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Distorted perceptual face maps

Matthew R. Longo*, Marie Holmes

Department of Psychological Sciences, Birkbeck, University of London, United Kingdom

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ABSTRACT

Recent research has shown that proprioception relies on distorted representations of body size and shape. By asking participants to localise multiple landmarks in space, perceptual body maps can be constructed. Such maps of the hand and forearm is highly distorted, with large overestimation of limb width compared to length. Here, we investigated perceptual maps of the face, a body part central to our sense of self and personal identity. Participants localised 19 facial landmarks by pointing on a board covering their face. By comparing the relative location of judgments, we constructed perceptual face maps and compared them to actual face structure. These maps were massively distorted, with large overestimation of face width, but not length. This shows that distortions in perceptual body maps are not unique to the hand, but widespread on the body, including parts like the face at the core of our personal identity.

1. Introduction

Our body is central to our sense of self and the core of our personal identity. While distorted body representations are a conspicuous feature of clinical disorders such as eating disorders (Bruch, 1962) and body dysmorphic disorder (Phillips et al., 2008), it has often been assumed that healthy adults have essentially veridical representations of their body. Recent research, however, has revealed large and highly stereotyped distortions of mental body representations (Longo, 2017). For example, Longo and Haggard (2010) measured proprioceptive hand maps by having participants localise their knuckles and fingertips in external space, finding large distortions including overestimation of hand width and underestimation of finger length. These results have been replicated in a number of studies from our own and other labs (e.g., Cocchini et al., 2018; Coelho & Gonzalez, 2019; Coelho et al., 2017; Longo, 2015; Longo & Haggard, 2012a; Longo, Mattioni, & Ganea, 2015c; Peviani et al., 2019; Saulton et al., 2016). The exact source of these distortions remains uncertain, with some evidence suggesting they may relate to distortions and anisotropies of somatosensory cortical maps (Longo & Haggard, 2010; Longo, Mancini, & Haggard, 2015b) and other evidence suggesting they may arise from more general perceptual and memory processes (Medina & Duckett, 2017; Saulton et al., 2014).

Such distortions are particularly striking given that the hand is a paragon of familiarity, as in phrases such as knowing something “like the back of my hand”. Hands, however, are not central to our personal identity. Indeed, it is surprisingly difficult to identify one's own hand from a lineup (Wuillemin & Richardson, 1982). We therefore investigated whether similar distortions characterize the face, a body part central to our personal identity and which we can recognize extremely well. Indeed, research has shown that the face is a focus of body image concerns in conditions such as body dysmorphic disorder (Phillips et al., 1993; Veale et al., 1996).

Previous research investigating representation of the structure of one's own face has reached diverging conclusions. Several studies report distortions in tasks involving estimation of face width (Dolan et al., 1987; Dolce et al., 1987), the relative location of facial landmarks (Fuentes, Runa, et al., 2013c), drawings of face outlines (Bianchi et al., 2008), tactile distance perception (Longo et al., in press; Longo, Ghosh, & Yahya, 2015a), and adjusting a picture of one's own face (D'Amour & Harris, 2017). Notably, in the majority of these cases overestimation of face width has been found. In another recent study, Carbon and Wirth (2014) found systematic biases in participants' drawings of faces, with the eyes being displaced substantially too high in the face, suggesting that people have distorted representations of the configurations of faces in general (not just their own face).

In an intriguing contrast to those studies, however, a series of studies by Edwards and colleagues (Edwards et al., 2005) reported a dissociation between the representation of the face and of other body parts. They investigated the so-called “over-grasp” response in which the aperture of the grasp is systematically larger than the object itself, presumably to allow a margin of error (Jeannerod, 1997). Edwards and colleagues showed that the over-grasp response was reduced when grasping movements were made towards targets on the face, compared

* Corresponding author at: Department of Psychological Sciences, Birkbeck, University of London, Malet Street, London WC1E 7HX, United Kingdom.
E-mail address: m.longo@bbk.ac.uk (M.R. Longo).

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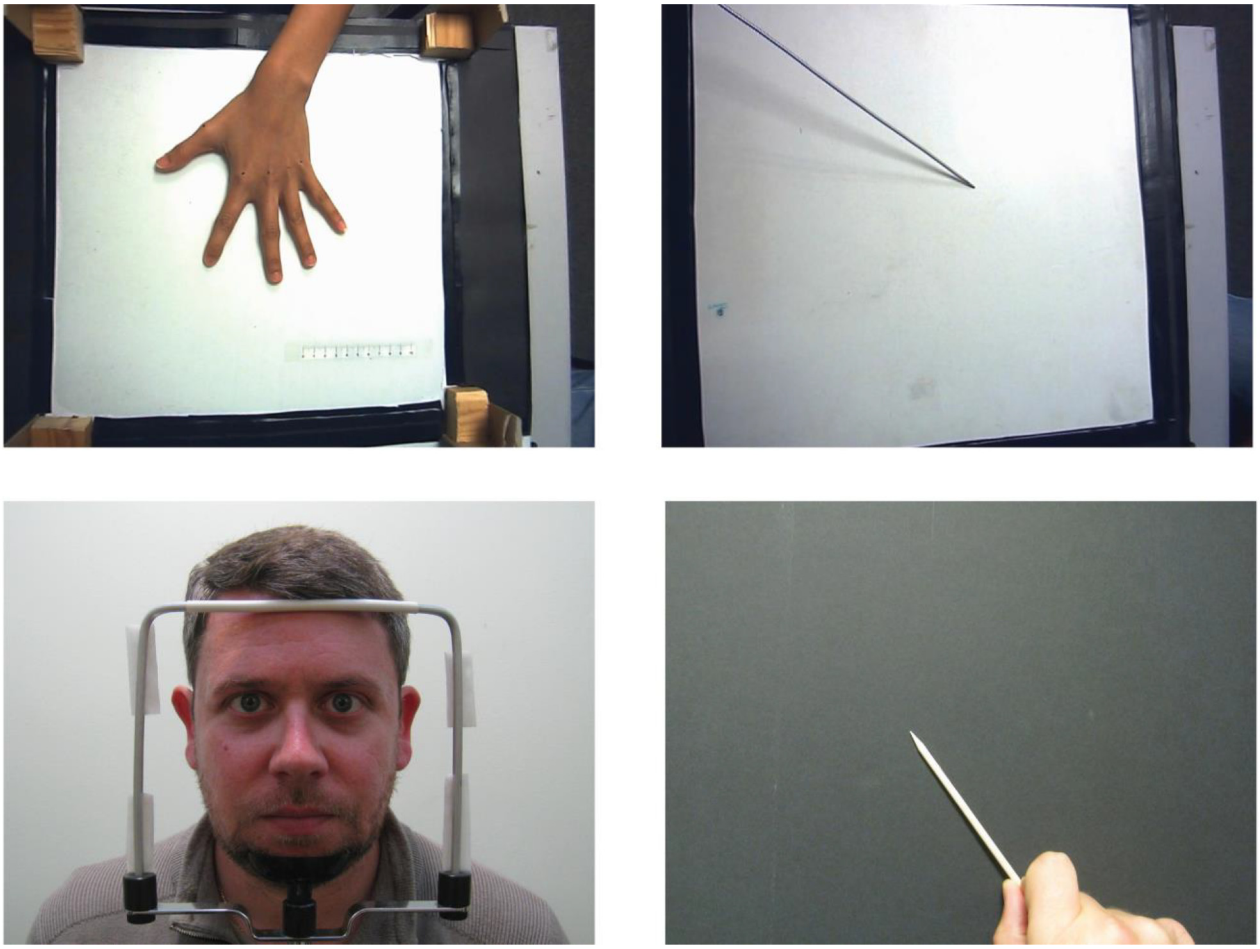

Fig. 1. The two mapping tasks. *Top row*: The hand mapping task. The top left panel shows the participant's hand resting flat on the table. The top right panel shows the hand covered by the occluding board and the participant using a long baton to judge the perceived location of each landmark on the hand. Photographs of the actual hand and pointing responses were captured by an overhead webcam for offline coding. *Bottom row*: The face mapping task. The bottom left panel shows the participant's face in the chinrest. The bottom right panel shows the face covered by the occluding board and the participant using a short wooden stick to judge the perceived location of each landmark on the face. Photographs of the actual face and pointing responses were captured by the same webcam as in the hand mapping task, but positioned on a tripod.

to grasps towards other body parts, such as the hands, or towards non-body objects.

A recent study applied the proprioceptive mapping task of Longo and Haggard (2010) to the face (Mora et al., 2018). Consistent with previous studies investigating proprioceptive hand maps, these authors reported substantial overestimation of face width, but not face length. Moreover, they reported a laterality effect, with the right side of the face overestimated in size compared to the left, analogous to other findings that right-handed participants overestimate the length of their right arm (Linkenauger et al., 2009). There are, however, some limitations of the study by Mora and colleagues. While they emphasize the laterality effect as particularly important, no actual statistical result reported in their paper directly compares distortion on the two sides of the face, making the status of this finding ambiguous. In addition, while overestimation of individual face parts (e.g., eyes, mouth) was quantified, there was no overall measurement of facial distortion in a more holistic way. Finally, only perceptual maps of the face were measured, meaning that the magnitude of distortions on the face could not be directly compared to distortions on the hands.

In this study, we replicated the main results of Mora et al. (2018) while addressing each of these limitations. Participants sat in a chinrest with an occluding board placed directly in front of their face. They judged the location of 19 facial landmarks by pointing on the board. We constructed perceptual face maps, which we compared to the actual structure of each participant's face. These maps were massively distorted, with overestimation of face width, but not face length, providing a clear replication of the recent study of Mora et al. (2018). By adapting a method to quantify overall stretch of perceptual maps which have recently developed for use with hand maps (Longo & Golubova, 2017; Longo & Morcom, 2016), we quantified the magnitude of facial distortions in a holistic way, which then allowed us to directly compare the magnitude of distortions on the left and right sides of the face. Finally, we also measured perceptual hand maps, allowing us to compare the magnitude of distortions on both body parts in the same sample.

2. Methods

2.1. Participants

Twenty individuals (10 female) between 18 and 45 years of age participated. Participants had normal or corrected-to-normal vision. There were 16 right handed and 4 left handed participants as assessed by the Edinburgh Inventory. Data from one participant was excluded due to mispositioning of the camera, resulting in responses outside the photograph. Procedures were approved by the Department of Psychological Sciences ethics committee at Birkbeck.

A weighted average of effect sizes from 15 previous experiments using the hand mapping task in our lab yielded an average Cohen's *d* of

1.78 for the underestimation of finger length and 1.89 for the overestimation of hand width. A power analysis based on a one-tailed *t*-test, taking the smaller of these two numbers using G*Power 3.1 with alpha of 0.05 and power of 0.95 suggested a critical sample size of 6. This suggests that our final sample size of 19 should have very good power to identify distortions of face maps of a comparable magnitude to those observed for the hand. Indeed, even in any potential distortion of face maps had an effect size only half as large as the hand, we would still have power greater than 0.95 to detect it.

2.2. Hand mapping task

We had two motivations for including measures of hand maps, in addition to face maps. First, in the event that distortions were not found on the face, it would be useful to show that the previously-reported distortions of perceptual hand maps were nevertheless replicated in that same sample. Second, we wished to be able to compare the magnitude of distortions on the two body parts, as well as investigate potential correlations between them. The hand task (Fig. 1) was similar to our previous experiments using this paradigm (e.g., Ganea & Longo, 2017; Longo, 2018; Longo & Haggard, 2010; Longo et al., 2012; Mattioni & Longo, 2014). Participants sat with their left hand resting palm-down on a table, aligned with their body midline. The hand was covered by a 40 × 40 cm board resting on four pillars (6 cm in height). Participants responded with their right hand using a long thin baton (35 cm in length, 2 mm in diameter) to indicate the perceived location of ten landmarks on their occluded left hand. Judgments were recorded by a camera (Logitech Webcam Pro 9000) suspended 27 cm above the table, under control of a custom MATLAB (Mathworks, Natick, MA) script. The photographs were saved as JPEG images (1600 × 1200 pixels) for offline coding.

The 10 landmarks judged were the tip of each finger (i.e., the most distal bit of skin) and the centre of the knuckle of each finger (i.e., the metacarpophalangeal joint). Participants were given a verbal instruction at the start of each trial about which landmark to localise by placing the tip of the baton on the occluding board directly above the perceived location. They were asked to be precise, to take their time, and to avoid ballistic pointing movements. They were also instructed to avoid strategies such as tracing the outline of the hand. When participants indicated they were satisfied with their response, a photograph was captured and the next trial began. To avoid response biases and to make each judgment as independent as possible, participants moved the baton to the side of the table following each response.

At the beginning and end of each experimental block, a photograph was taken without the occluding board to obtain information about actual hand size and position. A 10 cm ruler on the table allowed conversion between distances in pixels and cm. Before the start of the experiment, a small black mark was made with a pen on each knuckle to facilitate coding. There were 5 blocks of 20 trials. Each block consisted of two mini-blocks of 10 trials (one of each landmark, in random order).

2.3. Face mapping task

The face mapping task was broadly similar to the hand mapping task. Participants sat at a table with their head in a chin-rest which was adjusted in height to be comfortable for each participant. The webcam was positioned on a tripod approximately 30 cm from the chinrest, pointing directly at the participant's face. The height of the tripod was adjusted for each participant so that the camera was at the height of the centre of the participant's face. A sheet of black foamboard (60 cm wide, 40 cm high) was positioned in front of the participant's face (approximately 1 cm in front of the tip of their nose), providing a surface for them to point on. Participants judged the location of 19 landmarks on their face by pointing to the corresponding location on the occluding board. All participants responded with their right hand, regardless of handedness. Unlike the hand mapping task, participants could not see where they were pointing. Therefore, a short wooden stick (10 cm in length, 2 mm in diameter) was used for pointing, in contrast to the much longer stick we have used in most of our previous studies using this paradigm. Importantly, a previous study which compared hand maps obtained with versus without visual guidance found similarly distorted perceptual maps in both cases (Longo, 2014), suggesting that the absence of visual guidance of responses does not qualitatively alter the nature of the resulting maps. It is also important to note that there is clear evidence that people are able to perceive where wielded tools are touched quite well, even though no tactile signals come from the tool itself (Chan & Turvey, 1991; Miller et al., 2018).

The 19 locations judged were: the left and right ear (i.e., the base of the tragus), the inner edge of each eye (i.e., the medial canthus), the outer edge of each eye (i.e., the lateral canthus), the centre of the pupil of each eye, the top of the nose (i.e., the nasal root), the tip of the nose, the bottom of the nose (i.e., the subnasale), the left and right edges of the widest part of the nose, the left and right edges of the mouth (i.e., the labial commissures), the top of the lip (i.e., the centre of Cupid's bow), the bottom of the lip (i.e., the centre of the lower vermillion border), the lowest point of the chin (i.e., the gnathion), and the point where the forehead meets the hairline in the centre of the face. These landmarks were described to participants using non-technical language. A photograph of a face with each landmark labeled was shown to participants when the experimenter described the task to ensure they understood which landmarks they were being asked to judge.

As in the hand mapping task, a verbal instruction was given at the start of each trial to indicate which landmark the participant should judge. After each response, the participant moved the baton to the side of the table. At the beginning and end of each block a photograph was taken without the occluding board to allow coding of actual face size, shape, and location. Two landmarks 23 cm apart on either side of the chinrest allowed conversion from distances in pixels to cm. There were 5 blocks of 38 trials, each block consisting of two mini-blocks of 19 trials (one of each landmark in random order).

2.4. Analysis

The analysis was similar to our previous studies using this paradigm. The x/y pixel coordinates of each landmark were coded from photographs using a custom MATLAB script. These coordinates were averaged within each block, resulting in one perceptual map and one actual map of the hand or face in each block. Distances between pairs of landmarks were calculated for each map and converted to cm. For each distance of interest, percent overestimation was calculated as 100 x (judged length – actual length) / actual length. For hand maps, the distances quantified were the length of each finger (i.e., the distance between the knuckle and fingertip) and the distance between the knuckles of the index and little fingers, which was taken as an overall measure of hand width. For face maps, the distances quantified were the distances between the six pairs of homologous landmarks on the left and right sides of the face (i.e., the ears, the edges of the nose, the edges of the mouth, the inner edges of the eyes, the outer edges of the eyes, and the pupils) as well as the distance between the base of the chin and the centre of the hairline, which was taken as a measure of overall face length.

Statistical analyses focused on percent overestimation. To visualize the maps, however, we placed the maps from each condition into Procrustes alignment with actual hand/face shape. Procrustes alignment translates, rotates, and scales configurations of homologous landmarks to place them into best-fitting alignment (Rholf & Slice, 1990).

For the face maps, we also used Procrustes alignment to quantify overall distortion by stretching the maps of each participant's actual face along the medio-lateral axis by varying amounts and finding the stretch that minimized the dissimilarity to that participant's perceptual map, as in other recent studies from our lab (Longo & Golubova, 2017; Longo & Morcom, 2016). Stretches were defined by multiplying the x-coordinates of the map of each participant's actual face (reflecting location in the medio-lateral face axis) by a stretch parameter. Thus, a stretch of 1 indicates a veridical map of the person's face; a stretch greater than 1 indicates a wide, fat map of their face; and a stretch less than 1 indicates a thin, slender map of their face. To operationalize the medio-lateral face axis we first defined the proximo-distal face axis as the first principal component of the seven landmarks lying along the midline of the face (i.e., the base of the chin, the bottom edge of the lip, the top edge of the lip, the base of the nose, the tip of the nose, the top of the nose, and the centre of the hairline). The medio-lateral axis was defined as the axis orthogonal to the proximo-distal axis. Values of the stretch parameter between 0.5 and 2.0 were tested by exhaustive search with a resolution of 0.001 units in natural logarithm space (i.e., 1387 steps). Note that while we report mean stretch values as ratios, statistical comparison against stretch of 1 was done by comparing the logarithm of the ratios to 0, as ratios are not symmetrical around 1.

Mora et al. (2018) claimed that there was an overrepresentation of the right side of the face compared to the left. However, nothing in their statistical analysis provides clear support for their being a difference in the distortions on the two sides of the face. Our stretch analysis offers a clear way to assess distortion separately on each side of the face and to directly compare the magnitude of distortion on the two sides. In order to investigate laterality differences between the left and right sides of the face, we created whole-face maps by reflecting the points on each side across the proximo-distal face axis. This resulted in four maps for each participant, left face and right face maps for both the actual face and for perceptual maps. The overall stretch of perceptual maps in the medio-lateral axis was measured using the analysis described in the previous paragraph separately for the left face and right face maps.

In order to investigate whether there are systematic differences in the mental representation of the left and right sides of the face we used a form of representational similarity analysis. For each participant, we calculated the similarity in shape between their left face and right face perceptual maps to the grand average maps for the other 18 participants. Each grand average was calculated using generalised Procrustes alignment (Gower, 1975) using the Shape toolbox for Matlab, developed by Simon Preston (https://www.maths.nottingham.ac.uk/plp/pmzspp/shape.php). For each participant we calculated the mean Procrustes distance between ‘matching’ faces (i.e., the left/right face map for participant X and the grand average left/right face map for the other 18 participants) and ‘mismatching’ faces (i.e., the left/right face map for participant X and the grand average right/left face map for the other 18 participants). If there are consistent differences in the represented shape of the two sides of the face, the matching maps should be more similar in shape (i.e., have a smaller Procrustes distance) than the mismatching maps.

3. Results

3.1. Hand maps

Perceptual maps from the hand mapping task are shown in Fig. 2a. Consistent with our previous results, clear distortions were apparent, including: (1) underestimation of finger length, (2) a radial-ulnar gradient of magnification of finger length, and (3) overestimation of hand width. Across fingers there was clear underestimation of finger length (M: 37.66% underestimation, SD: 19.78%), $t(18) = -8.30$, $p < 0.0001$, $d = 1.90$ (Fig. 2c). We quantified the change in the magnitude of underestimation across the hand using least-squares regression, regressing percent underestimation for each finger on digit number (i.e., thumb = 1, little finger = 5), separately for each participant. We then tested whether the mean of the resulting regression slopes was significantly different from 0. Underestimation increased from the thumb to little finger (mean $\beta = -3.59\%$/finger, SD: 3.55), $t(18) = -4.41$, $p < 0.0005$, $d = 1.01$ (Fig. 2b). In contrast to the underestimation of finger length, hand width was clearly overestimated. Taking the distance between the knuckles of the index and little fingers as an overall measure of hand width, there was significant overestimation (M: 40.27% overestimation, SD: 32.62%), $t(18) = 5.38$, $p < 0.0001$, $d = 1.23$ (Fig. 2c).

3.2. Face maps

Results from the face mapping task are shown in Fig. 3. Fig. 4a shows overestimation of the distances between the six pairs of landmarks with left-right homologues. There was clear overestimation of all six pairs (all p's ≤ 0.01, Holm-Bonferroni correction). Across the six pairs, there was an average of 44.60% overestimation (SD: 27.82%), $t(18) = 6.99$, $p < 0.0001$, $d = 1.60$ (Fig. 4b). As Mora et al. (2018) assessed distortion separately for separate face parts, rather than comparing homologous landmarks on either side of the face, we also calculated overestimation of the width of each eye (i.e., the distance between the inner and outer edges of each eye) separately, for comparison with their results. There was clear overestimation of both the right eye (M: 48.38%, SD: 50.42%), $t(18) = 4.18$, $p < 0.001$, $d = 0.960$, and the left eye (M: 30.56%, SD: 52.41%), $t(18) = 2.54$, $p < 0.05$, $d = 0.583$. In contrast, taking the distance between the base of the chin and the centre of the hairline as an overall measure of face length, there was no significant deviation from actual length, but a modest trend towards underestimation (M: 5.59% underestimation, SD: 14.05%), $t(18) = -1.74$, $p = 0.10$, $d = 0.40$. An overall graphic depiction of these distortions is shown in Fig. 5.

Fig. 4c shows the mean Procrustes distance between perceptual face maps and stretched versions of each participant's actual face for values of the stretch parameter between 0.5 and 2. On average, the dissimilarity was minimized for a value of the stretch parameter of 1.45 (i.e., 44.79% overestimation of width), significantly greater than 1, $t(18) = 13.15$, $p < 0.0001$, $d = 3.02$. As can be seen from the light grey vertical lines in Fig. 4c, the value of the best-fitting stretch parameter was greater than 1 for all 19 participants. Because some of the landmarks on the boundary of the face are far away from the others (e.g., the ears, chin, and hairline), it is possible that the overall stretch in the preceding analysis might be driven by these specific landmarks. To investigate this possibility, we re-ran the stretch analysis excluding specific landmarks. Clear stretch in the medio-lateral axis remained in all cases, when the ears were removed (M: 40.19% overestimation of width), $t(18) = 10.62$, $p < 0.0001$, $d = 2.44$, when the chin and hairline were removed (M: 40.10% overestimation of width), $t(18) = 9.43$, $p < 0.0001$, $d = 2.16$, and when all four landmarks were removed (M: 36.96% overestimation of width), $t(18) = 8.14$, $p < 0.0001$, $d = 1.87$.

In order to investigate whether there are links between the distortions we have reported on the hand and on the face, we investigated correlations across participants in the magnitude of these effects. First, we compared the underestimation of finger length on the hand (i.e., the mean percentage underestimation of finger length averaged across the five fingers) to the underestimation of face height (i.e., the distance between the hairline and chin). Given the relatively small sample size for investigating correlation, we used a non-parametric correlation (Spearman's rho). There was a significant correlation between the magnitude of underestimation of length on the hand and face, $rho = 0.521$, $p < 0.05$. We next compared the analogous correlation for body part width, using overestimation of the distance between the knuckles of the index and little fingers for the hand and the mean of the six pairs with left-right homologues on the face. There was no significant correlation between the magnitude of overestimation of width on the hand and face, $rho = 0.028$.

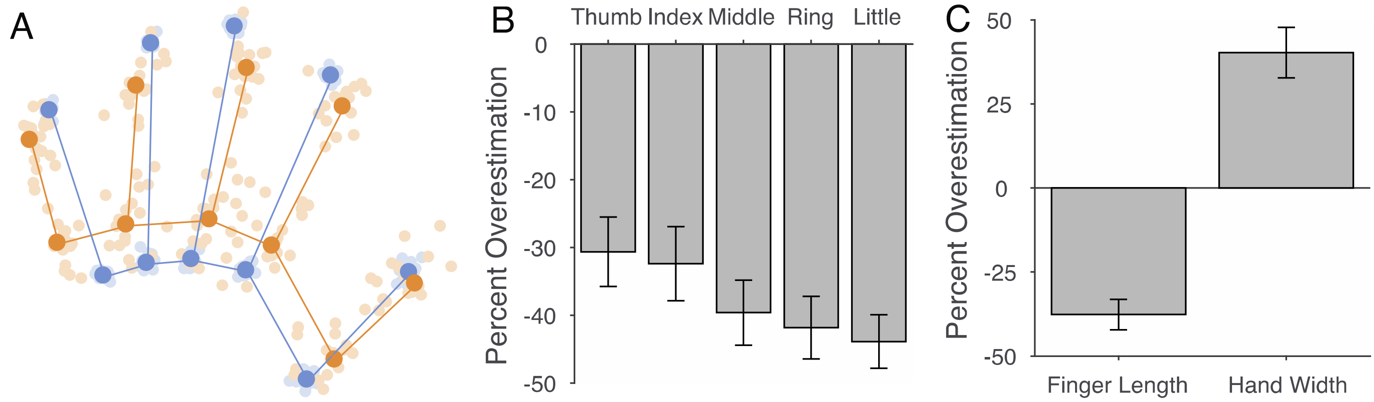

Fig. 2. Results from the hand mapping task. *Panel A*: Perceptual hand maps from individual participants (pale orange dots) placed into Generalised Procrustes alignment with maps of actual hand shape (pale blue dots). The dark dots and lines show the grand average shape of the perceptual maps (orange) and actual hand shape (blue). *Panel B*: Perception of finger length. Across all five fingers there was underestimation of finger length, which increased monotonically from the thumb to the little finger. *Panel C*: Percent overestimation of finger length (i.e., the average of the five fingers) and hand width (i.e., the distance between the knuckles of the index and little fingers). In contrast to the underestimation of finger length, there was large overestimation of hand width. Error bars are one standard error of the mean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

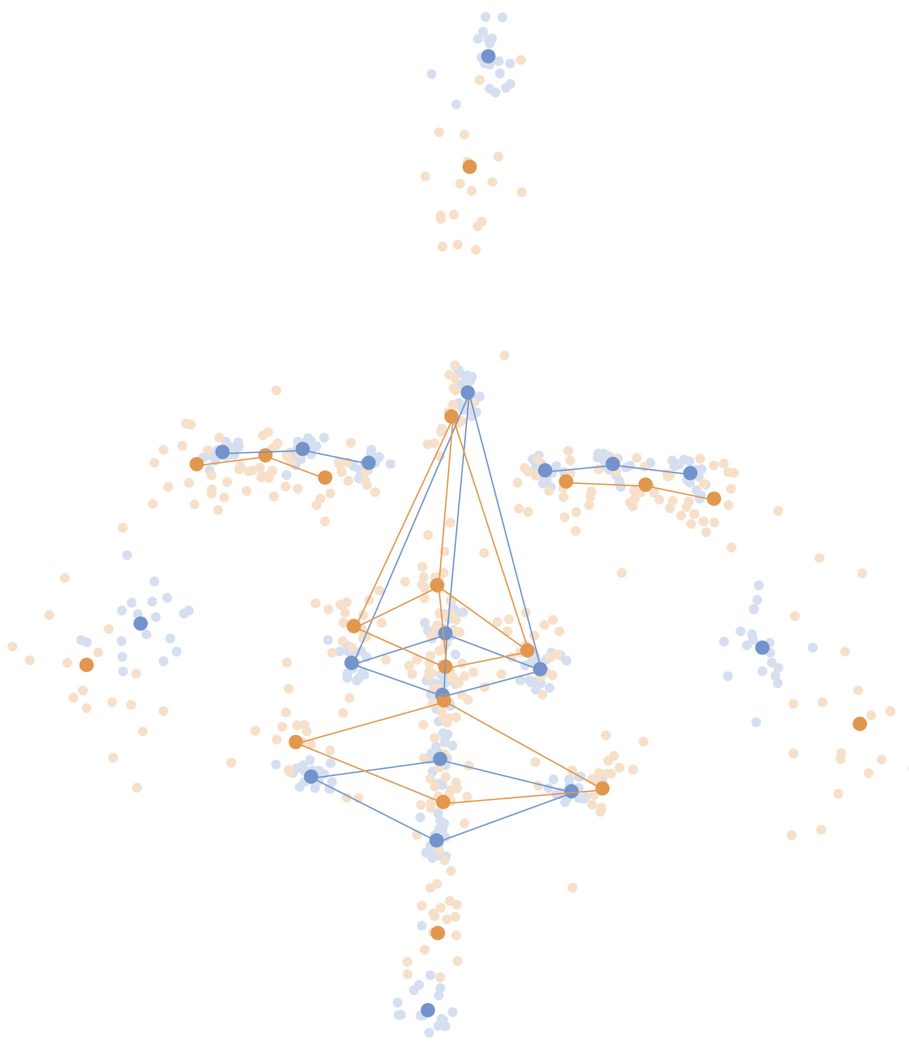

Fig. 3. Perceptual face maps from individual participants (pale orange dots) placed into Generalised Procrustes alignment with maps of actual face shape (pale blue dots). The dark dots show the grand average shape of the perceptual maps (orange) and actual face shape (blue). There is no good way to draw lines to make on overall face shape analogous to the hand skeleton in Fig. 2a. However, lines have been added connecting the landmarks of the eyes, nose, and mouth, to give a general sense of the overall configuration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

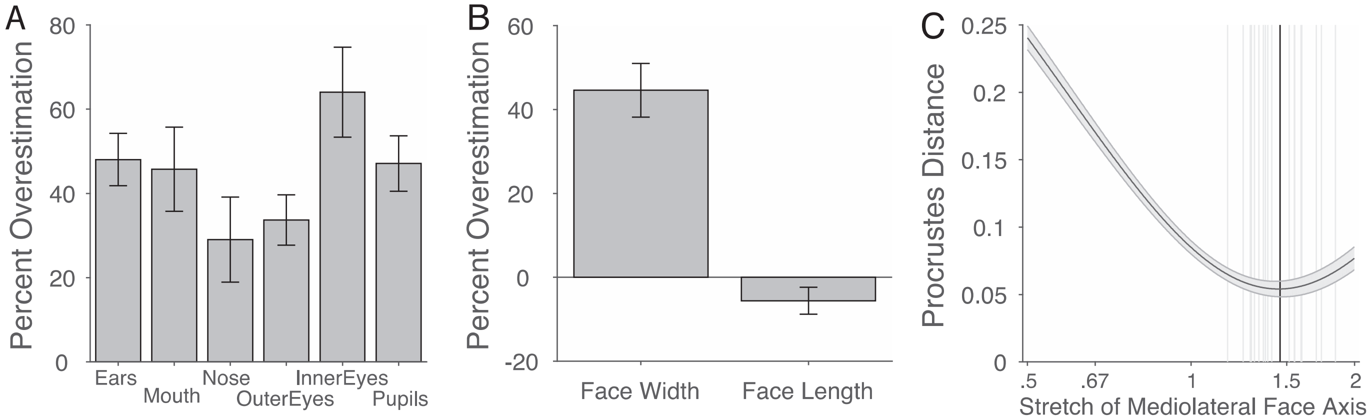

Fig. 4. Results from the face mapping task. *Panel A*: Percent overestimation of distances between pairs of landmarks with left-right homologues. Clear overestimation was apparent for all six pairs. *Panel B*: Percent overestimation of face width (i.e., the average of the six left-right pairs) and face length (i.e., the distance between the chin and the centre of the hairline). In contrast to the overestimation of face width, there was no significant deviation of fact length from its actual size. Error bars are one standard error of the mean. *Panel C*: Mean Procrustes distance between perceptual face maps and the actual shape of each participant's face which was stretched in the medio-lateral axis by various amounts. A stretch of 1 indicates the actual shape of each face; stretches greater than 1 indicate wide, fat face shapes; stretches less than 1 indicate tall, slender face shapes. The shaded region indicates one standard error of the mean. The light grey vertical lines indicate the stretch that minimized the Procrustes distance for each individual participant, while the black vertical line is the average of these numbers. For all participants, the best-fitting face shape to perceptual maps was stretched in the medio-lateral face axis, indicating that participants overestimated face width.

3.3. Laterality effects

We performed the same stretch analysis separately for the left and right sides of the face. Clear stretch in the medio-lateral axis was apparent for both the left side of the face (*M*: 41.2% overestimation of width), $t(18) = 11.21$, $p < 0.0001$, $d = 2.57$ (Fig. 6, left panel), and the right side of the face (*M*: 48.0% overestimation of width), $t(18) = 13.27$, $p < 0.0001$, $d = 3.04$ (Fig. 6, right panel). There was a non-significant trend for stretch to be larger for the right than the left side of the face, $t(18) = 2.07$, $p = 0.053$, $d_z = 0.48$, in the same direction as that reported by Mora et al. (2018). There was a strong correlation across participants between the magnitude of stretch on the two sides of the face, Spearman's $rho(17) = 0.718$, $p < 0.001$.

The correlation between the stretch for the two sides of the face shows that there are consistent person-to-person differences in these maps that are consistent across both sides of the face. Are there also systematic differences between maps on the two sides? To address this question, we compared the similarity (quantified by the Procrustes distance) between the left and right perceptual maps for each participant and the grand average of left and right side perceptual maps for the 18 other participants. If there are systematic differences between perceptual maps of the two sides of the face that are consistent across people, matching maps (i.e., left/left, right/right) should be more similar (i.e., have a smaller Procrustes distance) than mis-matching maps (i.e., left/right, right/left). Indeed, the mean Procrustes distance was significantly smaller for matching maps (*M*: 0.0411) than for mis-matching maps (*M*: 0.0464), $t(18) = 4.21$, $p < 0.001$, $d_z = 0.96$. This suggests that there are systematic differences between perceptual maps of the two sides of the face, which are likely to be more complex than one side simply being more distorted than the other.

3.4. Eye height

As described in the Introduction, Carbon and Wirth (2014) found highly systematic distortions of the placement of the eyes in drawings of faces, whether of the participant's own or of someone else's. In particular, they found that the eyes were placed too high in the head. To investigate whether similar distortions were apparent in our face maps, we projected the location of all 6 eye landmarks (pupil, inner edge, and outer edge of each eye) onto the face midline of both actual and perceived faces and calculated eye height as a percentage of the distance from the chin to the hairline. Collapsed across the 6 eye landmarks, there was a non-significant trend for eyes to be judged as slightly higher than their actual location (59.63%, *SD*: 5.10%, of the distance from chin

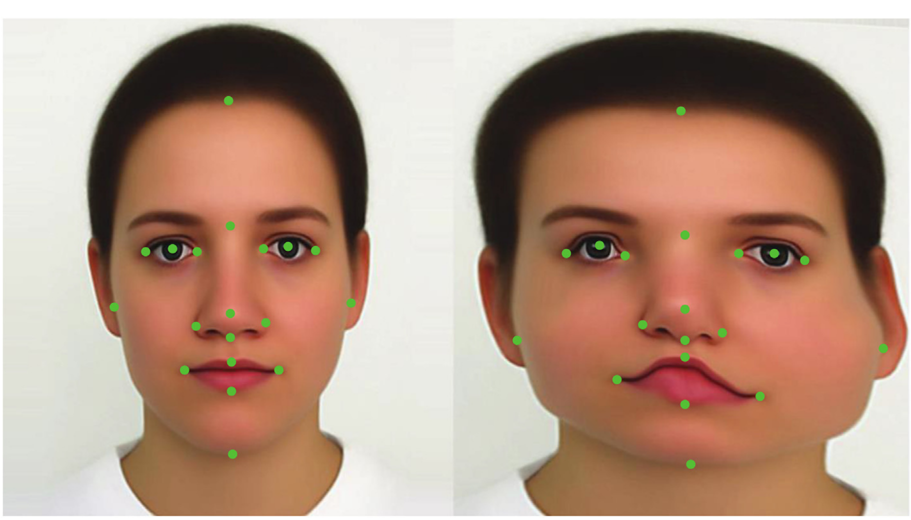

Fig. 5. Graphic depiction of the distortions in the face mapping task. The *left panel* shows an image of an average female face warped to have the same shape as the grand average of the actual faces of our 19 participants. The *right panel* shows the same base image warped to have the same shape as the grand average of the perceptual maps. The base image used for the warps is an average of 64 female images created by Martin Gruendl and is used with permission.

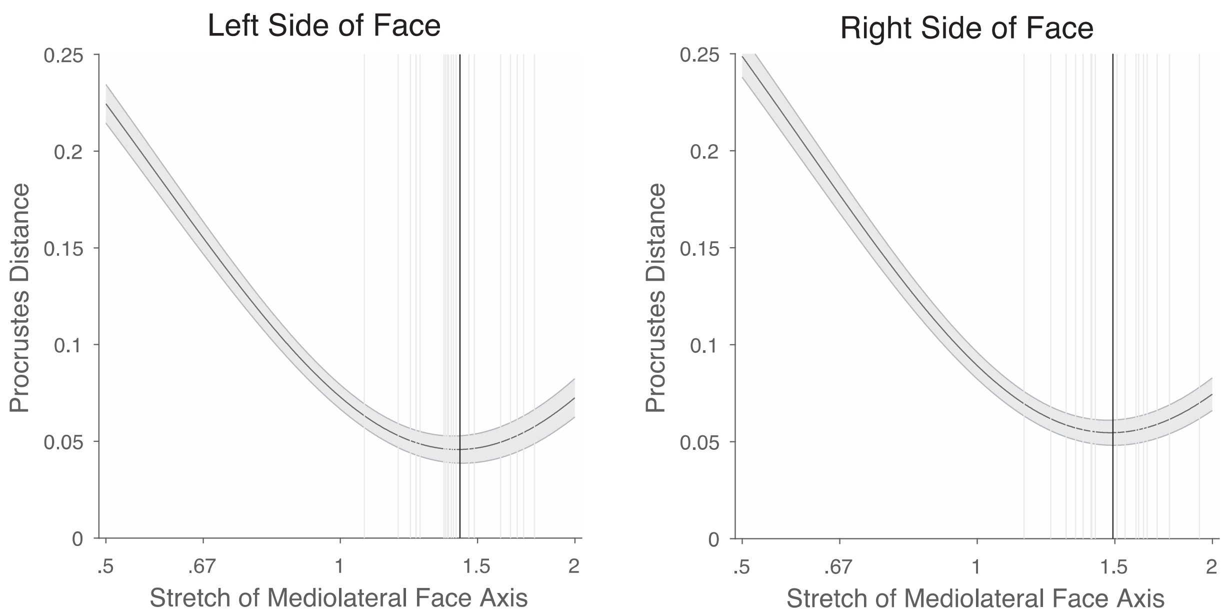

Fig. 6. *Left panel*: Mean Procrustes distance between perceptual face maps and actual maps of the left side of the face mirrored symmetrically around the proximo-distal face axis, for various stretches applied to the actual face maps. The shaded region indicates one standard error of the mean. The light grey vertical bars indicate the stretch that minimized the Procrustes distance for each individual participant, while the black vertical line is the average of these numbers. *Right panel*: the same data for the right side of the face. For both sides of the face, there was clear evidence that perceptual maps were stretched along the medio-lateral face axis.

to hairline vs. 57.43%, *SD*: 2.45%, on actual faces), $t(18) = 1.77$, $p = 0.094$, $d = 0.405$.

3.5. Upper vs lower face

The lack of significant under- or overestimation of face height reported above is consistent with the findings of Mora et al. (2018). These authors did, however, report differences within the face, the upper face (i.e., the hairline to the tip of the nose) being underestimated and the lower face (i.e., the tip of the nose to the chin) slightly overestimated. We therefore investigated these same pairs of landmarks in our data. There was clear underestimation of the upper face (*M*: 14.46% underestimation, *SD*: 12.96%), $t(18) = -4.86, p < 0.0001, d = 1.12$. There was overestimation of the lower face (*M*: 11.63% overestimation, *SD*: 31.36%), though this was not statistically significant, $t(18) = 1.62$, $p = 0.12$, $d = 0.37$. The magnitude of underestimation was significantly bigger on the upper than on the lower face, $t(18) = 3.70$, $p < 0.002$, $d = 0.85$. These results are consistent with the pattern reported by Mora and colleagues.

4. Discussion

These results show large and highly-stereotyped distortions of perceived face size and shape, with substantial overestimation of face width, but not face length. These results replicate the main findings of the recent study by Mora et al. (2018), who also reported large overestimation of face width using a similar paradigm. This shows that the distorted proprioceptive maps we have reported previously (Longo & Haggard, 2010) are not specific to the hand, but appear to reflect the representation of the body more widely, even body parts such as the face which are central to personal identity. Indeed, we find that the magnitude of distortions is broadly comparable on the hand and face, and as least in the case of length is correlated across participants.

The present results provide a clear conceptual replication of the main findings of Mora et al. (2018) study. Our results not only replicate the overestimation of face width compare to length reported by that study, but also replicate the reported differences between the top and bottom halves of the face. In addition, our results provide some evidence in support of the claim of Mora et al. that there are lateral asymmetries between the representations of the left and right sides of the face. Despite emphasizing that laterality effect, none of the statistical results reported in their paper actually demonstrated systematic differences between the right and left sides of the face. We found a trend for larger distortions on the right than the left side of the face (i.e., in the direction reported by Mora et al.) that just barely missed statistical significance. Thus, the question of lateral asymmetries in face representation remains ambiguous and should be further studied in future research. It is also worth noting that there were several differences between the two studies. The present study used a larger number of landmarks (19 vs. 11) than Mora and colleagues. In addition, whereas Mora and colleagues asked participants to respond using their fingertip, whereas we asked them to respond using a short stick. It is known that people are able to localise touch from wielded tools (Chan & Turvey, 1991; Miller et al., 2018), and one previous study found that perceptual hand maps could be produced from responses with a held stick in the absence of vision (Longo, 2014). That such similar results are found despite differences in the specific landmarks used and in the manner of responding provides evidence for the generality of these distortions.

Studies using explicit body size estimation procedures, such as visual comparison (Shontz, 1969), the moving caliper procedure (Dolan et al., 1987; Halmi et al., 1977), the adjustable light-beam apparatus (Dolce et al., 1987; Thompson & Thompson, 1986), and the image marking procedure (Meermann, 1983), have generally found overestimation of face width. The paradigm we used in this study differs from these methods in that participants were not asked to judge the distance between body parts, but only to judge the location of individual landmarks. It is thus notable that similar overestimation of face width is apparent in both cases. Indeed, overestimation of width has been found for the face in a variety of other tasks (e.g., Bianchi et al., 2008; D'Amour & Harris, 2017; Fiori & Longo, 2018; Fuentes, Runa, et al., 2013c; Longo, Ghosh, & Yahya, 2015a), as well as for several other body parts such as the hands (e.g., Longo & Haggard, 2010, 2011, 2012a, 2012b), the waist and hips (e.g., Dolan et al., 1987; Dolce et al., 1987; Shontz, 1969), the legs (Dolce et al., 1987; Green, 1982; Meermann, 1983), and the body as a whole (Fuentes, Longo, and Haggard, 2013a; Fuentes, Pazzaglia, et al., 2013b). The consistency with which overestimation of body width occurs, across a range of measurement methods and a range of body parts suggests it may be a quite general aspect of the mental representation of the body (Longo, 2017; Tamè, Azañón, & Longo, 2019). A large body of research has focused on the overestimation of body width seen in patients with eating disorders, such as anorexia nervosa and bulimia nervosa (Bruch, 1962; Cash & Deagle, 1997; Slade & Russell, 1973). Our results contribute to a growing body of evidence showing that such distortions, far from being a definite sign of pathology, are a normal part of healthy mental life.

The present results do, however, provide an intriguing contrast to those of Edwards et al. (2005) who found that grasping responses to facial landmarks were unusually precise. The pointing responses we used in this study may differ fundamentally from grasping. Several studies have found differences between pointing and grasping for spatial judgments such as line bisection (Edwards & Humphreys, 1999; Robertson et al., 1995) and judging the location of another person's body parts (Cleret de Langavant et al., 2009), with grasping performance showing less bias in each case. Similarly, unexpected changes in the location of a target object produce faster trajectory corrections for grasping than for pointing (Carnahan et al., 1993). Thus, grasping responses such as those used by Edwards and colleagues may rely on a different – and more veridical – source of information about the body than pointing responses such as we used in this study. This dissociation may be related to the dissociation between somatosensory processing for perception vs. action proposed by Dijkerman and de Haan (2007).

In their influential model of categorical face processing, Maurer et al. (2002) distinguish between three types of configural information: (1) 'first-order' spatial relations regarding the basic spatial arrangement of the face, (2) holistic processing of the face as a single Gestalt, and (3) 'second-order' spatial relations regarding the precise metric distances between landmarks. It is notable that the distortions we observed only affect the last of these, with perceptual maps preserving first-order spatial relations and the overall arrangement of a face. Recent studies of familiar face recognition have found surprising levels of tolerance for changes in the aspect ratio of the face (Hole et al., 2002; Sandford & Burton, 2014), suggesting that perceptual distortions of the face such as we describe may not critically impair self-recognition.

The present results along with those or Mora et al. (2018) provide evidence for different distortions of the upper and lower regions of the face. Differences in the neural representation of the upper and lower face in the somatosensory cortex have been reported since the classic work of Woolsey and colleagues (Ullrich & Woolsey, 1954; Woolsey et al., 1942) and confirmed by more recent neurophysiological work (Jain et al., 2001). There are documented double-dissociations of apraxia affecting the upper and lower face (Bizzozero et al., 2000) and independent distortions of these regions have also been reported in other types of localization paradigm (Fuentes, Runa, et al., 2013c). The upper and lower face are innervated by different branches of the trigeminal nerve, and these distinctions are known to be preserved in the somatosensory cortex (Dreyer et al., 1975). It is therefore an intriguing possibility that the differential distortions of the upper and lower face found in the present paradigm may reflect these low-level differences in the representations of these areas.

CRediT authorship contribution statement

Matthew R. Longo:Conceptualization, Methodology, Software, Formal analysis, Visualization, Supervision, Funding acquisition, Project administration, Writing - review & editing.**Marie Holmes**:Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft.

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