How Wearing a Glove Affects Perceived Weight: A Lower Tactile Precision Increases the Size-Weight Illusion

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Abstract. How heavy an object feels obviously depends on haptic information about the forces required to lift an object. But it is also influenced by visual and haptic information about less relevant properties, such as the object's size (the size–weight illusion). We hypothesized that the influence of size information would increase if we made force-related information less precise. We assumed that wearing a glove would reduce the precision of tactile signals. In two experiments, we examined whether wearing a glove increases the size–weight illusion. Contrary to our expectation, wearing the glove did not systematically affect the precision of judgments of how heavy objects are; the effect differed across participants. Crucially, though, the results provide strong support for the hypothesis that a reduced precision of force-related haptic information leads to an increased size–weight illusion.

Keywords: Multisensory perception · Cue combination · Bayesian integration

1 Introduction

It is still poorly understood how one perceives how heavy an object is. It is clear that it is not directly determined by the forces needed to lift the object, but is influenced by an estimate of the effort needed to move the object [1, 2]. This estimate takes visual information about the object into account, as is evident from the size-weight illusion and the material-weight illusion [3, 4]. Many authors interpret the effect of visual information as arising from the mismatch between the expected and required forces for moving the object [5–7]. If so, tactile information about the required forces is essential for evaluating the mismatch because these weight illusions are absent in an individual with peripheral deafferentation [8]. This mismatch interpretation is based on the notion that when lifting an object, one already expects its weight based on its size: larger objects are generally heavier. When a large object is lighter than expected based on its size, one judges it to be lighter than it actually is. Interestingly, the size-weight illusion also exists if the size is only known after the object is lifted [9]. Thus, the expectation that gives rise to the illusion is not an expectation about the heaviness, but an expectation about the

C. Pacchierotti et al. (Eds.): EuroHaptics 2026, LNCS 16594, pp. 66–74, 2027.
https://doi.org/10.1007/978-3-032-32350-7_5

relationship between size and heaviness [10]. The illusion presumably originates from a real-time combination of sensory information about force and size, combined with expectations about the relation between these variables and heaviness.

How do participants combine size and forces to judge heaviness? Physics gives the relation between the contact forces and mass: the force is the sum of the force to counteract gravity (weight) and the forces that accelerate the mass. Although the illusion is named a 'weight' illusion, it exists without gravitational forces [11], and the strength of the illusion is independent of which forces are available [12]. For size, the relation with mass is less straightforward. One might assume a typical density, depending on knowledge about material properties [13]. Some authors have argued that the expected density will be higher for small objects [14]. Moreover, size can be seen, but also felt, and either source of size information can induce the illusion [15]. The question of how these sources of information are combined has not been answered conclusively.

A first line of explanation of how information is combined assumes that one combines two independent estimates of heaviness: one based on force information, and one based on size information. The latter includes prior knowledge about the relation between size and weight. If one assumes that this density prior is independent of size and normally distributed, the size-weight illusion would have to originate from an anti-Bayesian combination [16]. Other lines of explanation release the requirement that the distributions are normal [17], and/or that the estimate of density is independent of the estimate of size [18, 19], or take into account the gradient of discriminability induced by efficient encoding [20], and argue that the combination may be Bayesian.

Our approach to try to get more insight into the mechanisms of the size-weight illusion is to perturb the information. We decided to perturb the force information by letting participants wear a sturdy glove. As such a glove reduces the tactile input, one might expect it to reduce the reliability of force information. One could therefore expect a larger contribution of size information, and thus a larger size-weight illusion. Such a relation between precision and illusion magnitude has indeed been reported: in an experiment involving objects of different materials, sizes, and masses, objects that gave rise to the largest size-weight illusion were the ones with poorer weight discrimination [21]. On the other hand, Wolf and Drewing [22] have argued for, and provided indirect evidence for, an opposite relation: precision was better in conditions that gave rise to a larger size-weight illusion.

The effect of gloves on the size-weight illusion has already been investigated; in contrast to our expectations, the gloves reduced the size-weight illusion [23]. However, in that study, the gloves reduced the quality of information about the object's size as well as about the force that was exerted, as participants could not see but only feel the objects. We therefore examine the effect that gloves have on the size-weight illusion when the objects are visible. We performed two experiments. In the first, participants lifted objects and verbally reported their estimate of weight. Since a potential effect of gloves on the precision in this task might be counteracted by changing the exploration duration, we repeated the experiment but with participants briefly pushing suspended objects [12].

2 Methods

2.1 Participants

The data were collected as part of a research project executed by two pairs of bachelor students as part of their educational program. Participants were other students of the same program, with a reported age range of 20–25 years. Participants used their preferred hand to lift or push the objects. Thirty-two students volunteered to participate in the lifting experiment. The collected data of two of the participants could not be used due to experimental errors. The remaining thirty participants were mostly right-handed (26 vs 4). Twenty-one other students volunteered to participate in the pushing experiment. The participants of this second experiment were also mostly right-handed (18 vs 3).

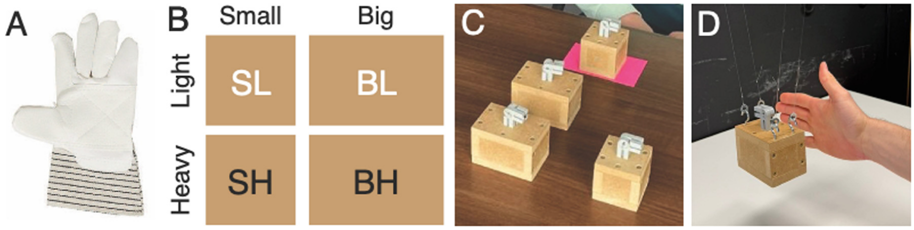

Fig. 1. The set-up. A) The glove used in the experiment. B) The four combinations of two sizes (6 and 9 cm) and two masses (210 and 260 g). C) In the lifting experiment, the four objects were always visible to the participants; they grasped the object that the experimenter placed on the pink paper. They had to grasp it by the sides using a precision grip, lift it, and judge its weight. D) In the pushing experiment, participants had to give a short push to one of the objects that was suspended from the ceiling.

2.2 Set-Up and Design

We used four objects that were lifted or pushed with and without an imitation leather working glove (Fig. 1A). The objects were the same as we used in an earlier study [9]: all four combinations of two sizes (6 × 6 × 6 and 6 × 6 × 9 cm) and two masses (210 and 260 g). In the lifting experiment, they could see the four objects during the whole experiment and grasped all objects by placing their digits on 6 × 6 cm sides. In the pushing experiment, they only saw the object that they had to push. For the large objects, they pushed the 9 × 6 cm side.

We used magnitude estimation [24] in a blocked within-participant design. In one block, participants lifted 64 times or pushed 32 times with their bare preferred hand, in the other block, they performed the same task wearing the glove. There were fewer trials in the pushing experiment because it took more time to present the objects. The participant performed the two blocks in a single session, with a break of one or two minutes between them. The order of the two blocks was counterbalanced across participants. Within a block, objects were lifted in a pseudo-random order: all four objects were presented in a random order before presenting the objects again. This was done to ensure that all masses and sizes were distributed equally across the experiment.

In the lifting experiment, the participants positioned themselves behind a table in such a way that they could comfortably grasp and lift the object that was presented on the pink square on the table. They held each object in the air for about two seconds, put it down, and verbally reported the estimated mass of the object. Subsequently, the experimenter replaced the object with a new one. In the pushing experiment, one of the objects was suspended from the ceiling using wires connected to four small hooks at the corners of each object. The participants were seated behind a table, with the suspended object in front of them such that they could touch it with the palm of their extended preferred hand (Fig. 1D). They were instructed to give the object a short push so that it moved about half a metre sideways, and then to verbally estimate its mass. Subsequently, the experimenter connected another object to the wires.

The participants could familiarize themselves with magnitude estimation using two other objects that differed 50 g:180 and 230 in the lifting experiment and 200 and 250 in the pushing experiment. In these familiarisation trials, they received veridical information about the masses. We instructed the participants that the relative judgments of the various objects were more important than their absolute judgments.

2.3 Data Analysis

The data and the MATLAB code used for the analysis are available at OSF [25]. We calculated the mean reported mass for each combination of participant, object, and glove presence. We based our measure of the strength of the illusion on the difference between the mean reported mass for small and large objects, divided by the average reported mass. The Size-Weight Index (SWI) is the average of these estimates across the two object masses:

$$SWI = \frac{1}{2}\left(\frac{SL - BL}{(SL + BL)/2} + \frac{SH - BH}{(SH + BH)/2}\right) \quad (1)$$

To estimate the precision of our participants' judgments of weight, we determined the Coefficient of Variation (CV) for every combination of participant, glove presence, and object. We did so by dividing the standard deviation of the reported mass by the mean reported mass. We averaged the values of the CV across the four objects. We determined the effect of the glove on both SWI and CV by calculating the difference between the average values with and without the glove for each participant. Whether the glove had a systematic effect on each of these values was tested using t-test. We anticipated that wearing the glove would reduce the precision (and thus lead to a larger coefficient of variation). As explained in the introduction, assuming a normally distributed density prior, we anticipated that this increase in variability would lead to an increase in the SWI. We tested this prediction by determining whether the effect of the glove on the coefficient of variation is linearly correlated across participants with its effect on the size-weight illusion (Pearsons r).

3 Results

We will start by describing the results of the lift experiment, as this experiment has the largest statistical power. We will subsequently present the results of the push experiment and discuss to what extent the results are similar. In the lifting experiment, participants reported values for the heaviness that were, on average, reasonably close to the actual mass (Fig. 2A). The difference between the reported masses for heavy and light objects (about 60 g) is slightly larger than the actual difference (50 g). The precision of the judgments was quite good: the average coefficient of variation (CV) was 0.09. This value differed considerably between participants: individual values range from 0.02 to 0.26. Most importantly, the CV was not larger with a glove. It was even slightly smaller (red bars lower than blue bars in Fig. 2B). This difference was not significant ($t(29) = -0.71$; $p = 0.29$).

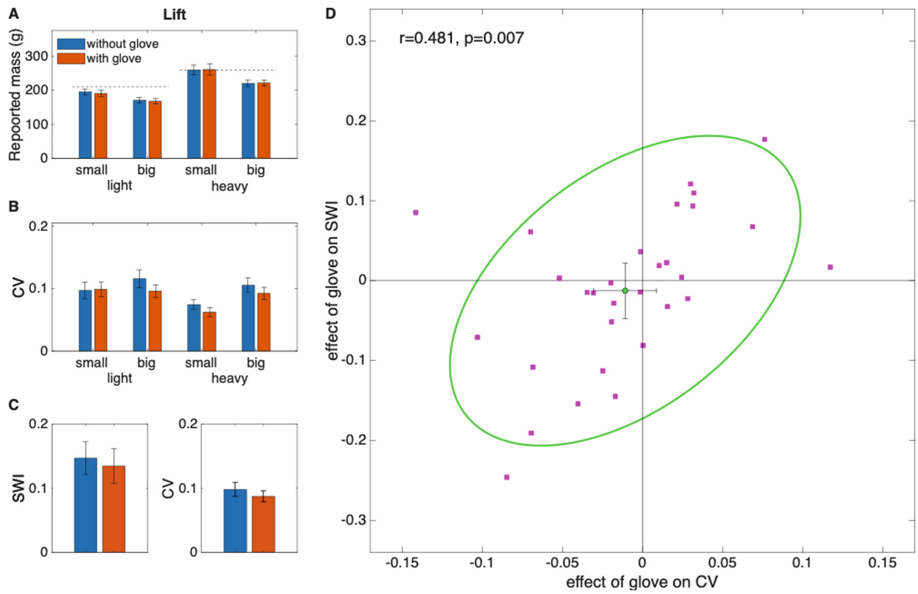

Fig. 2. The results of the lift experiment. **A)** reported mass for each of the four blocks, with and without a glove. (bars) and the actual mass (dashed lines) **B)** coefficients of variation (CV) of the reported mass **C)** The overall values for the size-weight illusion (determined from the reported masses panel A) and the CV (panel B) with and without a glove. Error bars in **A-C** indicate the standard error of the mean across participants. **D)** The effect of the glove on the size-weight illusion (i.e., the SWI with glove minus the SWI without glove) plotted as a function of the effect of the glove on the coefficient of variation. Each magenta symbol represents the average value for a single participant. The green symbol represents the overall mean, with error bars indicating the 95% confidence interval of that mean. The green ellipse indicates 95% of the distribution.

The average judgments indicate a clear size-weight illusion (SWI): the smaller objects are, on average, judged to be about 30 g heavier than the larger objects. However, there was a lot of variability across participants: the values for our measure of the SWI ranged from −0.08 to +1.38, with an average of 0.29. The overall difference between the judgments with and without a glove was negligible (~1 g). Also, the illusion strength was, on average, not affected by the glove ($t(29) = -1.08$; $p = 0.29$), not surprising as the CV was not affected. However, we did find that the glove's effect on the coefficient of variation was positively correlated with its effect on the size-weight illusion (Fig. 2D):

the more variable the judgements, the larger the illusion ($r = 0.481$, $p = 0.007$). Thus, we did not observe the predicted increase in variability when wearing the glove, but the expected relationship between changes in CV and changes in the SWI as a result of wearing the glove did hold.

When pushing the blocks away rather than lifting them, the pattern of results was similar (Fig. 3). Even the extents of the glove's influences and their positive correlation was very similar, although it did not reach significance in this case ($r = 0.321$, $p = 0.155$), presumably due to the low number of participants. Again, participants' weight judgments were more rather than less precise, and the size-weight illusion was smaller rather than larger.

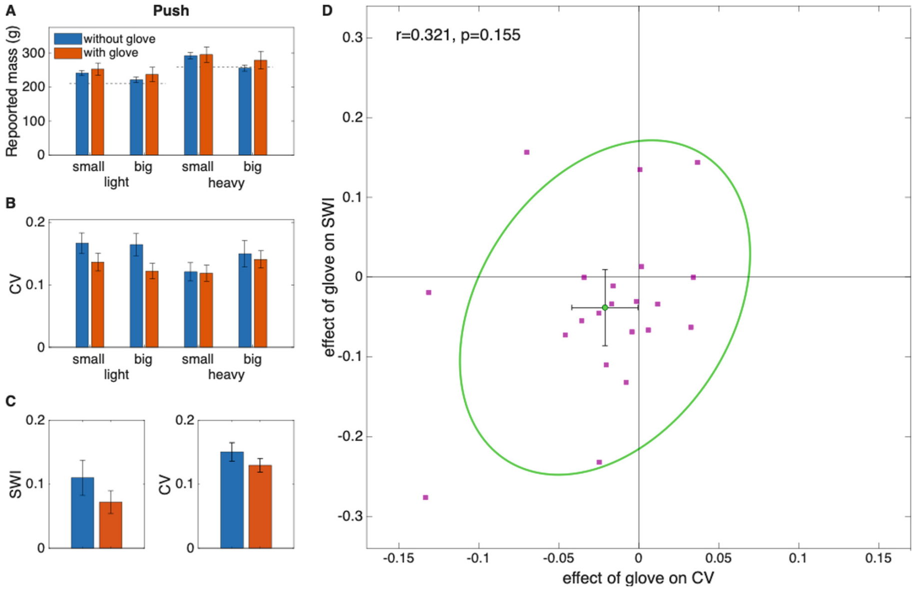

Fig. 3. The results of the pushing experiment. Details as in Fig. 2

4 Discussion

We questioned whether the magnitude of the size-weight illusion depends on the reliability of tactile information about the force required to lift the object. We hypothesized that the illusion would become stronger if the reliability of tactile information were reduced, because having less reliable haptic information would make one rely more on other information, such as any discrepancy between the expected force given the visually perceived size and the force that is actually needed to move the object. We tested this hypothesis by examining whether wearing a glove would influence the magnitude of the size-weight illusion. We found no clear overall effect of wearing a glove, neither on the illusion nor on the reliability of the judgments. However, we did find considerable idiosyncratic differences in both the coefficient of variation and the size-weight illusion (Fig. 2d and Fig. 3d). Importantly, despite the lack of an overall effect of wearing a glove, we did find the hypothesized correlation between the idiosyncratic effects of the glove on reliability and on illusion magnitude: participants whose judgements became more variable when wearing a glove had a stronger size-weight illusion when doing so.

A first question is why the glove did not lead to more variability overall. We expected the glove to reduce precision because wearing a glove presumably degrades the tactile information. For the lifting experiment, participants might have compensated for this degradation by taking more time holding the object, allowing them to average the less precise information over a longer period. However, this is unlikely to be the reason, because the weight appears to be judged within the first 30ms after liftoff [9]. Moreover, participants could not have used this strategy in the pushing experiment: the duration of the push was very short. Apparently, the glove degraded the tactile information for some participants, but for many other participants, the tactile information appears to have improved. Wearing a glove changes the tactile input by spreading forces over a larger area. This means that it changes which afferents will sense the force. For lifting, the change is categorical: without a glove, only the shear-sensitive SAII afferents at the location where the skin touches the object are stimulated, whereas when wearing the sturdy glove, the glove distributes the force to other afferents in other parts of the skin [26]. For pushing, the change in the tactile afferents involved will be more gradual: the glove will spread the contact force over a larger area, thus leading to the activation of more afferents with a lower intensity. Apparently, these changes in sensory input are advantageous for some participants, but not for others. A possible reason for this idiosyncrasy may be that some participants reweight the various haptic cues more than others when circumstances change [27].

Despite the lack of an overall effect of wearing a glove on the precision of mass judgements, we found that conditions in which participants were most precise were the ones with the smallest size-weight illusion, in line with an initial report [21]. This finding appears to contradict two recent studies that also manipulated the reliability of information [22, 23]. However, this apparent contradiction is easy to explain: in our study, we manipulated the precision by altering the reliability of the force information, whereas the other two studies manipulated the reliability of the size information. Therefore, in all cases, the shift was in the direction of the most reliable information.

Acknowledgments. We want to thank Mees van Leeuwen, Eyob Roding, David Ibragimov, and Max Velders for their contributions to the design and execution of the experiments.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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