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Research Report

Distortions of perceived volume and length of body parts

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ARTICLE INFO

Article history:
Received 20 May 2018
Reviewed 18 July 2018
Revised 14 August 2018
Accepted 13 October 2018
Published online 1 November 2018

Keywords:
Body image
3D body
Body size perception
Body proportions
Surface area to volume ratio

ABSTRACT

We experience our body as a 3D, volumetric object in the world. Measures of our conscious body image, in contrast, have investigated the perception of body size along one or two dimensions at a time. There is, thus, a discrepancy between existing methods for measuring body image and our subjective experience of having 3D body. Here we assessed in a sample of healthy adults the perception of body size in terms of its 1D length and 3D volume. Participants were randomly assigned to two groups using different measuring units (other body part and non-body object). They estimated how many units would fit in a perceived size of body segments and the whole body. The patterns of length and volume misperception across judged segments were determined as their perceived size proportional to their actual size. The pattern of volume misperception paints the representation of 3D body proportions resembling those of a somatosensory homunculus. The body parts with a smaller actual surface area relative to their volume were underestimated more. There was a tendency for body parts underestimated in volume to be overestimated in length. Perceived body proportions thus changed as a function of judgement type while showing a similarity in magnitude of the absolute estimation error, be it an underestimation of volume or overestimation of length. The main contribution of this study is assessing the body image as a 3D body representation, and thus extending beyond the conventional 'allocentric' focus to include the body on the inside. Our findings highlight the value of studying the perceptual distortions "at the baseline", i.e., in healthy population, so as to advance the understanding of the nature of perceptual distortions in clinical conditions.

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https://doi.org/10.1016/j.cortex.2018.10.016

1. Introduction

Distortions of the body image are central to several serious diseases, including eating disorders (Cash & Deagle, 1997) and body dysmorphic disorder (Phillips, Didie, Feusner, & Wilhelm, 2008). Indeed, since the seminal work of Bruch (1978) perceptual distortions of body image have been considered central to the aetiology of anorexia nervosa. Conversely, the body image in healthy individuals was assumed to be highly accurate—if not infallible, and as such it was used as a standard in early studies to interpret body size misperceptions, e.g., in anorexic or obese patients (Bell, Kirkpatrick, & Rinn, 1986). Calling this assumption into question, recent evidence showed systematic distortions of body representation in healthy cognition. The understanding of these neurotypical distortions may shed more light on the perceptual distortions in clinical conditions (Longo, 2015, 2017). One particularly interesting recent finding was that the body image distortions in healthy individuals appear to be linked to homuncular distortions in primary somatosensory cortex (SI) (Linkenauger et al., 2015; Longo & Haggard, 2012). Here we aimed to replicate these observations, and to address an important limitation of this research and of the work on perceptual body image in general. Traditional methods of body size perception in patients and healthy individuals alike come short of assessing our experience of having a 3D volumetric body of a certain size. We addressed this limitation by investigating the representation of body volume in healthy cognition. Analogous to the functional role of cortical magnification in SI, we also set out to investigate if body part's surface area relative to its volume (SA/VO), i.e., the proportion of its 3D size at interface with the outer world, predicted the perception of volumetric size.

A large literature going back several decades has investigated perceptual body size estimation, largely in the context of eating disorders such as anorexia and obesity. A number of paradigms for body size estimation have been developed, which Longo and Haggard (2012) grouped into two broad families. *Depictive* methods involve comparing the experience of one's own body with a visual image of a body, and include tasks such as the distorting mirror (Traub & Orbach, 1964), the distorted photograph technique (Glucksman & Hirsch, 1969), video distortion (Probst, Vandereycken, Van Coppenolle, & Pieters, 1998), and template matching (Gandevia & Phegan, 1999). *Metric* methods, in contrast, involve comparing the experienced size of one's own body to a physical length, and include tasks such as the moving caliper (Slade & Russell, 1973), the image marking procedure (Askevold, 1975), and the adjustable light beam apparatus (Thompson & Spana, 1988). Depictive methods thus involve comparing our body to a 2D image, while metric methods involve comparing our body to a 1D standard. The body size is not assessed in all three dimensions when judged with reference to 2D images (Benson, Emery, Cohen-Tovée, & Tovée, 1999; Cafri & Thompson, 2004; Gandevia & Phegan, 1999; Traub & Orbach, 1964; Walsh, Hoad, Rothwell, Gandevia, & Haggard, 2015). Similarly, metric methods come short of assessing the 3D body size given their focus on one dimension at a time, e.g., in width or length judgements (Linkenauger et al., 2015, 2017; Longo & Haggard, 2012; Reitman & Cleveland, 1964; Slade, 1985), or circumference judgements (Horne, Van Vactor, & Emerson, 1991; Mölbert et al., 2016; Salbach, Klinkowski, Pfeiffer, Lehmkuhl, & Korte, 2007; Schneider, Frieler, Pfeiffer, Lehmkuhl, & Salbach-Andrae, 2009).

To our knowledge, no studies have looked into what the mental image of our 3D body is like and how it may deviate from the actual 3D body form. This may seem surprising given our experience of having 3D bodies; however, the reasons become clear once the importance of the visual component in body size assessment is considered. Indeed, the term 'body *image*' itself suggests predominantly visual representation of a conscious body shape and size, akin to a 2D photograph of what we look like and how other people see us in a manner not dissimilar from other visual objects in the environment. In addition to our ability to assess it as if viewed from the outside, the body is however also perceived 'from the inside'. This internal access, clearly unavailable for other objects, comes with additional sources of information including touch, proprioception, and interoception. Although these senses may not appear as informative as vision in perceptual assessment of body size, recent research has validated their relevance. For instance, Longo and Haggard (2012) reported a dissociation between depictive and metric methods in judgements of hand size, with the metric measurements showing distortions qualitatively similar to those of a somatosensory representation (Longo, 2017; Longo & Haggard, 2012), while the performance was nearly veridical in the visual template-matching task. They suggested that the metric assessment did not involve the visual body representations alone but some weighted combination of the visual and (distorted) somatosensory body representations.

In another study, Linkenauger et al. (2015) asked participants to judge the length of body segments or of the whole body in units of the length of other body part (e.g., hand) or a non-body object (dowel). This assessment involved estimating how many measuring units would fit in a size of a judged body segment, or, to put it differently, by how much the body segment differed in size relative to the measuring unit. Linkenauger et al. (2015) found a robust pattern of length mis-estimation, which suggested that some body parts such as torso and arms were misperceived as longer more than others like the head and leg for instance. Notably, for judgements in body units, the pattern of misperception was predicted by the segment's actual size and tactile spatial sensitivity. Body parts which are underrepresented in primary somatosensory cortex (SI), i.e., showing reduced tactile spatial sensitivity (Mancini et al., 2014; Weinstein, 1968), were more overestimated in length, particularly if they were small in their actual size. Based on these findings, the authors developed a 'reverse distortion' theory whereby the distortions of body image were of compensatory nature to those of the distorted somatosensory maps (Penfield & Boldrey, 1937; Penfield & Rasmussen, 1950), alleviating thus the negative impact of the latter on somatoperception.

In this study, we aimed to fill the gap in existing body image literature, by assessing the experience of our body in terms of a perceived volume of 3D space contained by the skin on the body surface. We adapted the paradigm developed by Linkenauger et al. (2015; 2017) by asking participants, in addition to their length estimates, for judgements of the volume of body segments in units of a volume of their hand (body units) or an object (non-body units). An important novel aspect of this study therefore is the inclusion of the inside of the body, i.e., body's volumetric substance, rather than just its superficial exterior. Judging, for instance, how many volumes of a finger fit in a volume of the foot, may require partitioning in one's mind the volume of the foot into smaller parts, and thus a mental image of the volumetric body. To put it another way, these judgements are expected to extend the typical allocentric assessment of perceived body dimensions common in the body image literature, by probing the representation of 3D space that our bodies occupy. This has implications for relating the somatosensory body representation and body image the way Linkenauger et al. (2015) did. While the body in SI is two-dimensional, reflecting the two-dimensionality of the skin, the body volume is unlikely to be represented in SI since it is given by the volume of a musculo-skeletal body structure, its internal organs, and other tissue and liquids. The actual surface area is not linearly related to volume across body segments (Tikuisis, Meunier, & Jubenville, 2001) due to differences in their 3D *shape and size*. Mathematically, a sphere (e.g., the head) would have a smaller surface area than a truncated cone (e.g., the forearm) even if their volume was identical, and the increase in surface area relative to volume with an increasing object size is a power function (Schmidt-Nielsen, 1984).

The literature, however, suggests that the body image is related to both, the somatosensory representation and the awareness of interoceptive sensations from within the body. A recent review of the literature implicates the sensations generated by internal organs in a formation of body image (Badoud & Tsakiris, 2017). Intriguingly, it has been reported that patients with eating disorders show impaired tactile processing (Keizer et al., 2011; Keizer, Smeets, Dijkerman, van Elburg, & Postma, 2012) as well as reduced interoceptive awareness (Pollatos et al., 2008; Santel, Baving, Krauel, Münte, & Rotte, 2006). Notably, in healthy individuals, interoceptive sensations tend to reach conscious awareness less than signals from senses used to interact with the environment, including those from the skin on body surface. At a smaller scale, there are differences across body parts with regards to the size of their surface area relative to how volumetric they are (Tikuisis et al., 2001), which would imply differences in terms of a *conscious* accessibility of bodily information. The advances in body image research discussed so far suggest that alongside with vision this general access to tactile and interoceptive information may play important role in the assessment of body size. We therefore hypothesised that some body parts will be judged more accurately in volume than others, as is the case for their length estimation (Linkenauger et al., 2015; 2017), and that the less reliable volume estimates would be observed for body parts with smaller surface area relative to their volume.

2. Method

2.1. *Participants*

Forty individuals were randomly assigned to either the *Object Standard* group (8 females/12 males, Mean age ± SD: 32.75 ± 9.78 years) or the *Hand Standard* group (10 females, 10 males, 28.41 ± 5.79 years). Mean ± SD of body mass index was 23.95 ± 4.24. Participants in both groups were predominantly right handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971; Mean ± SD: 89.1 ± 34.4 in the *Object Standard* group and 85.8 ± 33.1 in the *Hand Standard* group). All procedures were approved by the Department of Psychological Sciences Research Ethics Committee at Birkbeck, University of London.

The average effect size (η_p^2) for differences in *length* estimation across body parts in previous studies was .3 (Linkenauger's et al., 2015). A sample of 14 participants, as determined in a G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007), would be large enough for this effect to be detected with a power of .95 at alpha level .05. Given that the perception of body volume has not yet been investigated, we determined the sample size for a small effect ($\eta_p^2 = .1$), using the same alpha level and power parameters. Our analysis shows that a sample of forty participants, in a repeated-measures design with two groups and six body parts to estimate, would be appropriately powered to find an effect of this magnitude.

2.2. *Stimuli, design and procedure*

The experiment began by measuring the length and volume of the participant's right hand and foot while they were blindfolded. The lengths were measured with a ruler while the body part rested flat on a sheet of a foamboard. Participants were seated and they did not wear shoes or garments on the measured body part (e.g., gloves, socks). The volume of each body part was measured using the water displacement method (WDM). The proximal boundary of the hand was the centre of the ulnar styloid process, which was marked with a pen. The proximal boundary of the foot was the centre of the lateral malleolus, which was also marked. Each body part was immersed in cool water (~10° Celsius). We recorded the weight of the water displaced by each body part using a scale (AMPUT APTP457A 7500 g, Shenzhen Amput Electronic Technology Co. Ltd). According to Archimedes principle, the volume of displaced water equals the volume of the immersed object. The downward force produced by this displacement is equal to the weight of the water displaced, regardless of the weight of the object doing the displacement. Given the known density of water (1 g/cm^3), the change in weight on the scale can be used to measure the volume of the displaced water, and therefore the volume of the measured body part.

We used the obtained estimates of hand length and volume to select objects to use as measuring units (*Object Standard* group), or items in the size judgement task (*Hand Standard* group). The exact volume and length of the measuring units were recorded. For length judgements, we used sticks cut out of a foamboard matched to the length of the participant's hand from the ulnar styloid process to the tip of the middle finger. For volume judgements, we selected seven books and wrapped them in a beige paper to eliminate extraneous visual features and reduce distraction (Mean volume: 415.06 cm^3, SD: 129.73). The books were selected to visually match the size of an average hand in depth and width/length ratio. The exact dimension correspondence was of course not possible since it would have inflated the object volume, inflating thus the size of a measuring unit in *Object Standard* group relative to the *Hand Standard* group. We therefore focused our efforts on matching the hand and object for each participant in volume first and foremost, and we added catch trials (cf. below) to understand the impact of other differences between the measuring units. Each book and item matched the participant's actual hand volume as closely as possible. We calculated for each participant the % of how the book deviated in volume from their hand (*M*: 97.85%, SD: 10.23). The participants in the *Object Standard* group used what they perceived to be the volume of a beige cuboid object and length of a stick as measuring units in their body estimates. Those in the *Hand Standard* group used a perceived volume of their right hand and its length from the centre of the wrist to the tip of the middle finger.

Participants were seated at a table facing the wall. They wore a black smock which prevented them from seeing their body. The experimenter sat behind them, out of their field of view. The instructions were to visualize their body in an upright posture with outstretched arms in order to judge the volume and length of different body parts. The judged body parts and how they were described to participants are given in Table 1. The region boundaries were explained in plain, non-technical language with an emphasis on clarity. Apart from the leg (crotch to ankle) and arm (excluding the hand), body part boundaries were identical to those used by Linkenauger et al. (2015). Each trial consisted of read-out instructions followed by a verbal response which was recorded by the experimenter. Participants made estimates of the perceived length or volume of each body part by estimating how many multiples of the measuring unit (i.e., their hand or the object) would fit in the length or volume of each part of their own body. The measuring unit was in the participant's full view throughout the experiment. Participants made unspeeded responses and they were instructed to respond as accurately as possible and to use fractions and decimal places.

The impact of different measuring units was assessed through catch trials, in which participants in the *Hand Standard* group judged the object (i.e., the book volumes or the stick lengths) while the participants in the *Object Standard* group made judgements of their hand. For the former, the object on a far-end of a 20×50 cm foamboard tray was placed on a table next to the participant, to their right. The participant had a full view of the object which was removed after the judgement was made. The correct answers for catch trials were 1, giving the accuracy ratio of 1, since the measuring unit and the judged item were matched in size. The number of catch trials in the block was the same as number of trials for individual body parts. The catch trial analysis is separate from the main analysis.

Each participant completed four blocks, two involving judgments of length and two involving judgments of volume. The blocks were counterbalanced in an ABBA fashion, with the initial condition counterbalanced across participants. Each block consisted of six repetitions of each of the six body parts and a catch trial item in random order, for forty-two trials in total.

2.3. *Estimation of actual body-part volume and length*

In the post-testing phase, we recorded the actual volume and length of the judged body parts. Together with 3D body scanning (Robinette, 2000; Tikuisis et al., 2001), water displacement is the most reliable way of estimating the volume of an object, and it is the gold standard in cadaver studies which have estimated the volume of different body parts (Clauser, McConville, & Young, 1969; Dempster & Gaughran, 1967). Without specialized water tanks, the WDM poses obvious difficulties when used with living people. Extremities like the hand and foot are straightforward to measure using water displacement, but more proximal body parts are less feasible. The data available from cadaver studies report the average volume of individual body parts and their ratios to total body volume. Although they are useful approximations, they are often limited to a particular demographic. The

Table 1 – Judged object boundaries. Participants visualized themselves standing upright with outstretched arms to make judgements of volume and length of body parts using either a non-body object (*Object Standard* group) or the right hand (*Hand Standard* group) as measuring units. The body part boundaries were explained in plain language to ensure participants' understanding. The anatomical terms are presented for comparison with anthropometric literature.

Judged object	Instructions (*anatomical definition*)	
	Volume	Length or height
1. right foot	From the ankle down (*girth of the lateral malleolus*)	Heel to toe (*tip of the longest toe to the end of the calcaneus*)
2. head	From the top of the neck up (*uppermost girth around the neck below the mandible*)	Chin to the top of the head (*mandible to the top of the head*)
3. right arm	Shoulder bone to wrist (*Acromion to ulnar styloid process*)	Shoulder bone to wrist (*Acromion to ulnar styloid process*)
4. right leg	Crotch to ankle (*gluteal fold to lateral malleolus*)	Crotch to ankle (*gluteal fold to lateral malleolus*)
5. torso	Shoulder bone to the top of pelvis (*Acromion to iliac crest*)	Shoulder bone to the top of the pelvis (*Acromion to iliac crest*)
6. body	Whole body	Body height

alternative methods in the literature include the multi-viewpoint photography (McConville, Churchill, Kaleps, Clauser, & Cuzzi, 1980), use of plaster moulds (Schneider, Robbins, Pflug, & Snyder, 1983), and geometric shape approximation (Katch & Weltman, 1975).

We estimated the volume of the right hand and foot using the WDM. The volume of the body was computed as a ratio of the participant's weight and body density of 1.003 g/cm^3 (Table 7 in Dempster & Gaughran, 1967), as determined in cadaver studies. We approximated the arm and leg to two truncated cones each, the head to a sphere, and the torso to a cylinder with an oval base. The measurements of the participant's body were recorded as detailed in Fig. 1. The volume formulas for truncated cones and sphere were used by Katch and Weltman (1975). The calculations required circumferences at the two bases and height of the cones. The volumes of individual cones were summed for a final body part estimate. A circumference of the head was used to compute the head volume. The volume of the torso was calculated from its height and averages of its three widths (major axis) and breadths (minor axis) at the level of chest, waist and pelvic bone.

We also computed the volume for the body parts proportional to the total body volume using cadaver data. These values, averaged across participants (Fig. 1, column 6), were then compared to anthropometric estimates. Clauser et al. (1969) and Dempster and Gaughran (1967) together provide an overview of anthropometric evidence from seven US-based studies using cadavers. Fig. 1 (column 7) presents the anthropometric data averaged across these studies. Our data for hand and foot which were also estimated with WDM, and for the arm, are nearly identical with the anthropometric evidence. Some deviation observed for the remaining body parts may be due to factors including the use of simplified geometric shapes, demographic differences, but also discrepancies in segment boundary across studies (we report the neck and pelvic region excluded from head and torso estimates, respectively).

Fig. 1 shows a summary of approximations to geometric shapes, the measurements, and mathematical formulas. A tape measure was held flat against the body to record the circumference of any given body part. The participants could wear their clothes but they would take off extra layers for better measurement accuracy. We subtracted 1 cm when appropriate due to a thick layer of clothing (e.g., jeans). A maximum girth around head, at temporal bones in the horizontal plane, was used in head volume computation. The arm and leg were approximated to two truncated cones each, separated at the elbow and knee. The circumferences were recorded for each truncated cone. The length (height) of body segments as specified in Fig. 1 (column 3) was marked with an erasable pencil with participants standing upright with their back against the wall. The widths of torso were marked at the level of chest, waist and pelvis while participants stood against the wall with their back and right side (Fig. 1). An empty box aligned with the body part was placed perpendicularly to the wall to ease the marking of round body parts. The distance between each pair of markings was recorded.

Judged object	Length (height) and volume computation				
	Shape approximation	Measurements	Formulas	Body part / total body volume: our data	Body part / total body volume: literature
1. right foot	n/a	weight of displaced water	$\frac{\text{weight of displaced water}}{\text{water density}}$	1.23 %	1.56 %
2. head	sphere	head circumference and height	$4.188\,(\frac{\text{head circumference}}{2\pi})^3$	4.98 %	7.70 % (Neck often incl.)
3. right arm (excl. hand)	truncated cones (1 and 2)	2 circumferences per cone (a1, b1, and a2, b2) length of each cone (length 1, length 2)	$\frac{\text{length}(1)}{12\pi}(a1^2 + b1^2 + a1 * b1) + \frac{\text{length}(2)}{12\pi}(a2^2 + b2^2 + a2 * b2)$	4.12 %	4.50 %
4. right leg (excl. foot)	truncated cones (3 and 4)	2 circumferences per cone (a3, b3, and a4, b4) length of each cone (length 3, length 4)	$\frac{\text{length}(3)}{12\pi}(a3^2 + b3^2 + a3 * b3) + \frac{\text{length}(4)}{12\pi}(a4^2 + b4^2 + a4 * b4)$	17.70 %	14.62 %
5. torso	oval cylinder	3 widths at major axis (average = ma) 3 widths at minor axis (average = mi) torso height	$\left(\frac{\text{torso height} * \pi}{4}\right) * mi^2 + \text{torso height} * mi(ma - mi)$	40.02 %	47.46 %
6. body	n/a	body weight	$\frac{\text{body weight}}{\text{body density}}$	100.00 %	100.00 %

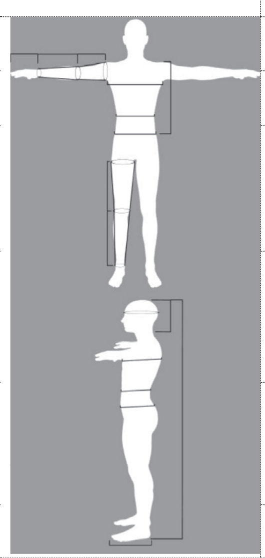

Fig. 1 — The actual length and volume of judged objects. The body segment boundaries were marked on the wall allowing for one-dimensional length (height) measurements. All circumferences were measured with a tape measure flat on the body. Three methods were used to compute the volume of body segments: WDM (hand and foot), weight to volume conversion (whole body), and geometry (arm, leg, head, torso). The arm and leg were each approximated to two truncated cones separated at the elbow and knee. The head and torso were approximated to a sphere and cylinder with an oval base, respectively. The last two columns show the segment volumes proportional to the volume of whole body in this experiment (column 6) and as reported in the anthropometric literature (column 7).

2.4. Data analysis

We computed ratios of judged and actual volume and length estimates to determine the judgement accuracy. Thus, values greater than 1 indicate overestimation, and values less than 1 indicate underestimation. The judged estimates were obtained by multiplying each judgement by the size of corresponding measuring unit. One of our objectives was a replication of the study by Linkenauger et al. (2015) which reported patterns of length misperception (overestimation) across six body parts. As in the original study, we used the hand and object (stick) measuring units and we analysed the length accuracy ratios in a 6-by-2 ANOVA. Our main interest, however, was in accuracy of volumetric size perception across body parts in hand and object (book) units, which was tested in a 6-by-2 ANOVA on volume accuracy ratios. We then report the analyses for the catch trials, in which the size of a judged item corresponds with the size of the measuring unit. Finally, we tested how well our predictor variables explained patterns of length and volume misperception (accuracy ratios). The influence of somatosensory representation was tested for 1D length estimates as in the original study by Linkeauger and colleagues (2015). Our predictor for volume judgements was the SA/VO – i.e., the ratio of body part surface area and its volumetric size. Our predictors relate to the role of body parts in external signal processing. The somatosensory homuncular distortions serve a functional role by enhancing skin sensitivity at regions required to read tactile signals most accurately, and the SA/VO indexes the proportion of 3D body size at interface with the external world.

To identify potential outlier data, we calculated z-scores for each trial in subsets of accuracy ratios grouped for each participant by the judgement type and judged object. Trials with z-scores greater than ±3 were excluded as outliers (.36%). To identify potential outlier participants, Cook's distance scores were calculated with an averaged accuracy ratio per participant and compared to a cut-off value of .1 (4/sample size; Bollen & Jackman, 1985). On this basis, one participant from a group using the hand measuring unit with a Cook's distance value .56 was excluded from the analysis. The type III sums of squares method which weighs group means equally in unbalanced designs was used in all ANOVAs (Keppel & Wickens, 2004). Apart from foot length judgements (Levene's test $p = .03$), the test assumption of homogeneous variances was not violated.

The Holm-Bonferroni correction (HB-corr) was used to correct for multiple comparisons. The corrected p values are reported for all post-hoc tests.

3. Results

3.1. Length judgments

In order to replicate the analyses of Linkenauger et al. (2015), we initially assessed the accuracy ratios for length judgements alone. We conducted an ANOVA with the judged body part (foot, head, arm, leg, torso, body) as a within-subject factor and measuring unit (hand, object) as a between-subjects factor. The response bias differed across judged body parts, $F(1.95,71.96) = 26.69$, $p < .001$ (GG-corr), $\eta_p^2 = .42$, following the pattern reported by Linkenauger et al. (2015). The post-hoc t-tests in Table 2 report that the torso is misperceived as longer the most, followed by the arm and body height, leg and head, and finally the foot.

As per previous findings, the participants who used their hand as a measuring unit gave larger responses than those who used an object, $F(1,37) = 8.96$, $p = .01$, $\eta_p^2 = .20$. We also found a trend for interaction (Fig. 2), $F(1.95,71.96) = 3.15$, $p = .05$, $\eta_p^2 = .08$ (GG-corr). It was driven by larger overestimations with hand measuring unit relative to those in object units for the torso, $t(37) = 2.82$, $p = .03$, $d_z = .63$, arm, $t(1,37) = 3.23$, $p = .02$, $d_z = .72$, and leg, $t(37) = 3.17$, $p = .02$, $d_z = .71$, but not the foot, head and body height ($p > .05$; HB-corr). Taken together, these results provide a clear replication of the main findings of Linkenauger et al. (2015).

3.2. Volume judgments

Next, we ran an ANOVA on volume estimates identical to the one used above for length estimates. In contrast to length estimates, the overall response bias for volume judgements was not modulated by the unit of measurement, $F(1,37) = 2.84$, $p = .10$, $\eta_p^2 = .08$, nor was there an interaction between body part and measuring unit (Fig. 3), $F(2.88,106.38) = .94$, $p = .42$, $\eta_p^2 = .03$ (GG-corr). There was, however, a clear pattern of differential judgments across body parts, $F(2.88,106.38) = 28.02$, $p < .001$, $\eta_p^2 = .43$ (GG-corr). Critically, however, this pattern (Table 3) was different from the pattern observed for length judgements. The volume of the torso was *underestimated* the most, more than the volume of the whole body and leg. The whole body and leg volume underestimation was greater than that observed for the head, foot, and arm.

Table 2 – The differences in length overestimation across body parts. The post-hoc *t*-tests for main effect of body part were conducted based on the overestimation pattern across body parts shown in Fig. 2. The largest overestimation for torso was compared against the second and third largest overestimation for the whole body and arm, which were then compared to each other. The data for each, the arm and whole body, were then compared to the data for head and leg, which followed in magnitude of overestimation error. The final three comparisons were of the head and leg, and of them each to the foot. The results confirm the largest overestimation for the torso, followed by the arm and body height, leg and head, and finally the foot.

Comparisons	Statistics[a]
Torso and body height	$t(38) = 6.54$, $p < .001$, $d_z = 1.05$
Torso and arm	$t(38) = 3.61$, $p = .004$, $d_z = .58$
Arm and body height	$t(38) = .54$, $p = .59$, $d_z = .09$
Arm and leg	$t(38) = 5.37$, $p < .001$, $d_z = .86$
Body height and leg	$t(38) = 2.65$, $p = .04$, $d_z = .42$
Arm and head	$t(38) = 4.38$, $p < .001$, $d_z = .70$
Body height and head	$t(38) = 4.45$, $p < .001$, $d_z = .71$
Head and leg	$t(38) = .40$, $p = .69$, $d_z = .06$
Leg and foot	$t(38) = 3.11$, $p = .01$, $d_z = .50$
Head and foot	$t(38) = 3.72$, $p = .004$, $d_z = .60$

[a] Holm-Bonferroni corrected p values are reported.

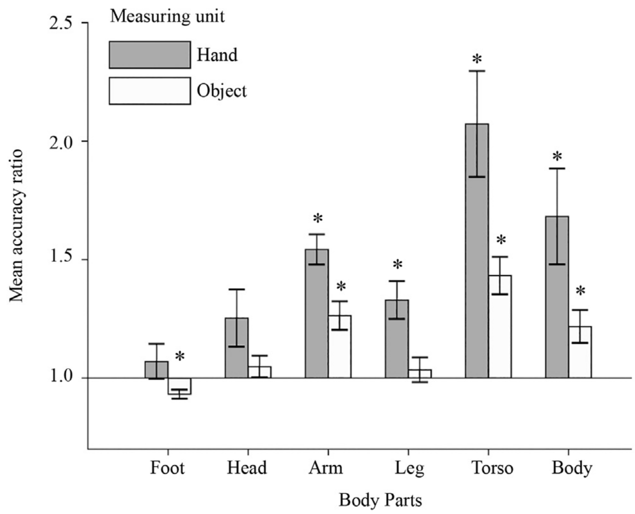

Fig. 2 – The accuracy ratios for body length estimates in hand and object measuring units. The plot shows a pattern of estimation error across body parts. The overestimation and underestimation bias is indicated by values > 1 and < 1, respectively. Error bars are ±1 SEM. The biases larger than 1, as determined by one-sample t tests using a Holm-Bonferroni correction for multiple comparison error, are marked by asterisks.

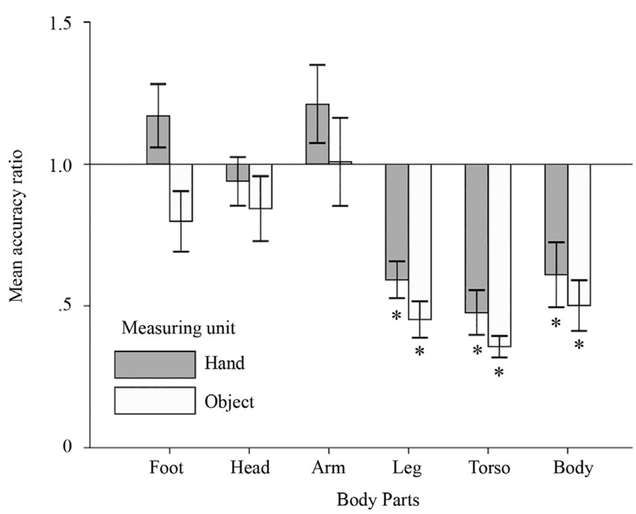

Fig. 3 – The accuracy ratios for body volume estimates in hand and object units. The plot shows a pattern of estimation error across body parts. The overestimation and underestimation bias is indicated by values > 1 and < 1, respectively. Error bars are ±1 SEM. The biases marked by asterisks deviate from the mean = 1, as determined by one-sample t tests using a Holm-Bonferroni correction for multiple comparison error.

3.3. *Measuring unit estimates (catch trials)*

In addition to body estimates, we presented catch trials in which the participants estimated the size of the other measuring unit. Thus, those judging in hand units would estimate the volume and length of objects which would have been their measuring unit if they were in the other group. Similarly, the *Object Standard* group judged their hand size in object units. As previously discussed, since the objects were selected to match the hand size as closely as possible the correct answers and the accuracy ratios for catch trials in both groups should be 1. The analysis shows that the length of sized-matched object (sticks) was overestimated in hand units, $t(18) = 4.54$, $p < .001$, $d_z = 1.04$, while the estimates of the hand length in object units did not deviate from veridicality, $t(19) = .82$, $p = .42$, $d_z = .18$. Similarly, the perceived volume of the size-matched object was overestimated in hand units, $t(18) = 5.55$, $p < .001$, $d_z = 1.27$, while the estimates of the hand volume in object units again did not deviate from veridicality, $t(19) = 1.17$, $p = .26$, $d_z = .26$ (HB-corr).

The measuring unit was in full view throughout the experiment. All accuracy ratios for size estimates in hand units, including those of a non-body object, were larger than accuracy ratios for estimates in object units. Nevertheless, a general underestimation of hand size can be ruled out, given the findings for hand size judgements in object units. One possible interpretation may be that the hand size is perceived differently, i.e., as smaller, when the hand is directly viewed compared to when it is covered by a cloak with other judged body parts The reason for that may be that the length of a *viewed* hand may be perceptually 'shrank' relative to its width, which is greater than the width of a stick-object in the *Object Standard* group. Similarly, the hand view may lead to a recalibration of perceived volume by a reduction, as it highlights the shape discontinuities in gaps between the fingers.

Table 3 – The differences in volume misperception across body parts. The post-hoc t-tests for main effect of body part were conducted based on the accuracy ratio pattern across body parts shown in Fig. 3. The comparison of volume accuracy ratios collapsed across measuring units confirmed the largest underestimation for the torso, followed by the leg and whole body, and finally by the head, foot and arm.

Comparisons	Statistics[a]
Torso and whole body	$t(38) = 3.51$, $p = .01$, $d_z = .56$
Torso and leg	$t(38) = 3.43$, $p = .01$, $d_z = .55$
Leg and whole body	$t(38) = .73$, $p = .62$, $d_z = .12$
Leg and head	$t(38) = 7.67$, $p < .001$, $d_z = 1.23$
Whole body and head	$t(38) = 4.97$, $p < .001$, $d_z = .80$
Head and arm	$t(38) = 2.46$, $p = .07$, $d_z = .39$
Head and foot	$t(38) = 1.03$, $p = .86$, $d_z = .16$
Arm and foot	$t(38) = 1.08$, $p = .86$, $d_z = .17$

[a] Holm-Bonferroni corrected *p* values are reported.

3.4. *Inverse distortion model of tactile size constancy*

In their original study, Linkenauger et al. (2015) found that the skin sensitivity alone (predictor 1) comes short of predicting the pattern of length overestimation across body parts; however, it interacts with body part's actual size (predictor 2). That is, body parts which are less represented in somatosensory cortex tend to be mis-judged as longer but this misjudgement is scaled down by body part's actual size. Those body parts which are already long will be less elongated perceptually.

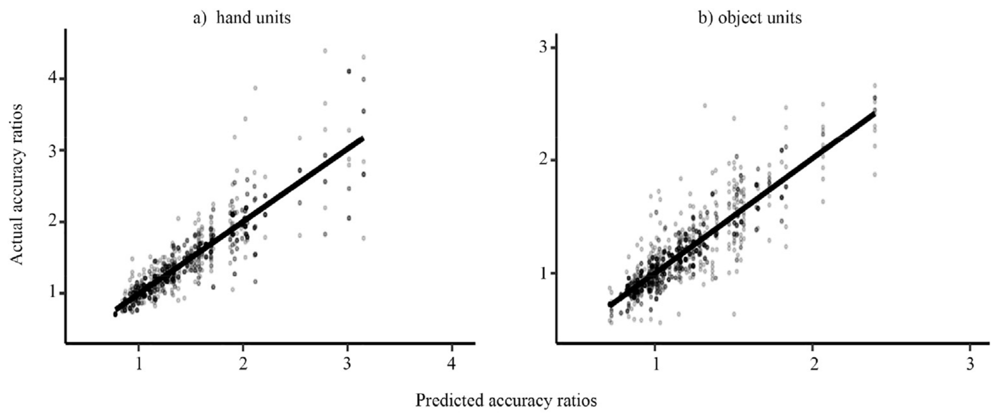

Fig. 4 – Length overestimation as a function of the overestimation predicted by a product of relative sensitivity and physical size. The judgements in hand and object units are shown respectively in panel a and b. Note a larger scale in (a) due to larger response variability. The black line is the regression line. The data is not averaged across trials, i.e., the scatter plots show *all* recorded observations. Darker circles reflect higher concentration of the values. This is a replication of previous findings (cf. Linkenauger et al., 2015, Fig. 6).

Linkenauger et al. (2015) also reported that the actual body part length alone (predictor 3) did not explain the pattern in length overestimation across body parts. The authors went on to introduce the inverse distortion model (Linkenauger et al., 2015) positing that the influence of somatosensory homuncular distortions may be counteracted by the distortions of the explicit body image. They reported their findings to be constrained to the *relative* body size judgements, i.e., not the judgements in object units.

To test the theory with our data, we used the tactile spatial sensitivity measurements from the whole-body mapping study by Weinstein (1968), which comprises the data of 48 subjects (24 males and 24 females). We obtained the composite sensitivity measure for each body part as an average across individual location measurements (e.g., leg: mean acuity for calf and thigh). The predictors were calculated following the procedures of Linkenauger et al. (2015). The acuity predictor was computed as the sensitivity of each body part powered by negative hand sensitivity or −1 for judgements in object units. The second predictor was a product of the acuity predictor and the proportional body part and measuring unit length. The body height overestimations were not included given the large tactile spatial variability across individual body parts (Linkenauger et al., 2015). The outcome variable were the raw clean accuracy ratios not averaged across trials.

We used R analysis software (R Core Team, 2012) and lme4 (Bates, Mächler, Bolker, & Walker, 2015) to perform a linear mixed-effects analysis of the relationship between tactile spatial sensitivity and length accuracy ratios. The maximal random effects structure (Barr, Levy, Scheepers, & Tily, 2013) in our design included the random participant and body part intercepts, and by-participant slopes. In a null model, only the random effects were entered ("empty model"; Quené & van den Bergh, 2004). The model improvement after inclusion of the predictor (fixed effect) was tested by assessing the reduction in the residual sum of squares with a Chi-square test. Our results show that the length overestimation in hand units was predicted by the product of tactile spatial sensitivity and body size (Fig. 4a), $X^2(1,N = 19) = 3.95$, $p < .05$. This is a direct replication of the previous findings (Linkenauger et al., 2015; refer to Fig. 6). However, we also found that the product of sensitivity and size reliably predicted the length overestimation in object units (Fig. 4b), $X^2(1,N = 20) = 11.54$, $p < .001$. Thus, rather than being restricted to *relative* body part misperception, the length estimation error in this experiment increases for less sensitive body parts which are smaller regardless of the measuring unit. Consistent with the literature, the acuity alone did not predict the length misperception, $X^2(1,N = 19) = 1.84$, $p = .17$ (hand units), and $X^2(1,N = 20) = 1.33$, $p = .24$ (object units).

3.5. *Body volume perception*

The length misperception was previously linked to tactile spatial acuity (Linkenauger et al., 2015). However, the tactile spatial acuity concerns only the skin on body surface, which is not linearly related to 3D volume of body parts (Tikuisis et al., 2001). Our predictor for volume judgements was the SA/VO – i.e., the ratio of body part surface area and its overall volume. Thus, analogous to a functional role of SI magnification in processing of external tactile signals, we tested how the size of 3D body parts' outer world interface impacted on their perceived volumetric size. We used linear mixed-effects modelling with the random effects structure reported in previous section. A freely available SA/VO (Tikuisis et al., 2001, Table 3) obtained in 3D-scanning was submitted to the analysis as a predictor. The SA/VO for the whole body was not provided and thus it could not be included. The measuring unit groups were collapsed together after removing the baseline difference by subtracting the grand mean from the raw accuracy ratios in each group. As expected, the null model including only the random effects was improved after the inclusion of SA/VO for the volume accuracy ratios, $X^2(1, N = 39) = 4.55$, $p = .03$, and there was a trend for it to improve also for the length accuracy ratios, $X^2(1, N = 39) = 3.14$, $p = .08$ (Fig. 5). The results thus show that the volume is underestimated less with the increasing SA/VO. There is a trend for the length to be overestimated less with the increasing SA/VO.

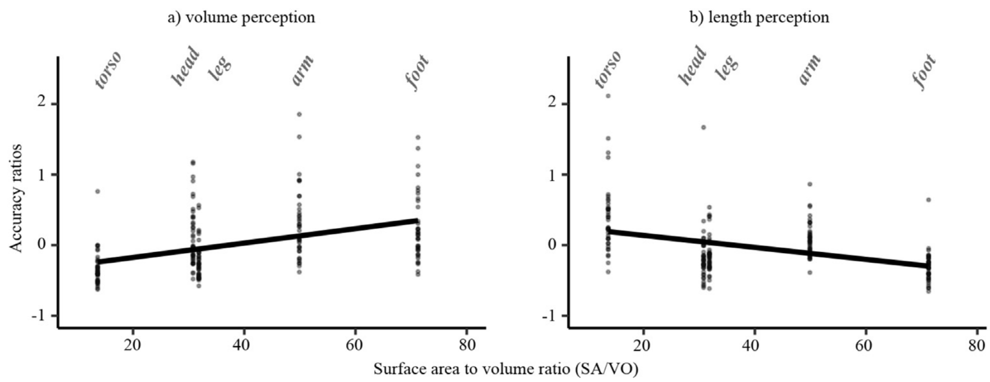

Fig. 5 – The volume (a) and length (b) estimation error predicted by the skin surface to volume ratios. The measuring units are collapsed together after the removal of their baseline difference. The volume underestimation decreases with larger SA/VO (m^2/m^3). There was a trend for the surface to volume ratios to predict the length estimation error. The empty circles at each body part on the x axis represent demeaned accuracy ratios for all participants. Darker circles indicate higher concentration of the values.

The final two linear mixed-effects models assessed how actual body volume and length alone predicted estimation error across all six judged body segments. The baseline difference between the measuring unit groups was again removed, and we used the previously specified random effects structure. The length overestimation was not predicted by the actual body length, $X^2(1,N = 39) = .01$, $p = .92$. Similarly, the volume underestimation was not increased simply due to body parts being more volumetric, $X^2(1,N = 39) = 1.62$, $p = .20$.

4. Discussion

Earlier, we introduced one particularly interesting recent development in the literature, namely that the perceptual distortions of body image in healthy cognition may be linked to classic homuncular distortions in SI (Linkenauger et al., 2015; Longo & Haggard, 2012). Our results replicated the findings of Linkenauger et al. (2015), providing more support for an increased length overestimation of less sensitive body parts (Weinstein, 1968) for which the somatosensory representation is compressed (Green, 1982; Sadibolova, Tamè, Walsh, & Longo, 2018; Weber, 1996). This suggests that the distortions of one representation may balance out those of the other (Linkenauger et al., 2015). Critically, we built on and extended this literature by testing the volumetric size perception (3D body image) and finding a pattern of underestimation across body parts. This underestimation was smaller for body parts with larger SA/VO ratios, i.e., larger interface between the body part and outer world relative to its volume on the inside. Our results add to the evidence suggesting a relationship between the role of body parts in external signal processing and body image. The absolute perceptual errors were in similar magnitude across body parts for both judgement types. Thus, while the actual size did not predict the misperception patterns, the smaller SA/VO was related to a larger volume underestimation, and a trend for a larger length overestimation.

The largest volume underestimation was found for the torso, followed by the leg and whole body, and finally by the head, foot, and arm. In the human body, the distal body parts actively used for interaction with the environment have larger SA/VO, whereas more proximal body parts help maintain the homeostasis and preserve the heat by being less exposed to the outer world on account of their smaller SA/VO (Romanovsky, 2014; Tikuisis et al., 2001). Notably, there is a rough correspondence between SA/VO and tactile spatial acuity, suggesting that the body parts which are more exposed to the environment are also equipped with greater skin sensitivity for interacting with it. The representation of 3D body proportions (panel b) thus shows some resemblance to a classic somatosensory homunculus (Penfield & Boldrey, 1937; Penfield & Rasmussen, 1950). There were no theoretical grounds to use the tactile spatial acuity as a predictor of volume misperception, however, because it only relates to skin on the body surface rather than to the 3D volume itself.

The length of body segments was misperceived as larger. The largest overestimation was found for the torso, followed by the arm and body height, leg and head, and finally the foot (Fig. 6c). Linkenauger et al. (2015) found that the body parts which are less represented in somatosensory cortex are misjudged as longer but this misjudgement is scaled down by body part's actual size. Those body parts which are already long will be perceptually less elongated. Our pattern of 1D length misperception and its relation to a product of actual length and tactile spatial acuity is a direct replication of Linkenauger's et al. (2015) findings. Unlike in their study, however, our effect was not constrained to relative judgements of body parts. Instead, our data in hand units and object units both attest to a relationship between the explicit body image and the implicit somatosensory representation. These findings were previously interpreted as evidence for the 'inverse distortion model' of tactile size constancy (Linkenauger et al., 2015). Given that the early somatosensory maps are distorted (Sur, Merzenich, & Kaas, 1980), the reliability of somatoperception based solely on them would be diminished. The inverse distortion model posits that the negative impact

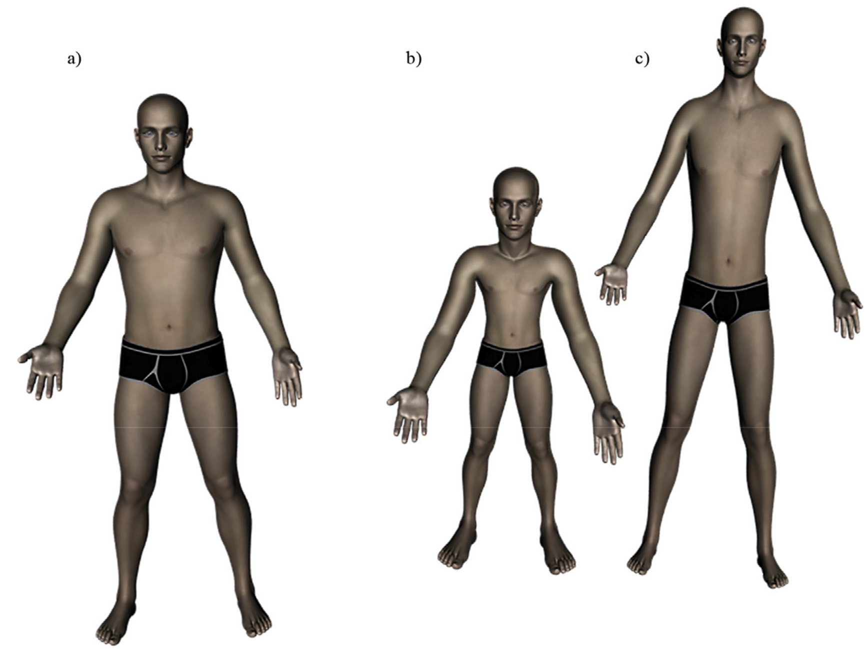

Fig. 6 – Perceptual distortions of body image. Panel (a) shows a body with normal proportions. The representation of 3D body proportions (panel b) show some resemblance to a classic somatosensory homunculus (Penfield & Boldrey, 1937; Penfield & Rasmussen, 1950). The body parts underestimated in volume tend to be overestimated in length, thus giving rise to a tall body shape (panel c). Perceived body proportions change as a function of the judgement type, showing similarity in a magnitude of the absolute error for individual body parts, be it an underestimation of volume or overestimation of length.

of early somatotopy may be alleviated by inversely distorted body image (Linkenauger et al., 2015). As a result, the size of objects touching the skin is judged more accurately (Linkenauger et al., 2015).

Conversely, Longo and Haggard (2012) pointed out a dissociation between the visual template-matching tasks and 1D body size judgements with the latter showing the somatosensory distortions but to a reduced degree. When their participants judged how the lengths of lines on a computer screen compared to the length of each of their fingers, perceptual distortions were observed, which were consistent but smaller than the distortions in their implicit size perception task. However, the performance was nearly veridical in their visual template-matching task. The authors suggested that the 1D size perception was not a pure measure of the body image, which they thought was veridical, but a weighted combination of both the visual and somatosensory representations. Thus, contrary to Linkenauger et al. (2015), Longo and Haggard (2012) assumed a positive relationship between the 1D length misperception and homuncular distortions.

The key to converge these theories may be in understanding how the body surface area is represented at the explicit level. The under-representation of the segment's volumes may be related to us being less aware of body's inside than of its surface. We are indeed much less aware of the interoceptive signals originating from the body, including our musculo-skeletal, gastro-testinal, respiratory, circulatory and hormonal systems (Seth, 2013; Tsakiris & Critchley, 2016), compared to the signals from our exteroceptive senses, including touch on the skin. Therefore, it could be hypothesised that the extent of a surface interface for contact with the world will not be as under-represented in the explicit 3D body image as is the volume. In this scenario, surface area would be overestimated relative to perceived volume across body parts, and increasingly so for those body parts which are more underestimated in volume. The 1D length misperception may reflect this relative body surface overestimation and body inside underestimation. Critically, the body parts with large SA/VO such as hands and feet are the least underestimated in volume and overestimated in length, while those with a small SA/VO like the torso show the largest magnitude of error in both directions. This arrangement could indeed counteract the effect of homuncular distortions, and it would not be detected when testing with sensitive fingers (large SA/VO) as did Longo and Haggard (2012). As such, if corroborated by more empirical evidence, it would expand on and potentially reconcile the two seemingly contradicting theories.

On the other hand, it could be assumed, that the body surface area will be explicitly underestimated akin to pattern of misperception found for the body volume. The 3D body image proportions would then be similar to those of the somatosensory homunculus albeit possibly distorted in a reduced magnitude as suggested by Longo and Haggard's (2012) evidence. In other words, the 3D body image measured by other than pictorial body-matching techniques would roughly be a 3D version of the 2D somatosensory homunculus. The overestimation of 1D length for perceptually shrunken body parts would be difficult to interpret in this scenario. It may be related to largely unexplored dissociations in body perception across different dimensions. For instance, the blockage of incoming signals in anaesthetised finger results in a perceptual enlargement of its width but not its length (Walsh et al., 2015). Similarly, Hashimoto & Iriki (2013) found an activation in two distinct cortical regions when participants made judgements about their body with reference to their photographs from two different viewing angles (front and the side). Finally, Mölbert et al. (2016) reported overestimations for body widths and depths but an underestimation of body circumference. There could be dissociations in body size perception studied in 1D, 2D and 3D space if different aspects of body representation are being probed for each.

Might these results be affected by perceptual illusions? A volume of water in a tall and slim glass for instance will be perceived differently as the same water volume in a short and wide glass. It is important to note that the body parts were not directly viewed, and as the catch trial evidence suggests, the unseen hand was not misperceived in object units while it may have been judged as smaller when viewed directly. Nevertheless, the role of perceptual illusions should be empirically studied and if possible dissociated. A study with non-body objects of similar shape and size is underway to address this concern. Correlations between body size estimation error and visuospatial dysfunctions have been reported (Thompson & Spana, 1991) given that the mental body image requires visuospatial abilities. Thus, similarities in body and non-body perception may be observed. However, differences were found when participants judged themselves as opposed to judging mannequins, which suggests a difference in size perception for *other* bodies or objects (Dolce, Thompson, Register, & Spana, 1987). Given that the volumetric body perception is fairly under-explored, there may be numerous other potentially important factors to address in future studies, such as how the feeling of satiety or the changes in body posture with their corresponding shifts in centre of gravity across body parts may interact with the perception of volumetric body size.

There could be a concern about the study being rather intrusive for a participant whose measurements had to be taken with a tape measure. Future studies may take advantage of a 3D body scanning (Stewart et al., 2012), with the added benefit of recording accurately the actual size of participant's body parts. Another issue that may be raised is the difficulty with mentally adding up more measuring units for large body parts. However, this does not seem to be a concern given that the magnitudes of misperception error were unrelated with actual body size in this experiment. An alternative method for investigating the 3D body size perception might be in virtual environments (Alcañiz et al., 2000). Still, there is an important point to be made. To our knowledge, our study is one of the pioneer studies exploring in healthy adults the representation of their 3D body size. As hinted in the term, the body image would be largely conceived of and studied as a mental image of how the body would be seen from the *outside*. This study has shown that the research may actually benefits from reducing the focus on this rather 'allocentric' photograph-like visual perspective when studying the 3D body perception. Nevertheless, it would be interesting to compare our results to those from a study in the virtual environment where again the emphasis will shift to how the 3D body looks from the outside.

To conclude, one of the main contributions of this study is addressing the body image for the first time as a representation of a 3D volumetric body, and in directing the research enquiry towards the 'body on the inside'. To our knowledge, no prior study assessed the representation of body size and shape in this respect before. Our results showed that healthy individuals tend to underestimate their body parts in volume while overestimating them in length. The patterns of misperception across body parts thus gave rise to proportionally distorted body shapes, that similar to a well-known depiction of a somatosensory homunculus and a tall beanpole, respectively. Our findings add to a growing evidence that healthy adults do not have highly accurate–if not infallible representation of their body size as previously assumed, and that their perceptual errors may be determined by a role of body parts in external signal processing. More generally, these findings and the corresponding recent advances in body image literature highlight the importance of studying the perceptual distortions "at the baseline", i.e., in healthy population, given their potential to further elucidate the nature of perceptual distortions in clinical conditions. Indeed, without understanding the distortions in healthy individuals, it is impossible to pinpoint the unique influence of clinical disorders on body image. Dissociating normal versus clinical body distortions will likely allow practitioners to develop more objective and reliable diagnostic criteria for patient populations. Thus, our study should provide a useful point of departure for future work to replicate and extend with clinical samples. Indeed, new testable theories were already introduced based on the related evidence; e.g., theories positing that individuals with eating disorders may be more reliant on distorted somatosensory representations than healthy people (Longo, 2015).

Declarations of interest

None.

Acknowledgments

This research was supported by a doctoral studentship from the Economic and Social Research Council, U.K. (ES/J500021/1), and the Welcome Trust/Birkbeck University ISSF funding (204770/Z/16/Z) to RS, and the European Research Council Grant ERC-2013-StG-336050 under the FP7 to MRL.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2018.10.016.

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