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Report

Experience Can Change Distinct Size-Weight Priors Engaged in Lifting Objects and Judging their Weights

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Summary

The expectation that object weight increases with size guides the control of manipulatory actions [1–6] and also influences weight perception. Thus, the size-weight illusion, whereby people perceive the smaller of two equally weighted objects to be heavier, is thought to arise because weight is judged relative to expected weight that, for a given family of objects, increases with size [2, 7]. Here, we show that the fundamental expectation that weight increases with size can be altered by experience and neither is hard-wired nor becomes crystallized during development. We demonstrate that multiday practice in lifting a set of blocks whose color and texture are the same and whose weights vary inversely with volume gradually attenuates and ultimately inverts the size-weight illusion tested with similar blocks. We also show that in contrast to this gradual change in the size-weight illusion, the sensorimotor system rapidly learns to predict the inverted object weights, as revealed by lift forces. Thus, our results indicate that distinct adaptive size-weight maps, or priors, underlie weight predictions made in lifting objects and in judging their weights. We suggest that size-weight priors that influence weight perception change slowly because they are based on entire families of objects. Size-weight priors supporting action are more flexible, and adapt more rapidly, because they are tuned to specific objects and their current state.

Results

To test whether the relationship between object size and expected weight can be inverted for a defined family of objects, we constructed a set of 12 objects, consisting of four shapes and three sizes, whose weights varied inversely with volume (Figure 1). A single linear function described the relationship between volume and weight for these inverted size-weight objects (Figure 1A). All objects were covered with a thin sheet of balsa wood and painted green so that they had the same general feel and appearance.

In all experiments, participants gained experience with the inverted size-weight objects by repeatedly lifting and replacing them, moving them from the tabletop to one of four force sensors or vice versa (Figure 1B; see Experimental Procedures). Thus, in one half of the lifts, which we will refer to as load-force lifts, we could measure the vertical load force that participants applied to the object prior to liftoff. Across three experiments, involving different participants, we varied both the number of days of lifting and the number of lifts performed per day in order to examine the effects of experience on weight predictions engaged in judging weight and in lifting objects. We also included a control group of participants who never lifted the inverted size-weight objects.

To assess predictions about weight used in lifting, we measured the load force at the time of the initial peak rate of change in load force applied to the object during lifting. If the weight of the object is accurately predicted when objects are lifted slightly above a surface, as in our experiments (see Experimental Procedures), this measure will be close to half the weight of the object [1, 2]. To assess predictions about object weight that influence weight judgments, we tested the size-weight illusion using a small and a large cube equal in volume to the small and large inverted objects, respectively, and both equal in weight to the midsized inverted objects (Figure 1A). These cubes were also covered in balsa wood and painted green, such that they were similar in feel and appearance to the inverted size-weight objects. To measure the illusion, we used the absolute-magnitude-estimation procedure, whereby participants assigned numbers corresponding to the weights of the two cubes after lifting them in turn [2]. To quantify the strength and direction of the size-weight illusion, we determined the percentage increase from the smallest to the largest magnitude estimate and assigned a positive value to this number if the small cube was judged to be heavier or a negative value if the large cube was judged to be heavier.

On average, the control participants judged the small cube to be 141% heavier than the large cube (Figure 2). This score was significantly greater than 0% ($t_{16} = 5.19$; $p < .001$), indicating that these participants, on average, experienced a robust illusion with our size-weight cubes. In Experiment 1, participants performed a total of 1050 lifts with the inverted size-weight objects in a single session, after which the illusion was tested. On average, these participants judged the small cube to be 18% heavier than the large cube (Figure 2). The strength of the illusion was weaker than that experienced by the controls ($t_{32} = 4.38$; $p < .001$) but still greater than 0% ($t_{16} = 2.42$; $p = .028$). Thus, these participants experienced an attenuated illusion. In Experiment 2, participants performed 1200 lifts a day for three successive days and 120 lifts on day 4, and the illusion was tested after the lifts on day 4. On average, these participants judged the large cube to be 3% heavier than the small cube (Figure 2). This score was not reliably different than 0% ($t_{15} = -.15$; $p = .88$), indicating that these participants, on average, did not experience the size-weight illusion. In Experiment 3, participants lifted the inverted objects 240 times a day for 11 days, and the illusion was tested after the lifts on Day 11. These participants exhibited a reversal of the size-weight illusion (Figure 2). Specifically, on average, they judged the large cube to be 67% heavier than the small cube, and this effect was significantly different than

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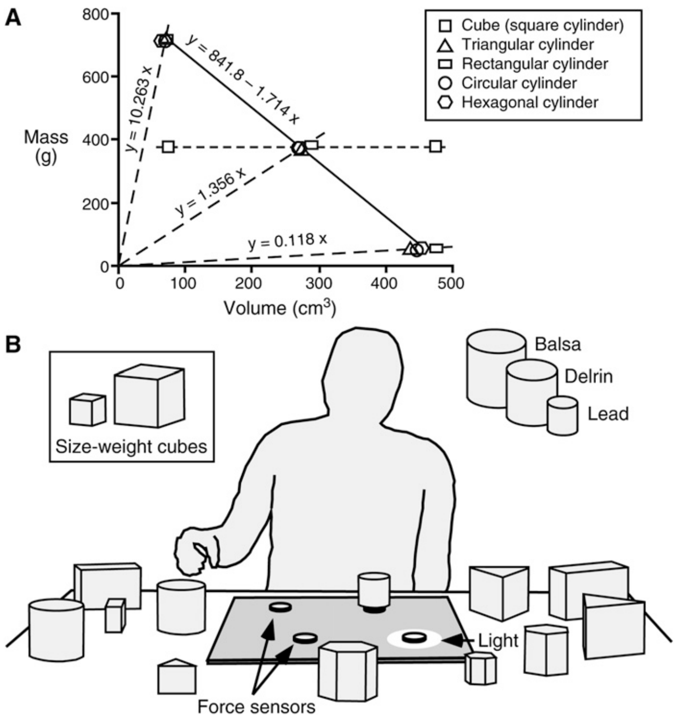

Figure 1. Stimuli and Experimental Setting

(A) Relationship between volume and size for the 12 objects whose weight varied inversely with size and for the small and large equally weighted cubes.

(B) While seated, participants lifted the objects from the tabletop and placed them onto one of four force sensors or vice versa. A data projector, located above the participant, provided instructions about which object to place on a given force sensor and which object to remove from a given force sensor.

0% ($t_8 = -2.94$; $p = .019$). Participants in Experiment 3 continued to lift the inverted objects for a total of 30 days, and additional tests of the illusion were carried out on days 12–15 and 26–30. The strength of the reversed size-weight illusion did not change after day 11 (see Supplemental Experimental Procedures and Figure S1, both available online).

In contrast to the extremely gradual adaptation of predictions about object weight that influence weight judgments, revealed by changes in the size-weight illusion, we found that predictions about weight used in lifting the inverted size-weight objects adapted quite quickly. As illustrated in Figure 3A, participants initially underestimated the weight of the small, heavy objects, and several increases in load force, associated with distinct peaks in load-force rate, were required for achieving liftoff (vertical gray lines). However, in later trials in the same session, participants accurately predicted the weight of the small objects, such that liftoff occurred after a single, rapid increase in load force. This adaptation of sensorimotor predictions about weight was evident in a larger initial peak in load-force rate generated in late trials as compared to early trials (black, dashed, vertical lines), as well as a greater load force at the time of the initial peak in load-force rate (horizontal dashed lines). We used the latter measure, which we will refer to as $LF_{1st\ peak\ rate}$, to assess sensorimotor performance, because it is stable across the changes in load-phase duration (i.e., the time period during which load force is increased up until liftoff) that can occur if participants select different lifting rates. We focused our analysis of adaptation of load forces on the small and midsized objects for which we could accurately measure the initial peak in load-force rate and, hence, $LF_{1st\ peak\ rate}$. When initially lifting the large, light objects, participants overestimated the weight and liftoff occurred while load-force rate was still increasing. On the basis of previous results [2, 8], we assumed that adaptation to the large, light objects follows a similar time course as adaptation to the small, heavy objects.

To assess how load forces applied to objects of different size (and weight) changed with practice, we computed the median value of $LF_{1st\ peak\ rate}$ for each successive block of five load-force lifts. Separate values were computed for each participant. This resulted in 35 blocks in Experiment 1, 40 blocks on days 1–3 and four blocks on day 4 in Experiment 2, and eight blocks per day in Experiment 3. Figures 3B–3D show mean $LF_{1st\ peak\ rate}$ values (averaged across participants) for the small and midsized objects, as a function of trial block, for Experiments 1–3. For Experiment 1, all 35 trial blocks are shown (Figure 3B, left panel). For Experiment 2, the first eight and last four blocks on day 1, the first and last four blocks on days 2 and 3, and all four blocks on day 4 are shown (Figure 3C). For Experiment 3, all eight blocks on day 1 and the first four blocks on days 2, 4, and 11 are shown (Figure 3D). The horizontal gray lines, located at the same height in panels B, C, and D, are included as visual references.

In all three experiments, the difference between $LF_{1st\ peak\ rate}$ values for the small and midsized objects was close to zero in the first block (on day 1) and then increased over the next 10–15 blocks. Paired t tests revealed that, for the first block in all three experiments, the $LF_{1st\ peak\ rate}$ values for the small and midsized objects in block 1 were not reliably different ($p > 0.16$ in all three cases). However, with the exception of block 2 in Experiment 3, in all other blocks $LF_{1st\ peak\ rate}$ was greater for the small objects than for the midsized objects ($p < 0.05$). To assess the rate of sensorimotor adaptation, for each experiment, we fit an exponential of the form $y = ae^{bx} + c$ to the mean $LF_{1st\ peak\ rate}$ values for the small object as a function of trial block (including blocks across successive days in Experiments 2 and 3). As illustrated in Figure 3, the exponential functions fit for the experiments were similar. The asymptotes for Experiments 1, 2, and 3 were 3.105, 3.102, and 3.205 N, respectively, and the corresponding half-lives were 3.52, 3.30, and 2.83 blocks. These results indicate the participants in all three experiments quickly adapted their lifting forces to the inverted size-weight objects over the first eight blocks (or 240 lifts) and had almost fully adapted their lifting forces by the 15th block. Moreover, as can be readily appreciated from Figures 3C and 3D, participants retained this adaptation across days. Note that when initially lifting the midsized, midweighted objects, participants estimated object weight quite accurately and modest changes in $LF_{1st\ peak\ rate}$ were observed across trial blocks. Nevertheless, as can be appreciated visually in Figures 3B–3D, the time course of this adaptation was similar to that observed for the small, heavy objects. Importantly, when participants in Experiments 1, 2, and 3 were tested on the size-weight illusion at the end of days 1, 4, and 11, respectively, their lifting forces were equally and fully adapted to the inverted size-weight objects. Thus, the differences in the size-weight illusion across the

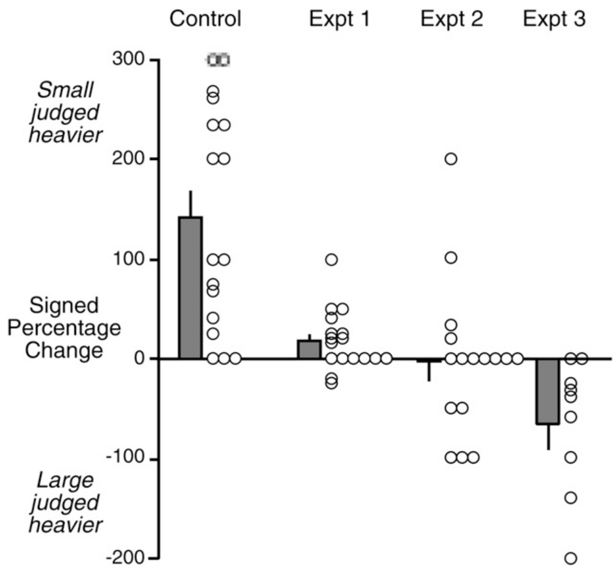

Figure 2. Strength and Direction of the Size-Weight Illusion in Different Experiments

The height of each bar represents the mean signed percentage-change score across participants, and the height of each error bar represents 1 SE. The symbols represent scores provided by individual participants. A positive score of 100 indicates that the small object was judged to be 100% heavier than the large object; a negative score of 50 indicates that indicates that the large object was judged to be 50% heavier than the small object.

three experiments are not due to differences in sensorimotor performance.

In Experiment 1, participants first lifted the circular, rectangular, and triangular cylinders 50 times each, for a total of 450 lifts (15 trial blocks). We then introduced the hexagonal cylinders, and participants lifted each object another 50 times each, for an additional 600 lifts (20 trial blocks). To examine transfer of sensorimotor adaptation to the new hexagonal shape, for each participant, we determined the $LF_{1st\ peak\ rate}$ values for the first lifts of the small and midsized hexagonal cylinders and the first lifts of any one of the other small and midsized objects after the introduction of the hexagonal cylinders. The right panel of Figure 3B shows the mean $LF_{1st\ peak\ rate}$ values, averaged across participants, for these four cases. For both the small and midsized objects, similar $LF_{1st\ peak\ rate}$ values were observed for the hexagonal and nonhexagonal cylinders. Paired t tests failed to reveal a difference between the $LF_{1st\ peak\ rate}$ values for the hexagonal and nonhexagonal cylinders for both the small ($p = 0.64$) and midsized ($p = 0.29$) objects. Thus, the adaptation of lifting forces to the inverted objects generalized to the new shape. This suggests that the sensorimotor system learned a size-weight map based on the circular, triangular, and rectangular cylinders and used this map to predict the weights of the new hexagonal cylinders.

In summary, these results indicate that, at the sensorimotor level, participants learned to predict the weights of the inverted size-weight objects quite accurately within about 240 lifts and retained this learning across days. Although this rate of sensorimotor adaptation is considerably slower than that observed when people lift a single object whose weight can vary [1, 9] or a pair of equally weighted objects of different size [2, 4], it is very fast in comparison to the extremely gradual adaptation of the size-weight illusion.

Discussion

Previous studies using the size-weight illusion have indicated that predictions about weight that bias weight judgments are independent of predictions about weight used in lifting [2, 10]. When repeatedly lifting a large cube and an equally weighted small cube in alternation, participants initially misjudge the forces required to lift the objects but adapt these forces to the object weights after about ten lifts. However, the strength of the size-weight illusion is as strong after 40 lifts as it is after the first two lifts [2]. This result also indicates that the size-weight illusion does not arise from errors in sensorimotor prediction, as previously postulated [11, 12]. The fact that participants in all three of our experiments fully adapted their lift forces to the inverted size-weight objects and yet exhibited differences in the strength and direction of the size-weight illusion supports the claim that sensorimotor predictions about weight used in lifting are independent of predictions about weight that influence weight judgments. This observation can be related to the broader idea, born largely from studies of visual processing, that the control of action and making of perceptual judgments rely on neural processes that use sensory information in different ways [13–15]. However, it has been well argued that this distinction between action and perception is overly general and that the processing of sensory information depends on the demands of the task rather than whether the task involves action or perceptual judgments per se [16].

Our findings provide powerful support for the dual proposition that people perceive object weight relative to expected weight, generated from learned size-weight maps associated with families of objects, and that experience can radically alter the nature of these maps. Specifically, we have shown that experience can invert the fundamental expectation that object weight will increase with size. Therefore, this expectation, which applies to virtually all families of objects, neither is hard-wired nor becomes crystallized during development.

The idea that the size-weight illusion arises because people judge weight relative to expected weight based on size, referred to as the expectancy hypothesis [2, 7], is not the only account of the size-weight illusion. In particular, it has been argued that the illusion arises because people's weight judgments are primarily based on object density [17, 18] or rotational inertia [19]. Our results effectively rule out these competing accounts, because these accounts cannot explain how weight judgments can be radically changed with experience as demonstrated by the inversion of the size-weight illusion.

Our analysis of load forces during lifting suggests that experience also can invert size-weight maps used for controlling actions, maps that are distinct from those engaged when judging weights. It is possible that sensorimotor adaptation to the inverted size-weight objects involves learning the weights of the individual objects being lifted rather than the modification of a size-weight map for the set of objects. However, our finding that sensorimotor adaptation generalizes to objects that are of a different shape but still belong to the same family of objects suggests that sensorimotor predictions about weight make use of size-weight maps (see also [3]).

Performance in a number of sensorimotor and perceptual tasks has been successfully described with the Bayesian approach, in which information about a stimulus is combined with prior assumptions, or priors [20–22], that may

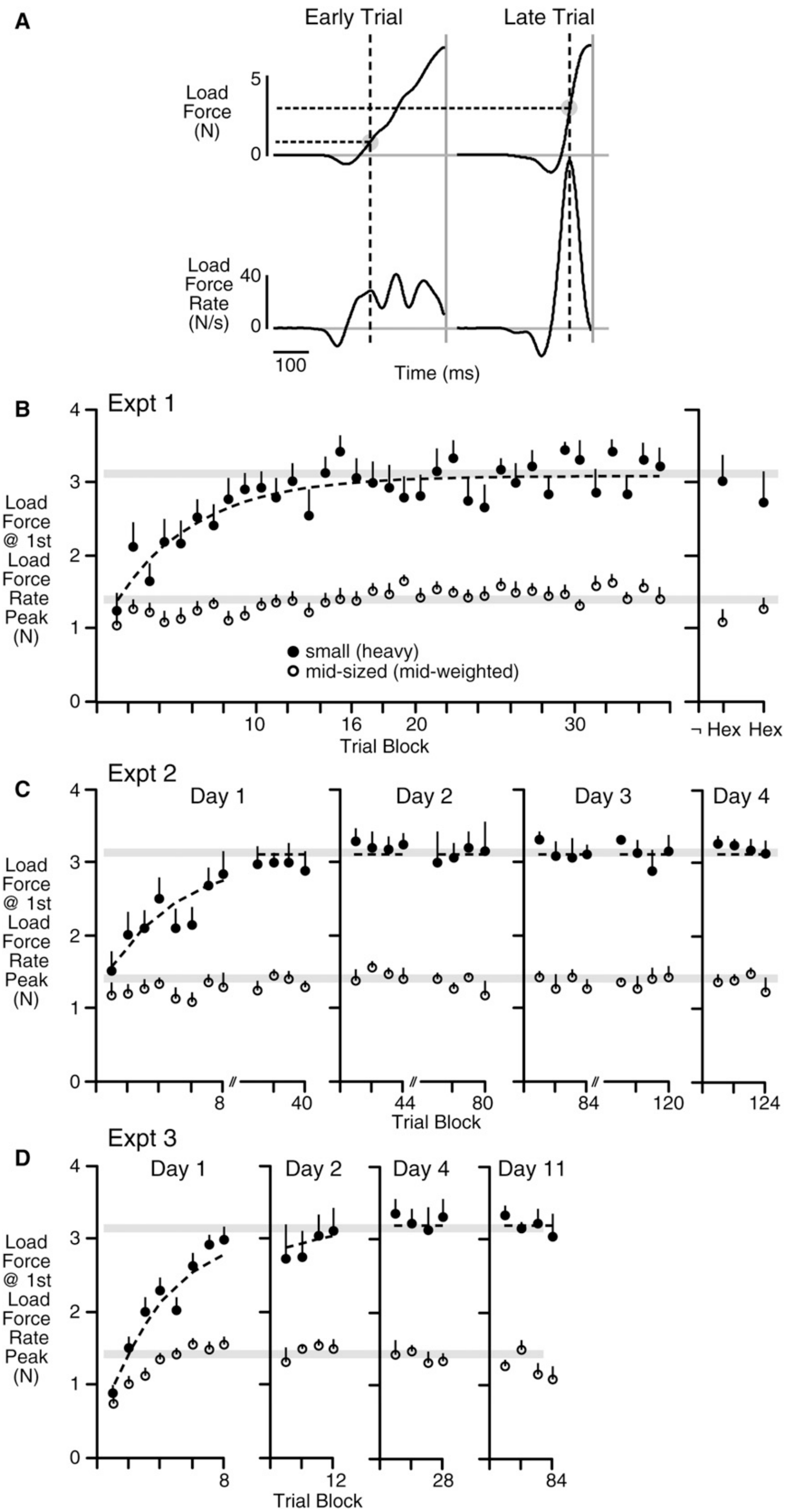

Figure 3. Load Forces during Lifting

(A) Individual load-force and load-force-rate records from an early and a late trial in which the small, heavy circular cylinder was lifted. The black, dashed, vertical lines mark the time of the initial peak in load-force rate, and the horizontal dashed lines mark the load force at the time of the initial peak in load-force rate. The gray vertical lines mark the time of liftoff.

(B–D) Load force at the time of the initial peak in load-force rate for the small and midsized objects as a function of trial block. Each point represents the average across participants, in which each participant's score represents the median of a block of five successive trials with the same object size. The dashed curves show exponentials fit to the mean data points for the small objects. The height of each vertical bar represents 1 SE.

(B) The right panel shows load force at the time of the initial peak in load-force rate for the first lift of the small and midsized hexagonal cylinders and the first lift of any one of the other small and midsized objects after the introduction of the hexagonal cylinders in block 16. Each point represents the average across participants.

change when the statistics of the environment are manipulated [23, 24]. Our finding that lift forces and the size-weight illusion adapt at different rates indicates that distinct size-weight priors underlie predictions about weight that are used in lifting objects and predictions about weight that bias weight judgments. It has been argued that the optimum rate at which priors are modified should be tuned to how parameters in the real world change [25]. We suggest that size-weight priors engaged in judging the weights of familiar objects are extremely resistant to change because they are based on correlations between size and weight that are well-established and stable and broadly generalize across behavioral situations and tasks. Thus, the size-weight prior for a given family of objects, used in weight perception, is only minutely affected each time an individual object categorized as belonging to that family is encountered. For weight perception, this resistance makes sense. If size-weight maps engaged in judging weight were modified quickly, we would effectively lose our ability to recognize and tag objects as being relatively heavy or light and to communicate this information to others. In addition, our ability to categorize objects into families, for which the nature of the size-weight relationship is an important classification feature, would be compromised. On the other hand, it is critical that sensorimotor predictions about weight adapt rapidly, because such predictions are essential for skilled actions with specific objects [26]. We suggest that because the sensorimotor system must deal with specific objects, including objects whose weight can vary, such as water bottles, information gained from a single lift can strongly modify the size-weight prior used when lifting objects. We conclude that the brain maintains two distinct representations involved in predicting the weights of manipulable objects: a slowly adapting representation that supports weight perception and a rapidly adapting one that supports manipulatory actions.

Experimental Procedures

Sixty-three healthy participants between 18 and 30 yrs of age took part in the study after providing written informed consent. Participants in all experiments repeatedly lifted, moved, and replaced 12 inverted size-weight stimuli of four shapes and three sizes (Figure 1). The four small objects were similar in volume and weight, as were the four midsized objects and the four large objects. The small, midsized, and large objects were constructed from lead, the plastic Delrin, and balsa wood and had densities of 10.263, 1.356, and 0.118 g/cm^3, respectively. To test the size-weight illusion, we constructed two equally weighted cubes, equivalent in volume to the small and large inverted objects. The small and large cubes were constructed from lead and Delrin, respectively, and their weights were tuned with narrow boreholes, so that the mass was evenly distributed in the volume.

In one half of the lifts performed with the inverted objects, participants lifted an object from a tabletop and placed it on one of four force sensors (Nano 17 F/T sensors, ATI Industrial Automation, Garner, NC, USA) located in front of them and capped with flat circular disks (diameter 3 cm). In the other half, participants lifted an object from a force sensor and placed it on the tabletop. In these lifts, we could measure the load force applied to the object during lifting (sampled at 1000 Hz).

Participants were asked to lift each object 1 cm off the surface, hold it stationary for a brief period, then replace it at a new location. To instruct participants to place a particular object on a particular sensor, an image, equal in size and shape to the object, was projected onto that sensor via an LCD projector. To instruct the participant to lift a given object located on a given sensor, a small circle (diameter 1 cm) was projected onto the center of the object. Forces from the sensors signaled when each instruction was completed, and a computer program controlled the sequence of instructions. The object to be lifted in a given trial was randomly selected, subject to the constraint that a given object could not be placed on a sensor and then lifted off again in successive trials. In trials in which an object was placed on a sensor, the sensor was randomly selected from the unoccupied sensors. On average, two objects were placed on the sensors at any time. The only additional constraint was that each object had to be lifted the same number of times within a session.

In Experiment 1, participants first lifted the circular, rectangular, and triangular cylinders 50 times each from a force sensor, for a total of 450 lifts. The hexagonal cylinders were then introduced to test for generalization across shapes, and participants lifted each object another 50 times, for an additional 600 lifts, after which the size-weight illusion was then tested. In Experiment 2, participants lifted all 12 inverted size-weight objects 100 times each over three successive days and ten times each on day 4, after which the illusion was tested. In Experiment 3, participants lifted the 12 inverted objects 20 times each over 30 successive weekdays, with the exception of days 15 and 30, on which no lifts of the inverted size-weight objects were performed. The size-weight illusion was tested on days 11–15 and 26–30 after the lifts (if any) of the inverted size-weight objects had been performed.

To test the size-weight illusion, the experimenter placed the small and large cubes on the two sensors closest to the participant while the participant looked away. The participant lifted one of the cubes first and, while holding it aloft, assigned a number representing its weight. After replacing the first cube, the participant then lifted the other cube and again, while holding it aloft, assigned a number best representing its weight. The locations of the two cubes and the order of lifting were counterbalanced across participants and, in Experiment 3, across days as well. Participants were informed about the procedure ahead of time and were told that they could use any numbers they wished, including fractions or decimal points. No range was provided. If a participant asked whether the number should indicate units of weights such as grams, we told them that this was not required.

In Experiments 1 and 2, we tested the size-weight illusion, a single time, after the participant had completed their lifts of the inverted size-weight objects. In Experiment 3 we tested the size-weight illusion on day 11 and on 9 subsequent days (see Supplemental Data). Based on the two magnitude estimates provided in each test, we computed a signed percentage change score to quantify the strength and direction of the illusion. Specifically, we took the difference between the largest and smallest estimates, divided this difference by the smallest estimate, multiplied by 100, and signed the resulting percentage change positive if the small cube was judged to be heavier and negative if the large cube was judged to be heavier.

Supplemental Data

Supplemental Data include Supplemental Experimental Procedures and one figure and can be found with this article online at http://www.current-biology.com/supplemental/S0960-9822(08)01272-4.

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