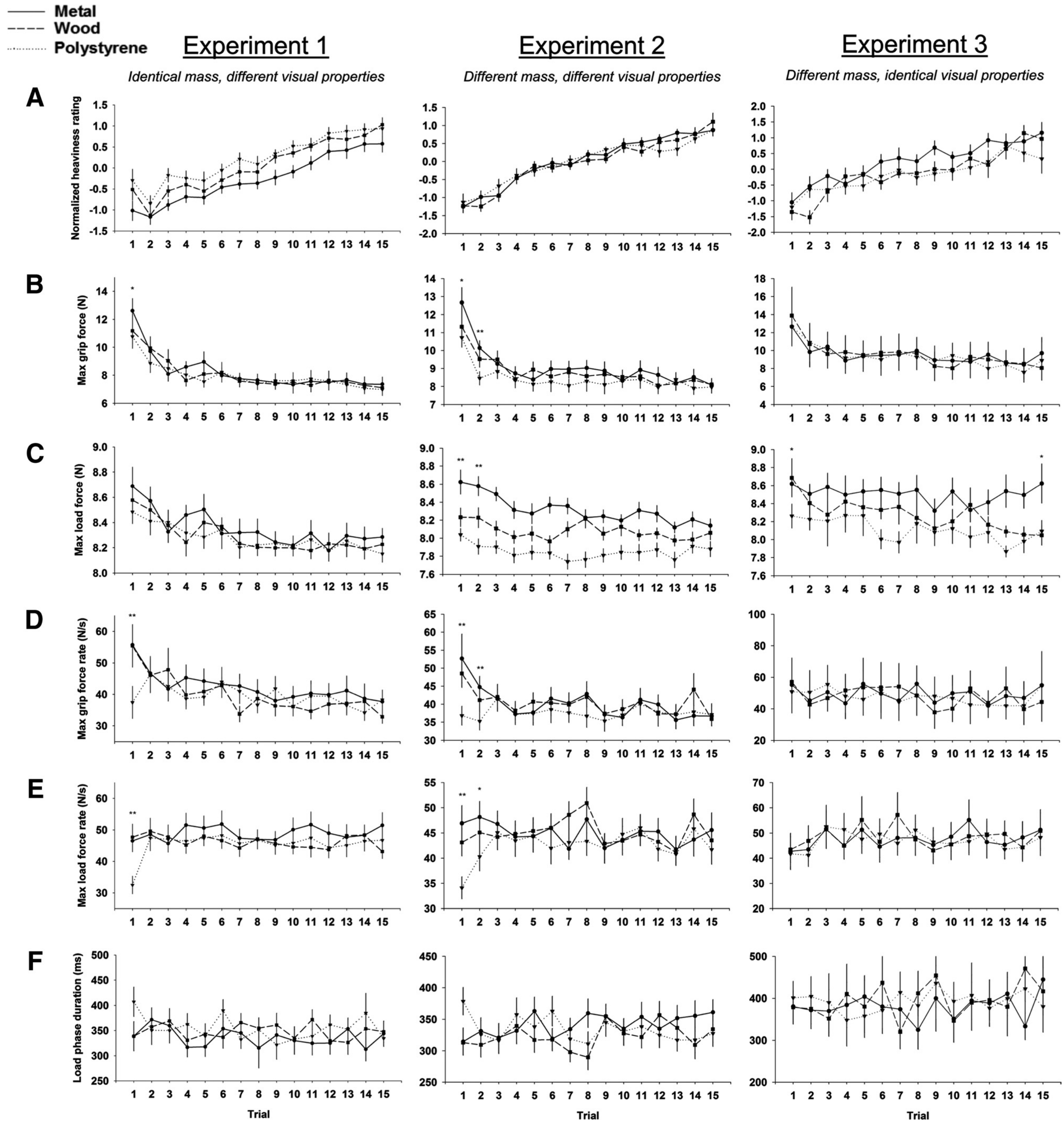

FIG. 4. *A*: the normalized ratings of heaviness, in addition to the maximum grip forces (*B*), maximum load forces (*C*), maximum grip force rates (*D*), maximum load force rates (*E*), and load phase durations (*F*) for each lift of each different material in *experiments 1–3*. *, significance at 0.05 level; **, significance at 0.01 level with Tukey HSD post hoc testing on *trials 1, 2,* and *15* between the metal and polystyrene blocks. Error bars show SE. Note the difference in scale between the force data presented in Figs. 3 and 4.

less mass than the wooden block, which in turn had less mass than the (lightest feeling) metal block. With this manipulation, we expected participants to apply different levels of force when lifting each type (and weight) of block, while still maintaining an opposing MWI.

Experiment 2

Once again, there was a substantial increase in the perceived heaviness of the blocks as the experiment progressed [i.e., a main effect of trial, $F(14,378) = 39.84$, $P < 0.001$; partial $\eta^2 = 0.60$]. In contrast to *experiment 1,* however, there was no main effect of material [$F(2,54) = 0.26$, $P = 0.77$; Fig. 4*A*], indicating that the blocks were judged to have equal weights (contrasting the difference in their *actual* masses). Furthermore, the trial and material variables did not interact [$F(28,756) = 1.16$, $P = 0.31$]. Thus rather than eliciting an illusory difference in weight (as in *experiment 1*), the MWI appears to have eliminated the participants' abilities to discriminate between differently weighted objects.

The data from the lifting measures also showed some subtle differences from the first experiment, reflecting the new difference in the mass of each block. For GF_{max}, there was a main effect of material, indicating that the heaviest (metal) block was gripped with more force than the lightest (polystyrene) block [9.05 vs. 8.41 N, $F(2,54) = 25.83$, $P < 0.001$; partial $\eta^2 = 0.49$]. Additionally, there was a main effect of trial [$F(14,378) = 12.49$, $P < 0.001$; partial $\eta^2 = 0.32$]. However, these variables did not interact with one another [$F(28,756) = 1.42$, $P = 0.07$], suggesting that this difference in the application of grip forces was maintained across the majority of the trials (Fig. 4*B*). This pattern of data were even more apparent with the LF_{max} measure, with the metal block being lifted with more force than the polystyrene block [8.32 vs. 7.85 N, $F(2,54) = 252.84$, $P < 0.001$; partial $\eta^2 = 0.90$]. However, the main effect of trial [$F(14,378) = 4.67$, $P < 0.001$; partial $\eta^2 = 0.15$] was also accompanied by an interaction with material [$F(28,756) = 1.72$, $P < 0.05$; partial $\eta^2 = 0.06$], indicating a small reduction in the difference between the forces applied to each block. This is not an unexpected finding, given that the actual difference in mass (only 40 g) is far less than the expected difference in weight. Post hoc testing indicated that significant differences in the application of forces did remain until the final trial of the experiment (Fig. 4*C*). A similar pattern of data emerged for GFR_{max}—a main effect of material indicated that the metal block was grasped at a higher rate than the polystyrene one [40.2 vs. 37.6 N/s, $F(2,54) = 9.79$, $P < .001$; partial $\eta^2 = 0.27$], and the main effect of trial [$F(14,378) = 2.60$, $P < 0.005$; partial $\eta^2 = 0.09$] was accompanied by an interaction between the variables [$F(28,756) = 1.62$, $P < 0.05$; partial $\eta^2 = 0.06$]. While this interaction suggests that the differences in force rates applied to each block changed with repeated lifts, there was a clear trend for the differences to be maintained past the initial trial (Fig. 4*D*). LFR_{max} was consistent with the previous measures—the metal block was lifted with a higher rate of force than the polystyrene one [44.9 vs. 42.6 N/s, $F(2,54) = 7.18$, $P < 0.005$; partial $\eta^2 = 0.21$]. Although there was no main effect of trial with this measure [$F(14,378) = 1.55$, $P = 0.09$; partial $\eta^2 = 0.05$], trial and material did interact with one another [$F(28,756) = 1.67$, $P < 0.05$; partial $\eta^2 = 0.06$]. As with the previous measure, post hoc analysis indicated that differences in the application of forces to each block were maintained throughout a longer portion of the experiment (albeit not until final trial—Fig. 4*E*). The data from the final measure, LP_{dur}, was similar to the previous measures. Although there was no main effect of trial [$F(14,378) = 0.89$, $P = 0.57$], there was a main effect of material [$F(14,378) = 3.98$, $P < 0.05$; partial $\eta^2 = 0.13$] and a trial by material interaction [$F(14,278) = 1.57$, $P < 0.05$; partial $\eta^2 = 0.06$]. This interaction, depicted in Fig. 4*F*, shows the characteristic trend of confounded expectations of heaviness on the first lift (where polystyrene takes longer to lift due to an insufficient initial application of force) and reflecting the actual mass of each object in the final trial (where metal takes longer to lift due to the increased force requirements of the lift itself).

The overall pattern that emerges from the lifting data on early trials is clear. On the first lift, the forces scaled to the expected weight of each object based on its visual appearance (Fig. 3) with the most force being applied to the metal block and the least force to the polystyrene block. After some experience with the objects, forces were scaled to the actual mass of each block—retaining the pattern described in the preceding text. Of course, the differences between the forces applied to each block are reduced as the experiment progresses, as the blocks themselves are still weighted inappropriately for their visual appearance (i.e., the expectations of weight are not entirely met). This accounts for why each different block often did not have a statistically significant different in the levels of force applied in the final trial (i.e., the post hoc tests between the different masses did not always persist fully to the end of the experiment after corrections for multiple comparisons). In fact, the actual differences in weight between each block were kept deliberately minimal (only a 5.6% difference in mass between the heaviest and lightest blocks) in an attempt to preserve the MWI—itself a comparatively small perceptual effect. However, the perceptual data indicated that participants generally felt that all the blocks weighed the same. This inability to discriminate the real mass of each object was likely to have been a consequence of the MWI—the illusory difference in weight was roughly equal to the actual (and opposite) difference in mass, with the two opposing "differences" canceling each other out. If this was the case, then removing the differences in surface visual properties that underlie the MWI should elicit judgments of weight that parallel the actual mass of each object as well as the force data that accompany each lift. To test this hypothesis, we removed the visual cues to each block's material with identical covers. Thus participants would be lifting three blocks of identical size and appearance, with slightly different weights, presumably still requiring different levels and rates of force to interact with (albeit to a lesser degree on the early trials given that the blocks no longer have expectations of weight associated with them).

Experiment 3

In contrast to *experiment 2,* and as predicted by our hypotheses, participants were able to accurately judge that the metal block weighed more than the polystyrene block [0.253 vs. −0.159, $F(2,16) = 7.78$, $P < 0.005$; partial $\eta^2 = 0.49$]. Given that the participants in this experiment were able to detect these small differences in mass, the inability of the participants in *experiment 2* to make these judgments must have been driven by each object's different visual appearance—the MWI. As the main effect of trial [$F(14,112) = 9.03$, $P < 0.001$; partial $\eta^2 = 0.53$] was not accompanied by an interaction with material [$F(28,224) = 1.13$, $P = 0.31$], we can also conclude that the participants' ability to judge the weights of these objects did not vary with practice (Fig. 4*A*). In contrast to the previous experiment, the perceptual data were now in agreement with the LF_{max} measure. The metal block was lifted with more force than the polystyrene block [8.51 vs. 8.11 N, $F(2,16) = 82.83$, $P < 0.001$; partial $\eta^2 = 0.91$]. This finding merely represents that the heaviest block was lifted with the most force. The main effect of trial [$F(14,112) = 2.06$, $P < 0.05$; partial $\eta^2 = 0.21$] was not accompanied by an interaction with material [$F(28,224) = 1.17$, $P = 0.26$], indicating that the difference between the forces applied to each block was retained throughout the majority of the trials (Fig. 4*C*). Because of the smaller sample size of this experiment, none of the other measures demonstrated main effects or interactions relating to the material variable and are not discussed further (they are, however, plotted in Fig. 4).

In this final control experiment, the load force data matched the pattern seen in *experiment* 2. This finding was not unexpected, as the actual masses of the objects were not altered between the studies. However, in contrast to *experiment 2*, the perceptual data now matched the load force data—without differences in the visual surface properties of each block to induce the MWI, the perception of heaviness and application of forces were no longer at odds with one another.

DISCUSSION

The ratings of heaviness that the participants gave for the three different blocks showed that they had experienced a robust MWI (*experiments 1* and *2*), similar to that reported in previous experiments (Ellis and Lederman 1999; Harshfield and DeHardt 1970; Seashore 1899). Remarkably, however, this illusion did not influence the grip and load forces that the participants used to pick up each type of block. Instead there was a clear disconnect between the perception of heaviness and the forces that were applied to the blocks, which disappeared as soon as the differences in visual appearance were eliminated (*experiment 3*). As the eventual application of forces was always scaled "correctly" to the actual mass of the objects, we can make the general conclusion that the action system has privileged access to more accurate mass information than the perceptual system (or, was at least able to use the information in a more accurate way, with respect to actual mass). The findings of the individual experiments are summarized in Table 1.

There are obvious similarities between the current findings and earlier work describing a disconnect between perception and action in the SWI. Flanagan and Beltzner (2000) examined grip and load forces to determine if a mismatch between the force application and the actual object weight caused the SWI. Because this "sensorimotor mismatch" did not persist past the first few trials (similar to the current finding), it was ruled out as an explanation for the continued misperception of object weight. Identical conclusions about the MWI can be drawn from the current work. Flanagan and colleagues have instead suggested that the SWI arises from a simple mismatch between what one expects an object to weigh and what it actually weighs (see Flanagan et al. 2008). If the perception of heaviness is a relative judgment based on a comparison between what the object weighs and what we expect it to weigh, an obvious question to ask would be what drives our expectation of heaviness. Although it is not entirely clear what factors drive the SWI (Ernst 2009), it is particularly intuitive to attribute the MWI to expectations of density—the factor which we directly manipulated by changing the material surface properties (e.g., Grandy and Westwood 2006). After many encounters with different materials, the general expectation that polystyrene will weigh very little while metal will be very heavy becomes a strong association. These associations are constantly reinforced and almost always provide reliable predictions about how much force is required to interact with a broad range of different objects. Consequently, these associations are not easily altered by a single erroneous encounter with a "rogue" object, or even after a half hour of lifting cubes in a contrived experiment. These long-held expectations are analogous to cognitive stereotypes; in other words, rather than predicting the behavior of an individual based on how the last similar-looking person behaved, it is a more efficient strategy to base it on the average behavior of that particular group (e.g., Macrae et al., 1994). As the MWI-eliciting stimuli have the visual surface properties of prototypical, or expected, representations of the relevant materials, one would expect it to have that material's weight. Put simply: if it looks enough like metal, it probably is metal—with all the associated expectations of heaviness. It is this expectation that is continually confounded in the MWI.

For the most part, the expectations of a particular material's density are extremely useful for calibrating the initial forces that we apply when we pick up a new object for the first time. But once we have experience with that particular exemplar, our motor system adapts to the actual physical requirements of the task during any subsequent interactions (Johansson and Westling 1988), ignoring the expectations about density that drove the initial application of forces. The implicit relationship between a visual property and a certain motor plan is easily replaced when the previous interaction with an individual object differed from expectations. This is a parsimonious solution for the role of the motor system in a constantly changing environment (see Ernst 2009 and Flanagan et al. 2008 for further details on this point). But even though our motor system adapts quickly to the task at hand, our general expectations about the density of the material from which the object is made remains unchanged. This persistence of expectation is why we continue to experience the object as being heavier (or lighter) than we should—because it is heavier (or lighter) than we expected it to be.

In fact, the single trial adjustment of grip and load forces from expected weight to actual mass offers a new interpretation of the recent Flanagan et al. (2008) findings. In this study, the perceptual SWI was inverted (so big objects were perceived as heavier and equally weighted small objects) after a period of training with objects that had their size and weight relationships reversed. Although the forces applied to these blocks showed the same pattern of motor adaptation as conventional SWI paradigms, the adaptation required far fewer lifts to occur—just as was observed in the current study. It is feasible that Flanagan and colleagues merely overlaid a MWI on top of the SWI. With participants now expecting the stimuli to have an inverted size-weight relationship, the inverted SWI can be considered as a MWI—expectations of weight for the individ-

TABLE 1. *Summary of the experimental manipulations and findings*

Experiment	Actual Mass of Blocks	Visual Appearance	Application of Forces During Initial Lifts	Application of Forces During Final Lifts	Perceived Weight of Blocks
1	Same	Different	Different	Same	Different
2	Different	Different	Different	Different	Same
3	Different	Same	Same	Different	Different

ual objects are signified by their surface material properties, having been learned in the lengthy training phase.

The fact that the initial calibration of grip and load forces makes use of top-down information triggered by visual cues is an excellent example of how the ventral visual stream contributes to the control of action (Milner and Goodale 2006). Nevertheless, how the dissociation between the eventual application of forces and the perception of heaviness is realized in the brain is not well understood. Recent neuroimaging work has suggested that the left ventral premotor cortex (PMv) plays a role estimating the density of objects based on their size and weight—a factor that is thought to be crucial for the SWI (Chouinard et al. 2009; Grandy and Westwood 2006). Interestingly, there is a report of a patient with a left inferior frontal lesion that appears to have included the PMv who was immune to the SWI (Halstead 1945; see also Li et al. 2007). It seems likely that this same area would be invoked at some stage during the MWI. Even less is known about the neural substrates of the learned associations between visual appearance and material density that trigger these illusions. One candidate region is the parahippocampal cortex, which has been shown to respond preferentially to both visual and auditory cues that signal differences in material properties (Arnott et al. 2008; Cant and Goodale 2007; Cant et al. 2009). It is interesting to note that the parahippocampal cortex has recently been hypothesized to be specifically involved in mediating contextual associations (Bar et al. 2008)—exactly the sort of learning that underlies the link between the visual appearance and expected density of different materials.

The current study demonstrated that perceptual experience and the calibration of motor output are affected differently by the MWI. Illusions such as this offer a unique opportunity to examine the interactions between the neural structures involved in the perception of size, weight, density, and material and subsequent actions. Further behavioral work must aim to refine the distinction between the processes underlying the perception of heaviness and the control of grip and load forces as well as both of these factors' relationship with expectations. This might be accomplished by training participants with various object classes (e.g., Flanagan et al. 2008) to manipulate of actual and expected weight of different stimuli.

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REFERENCES

Adelson EH. On seeing stuff: the perception of materials by humans and machines. *Proc SPIE* 4299: 1–12, 2001.

Arnott SR, Cant JS, Dutton GN, Goodale MA. Crinkling and crumpling: an auditory fMRI study of material properties. *NeuroImage* 43: 368–378, 2008.

Bar M, Aminoff E, Schacter DL. Scenes unseen: the parahippocampal cortex intrinsically subserves contextual associations, not scenes or places per se. *J Neurosci* 28: 8539–8544, 2008.

Cant JS, Arnott SR, Goodale MA. fMR-adaptation reveals separate processing regions for the perception of form and texture in the human ventral stream. *Exp Brain Res* 192: 391–405, 2009.

Cant JS, Goodale MA. Attention to form or surface properties modulates different regions of human occipitotemporal cortex. *Cereb Cortex* 17: 713–731, 2007.

Charpentier A. Analyse expérimentale: de quelques éléments de la sensation de poids. *Arch Physiol Norm Pathol* 3: 122–135, 1891.

Chouinard PA, Large ME, Chang EC, Goodale MA. Dissociable neural mechanisms for determining the perceived heaviness of objects and the predicted weight of objects during lifting: an fMRI investigation of the size-weight illusion. *NeuroImage* 44: 200–212, 2009.

Ellis RR, Lederman SJ. The material-weight illusion revisited. *Percept Psychophys* 61: 1564–1576, 1999.

Ernst M. Perceptual learning: Inverting the size-weight illusion. *Curr Biol* 19: R23–R25, 2009.

Flanagan JR, Beltzner MA. Independence of perceptual and sensorimotor predictions in the size–weight illusion. *Nat Neurosci* 3: 737–741, 2000.

Flanagan JR, Bittner JP, Johansson RS. Experience can change distinct size-weight priors engaged when lifting objects and judging their weights. *Curr Biol* 18: 1742–1747, 2008.

Gordon AM, Westling G, Cole KJ, Johansson R. Memory representations underlying motor commands used during manipulation of common and novel objects. *J Neurophysiol* 69: 1789–1796, 1993.

Grandy MS, Westwood DA. Opposite perceptual and sensorimotor responses to a size-weight illusion. *J Neurophysiol* 95: 3887–3892, 2006.

Halstead WC. Brain injuries and the higher levels of consciousness. *Res Publs Ass Nerv Ment Dis* 24: 480–506, 1945.

Harshfield SP, DeHardt DC. Weight judgment as a function of apparent density of objects. *Psychonom Sci* 20: 365–366, 1970.

Johansson RS, Westling G. Coordinated isometric muscle commands adequately and erroneously programmed for the weight during lifting task with precision grip. *Exp Brain Res* 71: 59–71, 1988.

Li Y, Randerath J, Goldenberg G, Hermsdorfer J. Grip forces isolated from knowledge about object properties following a left parietal lesion. *Neurosci Lett* 423: 187–191, 2007.

Macrae CN, Milne AB, Bodenhausen GV. Stereotypes as energy-saving devices: a peek inside the cognitive toolbox. *J Personality Soc Psych* 66: 37–47, 1994.

Milner AD, Goodale MA. *The Visual Brain in Action* (2nd ed.). Oxford, UK: Oxford Univ. Press, 2006.

Seashore CE. Some psychological statistics. II. The material weight illusion.*Univ Iowa Stud Psychol* 2: 36–46, 1899.

Zwislocki JJ, Goodman DA. Absolute scaling of sensory magnitudes: a validation. *Percept Psychophys* 28: 28–38, 1980.