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Perceptual Distortions of 3-D Finger Size

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Abstract
Our body is a volumetric, three-dimensional (3-D) object in the world, and we experience it as such. Existing methods for measuring the perceptual body image, however, have been based on judgments of one-dimensional (1-D) length or two-dimensional images. We developed a new approach to the 3-D perceptual body image of the fingers by asking people to judge whether each finger would fit through rings of varying diameter. This task requires participants to conceptualize their finger as a volumetric object entering the ring. In two experiments, we used an adaptive staircase procedure to estimate the perceived size of each finger. There were systematic distortions of perceived 3-D finger size, with the size of index finger and (to a lesser extent) the middle finger underestimated. These distortions were unaffected by changes in hand posture. Notably, the pattern of distortions is qualitatively different from that found in previous research investigating 1-D finger length, suggesting that 3-D judgments of the body may differ in fundamental ways from 1-D judgments of individual body dimensions.

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Distortions of perceived body size and shape are a core aspect of eating disorders such as anorexia nervosa (Bruch, 1962). A large literature has used body size estimation tasks to compare eating disordered patients and controls (e.g., Ben-Tovim, Whitehead, & Crisp, 1979; Garner, Garfinkel, Stancer, & Moldofsky, 1976; Horne, Van Vactor, & Emerson, 1991; Slade & Russell, 1973), and meta-analyses of this literature have consistently found that patients overestimate body width compared with controls (Cash & Deagle, 1997; Mölbert et al., 2017; Sepúlveda, Botella, & León, 2002; Smeets, Smit, Panhuysen, & Ingleby, 1997). Such differences, however, do not imply that healthy individuals show veridical judgments, and indeed, many studies have reported systematic misperception of body size and shape in nonclinical samples (e.g., D'Amour & Harris, 2017; Dolan, Birtchnell, & Lacey, 1987; Dolce, Thompson, Register, & Spana, 1987; Fuentes, Longo, & Haggard, 2013; Halmi, Goldberg, & Cunningham, 1977; Hundleby & Bourgouin, 1993; Linkenauger et al., 2015; Linkenauger, Kirby, McCulloch, & Longo, 2017; Sadibolova, Ferrè, Linkenauger, & Longo, 2019; for reviews, see Longo, 2017a; Thompson, 1986). Such results suggest that far from being a sure sign of disease, distorted representations of the body may be a ubiquitous part of ordinary cognitive life.

The clinical literature on body size estimation has focused largely on the body parts such as the torso, waist, and hips, given their obvious importance to body image concerns in the context of eating disorders. A more recent literature has focused on investigating perceptual representations of the hand, a body part of particular interest given its central role in skilled action (Jeannerod, 1997). A range of distortions of hand representation have been identified, including hand representations involved in position sense (e.g., Coelho, Zaninelli, & Gonzalez, 2017; Longo & Haggard, 2010; Longo, Long, & Haggard, 2012; Saulton, Dodds, Bulthöff, & de la Rosa, 2015), tactile distance perception (e.g., Green, 1982; Longo & Haggard, 2011; Taylor-Clarke, Jacobsen, & Haggard, 2004), tactile localization (e.g., Mancini, Longo, Iannetti, & Haggard, 2011; Trojan et al., 2006), and judgments of the configuration of landmarks within the hand (e.g., Longo, 2015a; Margolis & Longo, 2015).

Of particular relevance to the present study, three recent studies have used a simple perceptual matching task to measure the perceived length of the fingers (Longo & Haggard, 2012a; Longo, Mattioni, & Ganea, 2015b; Tamè, Bumpus, Linkenauger, & Longo, 2017). In this task, participants were asked to compare the perceived length of each finger (i.e., the distance from the knuckle to the outstretched fingertip) to the length of a line shown on a computer monitor. The perceived length of each finger was estimated using either a staircase procedure (Longo & Haggard, 2012a; Longo et al., 2015b) or the method of adjustment (Tamè, Bumpus, et al., 2017). In each case, there was substantial underestimation of finger length, which showed a clear gradient across the hand. Underestimation was smallest for the thumb and increased progressively across the hand toward the little finger. Intriguingly, these distortions are qualitatively similar to, but smaller in magnitude than, distortions of proprioceptive hand maps, where participants point to the location of the knuckles and finger tips of their occluded hand (Longo & Haggard, 2010), and differences between fingers in both tactile sensitivity (Duncan & Boynton, 2007; Manser-Smith, Tamè, & Longo, 2018; Sathian & Zangaladze, 1996; Vega-Bermudez & Johnson, 2001) and cortical magnification factors (Duncan & Boynton, 2007).

These studies have described distortions of the hand on a single dimension (e.g., length). However, our body is a three-dimensional (3-D), volumetric object, and we experience it as such. The 3-D nature of the body, in general, has not been well captured by existing methods of measuring the perceptual body image. The present study addresses this gap and investigates the body image of the fingers in 3-D. One class of methods measures one-dimensional (1-D) length, such as the moving caliper method (Slade & Russell, 1973), the adjustable light beam method (Thompson & Spana, 1988), the body image detection device (Ruff & Barrios, 1986), and the line length task described in the previous paragraph. Another class of methods measures two-dimensional (2-D) proportions (i.e., aspect ratio), such as the distorting picture method (Glucksman & Hirsch, 1969), the body-distorting mirror (Traub & Orbach, 1964), the video distortion method (Allebeck, Hallberg, & Espmark, 1976), and the template matching task (Gandevia & Phegan, 1999). Some other studies have attempted to address this issue by obtaining estimates of body depth (e.g., Button, Fransella, & Slade, 1977; Casper, Halmi, Goldberg, Eckert, & Davis, 1979; Dolce et al., 1987; Halmi et al., 1977), showing body images in profile (e.g., Brodie, Slade, & Rose, 1989; Fernández, Probst, Meermann, & Vandereycken, 1994; Freeman, Thomas, Solyom, & Hunter, 1984; Lindholm & Wilson, 1988; Urdapilleta, Aspavlo, Masse, & Docteur, 2010), or obtaining 1-D measures of perceived limb circumference (Horne et al., 1991; Keizer, van Elburg, Helms, & Dijkerman, 2016; Mölbert et al., 2016; Salbach, Klinkowski, Pfeiffer, Lehmkuhl, & Korte, 2007; Schneider, Frieler, Pfeiffer, Lehmkuhl, & Salbach-Andrae, 2009a; Schneider et al., 2009b). None of these approaches, however, involve judgments about the body as a 3-D object, but about different dimensions of the body, individually. It is unclear whether the perceived shape of a body part in 3-D is fundamentally different from what might be inferred from measuring judgments of each dimension in isolation. Thus, the nature of distortions in 3-D space for the body, and in particular for the hand, remains unclear.

In the present study, we use a new approach to investigate the body image of the fingers in 3-D, by asking participants to make judgments about whether their fingers would fit into circular rings of differing diameters. Rather than judging the size of each finger in any single dimension, this task requires that the participant conceptualize their finger as a volumetric object entering and moving through the ring. Because the thickest part of the finger is not necessarily at the base of the finger, this task also requires that participants consider the movement of the entire finger through the ring, and not merely judge cross-sectional area of any specific finger location. We used an adaptive staircase procedure to estimate the perceived size of each finger.

Experiment 1

Method

Participants. Twenty individuals (9 women, mean age = 32.4 years, range: 21–48 years) participated. Participants were all right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971; mean = 85.6, range = 50–100). Participants reported no known abnormalities of tactile perception and normal or corrected-to-normal visual acuity. Participants provided written informed consent and were paid for their participation.

Procedures were approved by the Department of Psychological Sciences Research Ethics Committee at Birkbeck.

Stimuli. Stimuli were 33 metal ring gauges (Digiflex, London, UK), examples of which are shown in Figure 1. The metal band of each ring was 2.35 mm in thickness. The inner diameter of each ring ranged from 12.1 to 23.4 mm in approximately equal steps.

Procedure. Participants were seated at a table facing the experimenter with their hands placed on their lap. They were asked not to look at their hands, which were covered by a black cloth. On each block, the participant was asked to make judgments about the size of one of the five fingers of their left hand. On each trial, the experimenter placed one of the ring gauges in front of the participant at approximately the height of the participant's eyes. The participant was given the following description of the task:

> In this task, we will ask you to imagine that one of the fingers of your left hand is going through a ring placed in front of you. On each block, I will let you know which finger you should judge. Your task is to judge whether the ring is big enough that your finger could pass through it without any friction. That is, it would be fine if your finger touched the sides of the ring, so long as it didn't put any pressure on your skin. If it seems like the ring is big enough that your finger would fit through it without friction, say "yes." If it seems like the ring is not big enough, say "no."

The ring was placed on a custom-made plasticine support, allowing it to rest upright giving the participant a clear view of its entire circumference at a viewing distance of approximately 50 cm. Responses were made verbally and were unspeeded.

The experiment consisted of five blocks, one for each finger, in random order. Each block consisted of 36 trials, for a total of 180 trials. On each trial, the QUEST Bayesian adaptive

Figure 1. Examples of the ring gauges used as stimuli. On each trial, the participant was shown one of the rings and judged whether one of their fingers would be able to fit through the ring. The penny is shown for scale.
Note: Please refer to the online version of the article to view the figures in colour.

staircase algorithm (Watson & Pelli, 1983), as implemented in the Psychtoolbox (Brainard, 1997) for MATLAB (Mathworks, Natick, MA), was used to select which ring gauge to present. QUEST analyses the participant's history of previous responses to find the stimulus (i.e., the diameter of ring gauge) which will be most informative for estimating the true threshold (i.e., the stimulus size for which participants would be equally likely to say "yes" and "no"). On each trial, the size of ring gauge to be displayed was determined by QUEST and displayed to the experimenter on a monitor. Each block consisted of two interleaved QUEST staircases, each consisting of 18 trials, one starting with a large stimulus (26 mm diameter) and the other starting with a small stimulus (18.5 mm diameter). At the start of the experiment, each participant completed five practice trials using a single staircase, and starting with the 18-mm diameter ring. The participant was allowed to take a short break midway through and after each block but was not allowed to look at their hands at any point.

At the end of the experiment, the actual size of each finger was measured using the same set of ring gauges by identifying the smallest one that would slide onto the finger all the way to the base without causing friction against the skin, using the same operationalization of friction as given in the instructions to participants, described above. Size was quantified as the inner diameter of the ring gauge.

Analysis. For each participant and each finger, the thresholds from the two staircases were averaged. Percent overestimation finger size was calculated as $100 \times$ (judged diameter – actual diameter)/actual diameter, as in previous studies of distorted hand representation (e.g., Longo, Mancini, & Haggard, 2015a; Longo & Haggard, 2010, 2012a, 2012b; Tamè, Bumpus, Linkenauger & Longo, 2017). Positive values of this measure indicate overestimation of finger size, whereas negative values indicate underestimation. We quantified ring gauge size in terms of the diameter of the ring rather than the circumference. However, as the circumference is equal to the diameter multiplied by a constant value (i.e., pi), these measures are mathematically equivalent. Note also that percent overestimation is mathematically equivalent to the body perception index, which has been widely used in body size estimation studies of patients with eating disorders (e.g., Pierloot & Houben, 1978; Slade & Russell, 1973; Thompson, Berland, Linton, & Weinsier, 1986; for discussion, see Smeets, Smit, Panhuysen, & Ingleby, 1998), but defines veridical judgments with a value of 0 rather than 100 as in the body perception index.

The preceding analysis quantifies finger size in terms of the diameter of the ring gauge, although the participant's task was not to judge 1-D diameter. We therefore conducted a second analysis expressing the size of the ring gauges, and of the participant's finger, in terms of 2-D area. Each threshold was reexpressed as an area (i.e., $\pi \times (\text{diameter}/2)^2$), as was the size of each finger (note that this assumes that the cross-section of each finger is circular, which is only approximately true). Because the area increases as the square of the linear dimensions, it is logically possible for qualitatively different patterns to hold for these two analyses.

For both dependent measures, repeated-measures analysis of variance (ANOVA) was used to test for differences in overestimation of size across fingers. Where Mauchly's test indicated a violation of the sphericity assumption, the Greenhouse-Geisser correction was applied. For each finger, one-sample t tests were used to compare judgments with veridical performance.

Results and discussion

We first investigated the relation between actual and judged finger size. Figure 2 shows scatterplots of the relation between actual and judged diameter (top row) and area

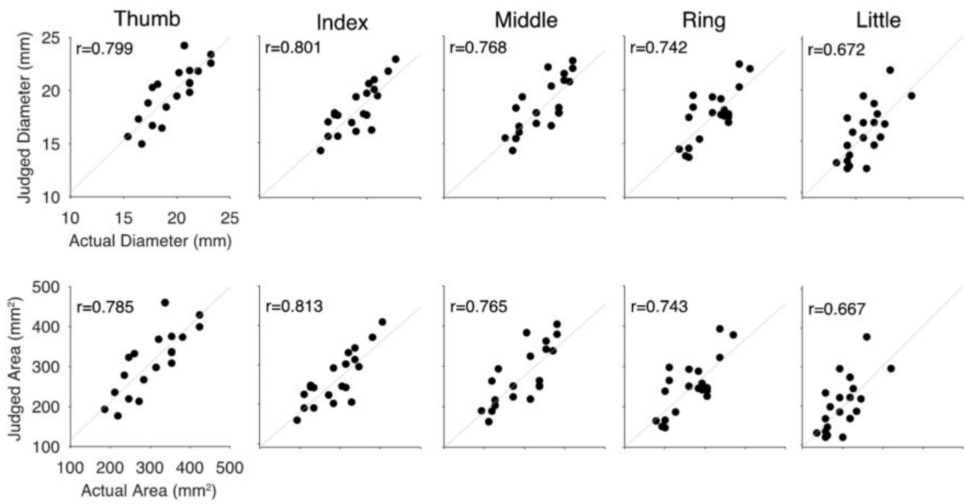

Figure 2. The relation between actual and judged finger size. *Top row*: scatterplots showing the relation between actual and judged ring diameter, for each of the five fingers. *Bottom row*: the same data for ring area. Gray lines show the least-squares regression line. Clear correlations between judged and actual finger size were apparent for all fingers.

(bottom row). Robust correlations were apparent for both measures in all five fingers (all ps $< .002$). These results demonstrate both that participants were effectively able to perform the task and also that their judgments assessed their own self-specific body image rather than a generic representation of fingers in general. These correlations are also notable in light of the fact that other measures of body size estimation (e.g., the moving caliper method) have been criticized on the basis that judged body size did not correlate with actual size (e.g., Ben-Tovim & Crisp, 1984; Ben-Tovim, Walker, Murray, & Chin, 1990).

The left panel of Figure 3 shows the results expressed in terms of the diameter of the rings. The magnitude of overestimation differed significantly across the five fingers, $F(4, 76) = 3.35$, $p < .02$, $\eta_p^2 = 0.15$. Absolute underestimation was found for the nonthumb fingers, though this only reached significance for the index finger (M: 5.51% underestimation), $t(19) = -3.49$, $p < .005$, $d = 0.78$, and the ring finger (M: 4.16% underestimation), $t(19) = -2.22$, $p < .05$, $d = 0.50$. No significant biases were found for the thumb (M: 1.00% overestimation), $t(19) = 0.53$, $p < .20$, $d = 0.12$, the ring finger (M: 3.77% underestimation), $t(19) = -1.81$, $p = .086.$, $d = 0.40$, or the little finger (M: 1.43% underestimation), $t(19) = -0.51$, $p < .20$, $d = 0.11$.

The right panel of Figure 3 shows the same data expressed in terms of the circular area of the rings. Results were similar to those described earlier, with a significant difference in the magnitude of overestimation across fingers, $F(4, 76) = 3.43$, $p < .05$, $\eta_p^2 = 0.15$. There was significant underestimation of the index finger (M: 10.25% underestimation), $t(19) = -3.51$, $p < .005$, $d = 0.78$, and marginally significant underestimation of the middle finger (M: 7.48% underestimation), $t(19) = -2.06$, $p = .053$, $d = 0.46$. There were no significant biases for the thumb (M: 2.71% overestimation), $t(19) = 0.69$, $p < .20$, $d = 0.15$, the ring finger (M: 6.57% underestimation), $t(19) = -1.58$, $p = .131$, $d = 0.35$, or the little finger (M: 1.34% underestimation), $t(19) = -0.24$, $p < .20$, $d = 0.05$.

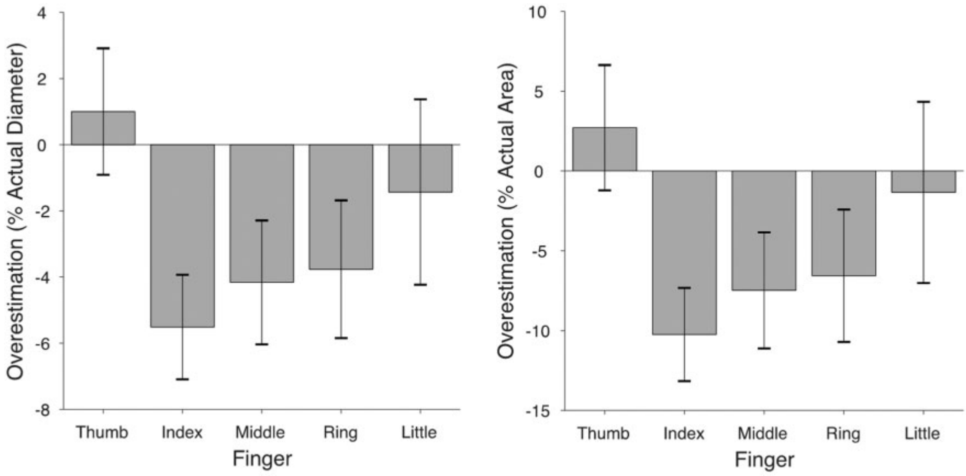

Figure 3. Results from Experiment 1. *Left panel*: overestimation of finger size as quantified by the diameter of the rings. *Right panel*: overestimation of finger size as quantified by the area of the rings. Error bars are 1 *SEM*. Positive values indicate overestimation of finger size, while negative values indicate underestimation.

Experiment 2

The results of Experiment 1 provide evidence for systematic distortions of perceived finger size in 3-D. In Experiment 2, we tested whether these distortions were affected by the actual configuration adopted by the fingers. Several studies have demonstrated that the internal posture of the hands produces a range of changes in tactile processing both perceptually (e.g., Medina & Rapp, 2008; Overvliet, Anema, Brenner, Dijkerman, & Smeets, 2011; Riemer, Trojan, Kleinböhl, & Hölzl, 2010; Sanabria, Soto-Faraco, & Spence, 2005; Tamè, Dransfield, et al., 2017; Tamè, Farnè, & Pavani, 2011; Yamamoto & Kitazawa, 2001; Zampini, Harris, & Spence, 2005) and neurally (e.g., Hamada & Suzuki, 2003, 2005; Sakata, Takaoka, Kawarasaki, & Shibutani, 1973; Stavrinou et al., 2007). Moreover, recent studies have found that changes in the internal posture of the hand (with fingers splayed vs. pressed together) modulate the perceived distance between touches on the hand (Longo, 2017b) as well as proprioceptive perceptual hand maps (Longo, 2015b). It is unclear whether such changes in hand posture also affect the conscious body image. Here, we therefore tested whether posture modulates the internal representation of finger size.

Method

Participants. Twenty individuals (8 women, mean age = 29.7 years, range: 19–48 years) participated. Participants were generally right-handed as assessed by the Edinburgh Inventory (mean = 85.4, range = -29.4 – 100). Participants reported no known abnormalities of tactile perception and normal or corrected-to-normal visual acuity.

Procedure. Stimuli and procedures were identical to Experiment 1, except that stimuli were presented while the participant held their left hand in two different postures, as shown in Figure 4. In the *Together* posture, the participant held their left hand on the tabletop with the fingers pressed together. In the *Apart* posture, the participant held their hand with the fingers splayed as far apart as would be comfortable to maintain throughout each

Figure 4. The two postures in Experiment 2. *Left panel*: the *Together* posture, in which the hand was held with the fingers pressed together. *Right panel*: the *Apart* posture, in which the hand was held with the fingers splayed at the maximum amount that would be comfortable to hold throughout the experimental block. *Note:* Please refer to the online version of the article to view the figures in colour.

experimental block. As in Experiment 1, the participant was not allowed to see their hand at any time during the experiment, and it was covered with a black cloth.

The structure of each block was identical to Experiment 1, but there were now 10 blocks, one for each finger in each posture. The order of the 10 blocks was randomized. To check that the participant was following the instructions, the experimenter took a photograph of the participant's hand just before and after each block and before each break. Participants were required to respond based on the size of the fingers of their left hand.

Analysis. Data analysis was identical to Experiment 1 except that posture was added as an additional factor to ANOVAs. In addition, we used Bayesian repeated-measures ANOVA (Wetzels, Grasman, & Wagenmakers, 2012), as implemented in JASP version 0.8.1.1 (JASP Team, 2018), to investigate whether the absence of a significant interaction between finger and posture provided positive evidence for the absence of an effect.

Results and discussion

Figure 5 shows the relation between actual and judged finger size, collapsed across the two postures. As in Experiment 1, positive correlations were apparent in all cases, though a few of them were somewhat weaker than in the previous experiment.

The left panel of Figure 6 shows overestimation of finger size expressed in terms of ring diameter. As in Experiment 1, the magnitude of overestimation differed significantly across the fingers, $F(2.55,\ 48.48) = 7.57$, $p < .0001$, $\eta_p^2 = 0.29$. There was no significant effect of posture, $F(1,\ 19) = 0.27$, $p > .20$, $\eta_p^2 = 0.01$, nor an interaction of posture and finger, $F(3.34,\ 63.37) = 1.33$, $p < .10$, $\eta_p^2 = 0.07$. To investigate whether the data provide positive

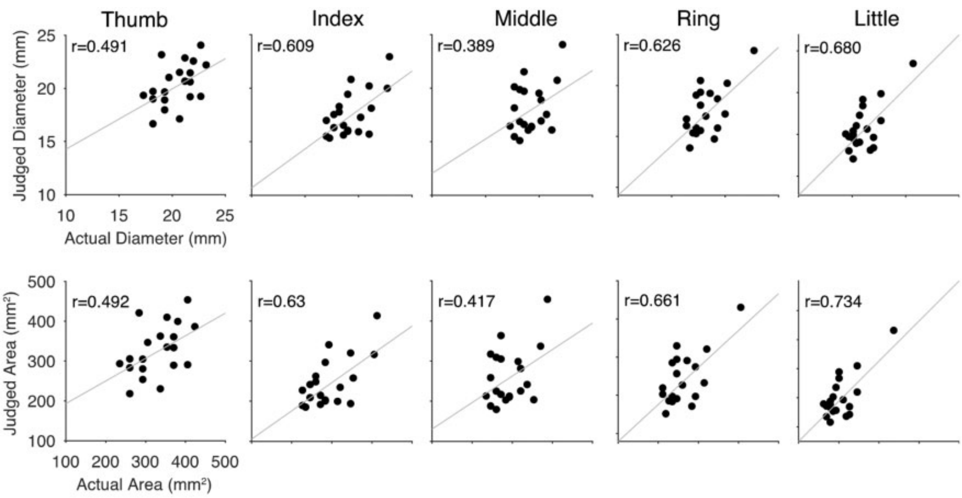

Figure 5. The relation between actual and judged finger size, collapsed across the two postures. *Top row*: scatterplots showing the relation between actual and judged ring diameter, for each of the five fingers. *Bottom row*: the same data for ring areas. Gray lines show the least-squares regression line. Positive correlations were apparent in all cases, though not all of them reached statistical significance.

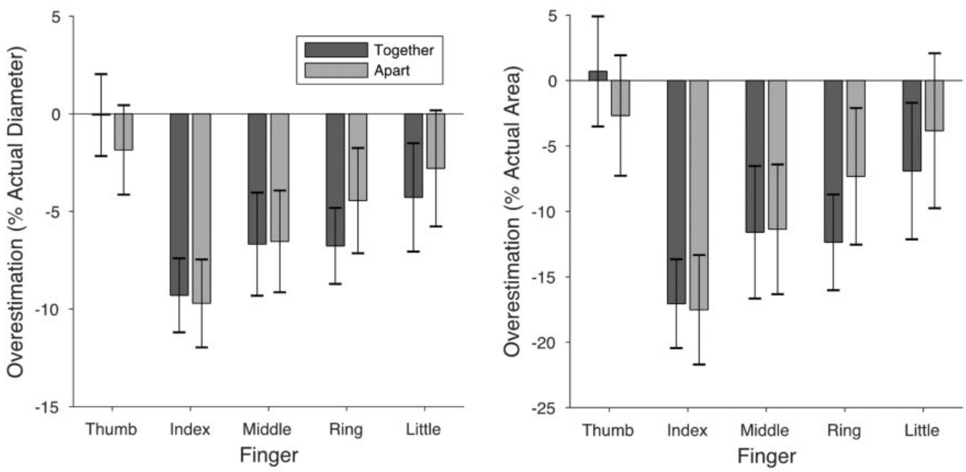

Figure 6. Results from Experiment 2. *Left panel*: overestimation of finger size as quantified by the diameter of the rings. *Right panel*: overestimation of finger size as quantified by the area of the rings. Error bars are 1 *SEM*. Positive values indicate overestimation of finger size, while negative values indicate underestimation.

evidence against the presence of a postural effect, we conducted a Bayesian repeated-measures ANOVA. The Bayes factor for the interaction provided substantial support for the null hypothesis, $BF_{01} = 9.87$.

Collapsing across the two postures, there was significant underestimation of the index finger (M: 9.51% underestimation), $t(19) = -4.98$, $p < .0001$, $d = 1.11$, the middle finger (M: 6.61% underestimation), $t(19) = -2.60$, $p < .02$, $d = 0.58$, and the ring finger (M: 5.61% underestimation), $t(19) = -2.50$, $p < .05$, $d = 0.55$. As in Experiment 1, there were no significant biases for the thumb (M: 0.96% underestimation), $t(19) = -0.46$, $p > .20$, $d = 0.10$, or the little finger (M: 3.54% underestimation), $t(19) = -1.28$, $p > .20$, $d = 0.29$.

The right panel of Figure 6 shows data from Experiment 2 expressed in terms of the circular area of rings. There was a significant difference in the magnitude of overestimation across fingers, $F(2.52, 47.80) = 7.30$, $p < .001$, $\eta_p^2 = 0.28$. However, there was no significant effect of posture, $F(1, 19) = 0.45$, $p > .20$, $\eta_p^2 = 0.02$, nor an interaction of posture and finger, $F(3.30, 62.62) = 1.47$, $p > .20$, $\eta_p^2 = 0.07$. A Bayesian repeated-measures ANOVA provided substantial support for the absence of an interaction of finger and posture, $BF_{01} = 9.50$.

Collapsing across the two postures, there was significant underestimation of the index finger (*M*: 17.29% underestimation), $t(19) = -4.97$, $p < .0001$, $d = 1.11$, the middle finger (*M*: 11.48% underestimation), $t(19) = -2.36$, $p < .05$, $d = 0.53$, and the ring finger (*M*: 9.84% underestimation), $t(19) = -2.26$, $p < .05$, $d = 0.51$. There were no significant biases for the thumb (*M*: 0.98% underestimation), $t(19) = -0.23$, $p > .20$, $d = 0.05$, or the little finger (*M*: 5.37% underestimation), $t(19) = -1.00$, $p > .20$, $d = 0.22$.

General Discussion

These results demonstrate systematic biases in the perceived 3-D size of the fingers. In both experiments, clear underestimation of the index finger (and to a lesser extent the middle finger) was present, which decreased progressively across the hand to the little finger. These biases were not affected by changes in the internal posture of the hand. Importantly, this pattern is qualitatively different from the pattern of underestimation found for 1-D judgments of finger length (Longo & Haggard, 2012a; Longo et al., 2015b; Tamè, Bumpus, et al., 2017). This suggests that judgments of the body as a coherent 3-D object may differ in fundamental ways from judgments about individual body dimensions (Longo, 2015c).

As in the present study, those studies reported overall underestimation of the size of the nonthumb fingers. In contrast, however, the pattern across the four fingers was completely reversed. In the studies of perceived finger length, the magnitude of underestimation increased progressively from the index finger to the little finger, with the largest distortion found for the ring and little finger. This pattern mirrors the cortical magnification of each finger in somatosensory cortex (Duncan & Boynton, 2007) and the spatial sensitivity of the fingers (Duncan & Boynton, 2007; Manser-Smith et al., 2018; Vega-Bermudez & Johnson, 2001), both of which decrease progressively from the index finger to the little finger, as well as the increase in underestimation of finger length in proprioceptive hand maps (e.g., Cocchini, Galligan, Mora, & Kuhn, 2018; Ganea & Longo, 2017; Longo & Haggard, 2010). In contrast, in the present study, the largest underestimation was found for the index finger, and underestimation decreased across the hand toward the little finger. The exact causes of these changes are unclear. However, this pattern suggests that judgments of the fingers in 3-D are importantly different from 1-D judgments of length. This is consistent with the recent results of Sadibolova et al. (2019) who found that judgments of body part volume showed a qualitatively different pattern of distortions from judgments of length.

One potential question about the present study is whether our task really required participants to make judgments of their fingers as 3-D objects. One might note that our actual quantifications are of ring diameter (a 1-D property) and area (a 2-D property), and not of an intrinsically 3-D measure such as volume. In our view, what makes this task assess the 3-D image of the fingers is the fact that participants have to imagine the finger going *through* the ring, and therefore need to consider the circumference of each finger along its entire length. The task used in the current study is interestingly different from that used by Sadibolova et al. (2019), who asked people to make explicit estimates of how many multiples of the volume of their hand or of a nonbody object would make up the volume of different parts of their body. While we have argued that the current task does assess the participant's experience of their finger as a volumetric 3-D object, it clearly does not measure perceived finger volume. While this does make it somewhat more ambiguous exactly what aspect of body image we are measuring in the present study compared with the study of Sadibolova et al. (2019), it is worth emphasizing that making quantitative judgments of how many multiples of the volume of an object make up the volume of a specific body part is a highly novel and nonintuitive judgment for participatns to make. In contrast, judging whether a ring will fit on one's finger is a familiar judgment to make, which relates much more closely to people's everyday experiences and activities.

In this respect, the task used in this study has similarites to studies investigating judgments of affordances, such as the ability to pass through apertures (e.g., Graydon, Linkenauger, Teachman, & Proffitt, 2012; Warren & Whang, 1987), to reach objects (e.g., Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Rochat & Wraga, 1997), and to sit on stools (e.g., Mark, 1987). Because we asked participants about the ability of part of their body to fit through a form of aperture, there is a sense in which our task is also an affordance judgment (cf. Gibson, 1979). The potential link to affordances, however, is particularly intruiging in light of several recent studies that have found that judgments of the ability to pass through apertures are altered in individuals with anorexia nervosa (e.g., Guardia et al., 2010, 2012; Keizer et al., 2013; Metral et al., 2014) and in healthy adults following embodiment of avatars of different body sizes in virtual reality (Piryankova et al., 2014). Such results suggest that the implicit use of body size information in making affordance judments has functional connections with the conscious body image. A recent study by Engel and Keizer (2017) is especially intriguing in that it used a task analagous to ours in which participants had to estimate whether hoops of different diameter would fit around their entire body. Patients with anorexia overestimed the required hoop size compared with control participants. Subsequently, Keizer, Engel, Bonekamp, and van Elburg (in press) found that 8 weeks of training with this task in patients with anorexia led to improvements in both affordance judgments and tactile distortions.

One recent study found that changes in perceived finger size following cutaneous anaesthesia (cf. Gandevia & Phegan, 1999) specifically affect judgments of finger width but not finger length (Walsh, Hoad, Rothwell, Gandevia, & Haggard, 2015). Another study by Hashimoto and Iriki (2013) identified distinct patterns of brain activation using functional magnetic resonance imaging when participants made judgments about different body axes. Such effects are intriguing as they suggest that there may be distinct mental representations of individual body axes. As mentioned in the previous paragraph, however, this does not imply that the experience of the body as a 3-D object can be predicted from judgments of each body axis in isolation. Rather, 3-D perception of the body may rely on distinct mental representations from judgments about individual body dimensions. It is intriguing in this light that whereas 1-D judgments of finger length appear to mirror differences between the fingers in sensitivity and cortical magnification factors (Longo & Haggard, 2012a), this relation does not hold for judgments of 3-D finger size in the present study.

This study contributes to an emerging literature detailing the way in which the body is represented as a volumetric, 3-D object in the world. One set of studies has approached this issue by comparing perception of the palmar and dorsal surfaces of the hand. These skin surfaces have different physiological properties (Mountcastle, 2005) and distinct representations in somatosensory cortex (Merzenich, Kaas, Sur, & Lin, 1978; Nelson, Sur, Felleman, & Kaas, 1980). Perceptual effects arising from low-level sensory maps of the hand may therefore show highly distinct patterns of performance on each surface. In contrast, if perceptual effects arise from higher-level representations of the body as a volumetric whole, similar patterns should be found on each surface. Interestingly, perceptual abilities appear to differ widely in this regard. For example, tactile localization (e.g., Mancini et al., 2011) and tactile distance perception (e.g., Longo, Ghosh, & Yahya, 2015; Longo & Haggard, 2011) appear to arise from fragmented 2-D maps of individual skin surfaces, as the pattern of distortions on each surface (i.e., palm and dorsum) differs. Tactile confusions between fingers (Manser-Smith et al., 2018) and explicit judgments of hand shape (Longo, 2015d), on the other hand, appear to arise from coherent 3-D representations of whole body parts, as the two sides of the hand show highly similar patterns of perceptual bias.

There was no apparent effect of posture on judgments of finger size. This is in marked contrast to a number of recent studies that have found that finger and arm posture modulates tactile processing (e.g., Longo, 2017b; Medina & Rapp, 2008; Overvliet et al., 2011; Riemer et al., 2010; Sadibolova, Tamè, & Longo, 2018; Tamè et al., 2011; Tamè, Dransfield, et al., 2017; Zampini et al., 2005), proprioceptive body maps (Longo, 2015b), and somatotopic maps in somatosensory cortex (Hamada & Suzuki, 2003, 2005; Stavrinou et al., 2007). This pattern suggests that splaying the fingers may modulate low-level somatosensory representations of the body, composed of fragmented 2-D maps of individual skin surfaces, but not higher-level representations of the body as a 3-D volumetric object.

It is noteworthy that judgments of finger size in the present study were strongly correlated with actual finger size. Some authors have highlighted the lack of such correlations for tasks such as the moving caliper method, arguing that this calls into question the extent to which distortions using this method are actually perceptual rather than attitudinal (e.g., BenTovim et al., 1979, 1990; Ben-Tovim & Crisp, 1984; see also Smeets et al., 1998). The presence of clear correlations in this study is therefore an important validation that participants are in fact basing their judgments on their experience of their own fingers specifically rather than a more generic representations of fingers in general. It further provides support for the interpretation that the distortions we report are genuinely perceptual distortions, and not artifacts of attitutes toward the fingers.

The present results contribute to a growing literature showing a range of systematic misperception and distortions of the mental representation of the hand (for review, see Longo, 2017a), focusing on the body as a 3-D object. Large and highly stereotyped distortions have been found for perceptual abilities including tactile localization (e.g., Mancini et al., 2011; Medina, Tamè, & Longo, 2018), tactile distance perception (e.g., Fiori & Longo, 2018; Taylor-Clarke et al., 2004), and position sense (e.g., Longo & Haggard, 2010, 2012b), as well as more explicit judgments of the location of landmarks within the hand (e.g., Ambroziak, Tamè, & Longo, 2018; Longo, 2015a), hand proportions (e.g., Longo & Haggard, 2012a; Longo & Sadibolova, 2013), and finger size (this study, Longo & Haggard, 2012a; Tamè, Bumpus, et al., 2017). Despite the hand's role as a paragon of familiarity and intimate knowledge, the brain nevertheless maintains highly distorted representations of the hand, which have widespread influences on perception.

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