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Brief communication

Haptic perception after a change in hand size

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ABSTRACT

When we actively explore with our hands (haptics), the brain must combine diverse sensory signals into a unified percept. Presumably, a key role is played by an internal model of the body, but the processes responsible for forming and maintaining such a model are poorly understood. We used a multisensory illusion to alter the internal model of one's hand by using fake hands smaller or larger than the participant's hand. After such brief illusion we observed a change in haptically perceived object size. These results demonstrate that the brain rapidly recalibrates haptic signals using an internal model of the hand and that this model is multisensory rather than merely visual or memory-based.

Exploring an object with our hands is a simple and natural task. Active touch (haptics) provides rich information about object structure (Gibson, 1962) from the activation of mechanoreceptors and stretch receptors in the skin and in the muscles, tendons, and joints (Jones & Lederman, 2006). These sensory units provide information about joint angles and local contact points with the object surface (Lederman, Klatzky, & Barber, 1985). To generate estimates of properties such as size and structure, however, the brain must combine these sparse signals into a unified and coherent representation. There is evidence that haptic estimates of object size depend on afferences from skin mechanoreceptors, combined with inputs from proprioceptive afferents signalling the spread between the digits (Berryman, Yau, & Hsiao, 2006). Computational considerations (Allen, Michelman, & Roberts, 1989; Klatzky & Lederman, 1993) suggest that the interpretation of haptic signals requires calibration relative to an internal model of the hand. For instance, the width of a felt object can be retrieved from the thumb-index angular aperture and the digit contact points if digit length and hand size are know. At present, however, little is known about the processes involved in constructing and maintaining the internal representations that calibrate haptic signals.

Visual (Haggard, Christakou, & Serino, 2007; Press, Taylor-Clarke, Kennett, & Haggard, 2004; Tipper et al., 1998) or multisensory (Longo, Cardozo, & Haggard, 2008) information about a body part can enhance tactile sensitivity, and visual signals can compensate for distortions due to variations in receptor density over different areas of the skin (Taylor-Clarke, Jacobsen, & Haggard, 2004). However, these results pertain to passive sensory reception, possibly involving the primary somatosensory areas (Serino, Padiglioni, Haggard, & Làdavas, 2009), rather than haptic processing. In a recent study, de Vignemont, Ehrsson, and Haggard (2005) applied vibration to the biceps or triceps tendons of their participant's right arm while the participants grasped the tip of their left index finger. They found that tactile distances between contact points on the left finger were altered when vibration induced a change in perceived finger size (the "Pinocchio" illusion, see Lackner, 1988). This suggests that tactile signals are processed with reference to an implicit representation of the body and that this representation can be modified by novel sensory signals. As these results pertain to passive tactile reception it is not clear how they might generalize to the more complex processes involved in active exploration.

Here we exploited the well-known fake hand illusion (Botvinick & Cohen, 1998), a paradigm whereby synchronous multisensory signals are reputed to induce a temporary reorganization of body-related internal models, creating the illusion that an artificial hand has somehow become one's hand (see Makin, Holmes, & Ehrsson, 2008). We tested whether a multisensory reorganization causing one's hand to be represented as larger or smaller would change the interpretation of haptic sensory signals in a size perception task. Can the illusion of a larger (smaller) hand make you fell a larger (smaller) object?

1. Method

1.1. Participants

Fifty-six members of the University of Liverpool student population took part in the study (mean age 21 years). Half were assigned to the synchronous condition

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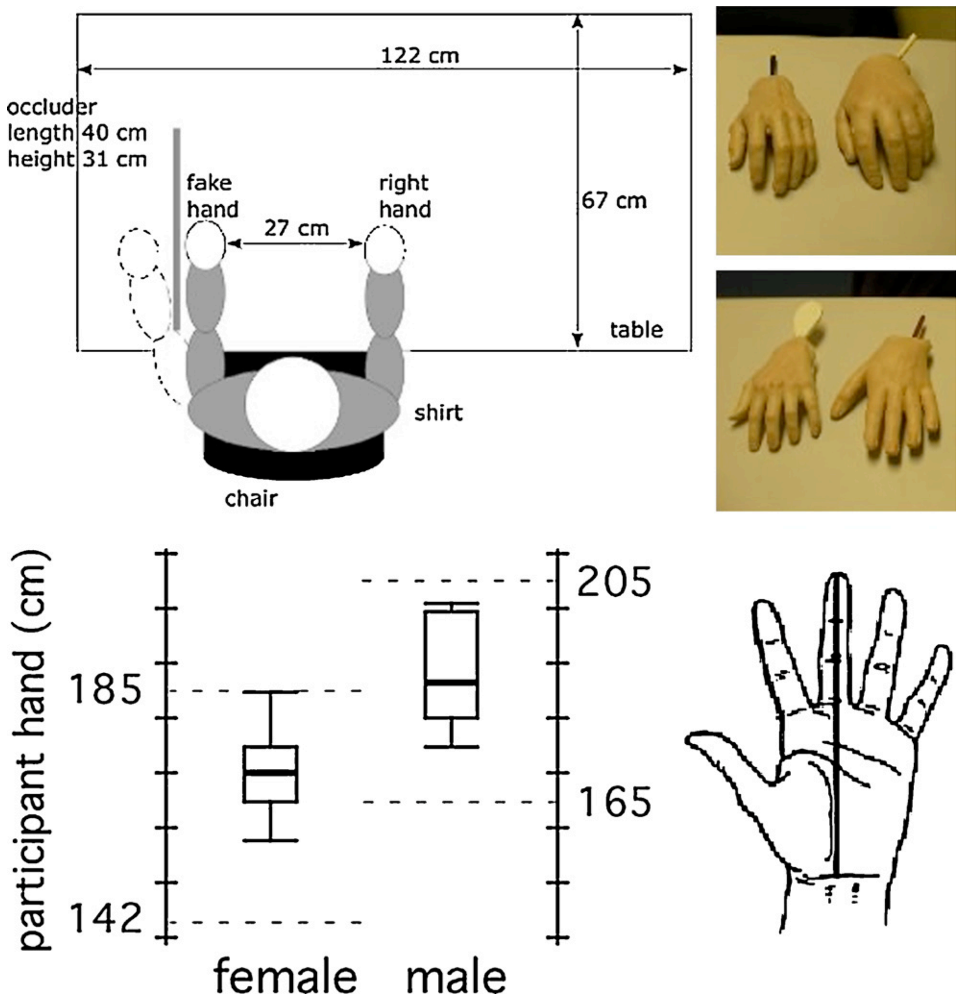

Fig. 1. Top panel, left: schematics of the experimental set-up; right; "small" and "big" hand replicas used for the male and female group of participants. Bottom panel: distribution of participant hand sizes (as measured by the linear extent between the base of the palm and the tip of the middle finger); dotted lines on the left, sizes of the small and big hand replicas for the female group; dotted lines on the right, corresponding sizes for the male group.

and half to the a synchronous condition. They were unaware of the hypothesis under investigation.

1.2. Materials

We cast two pairs of hands from alginate molds of real hands (Fig. 1), selected to be approximately at the 5th and 95th percentiles of male and female hand sizes, respectively. Therefore, they were within the range of anatomically plausible hands. The hands were painted by an artist with a realistic skin color. Participants wore a modified shirt on their right arm and torso but placed their left arm and hand behind a screen. The left sleeve was arranged with the fake hand jutting out as in Fig. 1. Two long-handle paintbrushes provided the stimulation.

To assess the extent to which participants experienced the illusion, we used a six-statement questionnaire. For each statement, participants responded by choosing a value between 1 (strongly agree) to 7 (strongly disagree). Statements were adapted from those of the original report of the illusion (Botvinick & Cohen, 1998). For validation purposes, they were chosen to include aspects that elicited strong, intermediate, as well as weak agreement in the original study. Specifically, statements 1 and 3 in our questionnaire were adapted from Botvinick and Cohen's statement 1 (re-location of tactile sensation to the fake hand), which elicited the most robust agreement. Statement 4 was adapted from Botvinick and Cohen's statement 6 (tactile sensation in between real and fake hand), which elicited medium agreement. Statements 2, 5, and 6 were adapted from Botvinick and Cohen's statements 4, 5, and 8, which elicited minimal agreement in the original study. Thus, if our participants experienced the illusion in a manner comparable to those of the original report, responses will reflect disagreement toward all statements in the asynchronous condition, but strong agreement to statements 1 and 3, medium agreement to statement 4, and relatively strong disagreement to statements 2, 5, and 6 in the synchronous condition.

Haptic judgments of size were collected using a metal disk with a 30 mm diameter as the standard (presented to the participant's right hand) and a set of six comparison disks (27, 28, 29, 31, 32, and 33 mm, presented to the participant's left hand). All disks were 4 mm thick.

1.3. Design and procedure

Half of the participants were randomly assigned to the synchronous condition whereas the other half was assigned to the asynchronous condition. Each participant contributed two blocks of haptic judgments, after multisensory stimulation with a big hand and after stimulation with a small hand. Block order was counterbalanced across participants. In each block, the multisensory stimulation lasted 4 min. In the synchronous condition, we brushed the same fingers of the fake (visual stimulus) and real (tactile) hand, starting with the index fingers, then the middle fingers, and so on. In the asynchronous condition we brushed different fingers of the two hands in sequence (one after the other), following a rotation scheme (fake index finger, then real middle, then fake ring, and so on). In both conditions, both hands were touched approximately once every second, and all fingers were touched an equal number of times. Participants could not distinguish between conditions on the basis of visual information alone. After 4 min, participants closed their eyes and received a metal disk in their right hand (diameter 30 mm). We explained that they had to use this as a standard (100 arbitary units) to verbally estimate the diameter of a second disk presented to their left hand. For instance, if the two disks felt equal they had to say "100", if the comparison felt half the size of the standard, they had to say "50"; if the comparison felt twice the size of the standard, they had to say "200". At this point comparisons were presented to the left hand (total 6 judgments in random order). Disks were never lifted from the table to prevent participants from weighing them. Participants felt the disk by two-finger grips (thumb vs. index) or three-finger grips (thumb vs. index and middle), with no time limit. After completing the two blocks

Table 1
Means (medians in brackets) in the asynchronous and synchronousstimulation conditions for the six questionnaire statements. Grey backgrounds identify statistically significant differences (Bonferroni corrected $p < 0.05$) in parametric tests (independent sample t-tests based on approximate degrees of freedom for unequal variances).

	Questionnaire statement					
	1	2	3	4	5	6
Asynchronous	5.3 (6)	5.6 (6)	5.4 (5.5)	5.4 (6)	5.6 (6)	5.3 (6)
Synchronous	3.0 (2.5)	4.6 (4.5)	3.4 (3)	4.0 (4)	5.3 (6)	5.1 (6)

of multisensory stimulation and haptic judgements, each participant completed the questionnaire.

2. Results and discussion

2.1. Participant hand sizes

As a measure of hand size we used the linear extent between the base of the palm and the tip of the middle finger. The hand replicas for the female group were 142 and 185 cm, whereas those for the male group were 165 and 205 cm. The distribution of the hand sizes in the two participant groups are summarized by the boxplots in Fig. 1. All participant hands were indeed within the range of small and large hand replicas. Because there were individual differences in hand size, we expect differences in the effect of the multisensory stimulation. There was a tendency for participant hands to be closer in size to the big fake hand than to the small fake hand. We may expect, therefore, a stronger effect of the multisensory stimulation using a small hand relative to that using a big hand.

2.2. Questionnaire statements

Table 1 shows mean and median agreement scores for the questionnaire statements in the synchronous- and asynchronous-stimulation conditions.

As expected, participants in the asynchronous condition manifested little agreement toward all six statements. In the synchronous condition, instead, participants tended to agree more with statements 1, 3, and 4 in comparison with statements 2, 5, and 6. This trend was confirmed by significant differences between the synchronous and the asynchronous groups for statements 1, 3, and 4: $t(48) = 4.8$, $p < 0.0001$, Bonferroni-correction $p < 0.0006$; $t(52) = 5.5$, $p < 0.0001$, correction $p < 0.0006$; and $t(43) = 3.2$, $p < 0.0027$, correction $p < 0.0162$; respectively. Conversely, no differences were revealed for statements 2, 5, and 6: $t(50) = 2.4$, $p < 0.0196$, correction $p < 0.1176$; and $t(52)$ and $t(53) < 1$. These results validate our questionnaire statements as measures of the subjectively felt illusion. Thus, we expect individual responses to statements 1, 3 or 4 to be predictive of modulations in haptic judgments if the multisensory stimulation induced a modification of the internal model of the hand.

Table 2
Mean magnitued estimates ±1SE after asynchronous or synchronous multisensory stimulation with a small or big fake hand. Note that that fake hand size was varied within participants whereas type of stimulation was varied between different groups of participants.

	Multisensory stimulation with	
	Small fake hand	Big fake hand
Asynchronous	29.8 mm ± 0.5 mm	30.0 mm ± 0.5 mm
Synchronous	28.7 mm ± 0.7 mm	30.4 mm ± 0.7 mm

2.3. Haptic judgements

Verbal judgments relative to the standard of 100 were converted to mm. These haptic size judgments were plotted, for each participant, as a function of the physical size of the comparison disk. For most participants in the synchronous group, these plots revealed two nicely separated lines similar to those in Fig. 2, left. On average, judgements after stimulation with the big hand were higher than the corresponding judgments after stimulation with the small hand.

Mean magnitude estimates and standard errors are provided in Table 2. In comparison to the asynchronous condition, participants in the synchronous condition produced smaller estimates after multisensory stimulation with a small hand and larger estimates after stimulation with a big hand. The fact that this difference tended to be larger after multisensory stimulation with a small hand is consistent with the analysis of hand size presented above. Pavani and Zampini (2007), see also de Vignemont et al. (2005) reported a stronger fake-hand effect for an enlarged hand compared to a reduced hand. This aspect of their results is inconsistent with this aspect of our own findings. The difference may be due to the optical means (video) used to alter the seen hand, which tend to confound size and distance. We also note that Pavani and Zampini (2007) observed an effect in an intermanual pointing task, but their questionnaire failed to reveal an illusion in either condition.

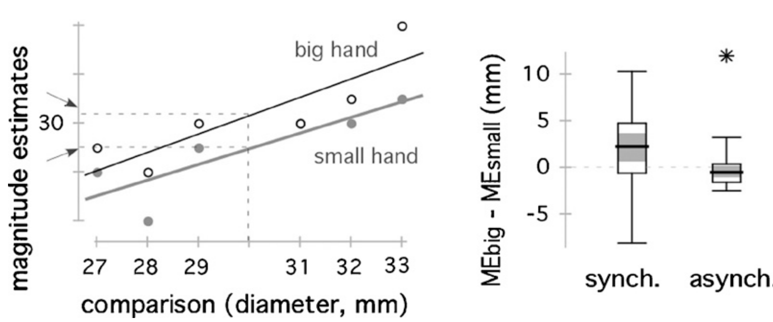

Fig. 2. Left: linear fits of haptic judgments as a function of comparison disk diameters, in one representative participant (synchronous condition), showing mean magnitude estimates in relation to the regression lines. Right: distributions of within-participant differences between estimates after multisensory stimulation with the big and small fake hands for the synchronous-and asynchronous stimulation groups (box-plots portray the distributions medians as thick lines, the first and third quartile as boxes, minima ad maxima as whiskers, the asterisk identifies one outlier value and the grey areas are approximate confidence intervals around the sample medians).

We analysed the magnitude estimates by a 2 (conditions, between participant) × 2 (fake hand, within participant) × 6 (comparison disk size, within participant) mixed-design ANOVA, using the participant × fake hand × comparison disk interaction as error term for the within factors and the whithin-participant error as error term for the between factor. This analysis yielded significant effects of fake hand, $F(1,594) = 6.8$, $p < 0.01$ and comparison disk size, $F(5,594) = 157$, $p < 0.0001$, as well as significant condition × fake hand, $F(1,594) = 4.7$, $p < 0.04$ and condition × comparison disk, $F(5,594) = 2.6$, $p < 0.03$ interactions. The effect of condition was not significant, $F(1,54) < 1$.

As the between-group differences were small in comparison with the within-group variability, a more sensitive indicator of a modulation of haptic judgments is the within-participant difference between estimates after multisensory stimulation with a big and small fake hand. The distributions of these differences in the two groups are summarized by the boxplots in Fig. 2. In the synchronous group most values were positive with a sample median of 2 mm (mean = 1.6 mm, $t(27) = 2.15$, $p < 0.05$). In the asynchronous group, conversely, values were centered around zero (mean = 0.1 mm, $t(27) < 1$).

Thus, exposure to multisensory stimulation with a small or big fake hand modified haptic estimates by most participants in the synchronous group, although some participants in the asynchronous group also showed some modification (see again box-plots in Fig. 2).

2.4. Differences as a function of self-reported illusion strength

Our analysis of the questionnaires suggested that the extent to which each participant experienced the fake hand illusion was captured well by his or her agreement scores to statements 1, 3, and 4. If the illusion causes a modification of the internal model of the hand, and this in turn produces a recalibration of the haptic data for haptic size perception, we would expect the illusion report to be correlated to the effect as measured by the differences between magnitude estimates. To test this possibility, we split participants based on the median of the distribution of the average agreement score from statements 1, 3, and 4 (median = 4.7), classifying participants as reporting a “strong” or “weak” illusion. As expected, most participants in the synchronous condition reported a strong illusion and yielded large estimate differences (1.9 ± 0.7 mm; $N = 23$), whereas most participants in the asynchronous conditions reported a weak illusion and yielded differences close to zero (-0.2 ± 0.3 mm; $N = 20$). In addition, some participants reported a weak illusion despite receiving synchronous stimulation. These showed essentially null differences (-0.1 ± 2.4 mm; $N = 5$). Conversely, participants that reported a strong illusion despite receiving asynchronous stimulation yielded a somewhat larger estimate difference (1 ± 1.6 mm, $N = 8$).

3. Conclusion

In our experiment, participants were exposed to multisensory stimulation that led them to report (in a questionnaire) that an enlarged or reduced hand replica had become their own hand (the fake-hand illusion, Botvinick & Cohen, 1998). Immediately after stimulation, they judged an actively felt object to be larger (after exposure to the enlarged hand) or smaller (after exposure to the reduced hand) than a standard object of identical size felt by the other hand. Therefore, a short exposure to multisensory stimulation altered the internal representation of one’s hand, affecting the interpretation of active touch. This effect tended to be more pronounced after exposure to the reduced replica, which was, on the average, more different from participants’ hands than the enlarged replica.

Another important finding in our experiment is that questionnarie reports indicating a stronger modification of participant’s internal model of the hand were associated with greater changes in the haptic judgments. In summary, our data suggest that when the internal model of the hand changed, haptic data were scaled accordingly. This effect occurred after synchronous stimulation, which has been shown to favor integration of the visual and tactual stimuli (see Makin et al., 2008) but not after asynchronous stimulation when vision of the hand was not integrated with the tactual stimuli. Thus, these results indicate that haptic signals were calibrated relative to an internal model of the hand, and that this model is multisensory rather than merely visual or memory-based. To our knowledge, this is the first report of a fake-hand effect on haptics.

Appendix A.

Listed below are the six question in our questionnaire. For each, participants chose a number between 1 (strongly agree) and 7 (strongly disagree.

1. Did you experience the sensation that your left hand was in the location where you saw the artificial hand?
2. Did you experience the sensation that your left hand was shifting towards the location where you saw the artificial hand?
3. Did you experience all of a sudden the sensation that your left hand was in a location where you saw the artificial hand?
4. Did you experience the paintbrush touches at the location intermediate between the location of your hand and the artificial hand?
5. Did you experience having more than one left hand attached to your body?
6. Did you experience the sensation that the artificial hand was drifting towards the real position occupied by your left hand?

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