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Perceived hand size and perceived hand weight

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ABSTRACT

The dimensions of objects and our body parts influence our perception of the weight of objects in our surroundings. It has been recently described a dramatic underestimation of the perceived weight of the hand. However, little is known on how perceived size informs the perceived weight of our own body parts. Here we investigated the effects of embodying an enlarged and a shrunken hand on perceived hand weight. We manipulated hand size using a visual-tactile illusion with magnifying and minifying mirrors. We then measured perceived hand weight using a psychophysical matching task in which participants estimate if a weight hanged on their wrist feels heavier or lighter than the experienced weight of their hand. Our results indicated that participants tended to underestimate the weight of their hand more when embodying a smaller hand, and less so when embodying a larger hand. That is, the perceived size of the hand plays a role in shaping its perceived weight. Importantly, our results revealed that the perception of the weight of body parts is processed differently from the perception of object weight, demonstrating resistance to the size-weight illusion. We suggest a model based on constant density to elucidate the influence of hand size in determining hand weight.

1. Introduction

The size of an object is a dominant feature in how we perceive its weight. Yet, we do not know if this is also true for the weight of parts of our body. Our body is not only an integral part of our self, but it is also a three-dimensional physical object, with measurable properties, including volume, density and weight. In the execution of every movement, we indeed have to exert effort to support the weight of our body parts. Yet, unlike the conscious awareness associated with the act of carrying objects, we often neglect the effort involved in carrying our limbs. This observation suggests a potential disparity in the perception of weight between objects and body parts. How does the brain determine the weight of objects and body parts? In physics, the mass of objects is derived from the product of volume and density. The weight is then calculated using Newton's law, equating mass with gravitational acceleration. However, it remains unclear how the human brain represents these physical properties. No receptors transmit information about weight. Rather, the brain must compute a representation of weight based on proprioceptive, vestibular-gravitational, auditory and visual signals and motor commands. Understanding how the perception of volume influences the perception of weight provides insight into how our brain computes weight, in general. Even though it is unclear how size influences the perceived weight of our body parts, this relationship has been widely studied for external objects.

For over a century, it has been recognised that the size of objects alters our perception of their weight. When we pick up a small and a large object with similar masses (Charpentier, 1891) or even just gently push them (Plaisier et al., 2019), the smaller object consistently feels heavier. This phenomenon is known as the *size-weight illusion* (SWI) and it is clear evidence that perceived size significantly influences the perceived weight of an object. There are competing hypotheses to explain the SWI (for a review, see Buckingham, 2014), with some linking it to the expectation built up throughout our lifetime that bigger objects tend to be heavier, resulting in a mismatch when lifting two objects of different size and same weight. However, even when participants expect the smaller object (a golf ball) to be heavier than the larger one (a beach ball), which is the reverse of the typical expectation that larger objects are heavier, they still experience the SWI, reporting the smaller object as heavier (Buckingham & MacDonald, 2016). The insufficiency of the prediction mismatch in explaining the SWI is countered by Saccone and Chouinard (2019) who argue for a fundamental and dominant influence of size in how we experience weight, which they attribute to a faster processing of size, compared to other features such as colour and material. Indeed, even though the appearance of the object's material also influences the illusion, size consistently has a stronger effect in how heavy an object feels (Buckingham et al., 2009; Buckingham & Goodale,

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2010, 2013). Strikingly, this effect was also verified even when the object's volume and density appear constant. In this paradigm, participants could clearly see that all objects consisted of the same two blocks, connected by a middle pole. The only variation was in how far the two blocks were positioned. As a result, some objects appeared larger, but had a hollow space in the middle, creating the illusion of increased size despite the same total volume (Plaisier & Smeets, 2015). These findings support a unique role of size in weight perception, suggesting that hand size might also influence the felt heaviness of *the hand itself*.

The perception of the weight of body parts is highly flexible. For example, studies of gravity alterations produced by parabolic flight or a short-arm centrifuge supported a dynamic gravity-based computation of perceived body weight, with hand and head perceived weight rapidly changing in function of the gravity load (Ferrè et al., 2019). During exposure to microgravity (0 g), the hand was felt to be lighter than in terrestrial gravity (1 g), and in hypergravity (1.8 g), heavier, showing the vestibular signals immediately updated perceived bodily weight when the experienced strength of gravity changed. Similarly, by manipulating the frequency of the sound of participant's footsteps, Tajadura-Jiménez et al. (2015, 2019) induced the feeling of having a lighter body. While the perception of bodily weight is shown to be flexibly changed by sensory signals, it remains unclear whether and how the size of body parts influences their perceived weight.

The perceived size of the body significantly influences perceptual experiences. Research on perceived hand size indicates that embodying a magnified hand can reduce pain (Mancini et al., 2011), increase perceived grasping ability (Marino et al., 2010), and change the perception of grasped objects (Bruno & Bertamini, 2010). Visually increasing hand size enhanced sensorimotor performance in healthy participants, in tactile discrimination tasks (; Kennett et al., 2001; Taylor-Clarke et al., 2004), and motor tasks in stroke patients (Ambron et al., 2018), which was associated with increased excitability of the motor system and greater cortical resources allocated to the enlarged body part (Ambron et al., 2018). Of particular interest to our study, embodying a larger hand through visual-tactile stimulation of a fake hand makes a held object to feel heavier (Haggard & Jundi, 2009), and magnified objects with goggles also feel heavier and smaller once they are seen next to one's also enlarged hand (Linkenauger et al., 2010). However, the reverse pattern is not as prevalent for smaller hands. While seeing a smaller hand may reduce analgesia (Mancini et al., 2011) and the perceived size of an object (Linkenauger et al., 2010), and while visual-tactile stimulation of a smaller hand also decreases object felt size (Bruno & Bertamini, 2010), it does not consistently change grip aperture size (Marino et al., 2010) or the felt weight of an object (Haggard & Jundi, 2009). This suggests that we may be less flexible in updating our bodily abilities when the size is reduced. Overall, these findings show that alterations in hand size change action ability, pain, tactile and motor perception, as well as how we perceive the objects around us. However, it is unclear whether alterations in hand size change the perceived weight of our own hand, and how.

Here we investigated whether perceiving an enlarged or shrunken hand changes the perceived weight of that hand. If felt hand size indeed changes felt hand weight, there are two hypotheses: a larger hand feels heavier or a larger hand feels lighter, and the opposite with the smaller hand. We will describe these two hypotheses with two models explaining how each possible effect is computing perceived size, mass and volume. If our body is perceived in the same way as any other physical object in the world, one might expect that experiencing a larger hand would make it feel lighter, while a smaller hand would feel heavier, consistent with the size-weight illusion described for objects. We refer to this hypothesis as the *constant mass model*, depicted in Fig. 1C, wherein the human hand is perceived to have a constant mass, resulting in it feeling lighter when perceived hand size increases. When the same mass is spread across a larger area, its density decreases. Consequently, while larger body parts are typically expected to feel heavier, the perception of an enlarged hand having the same mass results in it feeling lighter.

If the opposite trend is verified, an enlarged hand is perceived as heavier and a shrunken hand as lighter, with the new hand size being updated while maintaining consistent density. We call this the *constant density model*. This model, depicted in Fig. 1C, suggests that perceiving an enlarged hand composed of the same material without density changes results in it feeling heavier due to there being more "hand stuff". Size and weight are considered flexible in this model, while density remains constant. The perceived hand, whether larger or smaller, is computed as having the same structures and consistency as the actual hand, without muscles, fibers, bones, and tendons being stretched or

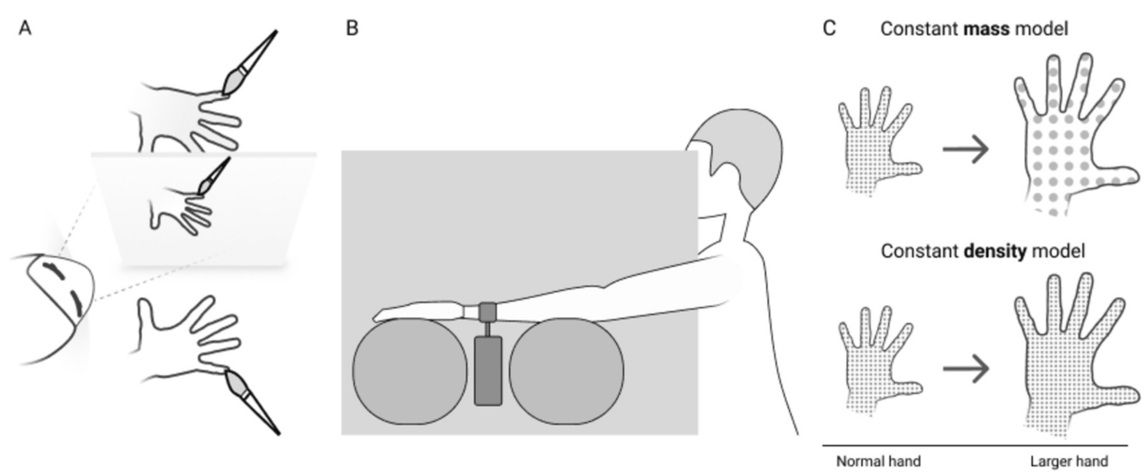

Fig. 1. Setup. A: Adaptation to the minified hand with visual-tactile stimuli. The participant saw the reflection of their right hand in the magnifying, minifying or normal mirror, which created the illusion of looking at their left hand, seen as magnified, shrunk or normal size. The experimenter stroked both hands synchronously and congruently to enhance the illusion, by matching felt touch on the real left hand with seen left hand. B: On each trial, one weight was attached to the wristband and the participant was asked to compare it to the experienced weight of their left hand, by responding whether the weight felt heavier or lighter that their hand felt like. After 15 trials, there was a top-up of the adaptation, followed by another 15 trials of the same condition. There were 3 blocks: magnified, minified and normal, corresponding to the type of hand size induced by the distortion mirrors. **Models** C: Constant mass and constant density models. In the first model, the same 'hand stuff' would be distributed by a larger area, hence eliciting the perception of a sparser and lighter hand when embodying a larger hand, and a more compact and heavier hand when embodying a smaller hand. In the second model, density is kept constant when feeling a larger hand: there would be more of the 'hand stuff', making the hand be perceived as heavier. When embodying a smaller hand, it would feel lighter. In both cases, the material that the hand is felt to be made of, it kept constant.

compressed. Consequently, a larger hand would feel heavier because it has more of the same material, whereas a smaller hand would feel lighter due to having less of the same material, while density remains unchanged.

Supporting the constant density model, Schilder (1918b) conducted an experiment where participants were asked to mentally visualise their left hand tripled in size. Participants were then instructed to describe their experiences, with some participants reporting sensations such as "a sensation of inner heaviness", or "heavy presence of the large hand", "a solely from engaging in this mental exercise. Although Schilder did not quantify perceived or actual hand weight, he inferred from these observations that visualising larger hand sizes induced sensations of actual heaviness, "there is no doubt that it is a perception of the weight of the imagined hand" (Schilder, 1918, p. 6). For our study, what stands out from these reports is the direction of the perception of heaviness, where imagining a larger hand would make it feel heavier. These reports, while anecdotal, are consistent with the constant density model.

Ferrè and colleagues recently developed a method to estimate the perceived weight of the hand (Ferrè et al., 2023). On each trial, a weight is suspended from the participant's wrist and they judge whether it feels heavier or lighter than their hand. Actual hand weight was collected using the water displacement method, to calculate overestimation ratios of estimated hand weight to actual hand weight. It was found that hand weight was systematically underestimated, with participants feeling their hand on average 49 % lighter than it actually is.

In the present study, we exploit this paradigm to investigate if the perception of hand weight is altered by changing perceived hand size. To do this, participants viewed their right hand through a magnified, a normal, or a minified mirror, while being stroked by a brush synchronously in both hands, to create the illusion of having an enlarged, a normal or a shrunken left hand. Participants judged whether the weight hanged on their left wrist, occluded from their view, was heavier or lighter than the experienced weight of their left hand, to determine the perceived hand weight in the three conditions. Aligned with the constant density model, we predicted that a larger hand would feel heavier, and a smaller, lighter.

2. Methods

2.1. Participants

Twenty healthy people (M ± SD = 32.3 ± 2.7 years; 15 females) participated after giving written informed consent. Haggard and Jundi (2009) analysed how light or heavy a cylinder felt when participants were induced a hand with different sizes. There was a significant weight overestimation error for synchronous stroking compared to asynchronous stroking of the large rubber hand, ($t(11) = 2.3$, $p = .042$, which has an effect size of $d_z = 0.664$. A power analysis using G*Power 3.1 (Faul et al., 2007) with a 2-tailed alpha of 0.05, a power of 0.80 and a Cohen's d of 0.664 based on Haggard and Jundi's study, indicated that 20 participants were required. Participants were all right handed as assessed by the Edinburgh Inventory (*M*: 78.2, SE: 6.1 range: 20.0 to 100) (Oldfield, 1971). All procedures were approved by the Department of Psychological Sciences Research Ethics Committee at Birkbeck, University of London and were consistent with the principles of the Declaration of Helsinki.

2.2. Hand size illusion

We used a paradigm similar to that used by Mancini et al.' (2011) to induce different hand sizes in three conditions: magnified hand (big), normal hand (normal) and minified (small). The hand size was manipulated using 3 mirrors: a concave mirror with a 2× magnification, a normal mirror, and a convex mirror with a 2× reduction. In the magnifying condition, the participant viewed an amplified version of their right hand in the magnifying mirror, which is perceived as the occluded left hand, an effect known as the mirror box illusion (Ramachandran et al., 1995; Ramachandran & Rogers-Ramachandran, 1996). The illusion was induced in the left hand to all participants, regardless of the participant's hand dominance, as in previous studies using the mirror size-illusion (Mancini et al., 2011) and the hand weight method we applied after the illusion (Ferrè et al., 2023). To induce the illusion, we included an adaptation phase to the reflected hand, in which the participant was asked to look in the mirror and fixate their hand reflected in the mirror, while the experimenter stroked the dorsal surface of both hands with a brush at approximately 0.5 Hz for 30 s before the task. The strokes were applied to both hands simultaneously and in congruent localisation (such as index finger with index finger), in a random pattern.

2.3. Perceived hand weight

We used the psychophysical weight matching task developed by Ferrè et al. (2023). Before the experiment started, a wristband was placed on both wrists of the participant's hands. Before each block, the correct mirror was positioned to match the condition, counterbalanced across participants. At the beginning of the task and once every 15 trials, the participant was asked to feel the weight of their left hand, which was hung freely with the arm resting on a pillow, as shown in Fig. 1A. This ensured that the way that the hand was hanging is an approximate match to the way the bag of rice was also hung during the trials, making the weight of the hand comparable with the weight of the bag. The hand was then placed back on a pillow, palm down, with the wrist uncovered, so the experimenter could place a weight on the participant's left wrist, which was occluded from their view. On each trial, one of 16 weights was hung on a hook attached to the wristband (Senshi Japan, weight: 76.5 g) that was strapped around the participant's left wrist (Fig. 1B). Each trial, the participant was asked to estimate if the weight they felt pulling on their wrist was heavier or lighter than the previously experienced weight of their left hand. They responded by saying 'lighter' or 'heavier'. By resting their hand on the pillow, participants did not feel the weight of their hand during the trials, allowing them to focus solely on the weight of the bag hanging from their wrist without needing to subtract the hand's weight to compare it to the felt weight when their hand was suspended. They wore wristbands on both wrists for visual congruency, and viewed their right hand's reflection in the mirror throughout the whole block, with the area below the right hand occluded, to prevent an unmatching of information when the weights were placed on the contralateral wrist. The right hand position consistently matched the hand position of the left hand. Between blocks, the experimenter switched mirrors while the participant rested for one minute and was asked to stretch their arms to avoid numbness from staying in the same position. The weights were made of plastic bags with rice so that the total weight suspended from the wrist produced 16 weights, logarithmically spaced between 100 and 600 g, rounded to the nearest gram (100, 113, 127, 143, 161, 182, 205, 231, 260, 293, 330, 372, 419, 472, 532, 600 g).

Every experimental condition was tested within a block, with the sequence of blocks counterbalanced across participants using a Latin Square design. Within each block, there were 30 trials, totaling 90 trials for the entire experiment. Each block featured two intertwined psychophysical staircases, using the QUEST algorithm (Watson & Pelli, 1983) implemented in the PsychToolbox (Brainard, 1997) for MATLAB (Mathworks, Natick, MA). The two QUEST staircases were given initial estimates of perceived hand weight that were either 200 g more than (i. e., 609.6 g) or less than (i.e., 209.6 g) the average hand weight (409.6 g) reported in a previous study (Kaye & Konz, 1986). On each trial, QUEST suggested which of the available stimuli to present based on a Bayesian analyses of the responses on the previous trials together with the initial estimated. The two staircases alternated across trials. The Psychtoolbox QUEST algorithm is a psychometric function that estimates a threshold using a maximum likelihood procedure, and in this procedure we used it to estimate with precision how much the hand is felt to weigh, in each condition. Hence, for each participant we obtained a high and a low intensity staircase, from which the QUEST algorithm in MATLAB's Psychtoolbox calculated a mean threshold value for felt hand weight. These mean threshold estimates were obtained for each participant, for the low and the high staircases. We then verified if both staircases correlated, as they should converge in similar values, and calculated the difference between intensity staircases to further establish that they do not differ. Though the two staircases started with different prior estimates of hand weight, they quickly converged on a common estimate of perceived hand weight (as shown in Fig. 3). For each condition, the low and high staircase values for each participant were averaged. These estimations were then used to calculate a ratio of overestimation to actual hand weight, as described in the results.

2.4. Hand size judgements

At the end of each block, we asked participants to judge the felt size of their left hand, by moving a rod along a slider apparatus on a covered ruler, a method used in previous studies to measure the size long and short sixth fingers, and hand length and width (Cadete & Longo, 2022; Longo & Sadibolova, 2013; Mancini et al., 2011). The distance from the beginning of the ruler to the place where the rod was placed represented the distance from the wrist to the middle finger fingertip, when measuring hand length. For hand width, the distance in the sliding apparatus from the beginning up to the sliding rod represented the distance from the index finger knuckle to the little finger knuckle.

At the end of the experiment, measures of hand volume were collected using the water displacement method. The participant placed their left hand (up to, but not including the ulnar styloid process) into a beaker of water resting on a digital scale (AMPUT APTP457A 7500 g, Shenzhen Amput Electronic Technology Co. Ltd). Since by definition, 1 g of water has a volume of 1 cc, the reading on the scale can be interpreted directly as the volume of water displaced, and thus of the hand itself. Three successive measures of hand volume were collected, and averaged. Measured hand volume was converted to an estimate of hand weight using the estimate of hand density (1.09 g/cc) reported by Kaye and Konz (1986). On average, participants' hands weighed 306.3 g (SD: 15.6 g). Finally, we collected measures of overall body weight using a standard commercial scale. Participants on average weighed 65.7 kg (SD: 2.27 kg).

We also measured actual hand length and width. At the end of the experiment, we took a photo of the participant's hand, positioned next to an horizontal and a vertical ruler to extract the actual finger length by converting distances in pixels to cm. The actual length and width were obtained to calculate the overestimation of hand size across conditions. Participant's hand was on average 17.8 cm long (SD: 0.6), and 10.2 cm (SD: 0.2) wide.

3. Results

3.1. Perceived hand size

We used the same methods of Longo and Sadibolova (2013) to analyse perceived hand size using line judgements. We took the ratio of perceived hand length/width to actual hand length/width separately for each condition (big, normal & small). We then obtained the means of the ratios and did a calculus of overestimation of actual hand length/width with the formulas: 100*(estimation - actual length)/actual length; 100*(estimation - actual width)/actual width. We conducted a linear trend repeated measures ANOVA for each orientation (width/length), with hand size as factor, with three levels: big, normal, small. We conducted pairwise comparisons with Holm Bonferroni corrections for the conditions: big against normal, small against normal, and big against small, for each orientation. To analyse the data, we used R in Jupyter lab, with the lme4 package (Bates et al., 2015). The Quest staircases and the plots were conducted in MATLAB, as detailed below.

Perceived hand length and hand width were calculated separately, as we systematically overestimate hand width and underestimate finger length (Longo & Haggard, 2010, 2012). This perceptual distortion was replicated in our results, with hand width overestimated and hand length underestimated (as hand length includes finger length) in the normal hand condition. This effect is also present in the non-significance of width underestimation in the small condition, and in the non-significance of length overestimation in the big condition, as both estimations end up being closer to actual hand length and width.

We conducted one-sample *t*-tests against 0, to estimate whether there was a significant overestimation or underestimation of hand weight in each condition, calculated as a ratio of perceived hand length to actual hand length, as described above. Shapiro-Wilk tests showed that the data follows a normal distribution for all individual conditions ($p > .05$). For conditions where normality was not met (weight and width ANOVAs), non-parametric tests yielded the same significance patterns. Additionally, we computed 95 % bootstrap confidence intervals using the bias-corrected and accelerated (BCa) method for all analyses, with 1000 bootstrap samples ($R = 1000$), and a seed set as 123 for reproducibility. The BCa method adjusts for both bias and skewness in the bootstrap distribution, providing more accurate interval estimates. All paired tests are two-tailed.

As shown in Fig. 2, participants perceived their hand shorter in the small condition, with a mean of −21.76 % ($SE = 5.29$) underestimation from their actual hand length, $t(19) = -4.11$, $p < .001$, $d_z = 0.92$, 95 % CI [30.63, 10.60], a non-significant underestimation in the normal hand condition, $M = -4.25$ % ($SE = 3.87$), $t(19) = -1.10$, $p = .14$, $d_z = 0.25$, 95 % CI [−10.96, 3.68], and a non-significant overestimation of 4.61 % ($SE = 4.13$) in the big hand condition, $t(19) = 1.17$, $p = .14$, $d_z = 0.25$, 95 % CI [2.60, 13.19]. There is a significant difference for length overestimation along the linear trend for the conditions 'small', 'normal' and 'big', $F(1, 39) = 39.01$, $p < .0001$, $\eta_p^2 = 0.93$, 95 % CI [−18.18, −8], with a significant difference between normal and big condition, $t(19) = 4.17$, $p < .001$, $d_z = 0.93$, 95 % CI [0.07, 17.19], normal and small, $t(19) = 2.11$, $p = .04$, $d_z = 0.47$, 95 % CI [8.65, 26.39], and big and small: $t(19) = 6.28$, $p < .0001$, $d_z = 1.40$, 95 % CI [15.44, 36.22].

Similarly to the hand length analysis, we conducted one-sample *t*-tests against 0 for the estimations of perceived hand width to actual hand width, to estimate whether there was a significant overestimation or underestimation of hand width in each condition. Hand width was overestimated by 26.1 % ($SE = 5.44$) in the big hand condition, $t(19) = 4.79$, $p < .001$, $d_z = 1.07$, 95 % CI [15.98, 37.00], and overestimated by 7.9 % ($SE = 2.94$) in the normal condition, $t(19) = 2.70$, $p = .007$, $d_z = 0.60$, 95 % CI [3.41, 14.77] whereas for the small condition there was no significant underestimation, ($M = -7.52$ %, $SE = 4.44$), $t(19) = -1.69$, $p = .053$, $d_z = 0.38$, 95 % CI [−15.86, 1.14]. Width overestimation significantly changed along the linear trend from small, to normal and big conditions, $F(1, 39) = 41.08$, $p < .0001$, $\eta_p^2 = 0.96$, 95 % CI [−23.68, −11.56], with a significant difference between normal and big hand conditions, $t(19) = 2.92$, $p = .006$, $d_z = 0.65$, 95 % CI [7.41, 28.79], normal and small: $t(19) = 3.42$, $p = .003$, $d_z = 0.76$, 95 % CI [5.66, 24.69], and big and small: $t(19) = 6.33$, $p < .0001$, $d_z = 1.42$, 95 % CI [21.15, 45.59].

Overall, these results show that the visual-tactile stimuli did induce did induce the feeling of having a smaller hand in the small hand condition, and a bigger hand in the big hand condition. This confirms that the manipulation of perceived hand size was achieved, which allows us to make inferences about the hand weight estimations, brought by changes in perceived hand size.

3.2. Perceived hand weight

We applied the same analysis of Ferrè et al. study (Ferrè et al., 2023), in which the perception of hand weight paradigm was developed. We ran correlations between high and low staircases for each condition, to

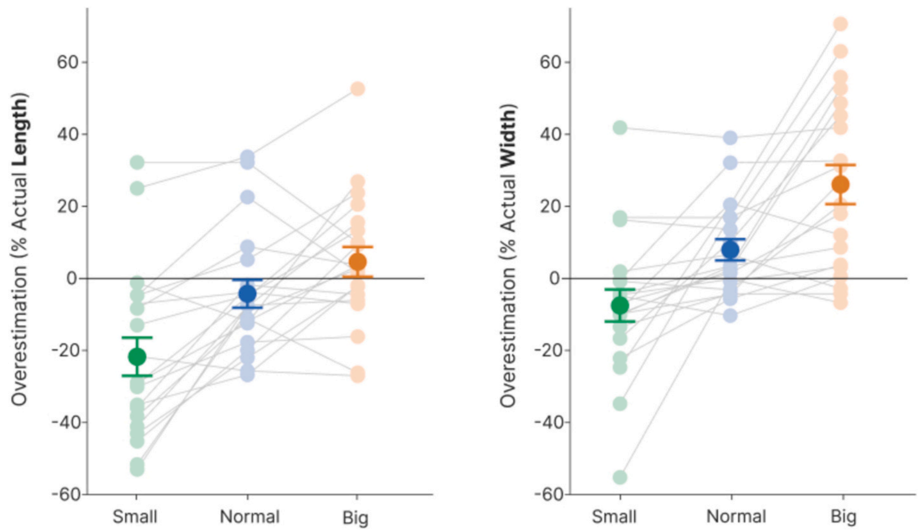

Fig. 2. Perception of hand length and width across conditions. *Left panel*: Hand length was slightly overestimated in the big hand condition, underestimated in the small condition, and slightly underestimated in the normal condition. *Right panel*: Hand length was slightly underestimated in the small hand condition, and increasingly overestimated in the normal to the big hand condition. Error bars are one standard error.

assess the reliability of the estimations.

For each condition, we took the ratio of perceived hand weight to actual hand weight separately for each condition (big, normal & small). We then obtained the means of the ratios and calculated overestimation of actual hand weight with the formula: 100*(estimation - actual weight)/actual weight. We conducted a one-sample *t*-test against 0 to assess whether there was a significant overestimation or underestimation of perceived hand weight to actual hand weight in each condition. We also did a linear trend repeated measures ANOVA with 3 levels (big hand, normal hand & small hand), and did pairwise comparisons with Holm Bonferroni corrections for the conditions: big against normal, small against normal, and big against small.

The results from the hand weight task are shown in Fig. 3. The low staircase started with a weight of 209.6 g, then calculating the weight stimulus for the next trial based on the previous value and the participant response, and the high staircase did the same procedure yet starting at a high intensity of a weight stimulus of 609.6 g. Both staircases were measuring the same threshold, which was perceived hand weight. If high and low staircases reached the same value after a few trials, despite starting with a difference of 400 g in the weight stimuli, it shows that the procedure is reliably estimating perceived hand weight, and that participants had a precise threshold for how heavy their hand felt, in each condition. Low and high staircases converged and highly correlated across participants, in the normal condition, $r(18) = 0.971$, $p < .0001$, big condition, $r(18) = 0.966$, $p < .0001$, and small condition, $r(18) = 0.937$, $p < .0001$, showing high reliability of the hand weight estimates. There was a weak positive correlation between hand width overestimation and hand weight overestimation, suggesting that perceived hand weight increases as hand width is also perceived to increase, $r(18) = 0.45$, $p = .046$, and no significant correlation between perceived hand length and perceived hand weight, $r(18) = 0.091$, $p = .70$.

We replicated the systematic underestimation of hand weight (Ferrè et al., 2023), with participants underestimating the weight of their hand in the normal condition, by 30.6 % ($SE = 6.86$), $t(19) = -4.45$, $p < .001$, $d_z = 1.00$, 95 % CI [−42.25, −16.71]. In the small hand condition, participants felt their hand even lighter, with a weight underestimation of 39.0 % ($SE = 5.74$), $t(19) = -6.79$, $p < .0001$, $d_z = 1.52$, 95 % CI [−48.74, −27.47]. In the big hand condition, hand weight was still underestimated by 20.1 %, ($SE = 8.97$) $t(19) = -2.24$, $p = .04$, $d_z = 0.50$, 95 % CI [−34.60, −0.74].

There was a significant difference for hand weight overestimation along the linear trend for the conditions 'small', 'normal' and 'big', F(1,

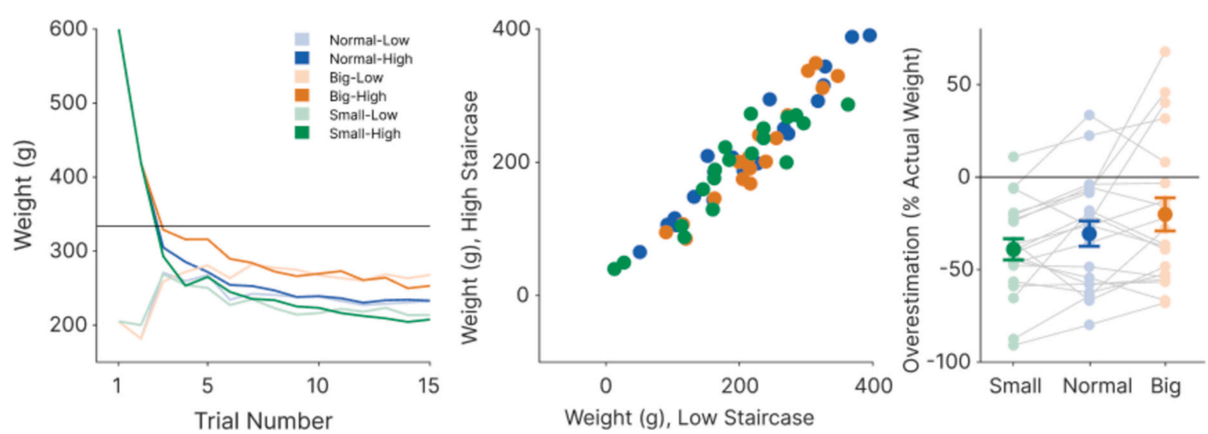

Fig. 3. Perception of hand weight across conditions. *Left panel*: The low and high staircases converged on common estimates of hand weight, in all conditions. The black horizontal line indicates the mean weight of the actual hand. *Centre panel*: Estimates of hand weight were strongly correlated between the two staircases for all conditions, $p < .001$. *Right panel*: There was a clear underestimation of hand weight in the three conditions, with higher underestimation in the small hand condition, and lower underestimation in the big hand condition, with a significant linear trend from small to big, $p = .009$. Error bars are one standard error.

39) = 10.20, $p = .003$, $\eta_p^2 = 0.87$, 95 % CI [−18.21, −3.33]. This shows that there was a significant linear increase in perceived hand weight from feeling a small, to a normal and a big hand. There was a significant difference between the big hand and the small hand conditions, $t(19) = 3.15$, $p = .009$ $d_z = 0.71$, 95 % CI [5.50, 35.30], with no significant difference between big and small hand conditions when compared to the normal condition (>0.05).

4. Discussion

We investigated whether changes in perceived hand size alter the perception of hand weight. The size of an object does change how heavy or light we perceive it to be, the well-known size-weight illusion (Buckingham, 2014; Buckingham & Goodale, 2013; Plaisier & Smeets, 2015; Saccone & Chouinard, 2019), but it was unclear if the same occurs for body parts. Our results show that our hand feels lighter when it feels shrunken, and heavier when it feels enlarged. This is strikingly different from human's perception of objects, where a large object feels lighter (Charpentier, 1891). Our results show that we do not estimate the weight of our body parts in the same way we estimate the weight of objects in the outside world. Recently, Ferrè et al. (2023) found that we consistently underestimate the weight of our hands. This distortion in the perceived weight of body parts is the baseline for how heavy or light we perceive our bodies, and we tested whether this perception can be influenced by its felt size. The illusion of having an enlarged and a shrunken hand was validated by the significant differences in hand length and hand width overestimation across conditions. The normal hand condition served as a baseline to compare it to the small and large hand conditions. Participants underestimated hand length and width in the small condition, and overestimated them in the big condition, whereas in the normal condition there was a mild overestimation of hand width and underestimation of finger length, both in the direction of known consistent distortions of perceived hand size (Longo & Haggard, 2012).

We altered the perceived size of hands to investigate how embodying various hand sizes affects the perception of hand weight. Our findings indicate that altering the perceived hand size indeed influenced the perception of hand weight. It has been recently showed that the experience of the weight of our hand is dramatically distorted (Ferrè et al., 2023). Under typical circumstances, participants tend to perceive the weight of their hand as lighter than its actual weight. This underestimation suggests a beneficial adjustment of perceived hand weight which might facilitate effortless actions. In our study, we replicated this underestimation of hand weight. Notably, this underestimation was also observed in both small and large hand size conditions. Upon inducing the illusion of having a smaller hand, participants perceived their hand as even lighter, exhibiting a 39 % underestimation compared to the actual weight. Conversely, when experiencing an enlarged hand, participants perceived their hand as heavier than in the small hand condition, yet still underestimated its weight by 20 %. That is, our brain must rely on hand size information, conveyed through visual-tactile signals, to adjust the perception of hand weight. Yet, even experiencing a hand twice its size, did not counteract the baseline underestimation. What seems to be happening is that size is updating perceived weight while maintaining an underestimation of perceived hand weight proportional to what the new weight should be as a result of experienced increased volume. While we report changes in how much hand weight is underestimated across conditions, if the hand was indeed larger and hence heavier, we can expect that the underestimation magnitude was similar to the baseline bias reported in the normal condition and in Ferrè et al.'s study (Ferrè et al., 2023). While perceived body part weight is flexibly represented and easily changed by the perceived size of the body part, its underestimation is not extinguished, just adjusted to the larger or smaller hand. It is useful to perceive some weight of our body parts, and to represent that weight flexibly for us to lift, hold and interact with objects when experiencing changes of body size but also gravitational changes, which interfere with perceived hand weight (Ferrè et al., 2019). However, the long-term representation of our body, we propose, is set to be experienced with much less weight than what it actually has at any given moment. This privilege is not extended to objects, as experiencing them as lighter than they are could be harmful and inefficient. We suggest that the perception of body parts weight is a dynamic process which is constructed and updated utilising sensory inputs, including visual, tactile, and vestibular signals.

Our results showed that the size-weight illusion does not apply to body parts, as an enlarged hand felt heavier and not lighter, even though it in fact weighs the same, and the reverse logic for the small hand. We, therefore, propose a model of constant density (Fig. 1C), in which a bigger hand feels heavier and a small hand feels lighter, as our results endorse. In this model, the representation of hand weight is updated upon perceived hand size changes, with a computation that maintains a constant density, that is, the hand substance does not oscillate into a denser or sparser hand. The material that the hand is made of is kept at the same proportion of weight compared to size (density), and within that strategy, felt hand weight increases as hand size also increases We propose the constant density model as a potential explanation of our results, and further research is needed to confirm whether this model maintains applicable when using different manipulations of perceived bodily features and expectations of bodily features. It is intriguing why the perception of object weight differs from body-part weight. We propose that bodily density is established as a stable long-term representation. Even though the actual density of the hand varies, with the metacarpals, phalanges and tendons of the hand being denser than its skin and fat, it may be perceived as a compound whole hand density. More importantly, hand density (and quite possibly whole-body density) may be constrained in the representation of our body parts, when volume and weight change. Yet, for objects, we are prepared to attribute different densities to different objects. Indeed, the size-weight illusion is modulated by visual cues of the material properties of the object, such as metal versus polysterene, which may suggest different densities (Buckingham et al., 2009). This is not to say that hand density is constrained for body parts; in the marble-hand illusion (Senna et al., 2014) participants felt their hand stiffer and heavier when induced a hand with different material properties, which may suggest different density. However, when hand volume is perceived to change, hand density is maintained fixed in the representation of hand weight. It is plausible that a hand, when increased in size, maintains the same density. It would be less likely that suddenly our hand is composed of different physical properties, whereas the larger object is more likely to have a different density than another object. In the size-weight illusion, perceiving the larger object as being less dense than the smaller one would solve the prediction mismatch of the larger object not being the heavier one.

Another hypothesis is that we have different expectations about body part weight than we do for objects, as our body is not only a more stable volumetric object, it is also just one object, whereas we held, lift and push multiple objects of varied sizes and weights, which arguably can lead to different size-weight expectations. It is true that we can think of our body as having several body-parts, and we can compare the right hand with the left hand or right foot, however the human body is symmetric, and typically the left hand has similar shape, size and weight as the right hand. In this sense, we lack the experience of comparing one body part with another and verifying that a larger hand is indeed heavier than a smaller hand. This absence of comparison prevents us from forming a correlation between hand size and hand weight. One limitation is that, in our paradigm, we are not comparing two hands of the same weight; the estimations are only obtained for the left hand, which means that we cannot directly compare to the size-weight illusion. Also, there was no significant difference in the weight overestimation compared to the normal condition, contrary to the size overestimation. We attribute this to the difference in the tasks, as weight perception was measured with greater precision, using a psychophysics staircase procedure, whereas size perception was measured with line judgements, meant to validate the illusion adaptation. Nevertheless, it is notable how size influenced the perceived weight of a hand differently than it typically influences the perceived weight of objects, as reported in other studies. This suggests a potential difference in how we perceive the weight of body parts versus external objects. Further research is needed to determine if we have two distinct mechanisms for perceiving the weight of objects and weight of body parts, or if it is the same mechanism and then half of its weight is deducted only for body parts.

In our study, we identified the way hand size changes perceived hand weight, however it is unclear in what way this is or is not distinct from how hand size changes perceived object weight. When there is a change in perceived hand size, we rescale the objects around us accordingly (Linkenauger et al., 2010). When the hand is felt to be larger, the object held is felt to be heavier (Haggard & Jundi, 2009). In our study, when our hand is felt to be larger, the hand is also felt to be heavier. Since we are manipulating perceived hand size and estimating the perceived weight of the same hand, we can also think of this as the same effect as for objects, but as if we are splitting the perception of our hand into two aspects: as our hand and as an object being weighed. It could be that we are calculating hand weight as a product of the effort to pull the hand in the same way as an object, as if the hand could be perceived both as a body part and an object to carry and move. This would mean that we are judging the weight of our hand as a separate event from the body, as if the exerted effort is rescaled similarly for lifting an object and our hand, once the size of the hand is perceived to change. A way to solve this would be to test how we estimate hand weight, holding it with the contralateral hand with induced change of size, compared to estimating it with a normal size hand.

Previous studies showed a directional effect of body-part size, with only enlarged hands updating other perceptual dimensions. Embodying a minified hand did not elicit changes in motor skills (Marino et al., 2010), neither in the perceived object weight held in the participants' hand (Haggard & Jundi, 2009). Our results show that feeling a minified hand decreased the hand's felt weight, possibly indicating a more direct link between body-part size and bodily weight perception. It may also be that when we experience shrinking of body-parts, our nervous system is prompt to update its perceived weight but not the weight of objects, guaranteeing a constancy in the world that is not granted when the body enlarges. The results of our study point to two different mechanisms in weight perception, one for body-parts and another for objects. Body size overestimation has been consistently linked to Anorexia Nervosa (Brown et al., 2021; Hagman et al., 2015; Keizer & Engel, 2022), being established as a clinical symptom of the disorder, in its onset, maintenance and relapse (Ambrosecchia et al., 2023). New evidence suggests that individuals with Anorexia Nervosa (AN) experience their body as an object (Scarpina et al., 2022), in which case it may help explain why the decrease of body weight may not be perceived by AN individuals, only its increase. The size-weight illusion is diminished in individuals with this disorder (Case et al., 2012), indicating a difference in how their brains dynamically compute the size and weight of objects. Investigating how individuals with anorexia and other eating disorders experience the bodily size-weight illusion, as presented in this study, can deepen our understanding of these disorders and their connection to bodily distortions.

There are fundamental differences in the way we experience the weight of a body part with a weight that is hung on the wrist. On Earth's gravity, to just hold our hand we have to use our tendons and muscles to support it, unless it is rested on an object. When suspending our hand from the wrist, the radius and ulna forearm bones, along with the forearm tendons and ligaments support the hand in a more distributed way than when holding a hanged weight on the wrist. This limitation is part of a broader set of challenges present in perception studies of body parts, as we do not experience a hand or a leg separately from the whole body.

Our results support body part weight as a flexible feature in the representation of our body. While flexible, the perceived weight of body parts is consistently subtracted from conscious experience, shown in the consistent underestimation of hand weight across conditions. However, its magnitude is changed when embodying a larger and a smaller hand. A larger hand is felt to be heavier, and a smaller hand, lighter. This is remarkably different from the way we perceive object weight, since we perceive the larger object as lighter, when holding two objects of the same weight and different size. We proposed the constant density model to explain the relationship between bodily size and bodily weight, in which density is maintained constant upon changes of hand size. If the density of the hand is the same, meaning it is felt to be composed of the same physical properties as the normal size hand, then a larger hand is felt to be heavier, as there is more of the same hand material. It is relevant to establish a model of the representation of body part weight for the integration of prosthetics in the body, and improve its usability and embodiment. It is also important to understand how alterations of body size change perceived weight, in the research of eating disorders and obesity, by understanding how perceived size impacts on perceived weight and how that relationship is working when the flexibility of body perception is maladaptive. The hypothesis that we maintain a constant density in the updating of perceived weight when perceived size is changed, offers a model to explain the physics of bodily perception. Here we show how the perception of size, weight and density interact to compute a coherent representation of the hand.

CRediT authorship contribution statement

Denise Cadete: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Vincenzo P. Marino:** Methodology, Formal analysis, Data curation. **Elisa R. Ferrè:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Matthew R. Longo:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization.

Data availability

Anonymous raw data OSF link: https://osf.io/qa4w9/?view_only=4807cc82847e454bb4920af95d938537.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2024.105998.

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