Short Papers

Characterization of the Haptic Shape-Weight Illusion with 3D Objects

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Abstract—The present study shows an effect of 3D shape on perceived weight of objects. This effect could be explained partly by the size-weight and the shape-size illusions, suggesting that the perceived size is not the only factor responsible for the shape-weight illusion.

Index Terms—Haptic perception, touch, weight.

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1 INTRODUCTION

THE study of weight perception has a long history. Weber [1] has often been indicated as the pioneer, studying the ability of human observers to perceive weight differences. In the following years, researchers started to investigate some interesting weight illusions. Examples are Charpentier's size-weight illusion, reported first in 1891 [2], and Wolfe's material-weight illusion [3]. In this paper, we have focus on another weight illusion that has been mentioned briefly by Dresslar in 1894 [4], but which has not been investigated in detail thereafter. In one of Dresslar's tests, subjects had to order eight different objects according to their weight. The objects were made of sheet lead, and were all of the same unreported thickness, area, and weight. Their shape varied along two dimensions from regular figures, such as a circle or a square, to irregular angled figures. The figures could be explored unrestrictedly and vision was allowed. The results showed that objects that appeared to be smallest or of the most compact form were judged to be heaviest. This suggests that the influence of shape on weight perception is mediated by the perceived size of objects.

The present study investigates whether comparable effects of shape on perceived weight would be found for 3D objects. During the experiments, vision was not allowed in order to study a purely haptic shape-weight illusion. The nature of this illusion could be predicted from the haptic size-weight [5] and shape-size [6] illusions. Ellis and Lederman [5] showed that a physically smaller object is perceived as being heavier: a doubling of the volume of cubes with the same physical weight resulted in a 26 percent decrease of their estimated weight. If we assume that this relationship holds for the whole range of volumes and weights, then it can be written as

$$\frac{W_2}{W_1} = \left(\frac{V_2}{V_1}\right)^{-0.43} \tag{1}$$

where W_i is the perceived weight and V_i the physical volume of objects. Kahrimanovic et al. [6] demonstrated that a tetrahedron was perceived as being larger in volume than a cube or a sphere of the same physical volume, and that a cube was perceived as larger than a sphere. The biases measured in that study are shown in Table 1.

If the haptic shape-weight illusion with 3D objects were mediated by the haptically perceived size (i.e., volume) of objects, comparable to Dresslar's 2D shape-weight illusion [4], then the perceptually smaller object will be perceived as being heavier. From this, we can predict that a sphere will be perceived as heavier than a cube or a tetrahedron of the same physical mass, and that a cube will be perceived as heavier than a tetrahedron. The magnitude of these biases can be predicted by substituting the biases found in [6] for the ratio V_2/V_1 in (1). The predicted direction and magnitude of these biases are shown in Table 1.

In this paper, these predictions are tested in two experiments. In Experiment 1, the existence of a purely haptic shape-weight illusion with 3D objects was investigated. Subjects had to compare two different objects (comparisons of spheres, cubes, and tetrahedrons) and to judge which of the two is heavier. In Experiment 2, another test method was used in order to investigate the robustness of the observed effects. Establishing an appropriate way to measure this illusion and to obtain reliable and replicable results is the first step toward understanding the mechanism behind this phenomenon.

2 GENERAL METHODS

2.1 Stimuli

The stimuli were sets of tetrahedrons, cubes, and spheres, which were the same as those from our previous study on volume perception [6]. The weight of these brass stimuli ranged from 16.8 to 117.6 g, in steps of 8.4 g (i.e., 1 cm^3). The volume covaried consistently with the weight, ranging from 2 to 14 cm^3.

2.2 Subjects

In total, 21 subjects participated in the two experiments. Seven subjects participated only in Experiment 1 and another seven only in Experiment 2. A last group of seven subjects participated in both experiments, for which the order of the experiments was counterbalanced. Consequently, each experiment consisted of 14 subjects. The mean age of all subjects was 21 years (SD 2 years). Eleven subjects were male and 10 female. All, but three subjects were right handed as established by Coren's handedness test [7].

3 EXPERIMENT 1: DIRECT COMPARISONS

In this experiment, pairs of stimuli of different shapes and weights were presented to blindfolded subjects and points of subjective equality were determined.

3.1 Methods

3.1.1 Conditions

Experiment 1 consisted of nine conditions: three object pairs (tetrahedron-sphere, tetrahedron-cube, and cube-sphere) and three reference weights for each object pair (small, medium, and large). For each condition, each object was reference in half of the trials and test in the remainder. The weight and volume of these references are presented in Table 2. These references were the same as in our previous study on haptic volume perception [6]. In that study, the selection of the reference stimuli was based on pilot studies showing that a tetrahedron was matched to both a larger cube and a larger sphere and that a cube was matched to a larger sphere. Therefore, within a range, the selected tetrahedron reference was smaller than the cube and the sphere reference, and the cube reference was smaller than the sphere reference.

The conditions were performed within three sessions, which were performed on different days or two on the same day, but with at least 3 hours between the sessions. Object pair was randomized between sessions, and reference weight and reference object were

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TABLE 1
Predictions for the Shape-Weight Illusion

Shape-Size [6]		Shape-Weight (predicted)	
Direction	Magnitude	Direction	Magnitude
T > S	30 %	T < S	-11 %
T > C	9 %	T < C	-4 %
C > S	19 %	C < S	-7 %

The magnitude of the biases indicates the relative difference between the physical volumes/weights of two differently shaped objects that are perceived as equal in volume/weight. The direction of the bias shows which object is expected to be perceived as lighter/heavier if objects of the same physical weight are compared. T is tetrahedron, C is cube, and S is sphere.

alternated within sessions. For each reference, 35 trials were performed, resulting for each subject in a total of 210 trials per session and 630 trials for the complete experiment. On average, 2 hours per subject were needed to perform all the conditions.

3.1.2 Procedure

On each trial, two stimuli (one test and one reference) were placed successively on the hand palm of the subject's dominant hand. The order of the reference and test stimuli was randomized on each trial. The blindfolded subjects were instructed to enclose each stimulus, thereby perceiving its 3D shape and volume. During enclosure, they were allowed to move their hand (hefting) in order to perceive the weight more accurately. These instructions were based on the stereotypic exploratory procedures associated with the perceptual encoding of object properties [8]. The task was to judge, which of the two stimuli felt heavier. The stimuli were presented according to a computer-driven one-up-one-down staircase procedure. The stimuli could be explored only once on each trial. The period of exploration was not restricted, but was often just a few seconds.

3.1.3 Data Analysis

Cumulative Gaussian distributions (f) as a function of the physical mass (m) were fitted to the data, using the following equation:

$$f(m) = \frac{1}{2}\left(1 + \operatorname{erf}\left(\frac{m-\mu}{\sigma\sqrt{2}}\right)\right),$$

where μ is a measure of the point of subjective equality (PSE). Relative biases were calculated from these PSEs. For each object pair (e.g., tetrahedron-cube), the physical weight of the object mentioned first (i.e., tetrahedron) was subtracted from that mentioned second (i.e., cube) and divided by the average physical weight of these two objects. For example, if a subject perceived a tetrahedron of 42 g as being equal in weight to a cube of 30 g, then the resulting relative bias would be -33 percent. A negative bias indicated that the object mentioned first in each object pair was perceived as being lighter. More details on this procedure can be found in [6]. A smaller set of the data from the present experiment has already been presented in a conference paper [9].

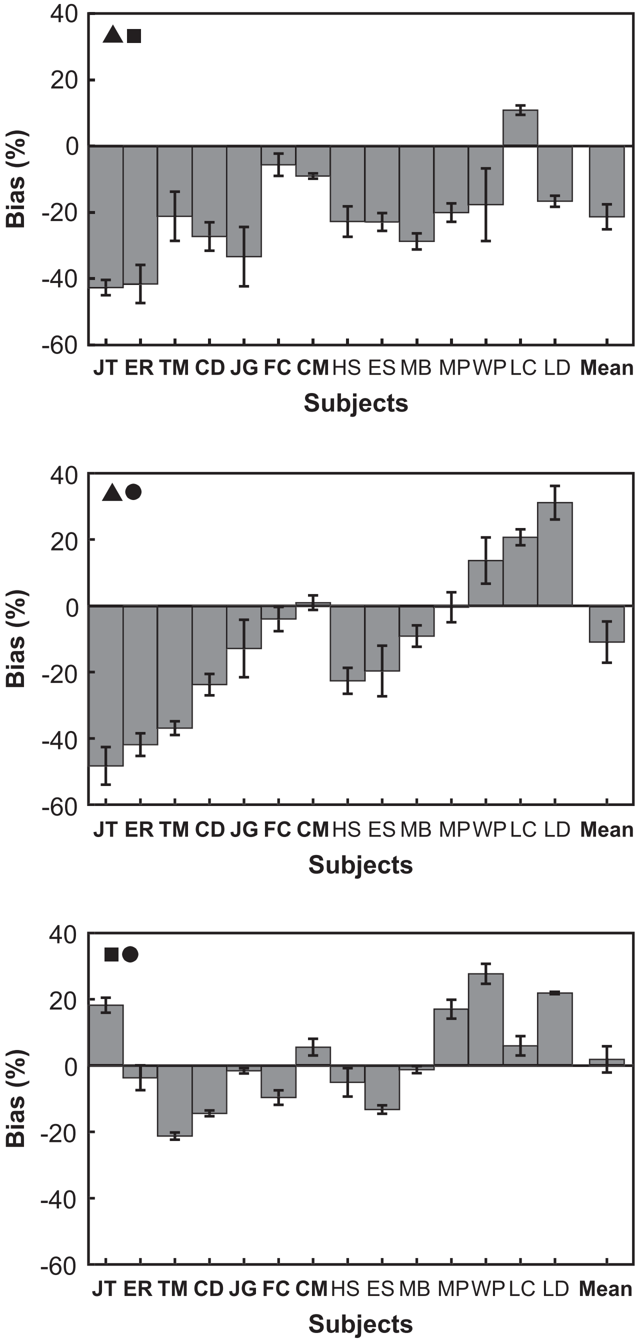

Fig. 1. Individual and average relative biases for the three object pairs. The object pairs are indicated by the 2D symbols in each figure. Each individual bar is an average of the biases measured for the six different references, with the standard deviation indicated with the error bars. The first seven subjects participated in Experiments 1 and 2 (indicated in bold print), and the last seven subjects only in Experiment 1. Within each subgroup, the subjects are ordered from the most negative to the most positive bias in the tetrahedron-sphere condition. The error bars for the mean represent the standard error.

TABLE 2
The Mass (m) and Physical Vol. (V) of the Reference Stimuli Used in Experiment 1

Shape-Size [6]		Shape-Weight (predicted)	
Direction	Magnitude	Direction	Magnitude
T > S	30 %	T < S	-11 %
T > C	9 %	T < C	-4 %
C > S	19 %	C < S	-7 %

T is tetrahedron, C is cube, and S is sphere.

These relative biases were used for the statistical analysis. The biases for different reference weights were averaged, since there was no significant difference between them (linear regression analyses, with the size as a continuous variable, showed that the slopes of the regression lines were not significantly different from zero, $p > 0.05$). One-sample t-tests were performed to test whether the biases in each object pair comparison were significantly different from zero.

3.2 Results

The individual and average biases for the three object pairs are shown in Fig. 1. The t-tests revealed that only the average tetrahedron-cube bias (mean $= -21$ percent, SE $= 4$ percent) was significantly different from zero, $t(13) = -5.7, p < 0.001$. The tetrahedron was perceived as being significantly lighter than the cube with only one subject (LC) performing differently. The average biases in the tetrahedron-sphere and cube-sphere conditions, -11 percent (SE 6 percent) and 2 percent (SE 4 percent), respectively, were not significant, $p > 0.05$. Nevertheless, some subjects showed large biases also in these conditions, but the direction of the biases was subject dependent. Some subjects perceived the sphere as being heavier than the tetrahedron or the cube (e.g., subjects ER and TM), while others perceived it as being lighter (e.g., subjects WP and LD). Overall, the subjects with negative biases in the tetrahedron-sphere comparison showed also negative biases in the cube-sphere comparison. Subject JT was the main exception to this pattern.

A possible test of the within-subjects consistency may be based on the assumption that the sum of the tetrahedron-cube bias and the cube-sphere bias should result in the tetrahedron-sphere bias. If, for example, a tetrahedron of 5 g is perceived as being equal in weight to a cube of 3 g, and this cube of 3 g is perceived as being equal to a sphere of 2 g, then consequently the tetrahedron of 5 g and the sphere of 2 g shall be perceived as equal, if individual subjects performed consistently between conditions. Pearson correlation analyses were performed on the calculated biases (the absolute bias in g for the tetrahedron-cube added to the absolute bias from the cube-sphere condition and expressed in terms of the tetrahedron reference) and the measured tetrahedron-sphere biases, revealing a strong correlation $(r = 0.8, p < 0.05)$.

4 EXPERIMENT 2: MAGNITUDE ESTIMATION

The second experiment investigated the robustness of the shape-weight illusion. In Experiment 1, subjects had to compare the weight of two differently shaped objects directly to each other. The results showed consistent biases in the tetrahedron-cube comparison and large individual differences in other object pair comparisons. Experiment 2 investigates whether the same pattern will occur with another test method, in which subjects had to provide an estimate of the weight of each stimulus separately. Obtaining comparable results with the two different methods will indicate that the shape-weight illusion is rather robust and that it does not only occur when two objects are compared directly (where the difference in shape is emphasized on each trial due to the direct comparison), but also when each object is judged separately.

4.1 Methods

4.1.1 Procedure

The same stimuli, as in Experiment 1, were placed on the hand palm of blindfolded subject, one at a time. As in Experiment 1, the subjects were instructed to enclose each stimulus before responding. They were asked to give each stimulus a numerical value proportional to the perceived weight of the stimulus. They could assign any number (i.e., integer, fraction, or decimal), but were asked to omit a response of zero. No standard stimulus was provided. Four blocks, each consisting of the total set of 39 objects, were performed with stimulus order randomized within each block. The four blocks were performed within one session lasting for about 40 minutes.

4.1.2 Data Analysis

For each stimulus, the median of the four magnitude estimates per stimulus was calculated and used for the data analysis. The data were analyzed in two ways. First, for each subject and each shape, the medians of the 13 stimuli were averaged, resulting in an overall magnitude estimate for each shape. Subsequently, the effect of shape on perceived weight was analyzed by forming three object pairs: tetrahedron-sphere, tetrahedron-cube, and cube-sphere. The overall magnitude estimates were used to compute relative biases for each object pair in the same way as in Experiment 1, with the exception that in this experiment the overall magnitude estimate given to the shape mentioned *second* was subtracted from that mentioned *first* and divided by the average magnitude estimate of these two shapes. These relative biases enabled us to test for effects of shape and to compare the results from the present experiment with the biases measured in Experiment 1. Note that the biases in Experiment 1 were measured directly, since two objects were compared directly on each trial, while in this experiment they were derived from the magnitude estimates.

A second analysis was performed in order to illustrate, for each shape, the relationship between the weight of the stimuli and the magnitude estimates. Since the subjects were free to use their own range, the data were first normalized; for each subject, the raw score for a given stimulus was divided by the mean of all scores for that subject. This number was then multiplied by the grand mean of all subjects. The same scale-equation procedure was used previously by Ellis and Lederman [10], [11]. Subsequently, power functions were fitted to these normalized magnitude estimates. A power function was chosen since Stevens proposed that magnitude estimations increase in proportion to the stimulus intensity raised to a power [12].

4.2 Results

Fig. 2 shows the calculated individual and average relative biases for each object pair. The average biases were -7 percent (SE 2 percent), -8 percent (SE 3 percent), and 0 percent (SE 2 percent) for the tetrahedron-cube, tetrahedron-sphere, and cube-sphere pairs, respectively. The figure also shows that, as in Experiment 1, large interindividual differences occurred during the comparison of a sphere to a tetrahedron or to a cube. The t-tests revealed that the biases for the tetrahedron-cube and the tetrahedron-sphere pairs were significantly different from zero, $t(13) = -3, p < 0.05$ and $t(13) = -2, p < 0.05$. The cube-sphere bias was not significant, $t(13) = -0.5, p = 0.7$. In addition, a comparison between the tetrahedron-cube and the tetrahedron-sphere biases, performed with a dependent t-test, showed that they did not differ significantly, $t(13) = 0.7, p = 0.7$.

A comparable pattern can be observed by plotting, for each object shape, the magnitude estimates as a function of object weights. Fig. 3 shows the average (normalized) magnitude estimates for the 13 object weights (horizontal axis) and the 3 object shapes (different symbols). Power functions were fitted to the data. The best fit functions were

$$\begin{array}{ccc} \text{Sphere} & \text{Cube :} & \text{Tetrahedron} \\ \left(\dfrac{m}{4.8\ \text{g}}\right)^{0.90} & \left(\dfrac{m}{4.3\ \text{g}}\right)^{0.86} & \left(\dfrac{m}{4.8\ \text{g}}\right)^{0.87}, \end{array}$$

with m indicating the mass in g. The 95 percent confidence intervals for the power function exponents were [0.8-1], [0.8-0.9], and [0.8-0.9] for the three shapes, respectively. As can be seen in the figure, the magnitude estimates for the tetrahedron are, on average, lower than these for the cube and the sphere, indicating that the tetrahedron was perceived as being lighter. The magnitude estimates for the cube and the sphere were almost the same.

5 DIRECT COMPARISON VERSUS MAGNITUDE ESTIMATION

As described earlier, seven subjects participated in both Experiments 1 and 2. The complete data set of these subjects is presented in Fig. 4. For the comparison of the two experiments, we are mainly interested in the direction of the biases. The magnitudes of the biases cannot be compared directly because the biases are derived in different ways. In Experiment 1, they are measured directly, whereas in Experiment 2 they are calculated from the magnitude estimates. A difference in the magnitude of the biases may be caused by this difference in calculation and not by the difference in the test method itself. Fig. 4 shows that the majority of the subjects performed consistently between the two experiments: those who had a negative (positive) bias in Experiment 1 also had a negative (positive) bias in Experiment 2. This was true for 16 of the 21 data

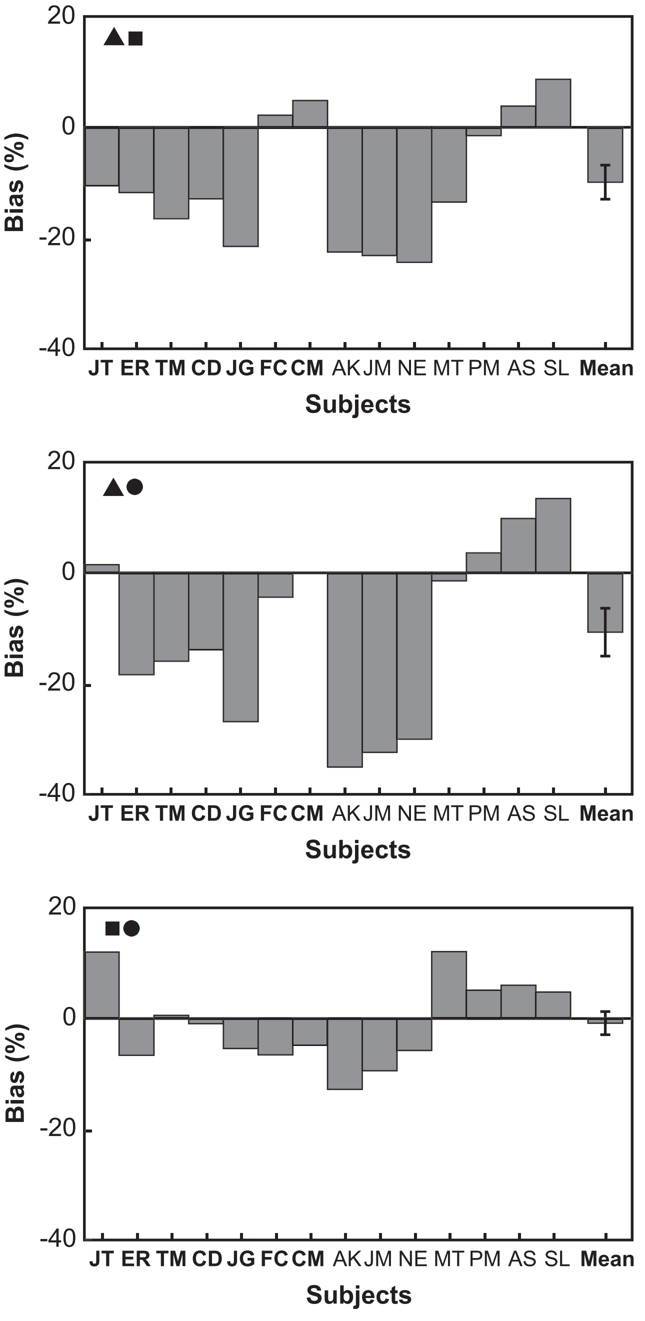

Fig. 2. Individual and average relative biases for the three object pairs for Experiment 2. The first seven subjects participated also in Experiments 1 and the ordering is the same as in Fig. 1. The error bars represent the standard error. Note that the cube-sphere bias follows directly from subtracting the tetrahedron-cube bias from the tetrahedron-sphere bias, because the biases are calculated from the magnitude estimates given to each shape.

points (76 percent). There are only some exceptions to this pattern: subjects CM and FC in the tetrahedron-cube comparison, JT in the tetrahedron-sphere comparison, and TM and CM in the cube-sphere comparison.

The similarity between the experiments is also apparent when we explore the complete data set as presented in Figs. 1 and 2 . The figures show a qualitatively similar pattern. For example, both figures show that the majority of subjects show negative biases in the tetrahedron-cube condition. The largest range of biases can be found for both experiments in the tetrahedron-sphere condition. Also, the biases in the cube-sphere condition are equally distributed around zero in both experiments. These similarities suggest that the direction of the biases is independent of the test method.

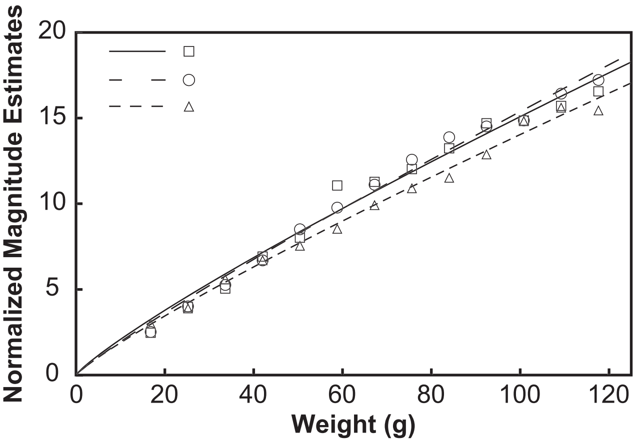

Fig. 3. Average normalized magnitude estimates for the different weights and shapes, with fitted power functions. The 2D plot symbols correspond to their 3D counterparts. Error bars were omitted for clarity.

6 GENERAL DISCUSSION

The present experiments reveal a large effect of shape on weight perception, although the direction and the magnitude of the biases were subject dependent. Comparable overall patterns of these biases occurred when subjects compared two differently shaped objects directly to each other (Experiment 1) and when subjects estimated the magnitude of each object separately (Experiment 2). Furthermore, from Experiment 2, we can conclude that the power function exponents of the best fit functions are less than 1. This resembles results by Curtis et al. [13] and Rule and Curtis [14], who showed (although for a different range of stimuli) that the power function exponent for lifted weights was 0.8 and 0.9, respectively.

The present two experiments revealed that in the tetrahedron-cube comparison, the perceptually larger object (tetrahedron) was perceived as lighter, with just a few exceptions. The direction of this effect is consistent with the predictions from the size-weight [5] and the shape-size illusions [6] as well as with Dresslar's study with objects that differed only along two dimensions [4]. This suggests that the effect of 3D shape on perceived weight is caused by the haptically perceived size of the objects. Koseleff [15] also showed that judgments of weight are influenced by the perceived size of an object, although the size information in his experiments was perceived visually by viewing objects through convex or concave lenses.

The results from the tetrahedron-sphere and the cube-sphere comparisons are not in line with this conclusion. Under these conditions, some subjects perceived the perceptually larger object as lighter, while others perceived the perceptually smaller object as lighter, with individual subjects showing large biases up to an absolute magnitude of about 40 percent. Despite this variation, the correlation analysis in Experiment 1 showed that the subjects performed consistently between conditions. It was expected that the direction of the shape-weight illusion would be consistent between subjects, since the directions of the haptic shape-size [16] and size-weight illusions (see the review in [17]) were fairly consistent between subjects. The large interindividual differences in the present study suggest that the occurrence of the haptic shape-weight illusion with small 3D objects cannot be explained completely by a combination of the results from the size-weight and the shape-size illusions. This conclusion is also supported by the difference in the magnitude of the measured and the predicted biases. It was predicted that the bias would be largest in the tetrahedron-sphere comparison and smallest in the tetrahedron-cube comparison (Table 1). In contrast, the present study shows the largest bias in the tetrahedron-cube comparison, with an average of about -14 percent for the two experiments together, and the smallest bias in the cube-sphere comparison, with an average bias

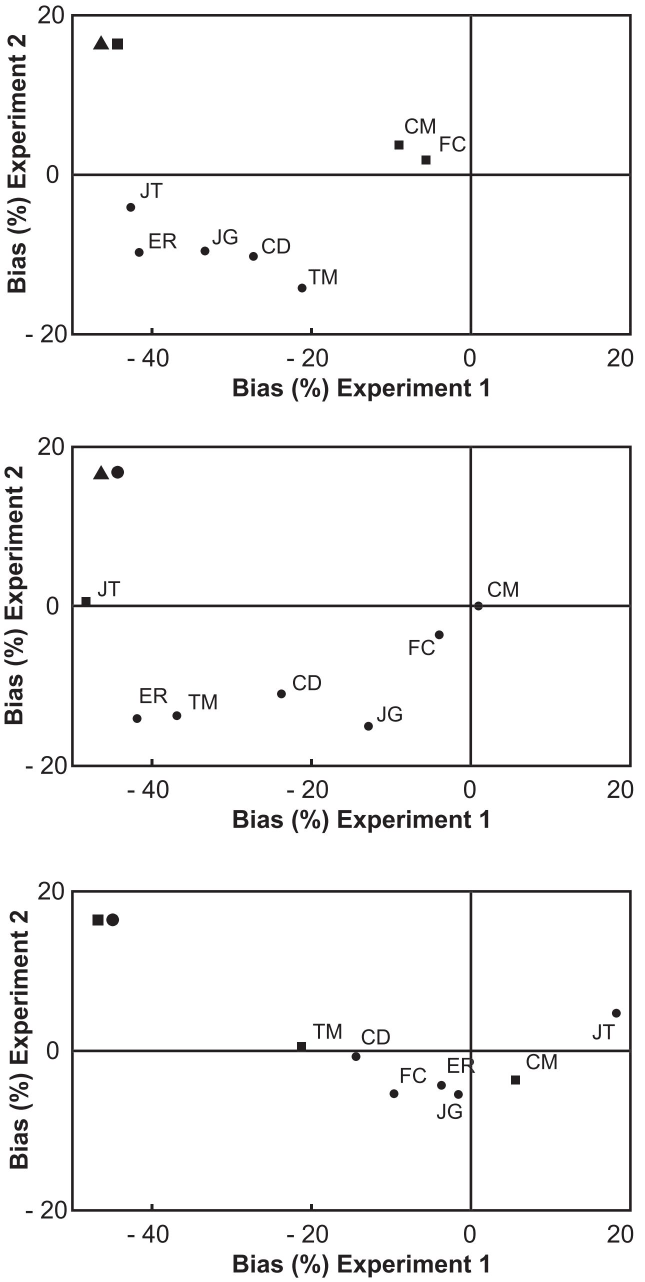

Fig. 4. Individual relative biases for the subjects who participated in both experiments. The letters indicate the different subjects. The square plot symbols indicate the subjects who performed inconsistently between the two experiments.

of about 1 percent. Hence, we have to conclude that the haptically perceived size is not the only factor that mediates the influence of 3D shape on perceived weight without visual information.

An interesting observation is that the individual differences in the direction of the biases are mainly observed in the conditions including a sphere. A possible interaction between the curved surface of the sphere and the subjects' hand posture may explain the variation in the data. Assuming that the judgment of weight is made at the moment that the objects are placed on the hand, the size of the object's area that is in contact with the skin at that moment would be smaller when the hand is stretched out than when it is cupped. How far the hand is cupped could differ between subjects, and this could result in the interindividual differences in the direction of the illusion. For a tetrahedron or a cube, the contact area did not differ because of a flat base, and maybe therefore smaller individual differences are observed for the tetrahedron-cube biases.

The present study emphasizes that we cannot ignore the influence of an object's 3D shape on weight perception, since large perceptual biases are observed. This effect cannot be explained completely by a combination of the size-weight and the shape-size illusions. At this moment, we can only speculate about possible explanations. Nevertheless, it is important to report the present experiments and their results for at least two reasons. First, this study provides a comprehensive characterization of the purely haptic shape-weight illusion with 3D objects. Second, studies mention the work of Dresslar [4] as the main study on the shape-weight illusion (for example [10], [11], [18], [19]). The present study, which is more systematic and controlled, agrees with Dresslar in that the shape of objects has an effect on the perceived weight. However, our results reveal that the processes involved in this phenomenon are not so unambiguous and simple, and that the illusion could not be explained by only the influence of haptically perceived size on perceived weight.

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