

RUNNING HEAD: Intuitive Anatomy

Intuitive Anatomy:
Distortions of Conceptual Knowledge of Hand Structure

Matthew R. Longo

Department of Psychological Sciences, Birkbeck, University of London

London WC1E 7HX, United Kingdom. m.longo@bbk.ac.uk

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Abstract

Knowledge of the spatial layout of bodies is mediated by a representation called the *body structural description*, damage to which results in the condition of autotopagnosia in which patients are impaired in judgments about the location and configuration of body parts. While a large literature has investigated disruption of the body structural description, little research has examined its accuracy in healthy individuals. I show that people have systematically distorted knowledge of the configuration of hands. Participants judged the location of their knuckles (i.e., the metacarpalphalangeal joint) by pointing with a baton on their palm. Participants showed clear distal biases, judging their knuckles as farther forward in the hand than they actually are for all fingers except the thumb. This effect appeared both when participants localized the knuckles of their own hand and another person's hand. These results suggest that intuitive beliefs about body form are systematically distorted.

Introduction

The English language holds up the hand as a paragon case of profound familiarity and intimate knowledge. To say that one knows something “like the back of my hand” is to emphasize the depth and accuracy of one’s knowledge of that thing. Such expressions suggest that we have highly accurate, or even infallible, knowledge of our bodies. There are, however, several reasons for suspecting that conceptual knowledge of the body might be inaccurate. First, research has demonstrated that even the most familiar objects may be remembered inaccurately, such as the U.S. penny in a classic study (Nickerson & Adams, 1979). Second, research investigating naive understanding of other domains such as physics (McCloskey, Caramazza, & Green, 1980; McIntyre, Zago, Berthoz, & Lacquaniti, 2001) and biology (Gelman & Wellman, 1991; Simons & Keil, 1995) has shown remarkably inaccurate beliefs. Finally, recent studies have documented large perceptual distortions of body representations underlying perceptual abilities including touch (Longo & Haggard, 2011; Taylor-Clarke, Jacobsen, & Haggard, 2004) and position sense (Longo & Haggard, 2010, 2012). These highly consistent perceptual distortions have been interpreted as reflecting implicit representations of the body, distinct from our explicit, conscious experience of our body. They nevertheless raise the question whether conceptual knowledge of hand structure may also be distorted in systematic ways.

Studies of neurological patients have shown that knowledge of human bodies is a distinct semantic domain, which can be selectively impaired or spared following brain insult (Coslett, Saffran, & Schwoebel, 2002; Kemmerer & Tranel, 2008; Laiacona, Allamano, Lorenzi, & Capitani, 2006). Knowledge of the spatial layout of the body is mediated by a representation called the *body structural description*, damage to which results in the condition of autotopagnosia in which patients are impaired in judgments about the location and configuration of body parts (Buxbaum & Coslett, 2001; Schwoebel & Coslett, 2005;

Sirigu, Grafman, Bressler, & Sunderland, 1991). Neuroimaging studies have localized the body structural description to the left parietal lobe (Corradi-Dell'Acqua et al., 2008; Felician et al., 2004; Rusconi et al., 2014), consistent with the location of lesions that cause autotopagnosia. Little research, however, has examined the nature of the body structural description in healthy people.

This study investigates conceptual knowledge of hand structure, finding highly stereotyped distortions in knowledge of knuckle location. Participants placed either their left or right hand palm-up on a table and judged the location of each knuckle (i.e., the metacarpophalangeal joint) by positioning the tip of a baton directly on their skin. In Experiment 1, participants responded with both visual and tactile cues. In Experiment 2 they responded without vision relying only on tactile cues. Finally, in Experiment 3, participants judged the location of the knuckles of both their own hand and the experimenter's hand. Across experiments, participants judged their knuckles as substantially too far forward in the hand.

Methods

Participants

Thirty people participated, ten in each experiment (Experiment 1: 7 women, M : 32.9 years, range: 19-53 years; Experiment 2: 6 women, M : 29.4 years, range: 19-40 years; Experiment 3: 5 women, M : 30.1 years, range: 19-45 years). Participants were generally right-handed as assessed by the Edinburgh Inventory (Experiment 1: M : 63.5, range: -82.6 - 100; Experiment 2: M : 71.9, range: -95.5 - 100; Experiment 3: M : 44.5, range: -91.7 - 100). One additional participant in Experiment 2 was excluded because he couldn't hold his hand flat and was replaced. Participants gave informed consent and procedures were approved by the local ethics committee.

Procedures

Participants sat with their hand resting palm-up on a table. A webcam (Logitech Webcam Pro 9000 HD) was suspended from a tripod directly above the table, pointing straight down. Photographs (1600 x 1200 pixels) were captured by a custom MATLAB script (Mathworks, Natick, MA) and saved for offline coding. A 10 cm ruler on the table allowed conversion between pixels and cm. At the end, photographs were taken of the back of each of the participant's hands to allow calculation of actual knuckle location. To avoid ambiguity in coding of knuckle location, a small black mark was made on each knuckle (i.e., the centre of the bump formed by each knuckle when the participant made a fist).

The experimenter explained that the study involved judgments about the location of the knuckles, indicating that this meant the joint all the way at the very base of the finger. The experimenter pointed to the knuckle of his own hand to make sure participants understood which landmark they were being asked to localize. Participants used a metal baton (35-cm length and 2-mm diameter) to indicate the location of each knuckle on the palm of their hand by placing the tip of the baton on the palm directly above each knuckle. Responses were untimed and participants were instructed to be careful and deliberate in their responses. They were free to move the baton as much as they liked and to adjust their response until they were satisfied. When the participant indicated verbally that they were happy with their response, the experimenter pressed a button on the keyboard to capture the photograph. To avoid hysteresis effects, participants moved the baton to the side of the table after each response.

In Experiment 1, there were four blocks of 25 trials, two blocks each of the right and left hands. The blocks were counterbalanced in ABBA order, with the first condition counterbalanced across participants. Participants held the baton in whichever hand was not

being judged. Each block consisted of five mini-blocks, each including one judgment of each finger in randomized order.

Experiment 2 was identical to Experiment 1 except that participants were asked to close their eyes while responding, relying only on tactile feedback about the location of responses. Participants were asked not to look at their hands during the study, though they were shown the experimenter's hand so that he could indicate which landmarks they were being asked to judge.

In Experiment 3, participants made judgments (with vision) of the location of the knuckles of their own left hand or the left hand of the experimenter, which was placed in on the board in front of the participant.

Analysis

From each photograph, the x-y pixel coordinates were calculated for: (1) the tip of the finger being judged, (2) the center of the crease at the base of each finger on the palm, and (3) the judged location of the knuckle. From these, distances from the tip to the crease and from the tip to the response were calculated and converted to cm. The actual distance from each fingertip to the knuckle was calculated from the photographs of the back of each hand taken at the end of the experiment. From these values, distal bias was calculated as the difference between these distances for the responses and actual knuckle location, as a percentage of actual finger length. 95% confidence intervals were computed using bootstrapping with 10,000 samples. As effect size estimates, Cohen's d was calculated for one-sample t-tests and d_z for paired t-tests.

Results

Experiment 1: Localization with Both Vision and Touch

Results are shown in Figure 1. As is clear from panels 1a and 1b, participants distally mislocated their knuckles (i.e., closer to the fingertips) for all fingers on both hands, except the thumbs. Panel 1c shows this distal bias as a percentage of actual finger length. Across fingers, there were clear distal biases on both the left hand ($M: 9.59\%$), $t(9) = 5.22$, $p < 0.001$, $d = 1.65$, and the right hand ($M: 10.18\%$), $t(9) = 6.17$, $p < 0.0005$, $d = 1.95$ (Fig. 1C). The effect was even stronger without the thumb included: left hand ($M: 11.20\%$), $t(9) = 5.37$, $p < 0.001$, $d = 1.70$; right hand: ($M: 11.25\%$), $t(9) = 5.39$, $p < 0.001$, $d = 1.70$. This effect was significant for all eight non-thumb fingers (all p 's < 0.002 , d 's > 1.49). There was no difference between the left and right hands, whether the thumb was included, $t(9) = 0.58$, *n.s.*, $d_z = 0.18$, or not, $t(9) = 0.07$, *n.s.*, $d_z = 0.02$. The amount of distal bias on the non-thumb fingers of the two hands was strongly correlated, $r(8) = 0.960$, $p < 0.0001$ (Fig. 1D).

Responses were made proximal to the crease at the base of each finger on the palm for all fingers except the thumb (Fig. 1A-B). Across fingers, this difference was clearly significant for both the left hand ($M: 9.35\%$ of total finger length), $t(9) = 4.91$, $p < 0.001$, $d = 1.55$, and the right hand ($M: 9.02\%$), $t(9) = 4.79$, $p < 0.001$, $d = 1.51$. This effect was significant for all eight non-thumb fingers (all p 's < 0.002 , d 's > 1.45). Across the non-thumb fingers, there was a strong correlation between the size of this effect on the two hands, $r(8) = 0.985$, $p < 0.0001$. This effect demonstrates that the distal bias in knuckle localization does not reflect confusion between the knuckle and the crease.

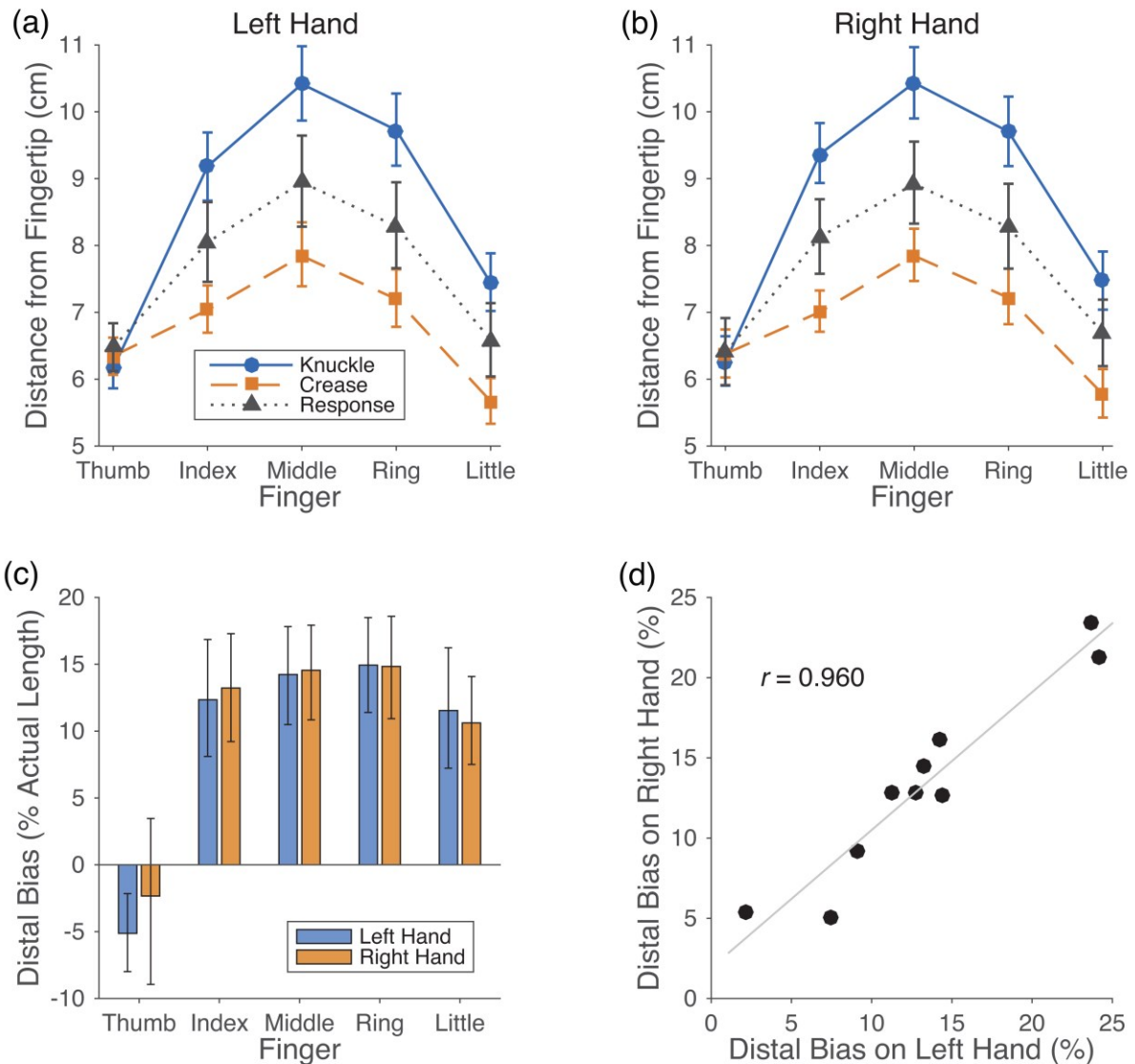


Figure 1: Results from Experiment 1. **(A-B)** Distances from the tip of each finger to the knuckle, the crease at the base of each finger on the palm, and participants' judgments of knuckle location for the left hand (A) and right hand (B). Participants judged their knuckles as distal to their actual location, but proximal to the crease. **(C)** Distal bias expressed as a percentage of the actual length of each finger. Clear distal biases were apparent for all non-thumb fingers. **(D)** Scatterplot showing the relation between distal bias on the non-thumb fingers of the two hands. Bias on the two hands was strongly correlated across participants. Error bars are 95% confidence intervals.

Experiment 2: Localization with Touch Alone

Experiment 2 replicated the results from the first experiment and investigated whether the effect might reflect a visual estimation bias or a visual attraction effect from the crease at the base of each finger on the palm. The procedure was identical to Experiment 1 except that participants kept their eyes closed while responding, so that judgments were based entirely on

tactile information. The results were nearly identical to Experiment 1 (Fig. 2A-D). An overall distal bias was apparent for both the left hand ($M: 7.51\%$, $t(9) = 3.74$, $p < 0.005$, $d = 1.18$, and the right hand ($M: 6.17\%$, $t(9) = 2.84$, $p < 0.02$, $d = 0.90$ (Fig. 2C). These effects were stronger without the thumb included: left hand ($M: 12.65\%$, $t(9) = 7.21$, $p < 0.0001$, $d = 2.28$; right hand ($M: 11.34\%$, $t(9) = 5.92$, $p < 0.0005$, $d = 1.87$. Indeed, unlike Experiment 1, there were strong effects in the opposite direction for both the left thumb ($M: -13.06\%$, $t(9) = -3.34$, $p < 0.01$, $d = 1.06$, and the right thumb ($M: -14.50\%$, $t(9) = -3.69$, $p < 0.01$, $d = 1.17$. There was no difference in magnitude between distal bias on the two hands, whether the thumb was included, $t(9) = 0.87$, $n.s.$, $d_z = 0.28$, or not, $t(9) = 1.12$, $n.s.$, $d_z = 0.35$. The distal bias for the non-thumb fingers was strongly correlated between the two hands, $r(8) = 0.799$, $p < 0.01$ (Fig. 2D).

As in Experiment 1, responses were made proximal to the crease at the base of each finger on the palm, both the left hand ($M: 11.54\%$, $t(9) = 5.77$, $p < 0.0005$, $d = 1.82$, and the right hand ($M: 11.71\%$, $t(9) = 5.71$, $p < 0.0005$, $d = 1.80$ (Fig. 2A-B). This effect was clearly significant for all eight non-thumb fingers (all p 's < 0.001 , d 's > 1.67), and unlike Experiment 1 was also apparent for both the left thumb ($M: 13.26\%$, $t(9) = 3.41$, $p < 0.01$, $d = 1.08$, and the right thumb ($M: 9.68\%$, $t(9) = 2.35$, $p < 0.05$, $d = 0.74$. Across the non-thumb fingers there was a clear correlation between the two hands, $r(8) = 0.887$, $p < 0.001$.

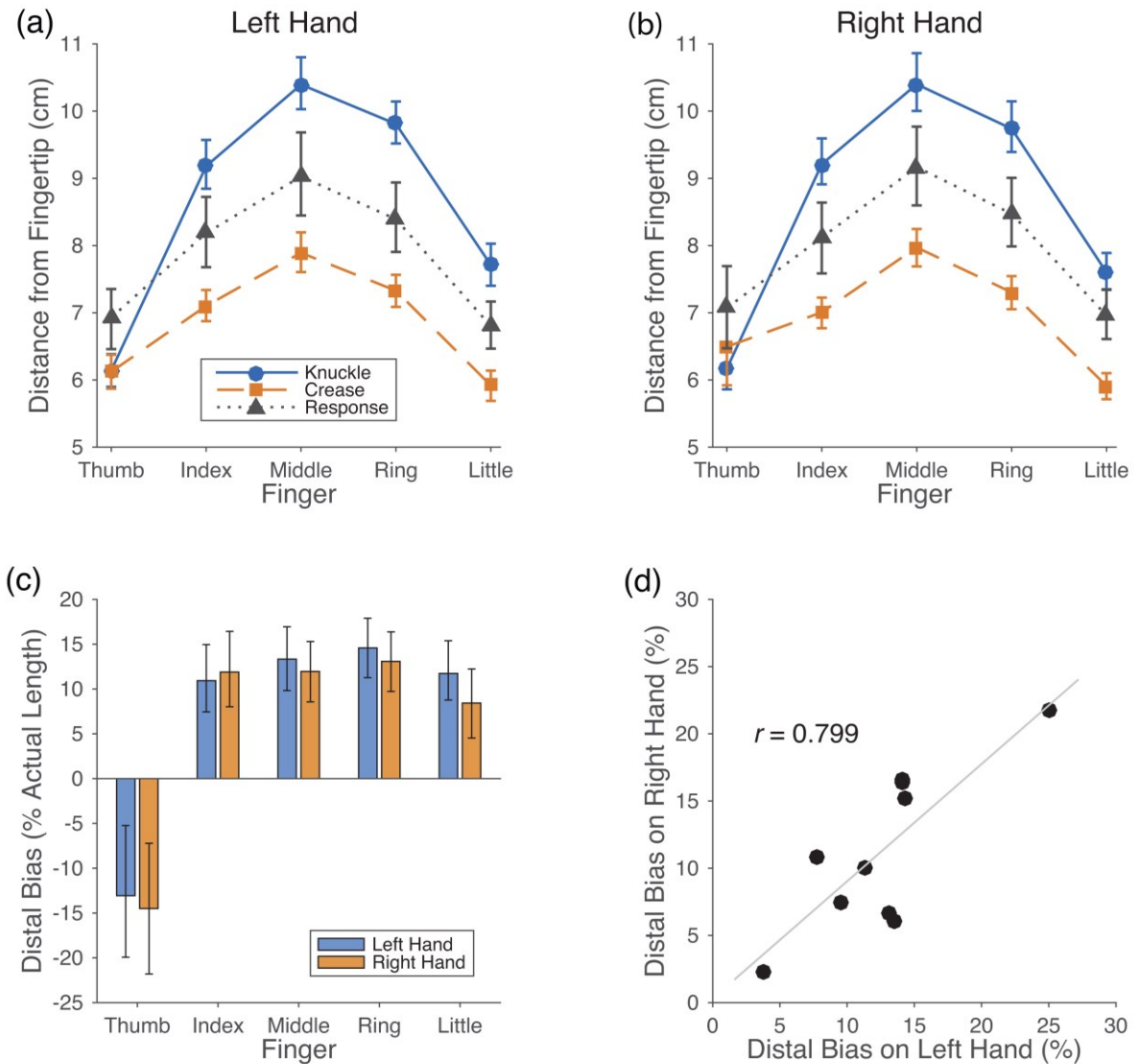


Figure 2: Results from Experiment 2 in which participants responded without vision. **(A-B)** Distances from the tip of each finger to the knuckle, the crease at the base of each finger on the palm, and participants' judgments of knuckle location for the left hand (A) and right hand (B). Participants judged their knuckles as distal to their actual location, but proximal to the crease. **(C)** Distal bias expressed as a percentage of the actual length of each finger. Clear distal biases were apparent for all non-thumb fingers. **(D)** Scatterplot showing the relation between distal bias on the non-thumb fingers of the two hands. Bias on the two hands was strongly correlated across participants. Error bars are 95% confidence intervals.

Experiment 3: Effects Generalize to Other People's Hands

Patients with autopagnosia are generally impaired when making judgments about the spatial configuration of not only their own body, but also those of other people and even or mannequins (Gerstmann, 1942; Sirigu et al., 1991). If the effect reported in the first two experiments reflects distortions of conceptual knowledge, it should show up also when

people judge the location of the knuckles of someone else's hand. Thus, Experiment 3 compared judgments of knuckle location on the participant's own left hand and the experimenter's left hand.

Results are shown in Figure 3. As in the first two experiments, there was a clear distal bias for the participant's own hand ($M: 10.92\%$), $t(9) = 6.26$, $p < 0.0001$, $d = 1.98$ (Fig. 3). More critically, the same bias was found for the other person's hand ($M: 10.82\%$), $t(9) = 10.83$, $p < 0.0001$, $d = 3.43$ (Fig. 3C). The effect was stronger without the thumb: own hand ($M: 14.53\%$), $t(9) = 10.85$, $p < 0.0001$, $d = 3.43$; other person's hand ($M: 13.04\%$), $t(9) = 13.86$, $p < 0.0001$, $d = 4.38$. The effect was clearly significant for all eight non-thumb fingers (all p 's < 0.001 , d 's > 1.98). There was no significant difference in distal bias on the participant's own hand and the experimenter's hand, whether the thumb was included, $t(9) = 0.07$, $d_z = 0.02$, or not, $t(9) = 1.86$, $d_z = 0.59$. Across the non-thumb fingers there was a strong correlation between distal bias on the two hands, $r(8) = 0.807$, $p < 0.005$ (Fig. 3D).

As in the first two experiments, judgments were made proximal to the crease at the base of the fingers, both for the participant's own hand ($M: 7.60\%$), $t(9) = 5.25$, $p < 0.001$, $d = 1.66$, and the other person's hand ($M: 9.17\%$), $t(9) = 9.34$, $p < 0.0001$, $d = 2.95$. This effect was significant for all non-thumb fingers (all p 's < 0.001 , d 's > 1.54). Across the non-thumb fingers, there was a significant correlation between the magnitude of this effect on the two hands, $r(8) = 0.892$, $p < 0.001$.

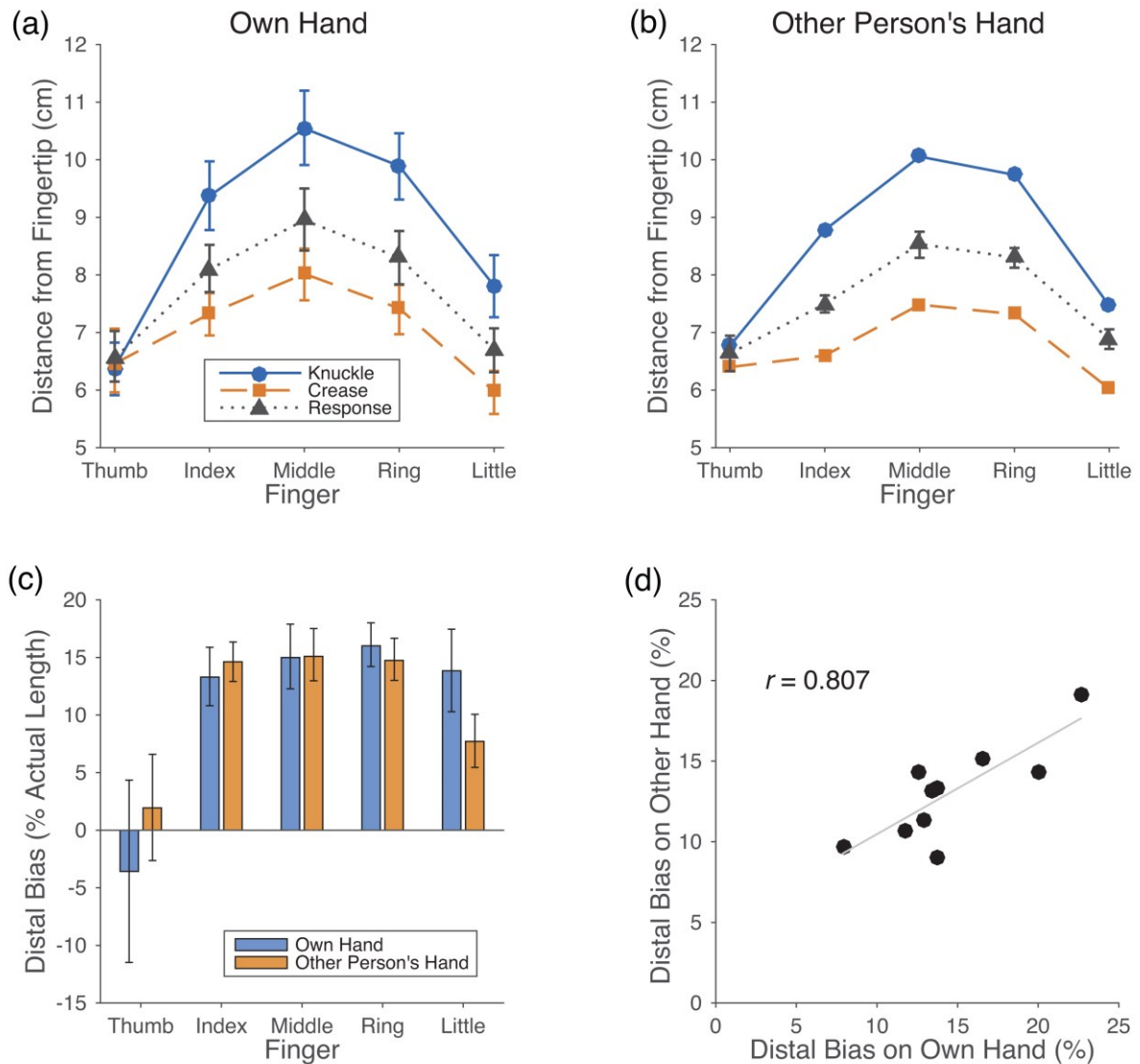


Figure 3: Results from Experiment 3 in which participants judged their own left hand or another person's hand. **(A-B)** Distances from the tip of each finger to the knuckle, the crease at the base of each finger on the palm, and participants' judgments of knuckle location for their own hand (A) and the other person's hand (B). Participants judged knuckles as distal to their actual location, but proximal to the crease. Note that there are no error bars for the knuckles and creases of the other person's hand because it was always the same hand. **(C)** Distal bias expressed as a percentage of the actual length of each finger. Clear distal biases were apparent for all non-thumb fingers. **(D)** Scatterplot showing the relation between distal bias on the non-thumb fingers of the two hands. Bias on the two hands was strongly correlated across participants. Error bars are 95% confidence intervals.

Discussion

People think their knuckles are farther forward in the hand than they actually are. This effect appears whether participants make their judgments with vision (Experiment 1) or purely through touch (Experiment 2). Further, it appears both when people judge the location

of their own knuckles and those of another person (Experiment 3), demonstrating that it reflects distorted conceptual knowledge of hand structure. Like the U.S. penny in Nickerson and Adams's (1979) classic study, people have remarkably inaccurate representations of the spatial layout of their hand. Unlike the penny, however, the hand representation is not merely inaccurate, but systematically distorted in a highly stereotyped way. All thirty participants across the three experiments showed distal bias for the non-thumb fingers in all conditions tested.

Among body parts, joints are believed to be particularly critical in providing spatial structure to bodily experience (Bermúdez, 1998). Joints are known to function as reference points for tactile localization (Cholewiak & Collins, 2003; Weber, 1834/1996) and to provide segmental boundaries for categorical perception of touch (de Vignemont, Majid, Jola, & Haggard, 2009; Le Cornu Knight, Longo, & Bremner, 2014). Bermúdez (1998) emphasizes the importance of joints as “hinges” for segmenting the body into parts. Thus, joints, and especially those – like the knuckles – which form a lexically-coded boundary in English and other languages, should be among the most spatially-salient body parts. It would be unsurprising if people were inaccurate in localizing internal organs, such as the spleen or gall bladder. But as the hinges of the hand, the systematic mislocalisation of the knuckles reported here is more striking.

Why do people misunderstand where their knuckles are located? One possibility is that this effect may be related to the distal bias seen for tactile localization on the hand dorsum recently reported by Mancini and colleagues (2011). Both effects could result from the known effect of intracortical inhibition in somatosensory cortex to shift receptive fields distally (Alloway, Rosenthal, & Burton, 1989). Such an interpretation in terms of low-level somatosensory mechanisms would not obviously predict that the effect would generalize to another person's hand as found in Exp 3, although this could be explained in terms of a

somatosensory ‘mirror’ system (cf. Keyzers, Kaas, & Gazzola, 2010). Another possibility is that the crease at the base of each finger on the palm may serve as an attentional attractor, biasing responses. While the present results showed that participants did not overtly confuse the knuckle and the crease, they do not directly rule out such an attentional interpretation. The absence of a localization bias on the thumb is potentially consistent with this interpretation, since the thumb is the one digit in which there is no deviation between the locations of the knuckle and the crease. However, the most natural way the crease could biasing localization would be for it to serve as a visual attractor. This interpretation, however, is ruled out by the results of Exp 2, showing that the bias in knuckle localization remains even in the absence of vision.

These results demonstrate a distortion of conceptual knowledge of hand structure, mirroring recent findings for other body representations such as those underlying tactile size perception (Longo & Haggard, 2011; Taylor-Clarke et al., 2004) and position sense (Longo & Haggard, 2010, 2012) For example, Longo and Haggard (2010) measured body representations mediating position sense by using localization judgments of the knuckle and tip of each finger to construct implicit perceptual maps of hand structure. These maps overestimated hand width, but underestimated finger length. The present results showing that people believe their knuckles are farther forward than they actually are provide a potential explanation for the underestimation of finger length, although the magnitude of the current effect is insufficient to account for the full effect in those studies. Longo and Haggard (2010) argued that the distortions they observed reflected an implicit body representation distinct from the conscious body image, since the distortions did not appear when participants selected from an array of hand images the one most like their own hand. The present results, however, suggest that there may be important connections between implicit body representations and higher-level conceptual knowledge of body structure. More generally,

this pattern suggests that rather than being an idiosyncrasy of any single body representation, distortion may be a general characteristic of how the brain represents the body.

The similar biases for localization of one's and of somebody else's knuckles suggests that the bias arises from an abstract representation of the structure of bodies generally, rather than a self-specific representation. This is consistent with studies of autotopagnosia, in which patients show similar difficulties in localizing parts on their own bodies and on bodies of other people or mannequins (Gerstmann, 1942; Ogden, 1985; Sirigu et al., 1991). This pattern indicates that the distortion arises from inaccurate conceptual knowledge of body structure, rather than from distortions of primary sensory maps, such as the Penfield homunculus (Penfield & Boldrey, 1937). As Kinsbourne (1998) notes, patients with autotopagnosia are almost invariably impaired for spatial judgments about the entire body. With just one exception, there are no local autotopagnosias. That exception, however, is of particular relevance. In *finger agnosia* (Kinsbourne & Warrington, 1962) the ability to recognize, name, and distinguish the fingers (whether the patient's own or those of other people) is selectively impaired. Finger agnosia suggests that the structural description of the hand may be distinct from the more general body structural description. The present results may reflect systematic distortion of this hand structural description.

We don't know the back of our hand like the back of our hand. The present results mirror findings from other domains showing that naive understanding of physical (McCloskey et al., 1980; McIntyre et al., 2001) and biological (Gelman & Wellman, 1991; Simons & Keil, 1995) principles is systematically inaccurate. For example, people commonly expect a ball exiting a curved tube to continue on a curved trajectory (McCloskey et al., 1980). Such beliefs, at odds with the actual principles of Newtonian physics, suggest that intuitive physics may be a basic aspect of human cognition (McCloskey, 1983), possibly reflecting innately specified 'core knowledge' (Spelke, Breinlinger, Macomber, & Jacobson,

1992; Spelke & Kinzler, 2007). The present results suggest that naïve understanding of the spatial configuration of bodies may similarly reflect a form of *intuitive anatomy*, which may systematically distort the representation of bodily form.

References

- Alloway, K. D., Rosenthal, P., & Burton, H. (1989). Quantitative measurements of receptive field changes during antagonism of GABAergic transmission in primary somatosensory cortex of cats. *Experimental Brain Research*, *78*, 514-532.
- Bermúdez, J. L. (1998). *The paradox of self-consciousness*. Cambridge, MA: MIT Press.
- Buxbaum, L. J., & Coslett, H. B. (2001). Specialised structural descriptions for human body parts: Evidence from autotopagnosia. *Cognitive Neuropsychology*, *18*, 289–306.
- Cholewiak, R. W., & Collins, A. A. (2003). Vibrotactile localization on the arm: Effects of place, space, and age. *Perception & Psychophysics*, *65*, 1058–1077.
- Corradi-Dell'Acqua, C., Hesse, M. D., Rumiati, R. I., Fink, G. R., Acqua, C. C., & Rumiati, I. (2008). Where is a nose with respect to a foot? The left posterior parietal cortex processes spatial relationships among body parts. *Cerebral Cortex*, *18*, 2879–2890.
- Coslett, H. B., Saffran, E. M., & Schwoebel, J. (2002). Knowledge of the human body: A distinct semantic domain. *Neurology*, *59*, 357–363.
- de Vignemont, F., Majid, A., Jola, C., & Haggard, P. (2009). Segmenting the body into parts: Evidence from biases in tactile perception. *Quarterly Journal of Experimental Psychology*, *62*, 500–512.
- Felician, O., Romaiquère, P., Anton, J.-L., Nazarian, B., Roth, M., Poncet, M., & Roll, J.-P. (2004). The role of human left superior parietal lobule in body part localization. *Annals of Neurology*, *55*, 749–751.

- Gelman, S. A., & Wellman, H. M. (1991). Insides and essences: Early understandings of the non-obvious. *Cognition*, *38*, 213–244.
- Gerstmann, J. (1942). Problem of imperception of disease and of impaired body territories with organic lesions: Relation to body scheme and its disorders. *Archives of Neurology And Psychiatry*, *48*, 890–913.
- Kemmerer, D., & Tranel, D. (2008). Searching for the elusive neural substrates of body part terms: A neuropsychological study. *Cognitive Neuropsychology*, *25*, 601–629.
- Keysers, C., Kaas, J. H., & Gazzola, V. (2010). Somatosensation in social perception. *Nature Reviews Neuroscience*, *11*, 417–428.
- Kinsbourne, M. (1998). Awareness of one's own body: An attentional theory of its nature, development, and brain basis. In J. Bermúdez, N. Eilan, & A. Marcel (Eds.), *The body and the self* (pp. 205–223). Cambridge, MA: MIT Press.
- Kinsbourne, M., & Warrington, E. K. (1962). A study of finger agnosia. *Brain*, *85*, 47–66.
- Laiacona, M., Allamano, N., Lorenzi, L., & Capitani, E. (2006). A case of impaired naming and knowledge of body parts. Are limbs a separate sub-category? *Neurocase*, *12*, 307–316.
- Le Cornu Knight, F., Longo, M. R., & Bremner, A. J. (2014). Categorical perception of tactile distance. *Cognition*, *131*, 254–262.
- Longo, M. R., & Haggard, P. (2010). An implicit body representation underlying human position sense. *Proceedings of the National Academy of Sciences of the United States of America*, *107*, 11727–11732.

- Longo, M. R., & Haggard, P. (2011). Weber's illusion and body shape: Anisotropy of tactile size perception on the hand. *Journal of Experimental Psychology. Human Perception and Performance*, *37*, 720–726.
- Longo, M. R., & Haggard, P. (2012). A 2.5-D representation of the human hand. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 9–13.
- Mancini, F., Longo, M. R., Iannetti, G. D., & Haggard, P. (2011). A supramodal representation of the body surface. *Neuropsychologia*, *49*, 1194-1201.
- McCloskey, M. (1983). Intuitive physics. *Scientific American*, *248*(4), 122–130.
- McCloskey, M., Caramazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. *Science*, *210*, 1139–1141.
- McIntyre, J., Zago, M., Berthoz, A., & Lacquaniti, F. (2001). Does the brain model Newton's laws? *Nature Neuroscience*, *4*, 693–694.
- Nickerson, R. S., & Adams, M. J. (1979). Long-term memory for a common object. *Cognitive Psychology*, *11*, 287–307.
- Ogden, J. A. (1985). Autotopagnosia: Occurrence in a patient without nominal aphasia and with an intact ability to point to parts of animals and objects. *Brain*, *108*, 1009–1022.
- Penfield, W., & Boldrey, E. (1937). Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. *Brain*, *60*, 389–443.
- Rusconi, E., Tamè, L., Furlan, M., Haggard, P., Demarchi, G., Adriani, M., et al. (2014). Neural correlates of finger gnosis. *Journal of Neuroscience*, *34*, 9012-9023.

Schwoebel, J., & Coslett, H. B. (2005). Evidence for multiple, distinct representations of the human body. *Journal of Cognitive Neuroscience*, *17*, 543–553.

Simons, D. J., & Keil, F. C. (1995). An abstract to concrete shift in the development of biological thought: The insides story. *Cognition*, *56*, 129–163.

Sirigu, A., Grafman, J., Bressler, K., & Sunderland, T. (1991). Multiple representations contribute to body knowledge processing. Evidence from a case of autotopagnosia. *Brain*, *114*, 629–642.

Spelke, E. S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, *99*, 605–632.

Spelke, E. S., & Kinzler, K. D. (2007). Core knowledge. *Developmental Science*, *10*, 89–96.

Taylor-Clarke, M., Jacobsen, P., & Haggard, P. (2004). Keeping the world a constant size: object constancy in human touch. *Nature Neuroscience*, *7*, 219–220.

Weber, E. H. (1996). De subtilitate tactus. In H. E. Ross & D. J. Murray (Eds.), *E. H. Weber on the tactile senses* (pp. 21–128). London: Academic Press. (Original work published in 1834)

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