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The magic hand: plasticity of mental hand representation

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ABSTRACT

Internal spatial body configurations are crucial to successfully interact with the environment and to experience our body as a three dimensional volumetric entity. These representations are highly malleable and are modulated by a multitude of afferent and motor information. Despite some studies reporting the impact of sensory and motor modulation on body representations, the long-term relationship between sensory information and mental representation of own body parts is still unclear. We investigated hand representation in a group of expert sleight of hand magicians and in a group of age matched adults naïve to magic (controls). Participants were asked to localise landmarks of their fingers when their hand position was congruent with the mental representation (Experiment 1) and when proprioceptive information was 'misleading' (Experiment 2). Magicians outperformed controls in both experiments, suggesting that extensive training in sleight of hand has a profound effect in refining hand representation. Moreover, the impact of training seems to have a high body-part specificity, with a maximum impact for those body sections used more prominently during the training. Interestingly, it seems that sleight of hand training can lead to a specific improvement of hand mental representation, which relies less on proprioceptive information.

Implementation of visuo-spatial, somatosensory and motor information leads to the formation of internal body representations (De Vignemont, Majid, Jola, & Haggard, 2009; Longo, Azañón, & Haggard, 2010). Internal spatial representations are crucial to successfully interact with the environment, as they provide information about our body size, shape, and its position in space (e.g., Longo & Haggard, 2010). The relationship between body parts and surrounding space is a stable association allowing a constant reciprocal remapping (Romano, Marini, & Maravita, 2017). Distorted body representations are linked to psychiatric disorders, such as anorexia (Spitoni et al., 2015) and neurological syndromes, such as personal neglect (Baas et al., 2011) and asomatognosia (e.g., Vallar & Ronchi, 2009). Patients with spinal cord injuries, whose sensory –motor information is compromised, show difficulties in constructing coherent body representations of the affected body part (e.g., Fuentes, Pazzaglia, Longo, Scivoletta, & Haggard, 2013; Ionta et al., 2016; Lenggenhanger, Pazzaglia, Scivoletto, Molinari, & Aglioti, 2012;). These patients can experience phantom limb usually associated with pain (e.g., Bors, 1951; Curt, Yengue, Hilti, & Brugger, 2011) and show an alteration of the relationship between own body and surrounding space (Scandola, Aglioti, Bonente, Avesani, & Moro, 2016). These studies highlight the detrimental impact that distorted body representations have on our ability to relate with the environment in everyday tasks. However, some degree of body misrepresentation is also common in the healthy population (e.g., Cardinali et al., 2009; Hach, Ishihara, Keller, & Schütz-Bosbach, 2011; Longo & Haggard, 2010; Longo & Haggard, 2012; Longo, Mattioni, & Ganea, 2015; Saulton, Dodds, Bülthoff, & de la Rosa, 2015), which suggests that internal representations are highly malleable. Indeed, a growing body of evidence demonstrates that sensory information can modulate our body representation. Mancini and colleagues (2011) observed that pain perception can be modulated by inducing visual distortion of one's own body size. This study implies that visual information can modify internal body representation, which, in turn, can modulate pain perception. As suggested by recent studies, illusions can also lead to body representation changes (Ekroll, Sayim, Van der Hallen, & Wagemands, 2016). Based on a well-known magic trick of multiplying balls, Ekroll and colleagues (2016) described the “shrunken finger illusion”. Holding a hollow semi-spherical shell on the top of a finger and looking at this from above induces an illusion of completeness, so that the shell is now perceived as a complete sphere. To ‘make space’ for the illusory volume of the ‘ball’, participants perceived their finger consistently shorter than its actual length. Finally, actions and repetitive use of tools also play a crucial role in spatial body representation, such as arm lengths (Canzoneri et al., 2013; Cardinali et al., 2009; Farnè, Serino, & Làdavas, 2007; Garbarini et al., 2015; Garbarini et al., 2014; Maravita, Clarke, Husain, & Driver, 2002; Maravita, Spence, & Driver, 2003; Scandola et al., 2016; Sposito, Bolognini, Vallar, & Maravita, 2012). Maravita and Iriki (2004) suggested a possible neural mechanism of tool-embodiment in monkeys that involves an enlargement of specific neuronal receptive fields to include the tool areas. In line with these findings, extensive training in complex actions has been associated with an increased representation of relevant body parts (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Linkenauger, Witt, Bakdash, Stefanucci, & Proffitt, 2009; Sterr et al., 1998). This modulation is also possible after extensive training with tools, such as a cane from blind people (Serino, Bassolino, Farné, Làdavas, 2007), robotic hands (Marini et al., 2014) or sport equipment (Foukas, Bonavolontà, Avenanti, & Aglioti, 2008).

These studies demonstrated that our body representations are highly malleable and can be affected by multimodal information, action goals and tool interaction. However, the long-term impact on mental representation of body parts remains unclear. Our study aims to address this question, considering a population of adults who have undergone a prolonged training in complex manual actions, and disentangling proprioceptive information from mental representation of own hands.

To this aim experts on fine motor skills, such as magicians, may offer a unique opportunity to address this research question. Magicians use a wide range of psychological tricks to deceive their audiences (Rensink & Kuhn, 2015), and many of these principles rely on sleight of hand. For example, The French Drop is a sleight commonly used to make a coin “vanish”. Here, the magician pretends to transfer a coin from the right hand to left hand, but in reality the coin never changes hand, and the left hand simply pretends to be holding the coin. Once this hand is revealed to be empty, observers are left with the impression that the coin has vanished, when in reality it remains secretly concealed in the magician’s right hand (Phillips, Natter, & Egan, 2015). Many of these sleights rely on the magician pretending to do one thing, when he/she is doing something else, which requires them to hold a representation of their own hand as close as possible to reality (i.e. real position and shape of fingers) (Cavina-Pratesi, Kuhn, Ietswaart, & Milner, 2011). However, it is also crucial to hold in mind the ‘illusory’ representation and position of the hand. Sleight of hand requires a highly refined mental representation of one’s own fingers as these need to be expertly moved in different positions at the right speed and, often, with little visual input.

Magicians spend large amounts of time rehearsing these types of movements (Rissanen, Pitkänen, Juvonen, Kuhn, & Hakkarainen, 2014), and it is likely that this extensive experience modulates their visuomotor processing. For example, people show marked differences in the kinematic profiles of their finger movements for real actions compared to pantomimed actions, but these differences are not apparent in magicians (Cavina-Pratesi et al., 2011). Cavina-Pratesi and colleagues suggested that magicians are capable of using a different form of visuomotor transformations and it is also possible that extensive practice in deceptive hand movements results in long-term changes in mental hand representations.

The long-term effect of practice is still unclear and investigation of this aspect in groups of ‘experts’ can shed light on understanding the complex interaction between environment and body representation. We therefore investigated hand representation in a group of expert magicians who used sleight of hand as the main aspect of deception and in a group of age matched adults naïve to magic (control group). Participants were asked to localise landmarks of their fingers across two experiments to investigate mental representation of participants' own hands when proprioceptive information was congruent (Experiment 1) or 'misleading' (Experiment 2). We expect that the extensive training in sleight of hand leads to magicians performing better in the first experiment. The outcome of the second experiment is less predictable. If the extensive training enhances magicians' ability to implement afferent information, we expect that their performance in the second experiment is very similar to those of controls. Alternatively, if sleight of hand training leads to a more refined, long-term representation of their hands, we expect that magicians maintain a similar 'advantage' over controls.

EXPERIMENT 1. POINTING TO OWN HAND

Methods and Procedures

Participants

Twenty male adults aged between 18 and 58 (mean= 31.78; SD= 11.16) were recruited to participate either as expert magicians or adults naïve to magic.

Eleven participants, all members of the Magic Circle in London, were recruited as expert magicians. There is no formal measure of magic expertise (see Rissanen et al., 2014), but we considered only magicians who passed the Magic Circle entry exam, which demonstrates a high level of conjuring competency, both in terms of practical experience (i.e. sleight of hand) and theoretical knowledge. Furthermore, all of the magicians had at least 5 years of training and performed at least one show each month (two participants were excluded as they did not fulfil the latter criteria). Demographical details, handedness scores and degree of expertise of the 9 magicians who finally entered the study are reported in Table 1. Handedness was assessed through the Edinburgh Handedness Inventory (Oldfield, 1971). Scores range from -100 to 100, where scores below -50 indicate left-handedness; scores over +50 indicate right handedness and scores within -50/+50 indicate ambidexterity. According to this scoring system, 2 participants were ambidextrous with right hand preference (+40 and +45, respectively) and 7 participants were right handed.

A group of 9 naïve control participants were recruited. The groups were matched by gender (all males), age, formal education and handedness with the 9 magicians (See Table 1). One participant was ambidextrous (Handedness score = +40) and 8 were right-handed. T-test analyses did not show significant differences between the two groups on age, level of education or handedness scores. None of the control participants played musical instruments or use their hands for other artistic or professional activities requiring fine movements of hands and related training.

The study was approved by the Goldsmiths Ethics Committee and participants provided written consent to take part in the study.

--- Insert Table 1 about here ---

Preliminary test

To ensure that participants showed no general difficulty in pointing to specific locations, nor relevant differences between hands, they were asked to point as quickly and accurately as possible to 10 targets (small numbered dots of 0.5 cm of diameter) printed on a A1 sheet displayed in front of them. The examiner read the numbers aloud in a random order and participants had to point with their right or left hand to the corresponding stimulus. With the exception of three errors (<1%) across both groups and both hands, all participants performed flawlessly.

Experimental task

Similar to previous research on mental hand representations (e.g., Longo and Haggard, 2012), participants were required to indicate the location of specific landmarks on a blank piece of paper whilst their hand was occluded from view. Participants were asked to close their eyes and place their hand wide open with all fingers straight and spread apart on an A1 sheet located on a table in front of them. The middle finger was in line with the midline of their body. The distance of the hand from the body was adjusted to avoid uncomfortable positions. Participants were then instructed to relax and not to move their hand for the entire test.

A picture of the hand was taken for later analyses from a fixed overhead camera (Canon EOS 700D) suspended directly at about 50 cm above the hand (see Figure 1a). There were four marks on each of the four A1 sheet corners for later reference when images of hand and participant's responses were superimposed for measurements. An occluding box (39 cm x 29 cm x 7 cm) was placed over the hand. Then participants were allowed to open their eyes and to point, with a short stick (14 cm) held on the other hand, to nine landmarks of the occluded hand.

Landmarks were defined by a short preliminary pilot study (with a different group of participants not included in this experiment). Unlike locations of knuckles, fingertips and locations between two fingers ('interspaces') were identified unambiguously on a drawing by all participants. Therefore the locations of the five fingertips and the four interspaces of the fingers were considered as landmarks for this experiment (see Figure 1b). Participants were asked to indicate the highest point (tip) of each finger and the point where two fingers join (interspace). For the thumb-index interspace, participants were instructed to indicate the most proximal point of the thumb where its skin meets the 'interspace'. The landmarks were asked in a set order (e.g. Tip of little finger; Interspace between little and annular fingers; Tip of annular finger; etc...), starting from the little finger (for half of the participants) or from the thumb (for the other half of participants). Before reading aloud each landmark, the participant was asked to point with the short stick to a starting point located in the lowest part of the sheet and align with the midline of their body (see Figure 1a). After each pointing, participants held the stick in place for a few seconds so a picture could be taken for later analyses, then they were asked to point to the starting position before hearing the next landmark. After the last trial, the cardboard was removed and a final picture of the hand was taken to control for possible minor movements.

The task was repeated for each hand (Hand condition) and for dorsal and palmar positions (i.e. palm of hand facing down or facing up, respectively) of the hands (View condition). View condition was counterbalanced with participants following ABBA order, and Hand condition was counterbalanced across participants. Therefore, each participant performed the pointing task four times, for a total of 36 trials.

Participants were instructed to take their time before pointing but to point to the location in a single movement, as corrections were not allowed.

--- Insert Figure 1 about here ---

Analysis

For each condition, first and final photos were compared and combined in case of minimal shift. Every photograph indicating the participant's response (i.e., the position indicated with the stick) was then overlaid on top of the initial (and combined in four cases across all conditions) photograph using Photoshop software CS6. An IBM Lenovo T60 computer with screen resolution 16000x1200 was used to carry out the measurements. Measurements were then converted in centimetres.

Each finger length was calculated by measuring the distance between the tip of the finger and the closest 'interspace' toward the little finger. For the little finger we considered the interspace shared with the annular finger (See Figure 1b).

The percentage of error was calculated as follow:

$$\frac{SubjectiveLength - ObjectiveLength}{ObjectiveLength} * 100$$

A negative value indicates underestimation of the finger length, a positive value indicates overestimation and a value equal to zero represents a perfect estimation.

All inferential analyses considered two-tailed p values.

The same measurements were considered for both hands and both views.

Inferential analyses. T-tests for independent samples are used for group comparisons of real hand sizes and of variance of distortion. T-tests for repeated sample are used to compare distortion (real versus real sizes) for each group. Effect size is calculated using Cohen's d formula for independent and repeated measure, as appropriate. A group x hand x view x fingers ANOVA is conducted. Appropriate post-hoc analyses are run on main effects, only. Effect size is reported as eta-squared values. Normality of the data was assumed if Skewness and Kurtosis values are within a -2 +2 interval and -7 +7 interval, respectively. Results on the Levine's test and Sphericity are used to investigate equality of variances. Finally a series of Spearman's correlations are run to compare relationship between views and hands.

Results

Overall magicians' real finger length (M = 6.96 cm; SD = 1.16) was very similar to controls' real size (M = 6.83 cm; SD = 0.42) and the difference was not significant ($t(16) = 0.332$; $p = .74$; $d = 0.15$. Both groups showed an overall distortion of their own finger lengths with magicians perceiving their fingers 20.4% shorter than actual size (i.e. M = 5.54 cm; SD = 2.17), and controls perceiving their fingers 39.4% shorter than actual size (i.e. M = 4.14 cm; SD = .79). Data for each condition were well within the normality intervals established for Skewness and Kurtosis. The distortion was significant for magicians ($t(8) = 3.31$; $p < .01$; $d = 1.10$) and controls ($t(8) = 12.13$; $p < .001$; $d = 4.04$), but significantly smaller for the magicians ($t(16) = 2.59$; $p < .05$; $d = 1.22$).

We also considered whether the two groups had overall differences in the variability of their estimates. To this aim we considered each overall individual's standard deviation across the five fingers for both hand and view conditions. Magicians showed an average variability of 13.8 (SD = 4.76) whereas controls showed an average variability of 13.0 (SD= 4.96). The group difference was not significant ($t(16) = 0.33$; $p = .75$; $d = .16$), suggesting that both groups showed similar variability across fingers for both hands and views.

More detailed analyses were run to consider distorted representation of each hand, view and fingers between groups. Figure 3 shows the mean percentage of errors for groups, hands, fingers and views. Inspection of Figure 3 suggests that both groups showed a persistent underestimation for both hands, all fingers and under both views. A 2 (group) x 2 (hand) x 2 (view) x 5 (fingers) ANOVA on percentages of error estimations confirmed a significant effect of group ($F(1,16) = 4.58$; $p < .05$; $\eta^2_{partial} = .222$), demonstrating that the magicians were significantly better at estimating their finger position than the control participants. There was also a significant effect of fingers ($F(4,64) = 7.61$; $p < .001$; $\eta^2_{partial} = .322$). Pairwise comparisons (Bonferroni correction for 10 comparisons; $p < .005$) amongst fingers revealed significantly smaller errors in the thumb than the middle ($p < .001$; $d = 1.08$) and annular fingers ($p < .001$; $d = 0.97$), and significantly smaller errors in the little than the annular finger ($p < .001$; $d = 0.91$). There were no significant main effects of view ($p=.166$) or hand ($p=.803$) but there was a significant interaction between view*finger ($F(4,64) = 3.52$; $p < .05$; $\eta^2_{partial} = .181$). There was a violation of sphericity for the three way interaction so Greenhouse-Geisser was considered resulting in a significant interaction between groups*view*hand*finger ($F(4,41,27) = 3.333$; $p <.05$; $\eta^2_{partial} = .172$). Clearly there were many ways to interpret such an interaction. Firstly, we compared magicians and controls in each combination of view, hand and finger, and we report here the highest differences between groups. The thumb and the index fingers of the left hand in palmar view showed the highest group differences (i.e. 40.3% and 27.5%, respectively) and a significant group effect ($t(16) = 2.94$; $p < .01$; $d = 1.39$; $t(16) = 2.98$; $p < .01$; $d = 1.40$, respectively; Bonferroni correction not applied). Secondly, since performance for thumb and index fingers did not differ significantly (see above post-hoc analyses), we compared groups for the combined performance of these two fingers (thumb-index) for both hands and views. Considering Bonferroni corrections for 4 comparisons (i.e. $p < .0125$), we found a significant group effect for the combined fingers of the left palmar hand condition ($t(16) = 3.23$; $p < .005$; $d = 1.52$), whereas other hand*view combinations for these fingers fall far from significance (lowest $p = .12$).

The outcome of these analyses suggests that magicians underestimate their own finger lengths, but to a lesser extent than controls. In addition, fingers were not perceived equally distorted and, compared to magicians, controls showed the greatest distortion of thumb-index fingers in the non-dominant (left) hand, in palmar (less usual) view.

--- Insert Figure 2 about here ---

We finally considered whether the group responses correlated across different conditions. The errors for dorsal and palmar views correlated significantly for both magicians ($r=.89$; $p<.001$) and controls ($r = .73$; $p < .05$). The correlation between the two hands was significant for magicians ($r = .84$; $p < .005$); however for controls the correlation was weak ($r = .35$; $p = .355$; n.s.).

Preliminary Discussion

In line with previous studies (e.g., Longo & Haggard, 2012), our control participants showed a significant distortion of hand representation as they consistently underestimated their finger lengths for both hands and under both dorsal and palmar views. Magicians performed significantly better than controls. However, they also showed a tendency to underestimate their finger length.

Our data also sheds some light on a debatable issue about the direction (i.e. underestimation) of the distortion. In previous studies, participants were asked to localize their knuckles and the underestimation could have been, at least in part, accounted by a conceptual distortion that knuckles are believed to be located as more distal than their actual position (Longo et al., 2015). However, in our study, participants were asked to locate the interspaces between fingers, unambiguous landmarks that all participants localised accurately during the preliminary test. Therefore, the underestimation cannot be accounted by a conceptual distortion. A possible explanation for the specific direction of distortion may rely on the fact that fingers are highly movable parts of the upper limbs and that fingers are moving towards the body whereas they cannot stretch beyond their actual length. This hypothesis supports the findings that distal parts are not represented as accurately as proximal parts (De Vignemont, 2014). This aspect becomes particularly important during sleight of hand, where finger movements are a crucial aspect of the tricks. It is therefore not surprising that magicians performed significantly better than controls, though their performance was far from perfect.

The pattern of finger distortion was similar to that reported in the literature (e.g. Longo & Haggard, 2012), whereby fingers were not equally distorted in both groups. The thumb was generally less underestimated than the middle and the annular fingers, and the little finger was less underestimated than the annular finger. Notably, most of our participants were right handed, and we observed the highest group difference when estimating the left thumb and index fingers under palmar view. A possible interpretation of these findings may be linked to the fact that only magicians used both hands extensively to practice and perform their tricks. Moreover, palmar view of the hands seems to represent a less common representation, resulting in slower processing and less accurate responses in a mental rotation tasks (Ionta, Fourkas, Fiorio & Aglioti, 2007). When control participants were asked to localise landmarks of the less used hand (i.e. left hand) and to represent it in the less usual way (i.e., the palmar view), the combination of these two detrimental conditions may have maximised the group differences. Interestingly, the two fingers showing the highest group difference are those more heavily used for fine motor actions and magic tricks (Cavina-Pratesi et al., 2011). Cavina-Pratesi and colleagues (2011) observed that extensive practice in sleight of hand has been linked to better performance in pantomime reaching actions and this was limited to the 'grip component' (i.e., using two fingers) of the reach-to-grasp task. The authors suggested that magicians' ability lies in their ability to "calibrate the grasping action" (p. 4). On view of our findings, we may interpret the successful 'calibration' to result, at least in part, from a better finger representation.

These outcomes advocate for a generally better performance in representing own finger length in magicians. Interestingly, the greatest advantage of sleight of hand is seen with the non-dominant hand and under unusual view. In other words, where we would expect less 'expertise' from controls and where practice of sleight of hand may lead to the greatest advantage of magicians over controls.

Phillips and collaborators (2015) suggested that specific motion and muscular behaviours are indicative of proficiency in intentional deception amongst magicians. It follows that magicians may implement somatosensory information more successful than controls. It remains, therefore, unclear whether the magicians' advantage reported in our first experiment was mainly due to a better implementation of afferent information of the hand lying flat on the table, or whether the substantial gain reflects a more accurate 'internal representation' as suggested by Longo & Haggard (2012; Longo et al., 2015).

To address this question, we ran a second experiment where somatosensory, in particular proprioceptive, information was in contrast with the internal mental representation requested to perform the task.

EXPERIMENT 2. POINTING TO THE IMAGINED HAND

According to the Longo & Haggard (2012; Longo et al., 2015), localizing external body landmarks requires us to successfully implement somatosensory information with our long term internal spatial representation. Our previous experiment suggests that extensive motor training can significantly improve body part localization, but it remains unclear whether the training mainly impacts on the implementation of sensory information or on the hand's long-term spatial representation. One way of addressing this question is to isolate these components, rendering the afferent information irrelevant and to consider whether the group effect is still present. In experiment 2, participants were asked to locate landmarks on their imagined open hand, as in Experiment 1, while holding their hand in a fist shape under the cardboard. Similar paradigm has been used in a recent study (Ganea & Longo, 2017) where authors concluded that 'proprioception and proprioceptive imagery rely on a common stored model of the body's metric properties' (p. 41). However, this manipulation created a mismatch between internal stored representation and afferent information. If the magicians' advantage observed in the previous experiment was guided by a better implementation of afferent information, we would expect an overall worse performance of magicians in Experiment 2 compared to the Experiment 1. In this second experiment, afferent information would not provide useful information about the finger locations and both groups would show an equivalent degree of distortion. As a result, the group difference would be negligible or considerably reduced. Alternatively, if extensive practice in sleight of hand leads to qualitative more refined mental representations of this specific part of the body, we would expect to find a relatively unchanged group effect as magicians would still be able to capitalise on their better mental representations of hands.

Methods and Procedures

Participants

A subgroup of 15 participants, 7 magicians and 8 controls who took part in Experiment 1, were also recruited for the Experiment 2, which was performed later on the same day. No feedback was provided after Experiment 1 and participants were engaged in general conversation before carrying out Experiment 2.

Experimental task

The main task, the method and the procedure were identical to Experiment 1; however now participants had their hand in a fist shape (with the thumb on the top) rather than spread out under the box. They were then instructed to imagine their hand wide open with the middle finger aligned to the mid-line of their body and to point to the different nine landmarks that were read aloud as in Experiment 1.

Both hands and views were tested and the order of presentation was counterbalanced as in Experiment 1. Also the order of landmarks (i.e., starting with the tip of thumb or the tip of little finger) was counterbalanced across participants as in the previous experiment.

Analyses

The pointing data were compared with actual finger lengths as measured in Experiment 1. All others analyses methods were as for Experiment 1. In addition, an ANOVA and a Pearson correlation are conducted to compare the group performance across the two Experiments. Spearman correlations are conducted between overall performance of each hand and Edinburgh Handedness Inventory.

Results

The magicians' overall real finger length (M = 7.47; SD = .65) was similar to those of the control subgroup (M = 6.90; SD =.38) and the difference did not reach significance (t(13) = 2.11; p = .054; d = 1.07). Both groups showed an overall underestimation of own finger lengths with magicians perceiving their fingers 7.82% shorter on average (i.e. M = 6.89 cm; SD = 1.95), and controls 31.87% shorter (i.e. M = 4.70 cm; SD = .98) than their actual size. Data for each condition were well within the normality intervals established for Skewness and Kurtosis. The control group significantly underestimated their finger length (t(7) = 6.68; p < .001; d = 2.36), whilst for the magicians there was no significant difference between the real and the estimated finger length, t(6) = 1.06; p = .33; d = .40. A group effect was found when we compare differences between real and perceived lengths (t(13) = 2.60; p < .05; d = 1.32), suggesting that controls underestimated their finger size significantly more than magicians who estimate their finger lengths very close to actual size.

As for Experiment 1, we also considered whether the two groups showed an overall different variability of data. To this aim we consider individuals' standard deviations across the five fingers for both hand and view conditions. Magicians showed an average variability of 11.44 (SD = 4.14) whereas controls showed an average variability of 12.69 (SD= 3.52). The group difference was not significant (t(13) = .63; p =.54; d = .32), suggesting that both groups showed similar variability across fingers for both hands and views.

More detailed analyses were run to consider performance for each condition during Experiment 2. Figure 4 shows the mean percentage of estimation errors for both groups, hands, fingers and views. Both groups underestimated finger lengths for both hands and under both views. A 2 (group) x 2 (hand) x 2 (view) x 5 (fingers) ANOVA on estimation errors confirmed a significant main effect of group (F(1,13) = 7.02; p = .02; $\eta^2_{partial}$ = .35), again illustrating that the magicians were more accurate in estimating their finger length than the control participants. There was also a main effect of fingers (F(4,13) = 7.25; p < .001; $\eta^2_{partial}$ = .358), and a series of post-hoc paired t-test (Bonferroni corrections for 10 comparisons; p < .005) revealed a significantly larger difference between the annular and all the other fingers (p < .001 with thumb; d = 1.03, index; d = 1.35 and little; d = 1.35; p < .005 with middle; d = 0.93). No significant main effect of view (p = .48) or hand (p = .13) were observed nor interactions between factors (group*hand*view*fingers interaction p = .16).

--- Insert Figure 3 about here ---

Pearsons correlations between dorsal and palmar views showed a significant positive coefficient for both magicians (r =.92; p < .005) and controls (r =.86; p < .01). Similarly, correlations between right and left hands were significantly positive for magicians (r = .95; p = .001) and close to significance for controls (r =.68; p =.062).

Comparisons between Experiments 1 and 2.

Figure 4 shows the overall underestimation for each finger of both sub-groups (i.e. 7 magicians and 8 controls) who took part in both Experiments. A 2 (groups) x 2 (experiments) ANOVA showed a significant effect of experiment (F(1,13) = 11.39; p = .005; $\eta^2_{partial}$ = .467) and a significant effect of group (F(1,13) = 8.06; p < .01; $\eta^2_{partial}$ = .383), but no interaction (F<1). The Pearson correlations of finger estimations between Experiments 1 and 2 were significant for both magicians ($r = .89$; $p < .01$) and controls ($r = .80$; $p < .05$). Finally, Spearman correlations between the overall performance for each hand and the Edinburgh Handedness Inventory scores showed a weak relationship ($r = -.126$; $p = .654$ for the right hand and $r = -.159$; $p = .571$ for the left hand, respectively).

--- Insert Figure 4 about here ---

General Discussion

Several previous studies (e.g., Longo & Haggard, 2012) have shown that participants hold a distorted metric representation of their own hands, where fingers are perceived as shorter. In line with these findings, our participants showed a systematic underestimation of their finger lengths across both experiments, for both hands and under dorsal and palmar views. We also observed that magicians using sleight of hand considerably outperformed controls in estimating their own finger lengths. Our results therefore demonstrate for the first time that intensive and long lasting training can modulate our metric body representation.

Findings from a recent Ganea and Longo's (2017) study suggest that proprioceptive imagery and proprioception hinge on the same stored body model. In our first experiment, representation and actual locations of landmarks were congruent, and it was therefore not possible to discern whether the sleight of hand expertise influenced the processing of afferent information or whether it changed internal representation. For this reason, we ran a second experiment where these two types of information were in contrast (i.e., imagine own hand wide open while holding it in a fist). If the advantage shown by magicians in the first experiment was mainly due to a better implementation of proprioceptive information, we predicted a reduced, if any, group effect when proprioceptive information could not be used to localise finger landmarks. On the contrary, in the second experiment we observed a significant group effect where magicians showed an almost identical advantage over controls (i.e. 21.97% in the first experiment and 22.49% in the second experiment). In addition, both groups showed a significantly better performance during Experiment 2, suggesting that while proprioceptive information is fundamental for action (De Vignemont, 2004), it plays a marginal role on the representation of own hand during our study (as they kept their hand still). It seems therefore that sleight of hand may contribute in the formation of more accurate internal metric hand representation than controls.

It remains unclear as to why congruent proprioceptive information resulted in worse rather than better performances. Though we expect that some degree of familiarization may have played a role during the second experiment, there is a third possible interpretation, which will certainly need specific investigation.

Somatosensory information is crucial for the formation of body representation (De Vignemont et al., 2009; Canzoneri, Ferre', & Haggard, 2014); however under some circumstances (e.g., when contrasting) this information can be detrimental and it can interfere with our internal representations. For example, a recent study by Longo et al. (2015) reported that participants showed less distortions to localise landmarks on a rubber hand than on their own hand. It therefore seems likely that under specific circumstances, knowing that proprioceptive information is clearly irrelevant (as in our second experiment) may have facilitated performance of a task, as this information will not interfere with the mental representation of this body part. This, together with a likely order effect of experiments, may explain why both groups performed better when they were asked to imagine their hand wide open while keeping it as a fist. Further studies would be needed to disentangle the role of these two variables.

A further possible limitation of this study is the sample size. We adopted a highly stringent inclusion criterion in selecting only highly experienced magicians who specialized in sleight of hand magic. Inevitably, this resulted in a relatively small sample size. Whilst the small sample did not limit our main findings, a larger sample of participants may allow us to reach more influential conclusions on correlation analyses and interactions amongst factors.

There is a convincing line of argument that extensive training in sleight of hand may have refined people's metric representation of this body part and, because of the specific type of training on deception, magicians may be better at ignoring proprioceptive information, especially if not relevant. This ability may become more evident under some conditions that could be less common for controls, and that may be more sensitive to extensive training of sleight of hand. For example, asking right-handed participants to localise fingers on the less used hand (left) and in the less usual view (palmar) may represent a crucial situation. Not surprisingly, under these conditions, magicians showed the greatest advantage.

In conclusion, our findings suggest that extensive training can profoundly affect body representation and this cannot be entirely accounted for by a better implementation of afferent information. Moreover, the impact of training seems to have a high body-part specificity, with a maximum impact for those body sections used more often during training. The degree of a possible generalisation of the 'benefit' is still unclear and it may be the subject of further studies.

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Figure Captions

Figure 1. (a) Setting for Experiment; (b) Finger length measurements for right hand dorsal view.

Figure 2. Experiment 1 - Percentage and standard error of participants’ underestimation of their right and left hands under both views.

Figure 3. Experiment 2 - Percentage and standard error of participants’ underestimation of their right and left hands under both views.

Figure 4. Percentage and standard error of participants’ performance during Experiment 1 (holding their hand open) and Experiment 2 (holding their hand as a fist).

Table 1. Participants' demographical and handedness characteristics with magicians' degree of expertise.

		Magicians N = 9	Controls N = 9
Age	mean	42.44	31.78
	sd	13.76	11.16
	range	26-67	23-58
Formal education (years)	mean	17.33	18.56
	sd	2.53	1.13
	range	12.21	16-20
Edinburgh Handedness Inventory	mean	79.89	87.13
	sd	26.22	21.39
	range	40-100	40-77
Degree of expertise as magician			
Years of practice	mean	23.89	===
	sd	14.26	
	range	6-50	
Practice per week (hours)	mean	6.67	===
	sd	9.17	
	range	1-30	
Shows per month	mean	4	===
	sd	2.7	
	range	1-10	

Figure 1. (a) Setting for Experiment; (b) Finger length measurements for right hand dorsal view.

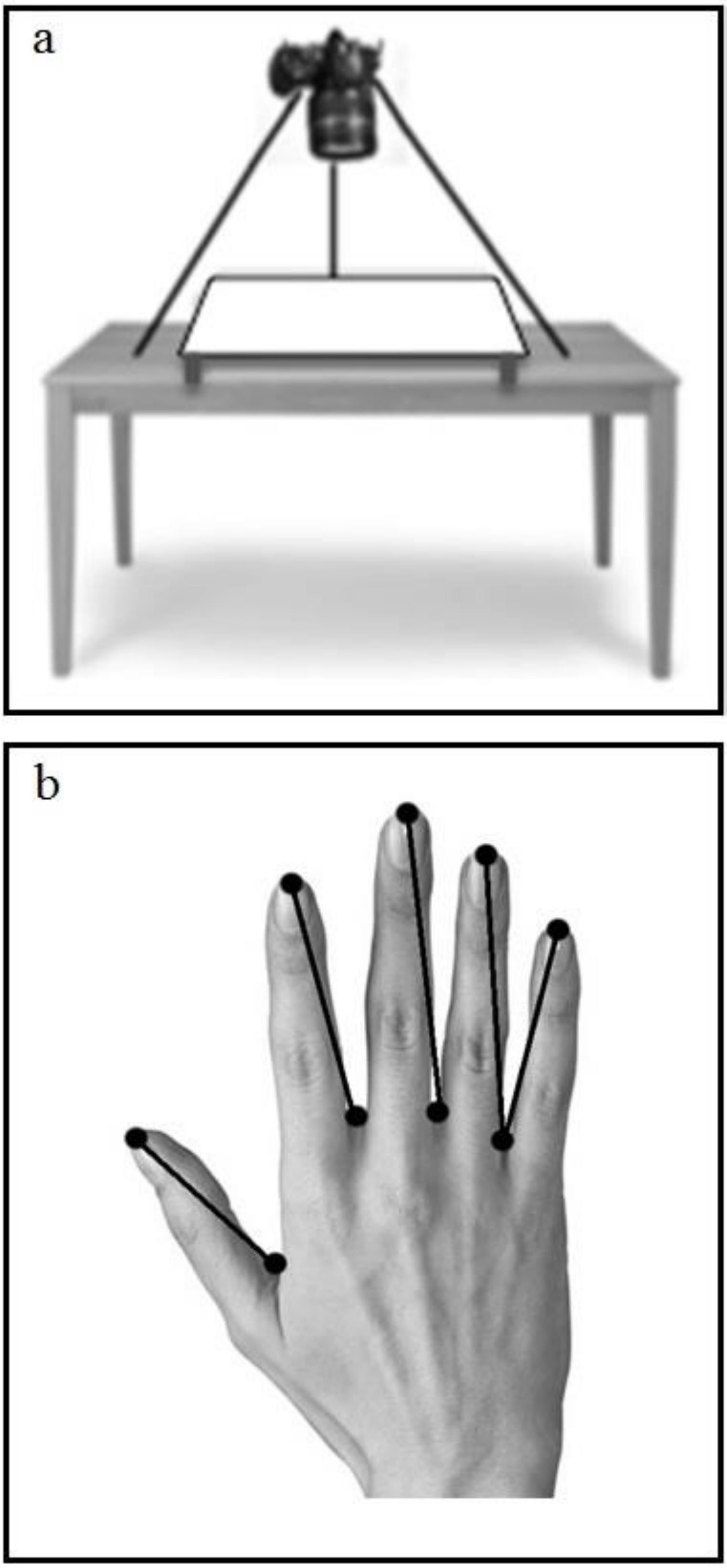

Figure 2. Experiment 1 - Percentage and standard error of participants' underestimation of their right and left hands under both views.

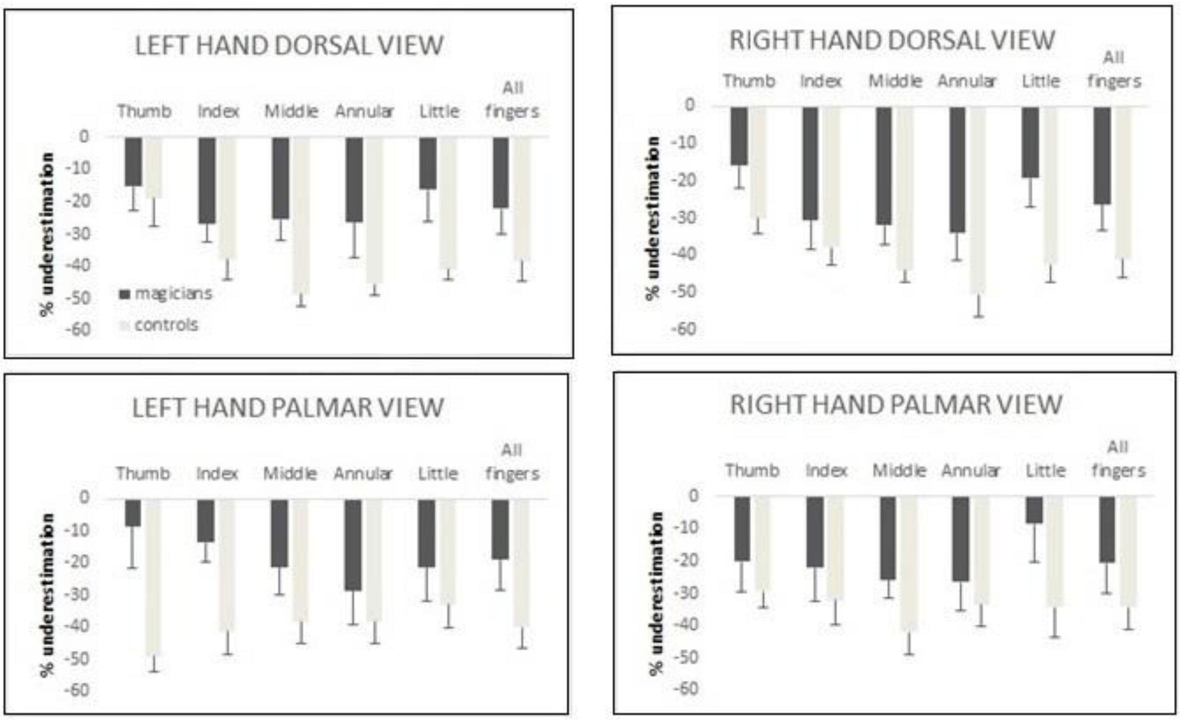

Figure 3. Experiment 2 - Percentage and standard error of participants' underestimation of their right and left hands under both views.

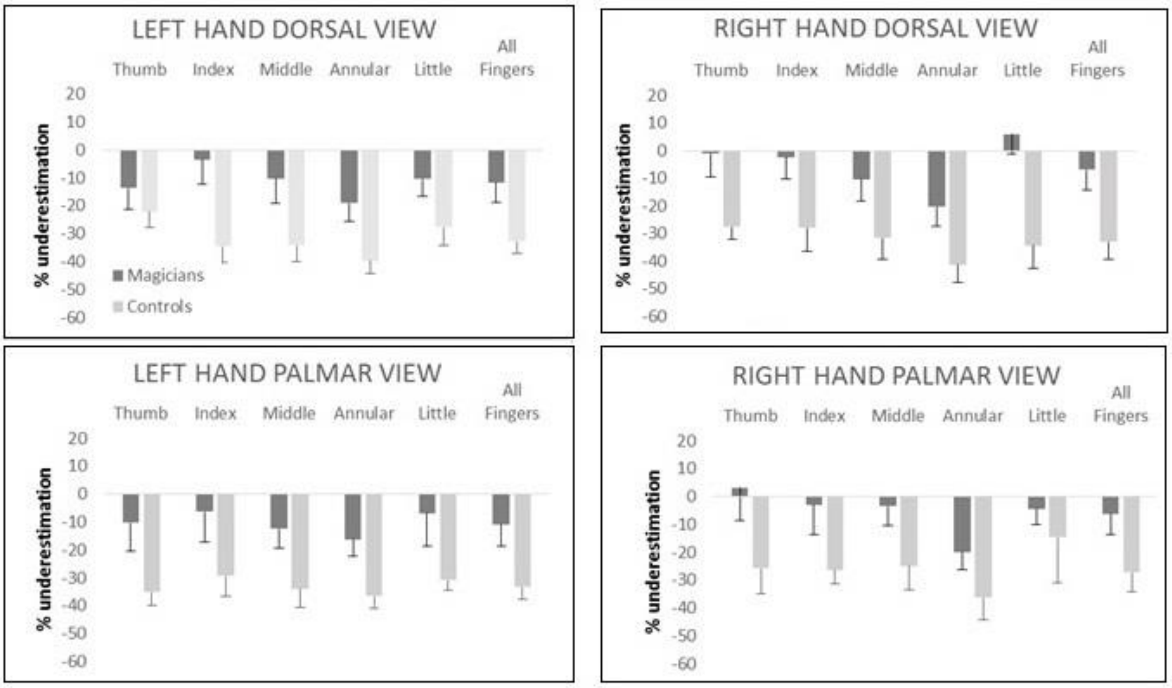

Figure 4. Percentage and standard error of participants' performance during Experiment 1 (holding their hand open) and Experiment 2 (holding their hand as a fist).