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Mass and density estimates contribute to perceived heaviness with weights that depend on the densities' reliability

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ABSTRACT

People perceive a smaller and denser object to be heavier than a larger, less dense object of the same mass. We developed a new model of heaviness perception that can explain this size-weight illusion. Modeling followed recent insights on principles of information integration. Perceived heaviness is modeled as a weighted average of one heaviness estimate derived from object mass and another one derived from object density with weights that follow estimate reliabilities. In an experiment, participants judged the heaviness of 18 objects using magnitude estimation methods. Objects varied in mass and density. We also varied the reliability of density information by varying visual reliability: Participants were blindfolded or had strongly impaired, mildly impaired or full vision. Because participants lifted each object via a string they required visual information on object size to assess object density. The pattern of mass and density influences on judged heaviness confirmed model predictions. Also as predicted, density influences on judged heaviness increased with increasing reliability, whereas mass influences decreased. Individual and average data were well fit by the model (r^2 s > 0.96). Density information contributed for 14%, 21% and 29% to heaviness, when vision was strongly impaired, mildly impaired or not impaired, respectively. Overall, the results highly corroborate our model, which appears to be promising as unifying framework for a number of findings on the size-weight illusion.

KEYWORDS: Size-weight-illusion, heaviness perception, visuo-haptic interaction, optimal integration.

INDEX TERMS: H.1.2 [Models and Principles]: User/Machine Systems—Human information processing; J.4 [Social and Behavioral Sciences]:—Psychology; General Terms: Experimentation, Human Factors

1 INTRODUCTION

What is heavier: One kilogram of feathers or one kilogram of lead? This seeming trick question has a surprising psychological answer: It is the lead that almost always feels heavier. In general, people perceive a smaller and denser object to be heavier than a larger, less dense object of the same mass. This phenomenon was first described by Charpentier in 1891 as a “size-weight-illusion” [1]. Most authors, so far, have interpreted the illusion in terms of the effects of object size on perceived heaviness (e.g., [2–4]). In contrast, Thouless [5] argued that a direct use of volume information predicts a reverse illusion than observed: Because larger objects are usually heavier than smaller ones, larger objects should, then, also feel heavier if mass is constant. This is not the case. Thouless suggested that we rather use information on object density, i.e. mass divided by volume, in heaviness perception (cf.

[6–8]). Because less dense objects are usually lighter than denser ones, this assumption correctly predicts that larger and less dense objects feel lighter than smaller and denser objects of the same mass. Here, we present a model, according to which heaviness perception is based on the weighted integration of two single heaviness estimates that are derived separately from mass and density information. The estimates' weights are predicted to depend on the estimates' relative reliabilities. We tested model predictions in an experiment using magnitude estimation methods.

As a starting point, our modeling follows the now established models of “optimal integration” [9,10], which in the last decade have been demonstrated to successfully describe sensory integration in the brain. According to these models, the brain operates as a maximum-likelihood integrator to maximize the reliability of the integrated percept. In detail, it has been suggested that information integration takes into account all signals available for a property [10]. Signal-specific estimates $\hat{s}_i$ for that property are derived from each signal s_i . Then all estimates combine into a percept by weighted averaging:

$$\hat{s} = \sum_i w_i \hat{s}_i \quad \text{with} \quad \sum_i w_i = 1; \quad w_i \in [0,1] \quad (1)$$

For optimal integration, as defined by the Maximum-Likelihood-Estimation (MLE) model, weights w_i are proportional to the normalized signal estimates' reliabilities ($R_i = 1/\sigma_i^2$, inverse of the percept's variance):

$$w_i = \frac{R_i}{\sum_{j=1}^N R_j} \quad (2)$$

Experimental data confirm the predictions that follow from these principles of information integration [11–15]—with respect to visuo-haptic and visuo-auditory integration of size, shape and location, even in their quantitative details [10,15]. While most authors agree that the weights depend on reliabilities, there is some controversy over the situations in which weights are set “optimally” [16]. Both optimal [10, 15] and suboptimal reliability-dependent weighting have been observed [16].

We suggest to model heaviness perception as a corresponding integration of mass and density information. According to this hypothesis, perceived heaviness $\hat{h}$ is the weighted average of separate heaviness estimates, $\hat{h}_m(m)$ and $\hat{h}_\rho(\rho)$, derived from object mass m and object density ρ , respectively:

$$\hat{h}(m, \rho) = (1 - w_\rho) \hat{h}_m(m) + w_\rho \hat{h}_\rho(\rho) \quad (3)$$

In the present as well as in most previous studies on the size-weight-illusion, perceived heaviness has been assessed by Steven's [17] method of magnitude estimation. Magnitude estimates have been shown to be a power function of the judged physical property (e.g., [18]). Hence, we assume that heaviness estimates derived from density or mass follow power functions:

$$\hat{h}_m(m) = am^x, \quad \hat{h}_\rho(\rho) = b\rho^y \quad (4)$$

Here, a , b , x , and y are constant and larger than zero. Basically, the suggested model predicts that heaviness estimates increase

independently with the mass and with the density of objects, whereby the relative contributions of mass and density shifts with the relative reliabilities corresponding to these two types of information. The model goes beyond earlier models in that it includes a role for information reliability in heaviness perception and the size-weight illusion. Reliability differences can, for instance, well explain why the illusion tends to be more pronounced when object size is felt and seen as compared to when it is only seen [19, 20]. We would argue that vision plus haptics allows for more reliable density estimates than vision alone and, hence, density contributes more to perceived heaviness when haptic cues are present. Furthermore, our model is in direct contrast to previous models that postulate an additive or multiplicative integration of mass with volume information [2–4]. Finally, there is a class of models that describes heaviness perception as a family of power functions of mass—with parameters of the power function that further depend on object volume [21–23]. Whereas these models yet provide good descriptions of the illusion, our model has been derived in line with recent evidence on the principles of information integration.

The present experiment aims to provide a first test of our model. In the experiment, participants judged the heaviness of different objects using magnitude estimation. We used three “density series” of objects: a big-volume series, a small-volume series and an equal-density series. Our model predicts that heaviness estimates increase with object mass and that they independently increase with density. It follows from the pattern of density differences between objects:

- Estimates are larger for small-volume objects than for big-volume objects with same mass—and in between for the equal-density series. This is the classical size-weight illusion.
- Estimates of the volume series increase more with mass than estimates of the equal-density series, because in the volume series higher mass coincides with higher density.
- The difference between heaviness estimates for small- and big-volume objects increases with mass, because the density differences between the two series increase. This prediction provides a crucial test for our model, as we will discuss later.

In the experiment, participants lifted each object via a similar string. In this situation, mass information is available from haptics, but density estimates require visual information on object volume as well. We manipulated the reliability of density estimates by manipulating visual reliability in four levels: No vision, bad vision, medium vision, full vision. Without vision, density information is not available and does not contribute to heaviness perception. In the model (Eq. 3), estimates derived from mass, then, should be weighted with 1 and entirely explain perceived heaviness. Therefore, the predicted differences between the density series should not be observed in this condition. However, they should be observed in the three conditions *with* vision. The model further predicts that density effects are larger with higher visual reliability and mass effects smaller. In fact, the predicted differences between density series, as regards average heaviness (a) and its increase with mass (b and c) should be more pronounced when visual reliability is higher, because these effects are predicted from density differences between the objects. In addition, according to the model, heaviness estimates of objects in the equal-density series differ only due to their differences in mass. Because we predict that the contribution of mass to heaviness estimates decreases with increasing visual reliability, heaviness differences between the objects in the equal-density series should become *smaller* with higher visual reliability.

2 EXPERIMENT

In the experiment, each participant estimated the heaviness of objects from each of the three object series under each visual

Figure 1. Complete set of stimuli (left), and glasses and blindfold to manipulate visual reliability (right).

reliability condition. The experiment always started with the no vision condition and visual reliability systematically increased from bad, through medium, to full vision. This fixed order was chosen to prevent memories of reliably perceived object density from influencing judgements under less reliable visual conditions.

In each trial, participants were presented with a single object. They were instructed to lift the object with index finger and thumb via a wooden bead and a string, weigh it two times up and down and then estimate its heaviness within 3 seconds using a free-modulus magnitude estimation task [17]. Estimates were given while the object was still held and participants were, when applicable, instructed to look at the object throughout the trial.

2.1 Methods

2.1.1 Participants

15 students from Giessen University aged between 19 and 44 years (average age 27 years; 12 females) took part in the experiment for course credit. The sample included 6 left- and 9 right-handers according to self-report. Participants reported to have no known sensory or motor deficits. Their vision was normal or corrected by contact lenses. They were naïve as to the purpose of the experiment and to the size-weight illusion.

2.1.2 Setup and Stimuli

Participants sat in front of a table with their elbows at about the same height as the table surface. On the table was a sound-absorbing felt pad (30 × 40 cm), on which the currently used stimulus could be placed. Other stimuli were hidden from the participant’s view. We created 18 stimuli using cylindrical white plastic cans with a screw cap (Fig. 1, left). The cans differed in volume, which we exactly assessed by the method of water displacement. Each stimulus had a homogenous mass distribution over its entire volume. An exception is the 60 g-stimulus with big volume, because the can alone already had a mass of close to 60 g and we distributed only some material homogeneously over this can’s inner surface. The filling materials were mixtures of iron or tungsten powder with silicone or with polyurethane foam. A string of 20 cm length and 1.3 mm diameter was attached to the centre of the screw cap. Participants lifted the object by grasping a wooden bead (16 mm diameter) at the other end of the string.

There were 6 stimuli with a volume of 595 cm³ and masses of 60, 100, 140, 170, 200, and 230 g (big-volume series, densities of 0.10, 0.17, 0.24, 0.29, 0.34, and 0.39 g/cm³), 6 stimuli with a volume of 32 cm³ and the same 6 masses (small-volume series, densities of 1.93, 3.19, 4.43, 5.36, 6.31, and 7.24 g/cm³), and 6 stimuli with a density of 0.39 g/cm³ and similar masses of 54.5, 85.3, 111.6, 138.9, 164.5 and 198.2 g. Masses in the equal-density series slightly deviate from the masses in the other series, because the available volumes of plastic cans were limited. However, mass deviations are smaller than 10 % for all masses except for 100 g. The 100 g stimuli were, hence, matched by two stimuli in the equal-density series, namely 85.3 and 111.6 g. Note also that the 230 g stimulus in the big volume series has the same density of 0.39 g/cm³ as the equal-density stimuli and was, partly, included in the analyses of the equal-density series.

In addition, we manipulated visual reliability by letting participants wear a standard sleeping mask, or one of two diving goggles (Fig. 1, right). In one pair of goggles, we stuck a transparent colourfree foil blind (“d-c-fix 7”) to the glasses in order to strongly impair vision. In the other goggles we laid 16 layers of regularly crumpled commercial wrapping film, resulting in an intermediate visual impairment.

2.1.3 Design and Procedure

The design comprised three within-participant variables: Density series (big-volume, small-volume, equal-density), Mass, and Visual Reliability (full vision, medium vision, bad vision, and no vision). In the no vision condition participants were blindfolded. In the bad and medium vision condition they wore the strongly and intermediately impairing diving goggles, respectively. No glasses or masks were used in the full vision condition. There were 18 stimuli representing the different Series and Mass conditions (see above). Participants were instructed to judge the stimuli according to perceived heaviness in a free-modulus magnitude estimation task [17]. Judgments were made by assigning a whole number or any fraction larger than 0 to each stimulus that best described its perceived heaviness. No standard or modulus was used.

In each single trial, the experimenter first silently placed a stimulus on the felt pad in front of the participant. The participant was instructed to extend his/her dominant hand at about 30 cm above the table with palm down and the experimenter placed the stimulus’ wooden bead between the participant’s thumb and index fingers. Then, the participant lifted the stimulus via bead and string and weighed it two times up and down. Within the next 3 seconds the participant had to judge the stimulus’ heaviness and, afterwards, to let the stimulus down to the felt pad. S/he was instructed to always move slowly in order to minimize lateral swaying of the stimulus and, thus, to minimize potential, but unwanted, haptic cues to mass distribution [24]. Finally, the experimenter removed the stimulus, noted the participant’s judgment on a sheet of paper and the next trial began. In the conditions including vision, the participant was instructed to look at the stimulus throughout the trial.

After initial instructions, each participant started with a block in the no vision condition that served to practice the exact procedure as well as to establish a subjective heaviness scale. During practice each of the 18 stimuli was presented once. After practice, participants were instructed to “keep the subjective scale constant” and the proper experimental trials began. Visual Reliability conditions were presented in a fixed order so that visual reliability increased during the experiment and no transfer of higher reliability information into lower reliability conditions could occur. Each participant started with the no vision condition, and went on with the bad, then, the medium and, finally, the full vision condition. Each Visual Reliability condition comprised six blocks. In each block of the no and full vision conditions, each of the 18 stimuli was presented once. In the bad and medium vision condition we only presented stimuli with masses of 60, 140 and 230 g from each series, amounting to 8 presentations per block, because the 230 g stimulus was the same for the big-volume and the equal-density series. Within each block, stimuli were presented in random order. Overall the experiment comprised 18 stimuli $\times$ 6 blocks $\times$ 2 conditions + 8 stimuli $\times$ 6 blocks $\times$ 2 conditions = 312 experimental trials. After the experiment proper we measured the participant’s visual acuity while wearing either pair of diving goggles. We used an enlarged version of Landolt rings with openings in the ring in a range of 0.5 to 32 mm. Landolt rings were placed at the same location as the heaviness stimuli. The experiment lasted about 3 hours including 3 breaks of 3 minutes.

2.1.4 Data Analysis

The raw data consisted of each participant’s six magnitude estimates of the heaviness of each stimulus in each visual reliability condition. In a first step, each single estimate was standardized: For each participant each single estimate was divided by that participant’s geometric mean over all single estimates [17]. From these values, we calculated the individual geometric mean per condition. These individual scores were used in additional statistical analyses. Data from the 230 g stimulus in the big volume series was used both in the big volume and the equal-density series. For an ANOVA we matched the data from each stimulus in the volume series with the data from that stimulus in the equal-density series that is closest in mass.

2.2 Results

2.2.1 Visual Acuity

Visual acuity was assessed by the minimal visual angle of the gap in the Landolt rings that participants were able to locate correctly. When wearing the goggles used in the medium vision condition, participants, on average, had a visual acuity of 12 arcminutes (range of individual acuities: 6–21’). With the goggles of the bad vision condition average visual acuity was 78’ (range: 32–139’). Acuity with goggles was, thus, clearly impaired as compared to normal visual acuity (which is about 1’), and it was significantly worse in the bad as compared to the medium vision condition, $t(14) = 7.9, p < 0.001$.

2.2.2 Inference Statistics

Individual heaviness estimates were entered into an ANOVA comprising the variables Series (big-volume, equal-density, small-volume), Mass (60 g, 140 g, 230 g) and Visual Reliability (no vision, bad vision, medium vision, full vision).

The analyses supported almost each model prediction. As predicted, heaviness estimates, on average, significantly increased with Mass. They were smaller for 60 g than for 140 g, which in turn were smaller than for 230 g objects (average heaviness estimates: 0.46, 1.23 and 1.84, respectively; Mass effect: $F(2,28) = 236, p < 0.001$, all pair-wise Bonferroni-corrected t -tests significant, $\alpha = 0.05$, one-tailed).

Heaviness estimates also, on average, significantly differed between the Density Series in the way predicted from the pattern of density differences: Overall, estimates were smaller for the big-volume series than for the equal-density series than for the small-volume series (average estimates: 1.05, 1.07 and 1.42, respectively). Furthermore, on average over all Visual Reliability conditions, differences between the equal-density series and the small-volume series increased with Mass and differences between the equal-density series and the big-volume series decreased with Mass, indicating here that estimates of the volume series increase more with Mass than estimates of the equal-density series. Also as predicted, differences between the small- and the big-volume series increased with Mass (main effect Density Series: $F(2,28) = 139, p < 0.001$, all corrected pairwise t -tests significant; interaction Mass $\times$ Series, $F(4,56) = 15, p < 0.001$, all three linear contrasts over Mass conditions of pairwise differences between Density Series significant, Bonferroni-corrected, see above).

In addition, Density Series-related effects from the last paragraph were further modified by Visual reliability. As predicted, influences of density increased with increasing reliability. This holds for the average differences between the three density series as well as for their modifications by Mass. Only, the increase of differences between the small- and the big-volume series with Mass did not significantly increase with Visual reliability (interaction Visual reliability $\times$ Density Series, $F(6,84) = 43, p < 0.001$, all three linear contrasts over Visual

Reliability conditions of pairwise differences between Density Series significant; interaction Visual Reliability $\times$ Series $\times$ Mass, $F(12,168) = 5.4$, $p < 0.001$, linear contrasts over reliability conditions $\times$ mass conditions of pairwise differences between Density Series significant for equal-density vs small/big-volume only). Other effects in the ANOVA were not significant, $p > 0.2$.

An additional analysis of the equal-density series alone showed that the heaviness differences between objects in this series were, as predicted, smaller with increased Visual reliability (interaction Visual Reliability $\times$ Mass, $F(6,84) = 3.1$, $p = 0.038$; linear contrast over reliability conditions $\times$ mass conditions, one-tailed, $F(1,14) = 3.4$, $p = 0.043$).

We additionally analyzed the data by a) calculating individual slopes of the linear regression of heaviness estimates on mass and b) submitting these slope values to an ANOVA with the variables Density Series and Visual reliability. This analysis makes use of heaviness estimates from each single object in each condition. The results did not change a single conclusion and, hence are not further considered.

2.2.3 Model Fit

We fit the cue integration model (Eqs. 3 and 4) to the heaviness estimates averaged over participants (Fig. 2). That is, we predicted average heaviness estimates for each object and visual reliability condition from the object's physical density and mass. The model had seven free parameters. a , b , x and y describe the postulated relation between physical density or mass and the heaviness estimate derived from either of these physical values by two power functions. The three weights w_{bad} , w_{medium} and w_{full} refer to the relative contribution of heaviness estimates derived from the object's density to the overall heaviness estimate in each visual reliability condition. Note that estimates derived from mass correspondingly contribute with $1-w$, because weights sum up to 1. For the no vision condition, the density's weight was set to 0%. The fit was done by numerically minimizing squared errors of the predicted from the measured values. The fit explained 99.2% of variance in the data. Fitted values were $a = 0.00557$, $x = 1.07$, $b = 1.27$, and $y = 0.543$. The weights increased, as expected, with visual reliability and were $w_{\text{bad}} = 14.3\%$, $w_{\text{medium}} = 20.6\%$ and $w_{\text{full}} = 28.8\%$. Heaviness estimates predicted from the model fit are included in Figure 2.

In addition, we fit the model to each individual data set (b was constrained to be below 3). The model explained more than 96% variance per individual and the individually fitted parameters were in feasible ranges (a : 0.0005–0.04, x : 0.7–1.6, b : 0.6–2.1, y : 0.33–1.4; w_{bad} : 1–38%; w_{medium} : 3–47%; w_{full} : 6%–57 %). In 27 out of 30 cases weights of single individuals were larger for medium as compared to bad vision and they were larger for full as compared to medium vision. Two pair-wise t -tests confirmed that weights increase with visual reliability, as predicted (w_{bad} vs w_{medium} : $t(14) = 5.1$, $p < 0.001$; w_{medium} vs w_{full} : $t(14) = 4.4$, $p < 0.001$). Figure 3 depicts average individual weights.

3 DISCUSSION

The present study aimed to test the model that perceived heaviness is a weighted average of two separate heaviness estimates: One derived from object mass, the other one from object density. Estimated weights are further predicted to depend on the estimates' relative reliabilities. Overall, the results are highly consistent with this view. According to the model, differences in perceived heaviness in the equal-density series are a function of mass differences alone, whereas in the two volume series the contribution of absolute density should add up. In line with this prediction, perceived heaviness increased more in the small-volume than in the big-volume than in the equal-density

Figure 2. Average heaviness estimates and standard error as a function of mass, density series and visual reliability. Gray lines indicate the fit of the additive model.

series. We conclude that absolute density values contributed to the heaviness percept in addition to the contribution of object mass.

Furthermore, we observed that with increasing visual reliability nearly all effects of density on perceived heaviness increased (i.e., the differences between density series), whereas the effects of mass decreased (observed in equal-density series). We conclude that higher visual reliability, and therefore more reliable density

information resulted in a larger contribution of heaviness estimates derived from density to perceived heaviness and a smaller contribution of estimates derived from mass information. This fits with the prediction that estimate weights shift with the estimates' relative reliabilities.

Finally, we directly fit the weighted-average model to the heaviness judgments. The model explained almost all variance both in the individual ($> 96\%$) and the average data (99.2%). The weights for heaviness estimates derived from density systematically increased with visual reliability, with, for the average data, 14% in the bad, 20% in the medium and 29% in the full vision condition. Weights shifted in the same manner with reliability for each single individual, but with considerable interindividual differences in the magnitude of the weights (6–57% for full vision). Taken together, the results both from the fit and from inference statistics strongly support our model of heaviness perception. We conclude that perceived heaviness is a weighted average of one estimate derived from mass and another estimate derived from density with weights that follow estimate reliabilities.

The finding of large individual differences in density weights fits with this view. Density does not provide valid information about mass per se. A possible reason, why density is nevertheless used in heaviness judgments, might be that in the natural environment object density correlates with object weight. Often “heavy” and “light” are used for “dense” and “not dense”. Lead is heavy, feathers are light. We talk about weight, we mean density. According to this argument the relation between density and weight tends to be loose and depends on the specific individual learning history. Hence, large individual differences in the usage of density information in heaviness perception can be expected.

Overall, the results are, thus, in line with maximum-likelihood models of sensory integration, and, consequently, with the wider framework of Bayes' law, which has in several recent studies been successfully applied to explain key features of perception and motor actions (e.g. [10, 33]). It might be fruitful for the model to also formalize how prior experience influences mass estimation from densities.

In contrast to our model, many previous authors explained the size-weight illusion in terms of an interaction between volume and mass information. This theory partly relates to the idea that large objects induce the expectation of being heavier than small objects and that discrepancies between actual and expected mass are emphasized in the heaviness percept; e.g., if a large object is unexpectedly light, it is perceived to be even lighter than it is. While there are some specific circumstances under which expectations seem to influence heaviness perception [32, 34], there are also several problems with expectancy-based theories. Earlier variants of the theory argued that mismatches between the actual mass of an object and forces programmed to lift the object are responsible for the illusion (e.g. [25]). The illusion, however, persists after participants have quickly learnt to match the forces to novel objects [26, 27]. Recent authors suggest a “Bayesian-like” perceptual variant of the theory, in that discrepancies between perceptual prior expectations from volume and actual sensory information on mass are responsible for the illusion [31, 36]. As the authors note this variant at the same time contradicts Bayes' law and, thus, contrasts with its manifold evidence [10, 33]. While Bayes' law predicts that perception is biased towards prior expectations, the explanation suggests “anti-Bayesian” perception shifted away from expectations [31, 36]. Furthermore, a strict application of Bayes' formalisms predicts an additive effect of mass expected from volume on perceived mass [31], which is usually not observed ([28], below). Finally, the illusion vanishes when (visual) volume information is given immediately

before, but not during lifting an object [35], which does also not seem to fit the notion of prior expectations very well.

The latter finding suggests that heaviness judgments are only based on such sensory information that is currently available. Within sensory-based explanations the illusion seems to be better explained by a direct contribution of density information than by a direct contribution of volume information: Because larger objects are usually heavier than smaller objects, they should, if volume information were used, also be perceived to be heavier. The opposite is the case. The present empirical results further argue against a direct contribution of volume information to perceived heaviness as specified by certain models. The comparison between the big- and the small-volume series in the present experiment is crucial. Objects within each of the two volume series differ in mass, but have the same volume. Heaviness judgments in each series increased with mass, but more so in the small than in the big volume series. This interaction between volume and mass cannot be explained by any additive effect of volume information on perceived heaviness (e.g. [2]; cf. [28]). Also the assumption that volume has a multiplicative influence on perceived heaviness can be ruled out by an additional comparison between results from the two volume series (e.g. [4]). A multiplicative influence of volume predicts merely additive effects of volume and mass for logarithmized estimates. But mass and volume significantly interact in an additional analysis of logarithmized estimates ($F(1,14) = 36, p < 0.001$ for the interaction [small vs big volume objects] $\times$ [60 g vs 230 g mass]). So, many models that assume a direct contribution of volume information to perceived heaviness can already be ruled out on the basis of the present experimental data. It is, however, still to be explored, to what extent predictions from our model can be directly contrasted with predictions from the more descriptive class of models that described heaviness perception as a family of power functions of mass [21–23].

But how can density be perceived? Huang's [29] experiments as well as own unpublished pilot data show that participants are able to judge density based on haptic information, but they are biased by mass. A direct haptic cue to density might be, for example, the pressure, i.e. the force per area, that an object exerts on the skin when being held in the hand [30]. In the present experiment such direct cues to density were not available. We argue that in the present experiment haptic mass and visual volume information were first combined into a density estimate, which was, then, directly used in heaviness perception. In line with this, [6] identified brain areas coding volume, mass and density of objects and found that illusory heaviness percepts are particularly associated to the higher-order areas that code for density. Similar to the present study, in [6] participants obtained separate visual volume and haptic mass information. So, we do, of course, not claim that visually perceived volume is not involved in the present illusion. But, we suggest that this volume information only indirectly influenced perceived heaviness, namely through its role in the integration of haptic mass and visual volume estimates into a density estimate. In contrast, we predict that in other settings density is directly estimated via haptic cues, e.g. when objects are placed on the palm. The claim that the brain directly uses cues that can only be available haptically is feasible given that heaviness perception and the illusion seem to be primarily related to haptics [19]. However, these claims remain to be tested.

4 CONCLUSION

Overall, we have good first evidence for our model that perceived heaviness is a weighted average of two separate heaviness estimates: One derived from object mass, the other one from object density. Estimated weights further depend on the estimates'

relative reliabilities. The model has been derived in line with recent evidence on the principles of information integration. It provides a new explanation for the so-called size-weight illusion. The model contrasts with alternative explanations by the assumption that perceived object density rather than perceived object volume is the crucial variable that directly influences perceived heaviness. And it goes beyond extant models, in defining a role for the reliabilities of mass and density information in heaviness perception. Difference in reliabilities might well be able to explain why the magnitude of the illusion depends so much on the specific experimental situation. That is, we regard the model as promising to unify a number of findings on the size-weight illusion under a coherent, theoretically well-supported framework. This work still has to be done in the future.

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