The Shape-Weight Illusion

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Abstract. In the present experiment, we investigated the influence of the shape of 3-dimensional objects on haptic perception of weight. A systematic shape-weight illusion was found when subjects compared a tetrahedron to a cube: a cube was perceived as being heavier than a tetrahedron of the same physical mass and volume. However, when subjects compared a sphere to a tetrahedron or to a cube, some subjects perceived the sphere as heavier than the other objects, while other subjects perceived the sphere as being lighter. These results indicate that the influence of shape on haptic perception of weight is not mediated only by the perceived volume, as would be predicted from previous studies, but that some subject dependent factors are involved.

Keywords: Weight, Size, 3-D shape, Touch, Haptics.

1 Introduction

When a human observer wants to lift or to move an object, weight information is necessary for the determination of the force that has to be applied in order to perform efficiently the required manipulation of that object. The initial weight percept can be biased by different physical object properties. For example, when human observers compare two objects of the same mass but of different size, they perceive the smaller object as being heavier. This is known as the size-weight illusion [1]. Dresslar [2] and Ellis [3] proposed that weight perception is also influenced by the shape of objects. To study this illusion, Dresslar used a set of objects that were made of sheet lead. They were all of the same unreported area and weight. Their shape varied from regular figures, such as a circle or a square, to irregular cornered figures. The objects could be explored unrestricted. On the other hand, Ellis used a set of solid objects with the same weight (350 g) and volume (132 cm³). The objects were rectangular cuboids with different dimensions and cylindrical objects with different lengths and diameters. The objects were explored in separate visual, haptic and bimodal conditions. The exploration was restricted to a four-finger/opposing-thumb grasp and the subjects were allowed only to lift the objects in a vertical motion.

These two studies revealed contradictory results. Dresslar showed that objects that appeared to be the *smallest* or of the most compact form were judged to be the heaviest. In contrast, Ellis showed that the *largest* objects were perceived to be the heaviest. Regardless of which of these results is more convincing, it is more important to question if these experiments are an appropriate way of measuring the shape-weight illusion. The main problem that we have with Dresslar's study is that the objects varied

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only along two dimensions. On the other hand, Ellis used 3-dimensional objects, but the exploration was restricted in such a way that mainly the width of the objects was perceived. The present experiment was designed to omit these problems, and to study the possible existence of a shape-weight illusion in a more appropriate way. We used a set of cubes, tetrahedrons and spheres, which could fit in the hand when explored. Subjects were blindfolded and the exploration was not restricted, encouraging the subjects to perceive shape, volume and weight of the objects as thoroughly as possible.

The bias for the shape-weight illusion can be predicted from the size-weight [4] and the shape-size [5] illusions. Ellis and Lederman [4] investigated a purely haptic size-weight illusion and showed that a doubling of the volume of cubes with the same physical weight resulted in a 26 % 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

$$\frac{W_{new}}{W_{old}} = \left(\frac{V_{new}}{V_{old}}\right)^{-0.43}, \qquad (1)$$

where W is the perceived weight and V the perceived volume of objects. Kahrimanovic et al. [5] demonstrated the occurrence of a shape-size illusion when subjects compared differently shaped objects. A tetrahedron was perceived as being larger than a cube or a sphere of the same volume, and a cube was perceived as larger than a sphere. The measured biases are shown in the second column of Table 1.

If the shape-weight illusion is mediated by the perceived size of objects, as proposed by Dresslar [2], then 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 Kahrimanovic et al. [5] for the ratio $V_{\mathrm{new}}/V_{\mathrm{old}}$ in Equation (1). The biases predicted from these studies are shown in the third column of Table 1. On the other hand, if the shape-weight illusion is not mediated by the perceived volume, as proposed by Ellis [3], then the biases will be in the opposite direction and/or their magnitude will deviate from the expected magnitude. The present study will investigate these possibilities.

Table 1. Predictions for the shape-weight illusion. 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 biases are expressed with respect to the first mentioned object in each object-pair. 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.

Condition	Magnitude of the bias		Direction of the bias	
	Shape–Size [5]	**Shape–Weight (prediction)**	**Dresslar [2]**	**Ellis [3]**
▲ - ●	32 %	- 11 %	▲ < ●	▲ > ●
▲ - ■	11 %	- 4 %	▲ < ■	▲ > ■
■ - ●	21 %	- 8 %	■ < ●	■ > ●

2 Methods

2.1 Subjects

Eight subjects participated in this experiment. Subjects 2, 3, 6, 7 and 8 were male and subjects 1, 4 and 5 were female (mean age 20 years). All subjects were strongly right-handed, as established by Coren's handedness test [6].

2.2 Stimuli and Procedure

Tetrahedrons, cubes and spheres were used as stimuli (see Fig. 1). They were made of brass and their mass ranged from 16.8 to 117.6 g, in steps of 8.4 g. The volume of the objects co-varied consistently with their mass. Hence, the volume ranged from 2 to 14 cm^3, in steps of 1 cm^3. These stimuli are the same as those used in our previous paper on the effects of shape on volume perception [5].

The stimuli were placed in the centre of the hand palm of blindfolded subjects (see Fig. 1). The subjects were instructed to enclose the stimuli, thereby perceiving their 3-D shape and volume. During enclosure, they were allowed to perform an up and down movement with the hand, in order to perceive the weight. These instructions were based on the stereotypic exploratory procedures associated with the perceptual encoding of these object properties [7]. The subjects were instructed to maintain the same exploratory procedure during the complete experiment. The period of exploration was not restricted, but was often just a few seconds. After exploration of the first stimulus, this stimulus was replaced by a second stimulus, which was explored in the same way as the first one. The order of the reference and comparison stimuli was randomized. The participants judged which of the two explored stimuli was heavier.

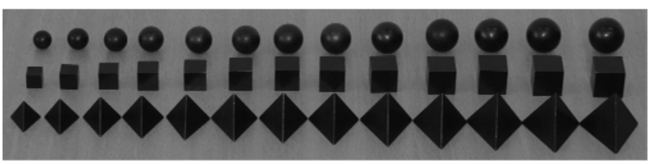

Fig. 1. On the left: the stimulus set. On the right: stimulus placed on the hand of the subject.

2.3 Conditions

The experiment consisted of 9 conditions; 3 object-pairs (tetrahedron-sphere, tetrahedron-cube, cube-sphere) and 3 reference-weights (small, medium, large). The reference weights were for the tetrahedrons 25.2, 42 and 58.8 g, for the cubes 33.6, 50.4 and 67.2 g, and for the spheres 42, 58.8 and 75.6 g. These references were the same as in the study on haptic volume perception [5]. The conditions were performed within 3 sessions. Object-pair was randomized between sessions and reference-weight was randomized within sessions. For each combination of object-pair and reference-weight, each shape was the reference stimulus in half of the trials and test in the remainder. 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.

2.4 Data Collection

The data were collected by way of a computer-driven 1-up-1-down staircase procedure (see Fig. 2A). For each object-pair by reference-weight combination, two staircases were intermingled, each starting at one end of the stimulus range, i.e. at 16.8 and 117.6 g. For each stimulus combination, the fraction was calculated with which the subject selected the test stimulus to be heavier than the reference stimulus. This calculation was performed for all test weights. A cumulative Gaussian distribution (*f*) as function of the physical mass (*x*) was fitted to the data with the maximum-likelihood procedure [8], using the following equation:

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

where σ is a measure of the discrimination threshold, and μ a measure of the Point of Subjective Equality (PSE). This point indicates the physical weight of the test stimulus that is perceived to be of the same heaviness as the reference stimulus (see Fig. 2B).

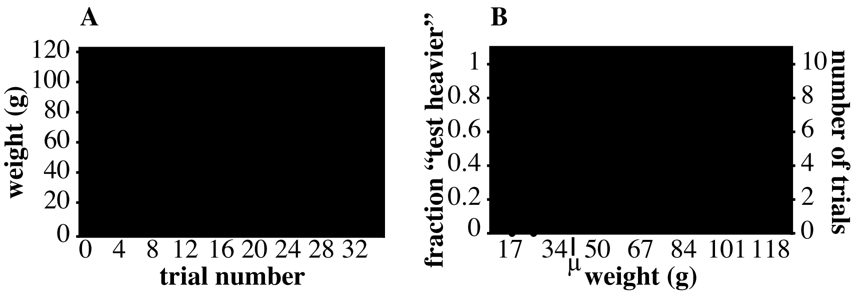

Fig. 2. (**A**) An example of the staircase. (**B**) The psychometric curve fitted to the data.

Relative biases were calculated from these data. For each matched object pair (tetrahedron-sphere, tetrahedron-cube and cube-sphere), the mass of the object mentioned first was subtracted from that mentioned second and expressed as a percentage of the mass of the object mentioned first. Hence, the magnitude of these biases indicated the relative difference between the physical weights of two differently shaped objects that are perceived as equal in weight. These relative biases were used for the statistical analysis.

3 Results

Fig. 3 shows the individual and average perceptual biases for the different object comparisons. The biases from the different reference-weights are taken together, since no significant effect of reference-weight was measured ($F_{2,14} = 3.7$, $p = 0.08$). A t-test revealed only significant biases for the tetrahedron-cube comparison ($t_7 = -9.3$, $p < 0.001$). The left part of the figure shows that these biases are consistently negative, with an average of about -18 %, SE 2 %. A negative bias in this condition means that a cube is perceived as being heavier than a tetrahedron of the same volume. The analysis revealed that the average biases in the other conditions were not significantly different from zero (t_7 = -0.4, p = 0.7 and t_7 = 0.8, p = 0.4 for the tetrahedron-sphere and cube-sphere comparisons respectively). However, we cannot ignore the large individual differences in these conditions. As the middle and right parts of Fig. 3 demonstrate, the sphere is perceived as being either heavier (negative bias) or lighter (positive bias) than a tetrahedron or a cube of the same physical mass. This pattern is consistent within subjects.

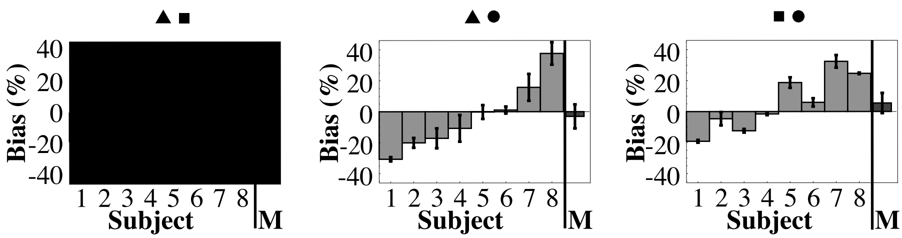

Fig. 3. Individual and mean data (M) for the different conditions. The subjects are ordered from the subject with the most negative bias to the most positive bias in the tetrahedron-sphere condition. The error bars for the individual subjects represent the standard deviations, and for the average data they represent the standard errors of the mean.

4 Discussion

The present study demonstrates that the weight of a tetrahedron is consistently underestimated compared to the weight of a cube with the same physical mass and volume. The average bias in that condition was -18 %. The direction of the bias corresponds to the prediction from the study by Dresslar [2], who showed that (2-D) objects that appear smaller are perceived to be heavier. The magnitude of the measured bias is larger than the predicted bias of -4 % (see Table 1). This indicates that the shape-weight illusion cannot be explained only on the basis of a direct influence of perceived volume on perceived weight. This conclusion is supported by the large individual differences observed in the tetrahedron-sphere and cube-sphere comparisons. Ellis [3] concluded that, instead of perceived volume, the profile area (defined as the area of the largest face) is the best predictor for perceived weight. However, the influence of the profile area may be triggered by the restriction of the exploration strategy to a four-finger/opposing-thumb grasp. In our experiment, the exploration was not restricted and each subject could select its own strategy, which probably caused the large individual differences. An interesting observation is that the individual differences in the direction of the bias are only observed in the conditions including a sphere. This may be caused by the variation in the size of the object's area that is in contact with the skin during exploration. This contact area for a sphere is smaller when the hand is stretched out than when it is cupped. How far the hand is cupped could differ between subjects. For a tetrahedron or a cube the contact area did not differ because of a flat base. This may be a relevant point to investigate in further experiments.

The present study emphasizes that we cannot ignore the influence of an object's shape on weight perception, since large perceptual biases are observed. Nevertheless, with these results we cannot explain the shape-weight illusion in detail, and more research is needed to understand this phenomenon. A comprehensive understanding of these effects can be important for different problems of more applied nature. As we noted in the introduction, a proper estimation of the weight of objects is necessary for the determination of the force that has to be applied in order to manipulate the object efficiently. This object could also be, for example, a handle of a machine. For the construction of such handles, it is necessary to consider the factors that could influence the perception and action of a human operator. The shape of objects seems to be one of them.

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