Your Place or Mine: Shared Sensory Experiences Elicit a Remapping of Peripersonal Space

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Abstract

Our perceptual systems integrate multisensory information about objects that are close to our bodies, which allow us to respond quickly and appropriately to potential threats, as well as act upon and manipulate useful tools. Intriguingly, the representation of this area close to our body, known as the multisensory 'peripersonal space' (PPS), can expand or contract during social interactions. However, it is not yet known how different social interactions can alter the representation of PPS. In particular, shared sensory experiences, such as those elicited by bodily illusions such as the enfacement illusion, can induce feelings of ownership over the other's body which has also been shown to increase the remapping of the other's sensory experiences onto our own bodies. The current study investigated whether such shared sensory experiences between two people induced by the enfacement illusion could alter the way PPS was represented, and whether this alteration could be best described as an expansion of one's own PPS towards the other or a remapping of the other's PPS onto one's own. An audio-tactile integration task allowed us to measure the extent of the PPS before and after a shared sensory experience with a confederate. Our results showed a clear increase in audio-tactile integration in the space close to the confederate's body after the shared experience. Importantly, this increase did not extend across the space between the participant and confederate, as would be expected if the participant's PPS had expanded. Thus, the pattern of results is more consistent with a partial remapping of the confederate's PPS onto the participant's own PPS. These results have important consequences for our understanding of interpersonal space during different kinds of social interactions.

Keywords: *peripersonal space; multisensory stimulation; body ownership; audiotactile integration; social cognition.*

1. Introduction

Peripersonal space is the space immediately surrounding the body (Rizzolatti, Fadiga, Fogassi & Gallese, 1997). Objects and events occurring in our peripersonal space (PPS) are reachable, and thus can be immediately acted upon and manipulated (Rizzolatti et al., 1997). Equally, because of their close proximity to the body, approaching objects in PPS can also be potentially directly threatening and thus can elicit rapid and automatic defensive movements (Graziano & Cooke, 2006; Graziano, Taylor & Moore, 2002). It makes sense, therefore, for events occurring within PPS to be processed differently from those occurring outside PPS. Indeed, early neuroscientific studies in non-human primates reported specialised multisensory neurons in intraparietal and premotor cortices which respond both when a body part is touched, and when a visual or auditory stimulus occurs near that body part (Rizzolatti, Scandolara, Matelli & Gentilucci, 1981a, 1981b). Neuroscientific and neuropsychological studies have now provided evidence supporting the existence of a similar system in humans, whereby a specialised neural mechanism supports the multisensory processing of events within peripersonal space (See Holmes & Spence, 2004; Làdavas, 2002 for reviews).

An important property of the PPS representation is that it can be dynamically modulated by experience, growing or shrinking in order to optimise our processing of self-relevant events. This modulation allows the representation of the PPS to adapt to the constantly changing action requirements of our environment. For example, experience with using a tool to achieve a goal in a normally-unreachable location can lead to a rapid extension of the PPS representation to include the area around the tip of the tool (e.g. Farnè & Làdavas, 2000; Iriki, Tanaka & Iwamura, 1996). However, tools and objects are not the only aspects of the environment that are salient to us. We also regularly perceive and interact with other people, both within and outside of our PPS. A study by Teneggi, Canzoneri, di Pellegrino and Serino (2013) has shown that the mere presence of another person can also elicit changes in the way PPS is represented. Using a standard audio-tactile integration task, they measured the effects of a looming sound on reaction times to tactile stimuli delivered to the participant's body. As previously shown (Jacobs, Brozzoli, Hadj-Bouziane, Meunier & Farnè, 2011), both audiotactile and visuotactile integration facilitate sensory detection, but only

when the visual or auditory stimuli are presented near the body. This facilitation effect reduces in strength as these stimuli move away from the body (Làdavas, Pavani, & Farnè, 2001). As a consequence, in Taneggi et al., the distance at which the sound began to speed up tactile reaction times was taken as a proxy for the boundary of the multisensory PPS representation. Results showed that the presence of another person in far space, as compared to the presence of a mannequin, led to a contraction of the perceived PPS back towards the participant's body.

Importantly, these socially-induced changes in how we represent our PPS can be bidirectional; a second experiment by Tennegi et al. (2013) demonstrated that a positive social interaction with another person can actually induce an *expansion* of the participant's PPS. After a cooperative social task, whereby another person behaved in a trustworthy way towards the participant by sharing money, the normal area of audio-tactile integration around the participant's body was extended towards the other person, such that sensory stimuli occurring in the PPS of the other person were processed in the same way as those occurring in the participant's own PPS. These results suggested that after a cooperative social exchange, our PPS representation extends to encompass the space between ourselves and the other. Overall, these intriguing studies suggest that high-level sociocognitive processing can have a top-down effect on the way we perceive the space around our bodies.

However, the expansion and contraction of our PPS representation may not be the only change induced by the presence of others. In some situations, we may instead *remap* the space of others onto our own PPS representations. There is already a large body of evidence suggesting that we remap observed sensory and motor experiences of others onto our own bodily representations (e.g. Keysers & Gazzola, 2009). For example, tactile sensitivity on our face is enhanced when viewing another person being touched on the face at the same time, a phenomenon known as Visual Remapping of Touch (VRT: Serino, Pizzoferrato, & Làdavas, 2008; Cardini, Costantini, Galati, Romani, Làdavas, & Serino, 2011). This is thought to be underpinned by a somatosensory mirror system in the brain, which activates both when we are touched ourselves, and when we view others being touched (e.g. Blakemore, Bristow, Bird, Smith & Ward, 2005). Interesting evidence from both

human and non-human primates has suggested that there are similar 'mirror' systems in the brain, not only for events occurring on the other's body, but also for events occurring in the space *near* the other's body. Single cell recordings in non-human primates have revealed bimodal parietal neurons which encode sensory events occurring in the space around the monkey's own hand as well as the space round another monkey's hand (Ishida, Nakajima, Inase & Murata, 2010), and similar findings have recently been reported in human premotor cortex (Brozzoli, Gentile, Bergouignan, & Ehrsson, 2013).

These findings support the existence of neurons that code peripersonal space with mirror-like properties, which are active for sensory stimuli both in one's own PPS and in the PPS of others. Importantly, there is a clear distinction between this 'remapping' of the other's PPS onto one's own PPS representation, and the *expansion* of one's own PPS representation to include the other, as demonstrated by Teneggi et al. (2013). The PPS mirror neurons are only active for visual stimuli near to one's own body, or near to the other's body, and not in the interim locations between the two spaces. In contrast, after a cooperative social encounter, Teneggi et al. demonstrated that the participants' PPS extended towards the other's body, such that the space between the two bodies was treated as a continuation of the participant's own PPS. Thus, in the expansion situation, the other person's PPS is no longer represented; our own representation of PPS expands such that now the other person is situated within it. In contrast, in the remapping situation, the representations of one's own and the other's PPS remain distinct, but the perception of events happening in the space near the other's body is enhanced. It seems, therefore, that a socially-induced *remapping* of PPS, rather than an *expansion* of PPS, has not yet been shown behaviourally. What type of social interaction could specifically induce a measurable remapping of the other's PPS, rather than an expansion of one's own?

One interesting possibility involves shared sensory experiences. When we synchronously experience touch on our own body and observe touch on the body of another person, it can induce changes in a broad range of sociocognitive processes. This is demonstrated in experimental settings using a bodily illusion known as 'enfacement' (e.g. Sforza, Bufalari, Haggard & Aglioti, 2010;

Tajadura-Jimenez, Longo, Coleman & Tsakiris, 2012). A participant is touched on the cheek, whilst watching another person being touched in a specularly congruent location, in exact synchrony. Such 'synchronous multisensory experience' can be used to simulate, in an experimentally controlled way, the type of embodied interactions between individuals which occur in real-life social situations (see Wheatley, Kang, Parkinson & Looser, 2012 for a review). Indeed, the enfacement illusion appears to have a strong social component, as it has been found to influence a number of social processes, including affiliation, trust, and conformity (e.g. Mazzurega, Pavani, Paladino, & Schubert, 2011; Paladino, Mazzurega, Pavani, & Schubert, 2010). These effects are strikingly similar to those elicited by more ecologically valid social interactions with a synchronous, embodied component, such as interpersonal motor synchrony, which has been shown to similarly increase affiliation (Hove & Risen, 2009), trust (Wiltermuth & Heath, 2009) and conformity (Wiltermuth, 2012).

Importantly, recent findings also show that enfacement induces changes in the remapping of bodily experiences from the other to one's self (e.g. Ehrsson, Wiech, Weiskopf, Dolan & Passingham, 2007; Tajadura-Jimenez et al., 2012; Cardini, Tajadura-Jimenez, Serino & Tsakiris, 2013). For example, Cardini et al. (2013) found that a period of synchronous tactile stimulation shared between two people enhanced the 'visual remapping of touch' effect, such that seeing touch on the other's face enhanced participants' own tactile sensitivity to a greater degree after sharing sensory stimulation. Therefore, evidence suggests that shared sensory experiences, such as those provided by enfacement, may enhance the remapping of sensory events occurring to another person's body, onto one's own body representation. However, it is not yet known whether a similar remapping can be induced for events occurring *near* the other's body. Could shared sensory experiences induce a remapping of the other's PPS onto the representation of one's own? Here we test for a possible mechanism underlying this effect: if shared sensory experiences enhance the saliency of the other's PPS representation, stimuli occurring close to the other might be more strongly integrated with tactile stimulation perceived on one's own body, which would boost tactile remapping.

In order to test this hypothesis, we investigated how a synchronous multisensory experience, shared between two individuals, affects the way PPS is represented during a social encounter. We

used an audio-tactile integration task (as used by Taneggi et al., 2013), in which reaction times to tactile stimuli are modulated by the perceived position of a sound relative to the participant's body. We employed this task to estimate perceived PPS boundaries before and after a shared sensory experience (Interpersonal Multisensory Stimulation, or IMS) between the participant and a confederate. We aimed to distinguish between an *expansion* of one's own PPS representation to include the other (as in Teneggi et al. 2013), and a *remapping* of the other's sensory events onto one's own body representation (as in Fini, Cardini, Tajadura-Jimenez, Serino & Tsakiris, 2013). Importantly, the *remapping* mechanism is distinct from the *expansion* mechanism, in that it does not seem to involve any attempt to incorporate the other's PPS into one's own, but rather it reflects a strengthening of the link between the representations of one's own and of the other's body (Cardini et al., 2013; Cardini, Bertini, Serino & Làdavas, 2012; Fini, et al., 2013; Serino et al., 2009).

To allow us to distinguish between these two outcomes, we measured audio-tactile integration at five distances between the body of the participant and that of the other. If shared sensory experiences induce a remapping, rather than an expansion, it will show how sharing experiences with others, as opposed to social exchanges, can lead to qualitatively different spatial representations around our bodies. This will play a key role in our understanding of the functional properties of PPS in different types of social situations.

2. Method

2.1. Participants

Sixteen healthy female volunteers (M_{age} = 21.4; range = 19-23, all but one right-handed, with normal or corrected-to-normal vision) gave their informed consent to participate in the study, which was approved by the Royal Holloway Psychology Ethics Committee.

2.2. Design

Participants' reaction times to tactile stimuli were measured whilst they listened to a task-irrelevant sample of pink noise, which was manipulated to create the perception of the sound approaching the participant's body (and away from an unfamiliar female confederate's body, seated in

front of the participant). Sensitivity was measured at five different time points whilst the sound was approaching (D1-D5, with D1 being the time point at which the sound was perceived as the furthest distance from participant and D5 being perceived as the closest distance to participant). This was carried out in two testing phases, one before and one after a period of interpersonal multisensory stimulation (IMS). The stimulation delivered was either synchronous or asynchronous with the observed touch on the confederate. Thus, the experiment had three factors, in a 5(Sound-Distance: D1 vs. D2 vs. D3 vs. D4 vs. D5) x 2(Test-Phase: pre vs. post IMS) x 2(Stimulation: synchronous vs. asynchronous IMS) repeated-measures design.

2.3. Tasks

2.3.1. Audiotactile Task

This followed the procedure reported by Canzoneri, Magosso and Serino (2012), in order to establish the boundaries of the participant's PPS representation when facing another person. During the audio-tactile interaction task participants sat with their right arm resting palm down on a table beside them. An unfamiliar female confederate, approximately the same age as the participants, was seated at a distance of 100 cm from the participant. On each trial, a sound was presented for 3000ms. The sound was generated by two loudspeakers: one was placed close to the participant's hand and the other one, close to the confederate. Both loudspeakers were hidden from the participant's view. Auditory stimuli were samples of pink-noise, at 44.1 kHz. Sound intensity was manipulated by using Audacity software, so that the sound had exponentially rising acoustic intensity from 55 to 70 dB Sound Pressure Level (SPL) as measured with an audiometer positioned at the participant's ear at the beginning of the experiment. The sound was a combination of two identical samples of pink noise, one of increasing and the other one of decreasing intensity, emitted by the near and far loudspeakers respectively. Both loudspeakers were activated simultaneously, but whereas the far loudspeaker activated at the maximum intensity and then its intensity decreased up to silence along the trial, the near loudspeaker activated at the minimum intensity, and then its intensity increased up to the maximum value along the trial. In this way, participants had the impression of a sound source moving from the far to the near loudspeaker, i.e. towards their own body.

While the sound was played, a constant-current electrical stimulator (Digitimer DS7A, Welwyn, Hertfordshire, England) provided square-wave pulse current via two couples of surface electrodes placed on the participants' right hand dorsum, for 0.2ms, at an intensity 1.4 times higher than individual sensory detection threshold as measured by an initial staircase procedure. This procedure followed that of Cornsweet (1962), whereby participants were asked to report the presence or absence of the electrical stimulus delivered to the right hand by verbal 'yes' or 'no' responses. Shock intensity began at 0 mA increasing in steps of 10 mA until the participant reported the presence of the stimulus. If the participant responded 'yes' three times consecutively, the shock intensity was reduced by 5 mA. If they responded 'no', intensity was increased. Progressively smaller changes were made until the participant was able to detect between 55% and 60% of shocks delivered. Once the perceptual threshold was found, the intensity was set to be 1.4 times stronger than the threshold in order to allow the participants to feel a clear, but not painful stimulation (M intensity = 44.5 mA, SD = 17.8mA). In each trial, the tactile stimulation could be delivered at any of five possible delays from the onset of the sound: D1, tactile stimulation administered at 300ms after the sound onset; D2, tactile stimulation administered at 800ms after the sound onset; D3, tactile stimulation administered at 1500ms after the sound onset; D4, tactile stimulation administered at 2200ms after the sound onset; D5, tactile stimulation administered at 2700ms after the sound onset. In this way, tactile stimulation occurred when the sound source was perceived at different locations with respect to the body: i.e., far from the participant's body - and near the confederate's body - at short temporal delays; and gradually closer to the participant's body - and gradually further from the confederate's body - as the temporal delays increased. Participants were asked to respond as quickly as possible to the tactile stimulation by pressing a key with the unstimulated left hand. Ten trials for each temporal delay were presented in a random order, resulting in a total of 50 trials. The task lasted approximately 3 minutes. This procedure is illustrated in Figure 1.
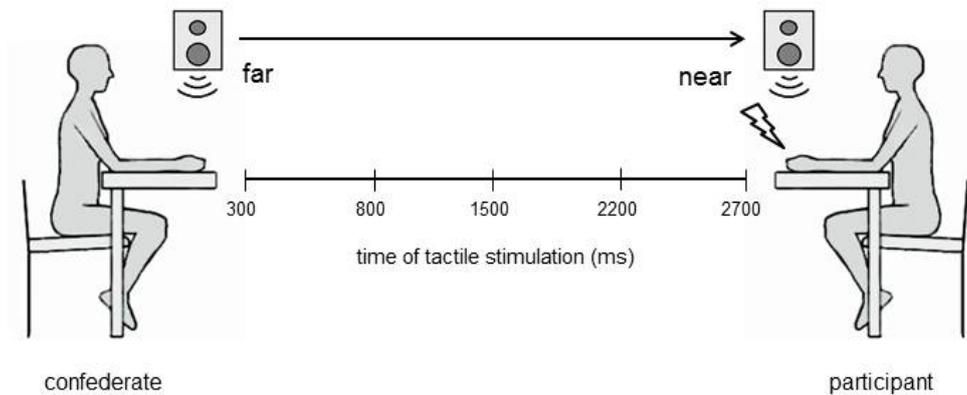
Figure 1. Figure illustrating the set-up of the audio-tactile task. Participants made speeded button-press responses to tactile stimuli (shocks delivered to the hand), whilst seated 100cm from a confederate. During each trial, a looming auditory stimulus was played via two speakers which gave the perception of a sound travelling towards the participant's body. The tactile stimuli could be presented at one of five time-points during the sound, which corresponded to five perceived distances from the participant's body ranging from far (300ms, close to the confederate) to near (2700ms, close to the participant).

2.3.2. Interpersonal Multisensory Stimulation (IMS)

After the first audiotactile Task, participants were exposed to a period of IMS, lasting 2 minutes. Participants were touched by a cotton bud on the left cheek every 2 seconds while watching the confederate's face being touched with a cotton bud in a specularly congruent location, either in synchrony or asynchrony with respect to the touch delivered on the participants' face.

To independently assess whether each participant experienced the enfacement illusion, we included a questionnaire session that followed each post-IMS audiotactile task (one after synchronous IMS and one after asynchronous IMS). Therefore after the completion of each post-IMS audiotactile task, participants were asked to rate their level of agreement with a set of twelve statements related to their subjective experience during IMS (see Table 1, Results section). Previously, subjective reports on the experience of the enfacement illusion have provided evidence of changes in the perceived physical similarity between the two faces (Tajadura-Jiménez et al., 2012). The statements in the questionnaire were adapted from previous studies on the effects of IMS on the experience of self-identification across several dimensions, such as identification with and ownership of the other's face,

mirror-like exposure, feelings of control over the other's face and affect towards the other's person (Paladino et al.,, 2010; Sforza et al., 2010; Tajadura-Jiménez et al., 2012)

2.4. General Procedure

The experimental session was split into two consecutive blocks. In each block, participants completed an audiotactile task before and after a period of IMS. The blocks differed with respect to the type of IMS received (synchronous vs. asynchronous), and also with regards to the identity of the female confederate that sat in front of the participant during each block (Confederate A or Confederate B). One of the confederates sat in front of the participant for the entire duration of the first block (i.e. in the pre-IMS audiotactile task, during the IMS, and in the post-IMS audiotactile task), whereas the other confederate sat in front of the participant during the second block. Confederates were instructed to look towards the participant's face throughout, and keep a neutral facial expression. The order in which the two types of IMS were delivered was counterbalanced between participants. Moreover, to avoid any confounds due to aesthetical, perceptual or idiosyncratic features of the two confederates, the confederate facing the participant in each experimental block was also counterbalanced between participants.

3. Results

First, responses to the Illusion Questionnaire were analyzed to investigate the subjective experiences of the participants during IMS. The response given to each question after synchronous IMS was compared to the response given after asynchronous IMS using paired Wilcoxon signed ranks tests. Mean agreement and results of the statistical comparisons are presented in Table 1.

Table 1

Table showing mean Likert responses to each Enfacement question ranging from -3 (strongly disagree) to +3 (strongly agree), for Synchronous and Asynchronous conditions. Paired Wilcoxon Signed-Ranks tests give statistical significance of differences in responses between conditions.

Enfacement question	Synchronous M(SD)	Asynchronous M(SD)	z	p
"I felt like the other's face was my face"	-0.31 (1.74)	-0.25 (2.21)	-0.33	.746

"It seemed like the other's face belonged to me"	-0.50 (2.00)	-0.44 (1.75)	-0.39	.697
"It seemed like I was looking at my own mirror reflection"	0.88 (1.96)	-0.31 (2.06)	2.06	.040*
"It seemed like the other's face began to resemble my own face"	0.06 (2.05)	0.13 (1.86)	-0.35	.724
"It seemed like my own face began to resemble the other person's face"	0.00 (1.97)	-0.56 (1.59)	0.76	.448
"It seemed like my own face was out of my control"	0.20 (1.26)	0.20 (1.42)	-0.14	.886
"It seemed like the experience of my face was less vivid than normal"	0.38 (1.63)	0.81 (1.47)	-0.80	.426
"It seemed like the person in front of me was attractive"	1.06 (1.12)	0.88 (1.09)	1.09	.276
"It seemed like the person in front of me was trustworthy"	1.63 (1.31)	0.69 (1.40)	2.72	.006**
"I felt that I was imitating the other person"	-0.31 (1.70)	0.69 (1.85)	-1.74	.082
"The touch I felt was caused by the cotton bud touching the other's face"	-0.50 (1.79)	0.75 (1.44)	-2.38	.017*
"The touch I saw on the other's face was caused by the cotton bud touching my own face"	-0.56 (1.90)	-1.00 (1.83)	1.19	.233

*$p < .05$. **$p < .01$, uncorrected.

To investigate whether peripersonal space representation in the presence of another person changes as a function of the interaction with that person, mean RTs to the tactile stimulus administered at the different delays were calculated and compared before and after the two IMS conditions by means of an 2x2x5 ANOVA with within-subjects factors of Test-Phase (pre- vs post-IMS); Stimulation (Synchronous vs Asynchronous IMS); and Sound-Distance (D1-D5 with D1 = farthest Distance and D5 = closest Distance). Participants omitted 9% of trials on average in all conditions. RTs exceeding more than 2 standard deviations from the mean RT were considered outliers and excluded from the analyses (5% of trials on average in all conditions).

A main effect of Test-Phase [$F_{(1,15)}$ = 10.86, p< .01] showed generally faster RTs after the IMS (M = 384.49, SE = 8.22) than before (M = 396.47, SE = 8.73). A main effect of Sound-Distance was also found [$F_{(4,60)}$ = 53.61, p < .001]. Post-hoc paired samples t-test comparisons revealed a general pattern of faster RT when the sound was perceived closer to the body at the point of stimulus delivery, than when the sound was perceived as further from the body. More importantly, an interaction between Test-Phase, Stimulation and Sound-Distance was significant [$F_{(4,60)}$ = 2.81, p = .033].

To further investigate the source of this three-way interaction, we first compared the RTs obtained in the two pre-IMS sessions by running a 2x5 ANOVA with within-subjects factors of Stimulation (Synchronous vs Asynchronous IMS) and Sound-Distance (D1-D5). Whereas a main effect of Distance was observed [$F_{(4,60)}$ = 37.57, p < .001], no main effect of Stimulation nor Stimulation x Sound-Distance interaction were significant, confirming the two pre-IMS sessions as appropriate baselines. Therefore, we then carried out two separate 2x5 ANOVAs for Synchronous and Asynchronous stimulation with the factors Test-Phase (pre- vs post-IMS) and Sound-Distance (D1-D5) as independent variables. In the Asynchronous block, the only significant result was a main effect of Sound-Distance [$F_{(4,60)}$ = 46.36, p < .001]. Post-hoc paired samples t-test comparisons showed that RTs for tactile stimuli were significantly faster when concurrent sound was perceived at D3, D4 and D5 as compared to when sound was perceived at D1. Moreover RTs at D3, D4 and D5 were significantly faster than RTs at D2. Finally, RTs to tactile stimuli delivered when sound was perceived

at D4 were significantly faster than RTs at D3 (t > 4.47 and p < .005 in all cases, Bonferroni corrected).

Similarly, for the Synchronous stimulation a main effect of Sound-Distance was found [$F_{(4,60)}$ = 37.97, p<.001]. However, for the Synchronous stimulation, this main effect was modulated by Test-Phase, since the two-way interaction was significant [$F_{(4,60)}$ = 3.77, p = .008]. Post-hoc paired samples t-tests were used to compare RTs measured at each Sound-Distance, before and after Synchronous IMS. A significant change was observed only at D1 [$t_{(15)}$ = 5.36, p < .001], with faster RTs after (M = 423.50, *SE* = 12.62) as compared to before (M = 464.70, *SE* = 14.56) Synchronous IMS. Importantly, clear differences remained between RTs measured at each Sound-Distance after synchronous IMS; post-hoc paired samples *t-test* comparisons showed that RTs for tactile stimuli were significantly faster when concurrent sound was perceived at D4 and D5 as compared to when sound was perceived at D1 or D2. Moreover, RTs to tactile stimuli delivered when sound was perceived at D4 and D5 were significantly faster than RTs at D3 (t > 4.43 and p < .005 in all cases, Bonferroni corrected). These results are illustrated in Figure 2.
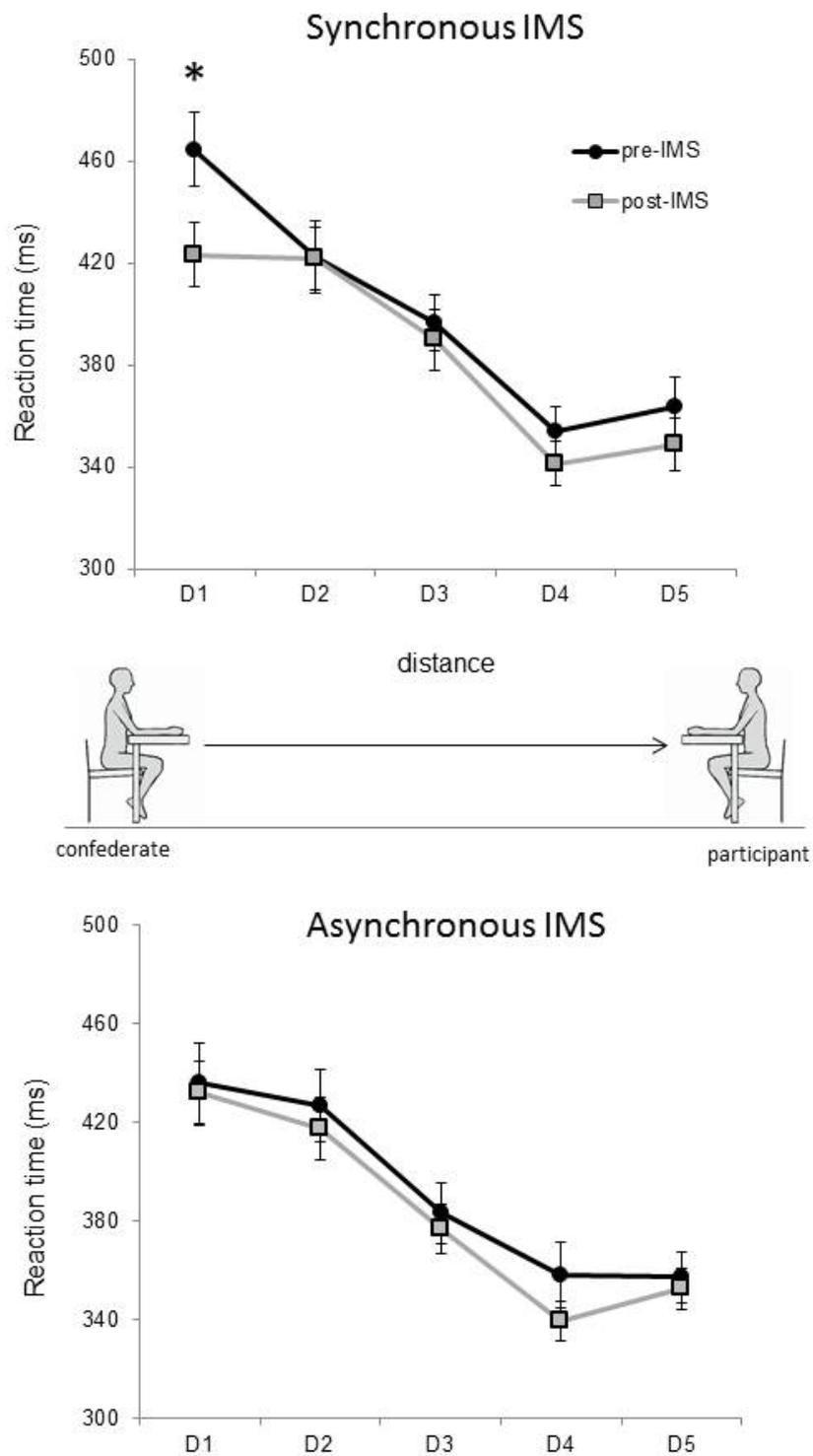
Figure 2. Graphs showing performance on the audio-tactile task, before and after a period of synchronous (top panel) or asynchronous (bottom panel) interpersonal multisensory stimulation (IMS). Mean reaction times to tactile stimuli (in msec, y axis) were measured at five distinct time periods, during which an auditory stimulus was perceived moving away from a confederates body (D1), towards the participant's own body (D5). Error bars reflect standard error of the mean, and asterisk indicates p-value < .05, two-tailed.

4. Discussion

Shared sensory experiences, such as those elicited by bodily illusions such as the enfacement illusion, can induce feelings of ownership over the other's body (Sforza et al., 2010) which has also been shown to increase the remapping of the other's sensory experiences onto our own bodies (Cardini et al., 2013). The current study investigated whether such shared sensory experiences between two people could also alter the way the space around the other's body (the peripersonal space, PPS) was represented, and whether this alteration could be best described as an expansion of one's own PPS representation towards the other (as in Teneggi et al. 2013) or a remapping of the representation of the other's PPS onto one's own (as in Cardini et al. 2012). An audio-tactile integration task allowed us to measure the extent of the PPS representation before and after a shared sensory experience with a confederate.

Our results showed a clear change in the perception of the other's PPS after a period of shared sensory stimulation. Before IMS, the audio-tactile integration task replicated the standard pattern of results reported by previous studies (Canzoneri et al., 2012; Serino, Canzoneri & Avenanti, 2011; Teneggi et al., 2013), whereby an auditory stimulus speeds up reaction times when it is perceived as occurring close to the participant's body. After a period of asynchronous interpersonal stimulation, this pattern of results remained unchanged. However, after participants experienced *synchronous* interpersonal stimulation shared with the other, reaction times to tactile stimuli delivered when an auditory signal was perceived as close to the other's body were faster, demonstrating increased audio-tactile integration in the other's PPS.

Could a shared sensory experience, such as that provided by the enfacement illusion, elicit these changes merely by increasing attention to the space around the other's body? We argue that a purely attentional account such as this fails to explain why such enhanced attention is specifically induced by synchronous, and not asynchronous stimulation. Furthermore, a general effect of enhanced attention cannot explain any of the other striking effects of interpersonal stimulation, such as increased trust and conformity (Paladino et al., 2010). Instead, these findings suggest that the synchronicity between tactile stimulation on one's own face and visual stimulation on the other's face

established a new functional link between those two portions of space, so that events occurring close to the other acquired an increased saliency in interacting with stimuli occurring on the participant's body. We speculate that such saliency change relies on a change in the properties of receptive fields of multisensory neurons representing the PPS, which normally minimally respond to far stimuli, whereas after synchronous visuo-tactile stimulation of near and far space, a proportion of these neurons show increased responding to events occurring at the stimulated location (see Magosso, Zavaglia, Serino, di Pellegrino & Ursino, 2010; Magosso, Ursino, di Pellegrino, Ladavas & Serino, 2010 for a computational account). However, this proposal needs empirical support from neurophysiological data (see e.g., Makin, Holmes & Ehrsson, 2007 and Brozzoli, Gentile & Ehrsson, 2012 for a similar account in the case of the RHI).

Importantly, the pattern of our results is qualitatively different from that induced by a cooperative social exchange, as reported by Teneggi et al. (2013). We found a significant increase in audiotactile integration in position D1 only, which is close to the other's body. Processing in the interim positions between the other's body and the participant's body were unchanged. Crucially, although RTs to tactile stimuli were significantly increased at D1 (when the sound was perceived close to the other's body), differences in tactile reaction times between D1 and D5 (when the sound was perceived as close to the participant's own body) were maintained. In contrast, Teneggi et al. reported a general change in audio-tactile integration across the distance between the two bodies, which removed any differences in the way sensory information was integrated between any of the distances measured. In other words, after a cooperative exchange, sounds perceived at any distance between the participant's and the other's body equally influenced tactile processing.

These results have important consequences for our understanding of interpersonal space during social interactions. In our study, sharing a sensory experience with another person did not lead to an expansion of the PPS representation, as it only induced changes in the way information was integrated within the other's PPS, and not in the interim space between self and other. This pattern of results is therefore more accurately described as a 'remapping' of the representation of the other's PPS: after stimulation, participants' responses to events occurring in the other's PPS was enhanced.

However, this change did not reflect a 'complete' remapping of the other's PPS as one's own PPS; indeed, responses to events within the participant's own PPS representation were still distinguishable from those to events in the other's PPS, suggesting that a distinction between self- and other-PPS was partially maintained. This is consistent with a number of studies investigating the remapping of sensory events from another's body onto one's own. For example, a robust vicarious activation of secondary somatosensory cortex is elicited when one observes someone else being touched, but certain areas in the central sulcus and postcentral gyrus only reliably activate when one's own body is touched (e.g. Blakemore et al., 2005; Ebisch, Perrucci, Ferretti, Del Gratta, Romani & Gallese, 2008; Cardini et al., 2011). Thus, in addition to brain areas supporting shared body representations for tactile stimuli, there are additional 'private' areas, whose activation is reserved for personally experienced tactile sensations. Their role may be crucial in preserving the distinction between self and other (see de Vignemont, 2014), essential for complex social cognition mechanisms such as perspective taking and empathy (Decety & Somerville, 2003; Ruby & Decety, 2004).

Shared sensory experiences may function to modulate the processing of self-relevance of approaching objects in the environment. In everyday life, observing an object approaching another person bears little relevance to events occurring near our own body. However, when we have consistently shared sensory experiences with that person, i.e. during IMS, events which we observe occurring on the other's body are synchronously felt on our own body. Having set up a strong association between events we observe occurring on the other's body, and those which occur to ourselves, it makes sense for objects approaching the other's body to be processed in a more efficient way, so they can be responded to accordingly. In this way, shared sensory experiences may increase the saliency of that person in relation to oneself, and as a consequence, enhance the ability to remap events approaching the other's body onto one's own PPS representation.

There are some interesting similarities between the way we represent our PPS when viewing another person after a shared sensory experience, and when we view direct visual representations of our own body, such as a mirror reflection or shadow. For example, when viewing a distant mirror image of one's body, a rapid remapping of the visuotactile peripersonal space occurs to surround the

mirror image (Maravita, Spence, Sergent & Driver, 2002). A similar remapping occurs when viewing body shadows, but only if ownership is felt over the shadow (Pavani & Galfano, 2007). In these studies, the remapping is induced by the spatio-temporal congruity between one's own body movements and the movements of the mirror image or shadow. In our study, we find a similar result by inducing a spatio-temporal congruity between touch on the other's body and touch on one's own body, which importantly also induces a subjective experience of looking at oneself at the mirror while facing the other. This raises the possibility that the other body may in some way be treated as a mirror-image, or shadow, of one's own body, and the PPS representation is remapped accordingly.

The 'mirror experience' induced by shared sensory experiences may be a particularly intense version of a process that occurs naturally in human social interactions. Individuals automatically mimic each other in social interactions (see Chartrand & Bargh, 1999; Lakin, Jefferis, Cheng & Chartrand, 2003), essentially behaving as 'social mirrors' (Prinz, 2013). Thus, when we interact with others, they provide us with an embodied reflection of our own actions, postures and expressions. This may give us privileged access to information regarding our bodies in the environment, from a third-person perspective (Prinz, 2013). Whether it can also provide us with a mirror reflection of the space *around* our bodies is a possibility which requires further research.

This study has several limitations, which are important to discuss. First, the distance between the participant and the confederate was 100cm, and five distances were mapped. Whilst consistent with previous research (see Teneggi et al., 2013; Canzoneri et al., 2013; Canzoneri, Marzolla, Amoresano, Verri & Serino, 2013), using a larger distance and more data points would have allowed us to view the full pattern of response times and apply a curve-fitting analysis to fully elucidate how participants' perception of PPS was affected by the shared sensory experience. Second, a direct comparison of the effects of a cooperative exchange and the effects of shared sensory experience, from within the same experiment, would provide a stronger test of the distinct effects of each. Finally, our subjective measure of the enfacement illusion did not reveal significant differences between the synchronous stimulation and the asynchronous control stimulation for a number of the questions in the Illusion Questionnaire. This may be due to the live nature of the enfacement procedure. In a live

set-up, the task demands and the participants' awareness of the social aspects of the task may be very different from the more commonly used video set-up. Although both methods have been used successfully (Sforza et al., 2010; Tajadura et al., 2012), there are currently no studies directly comparing the two methods. Therefore, we do not know how this factor might have affected the responses to the standard twelve-item questionnaire in the current study. However, one of the crucial questions of the Illusion Questionnaire, "It seemed like I was looking at my own mirror reflection" was agreed with significantly more after synchronous than asynchronous stimulation. Given that Maravita et al. (2002) showed a remapping of the PPS around the mirror-reflection, this may identify an interesting avenue for further research.

A number of studies have now demonstrated that shared sensory experiences, such as those provided by IMS in the enfacement illusion, have wide-reaching effects on sociocognitive processes (e.g. Cardini et al., 2013; Farmer, Maister & Tsakiris, 2014; Fini et al., 2013; Maister, Tsiakkas & Tsakiris, 2013a; Maister, Sebanz, Knoblich & Tsakiris, 2013b; Paladino et al., 2010). However, this study is the first to demonstrate changes in the way space surrounding the bodies of self and other are represented. This finding has several interesting implications for our understanding of social interaction. A remapping of another's PPS onto our own spatial representations essentially allows for us to respond to threats approaching the other's body in a more efficient and prompt way. This may optimise defensive behaviours towards threats that are likely to be most relevant to the self. This bears similarities to earlier findings regarding the effects of shared sensory experiences on emotion recognition. Maister and colleagues (Maister et al., 2013a) demonstrated that after a period of IMS, participants were significantly more sensitive to their enfacement partner's facial expressions of fear, while Cardini et al. (2012) showed that the visual remapping of touch effect is stronger not only for viewing one's own face, but also the face of another person displaying a fearful expression. These findings are compatible with a possible enhancement of a somatosensory remapping mechanism, in which the other's expressions of fear were prioritized as particularly relevant to the self. It makes sense that sensory signals of potential threat to another person should be preferentially remapped when one consistently 'feels what they feel'. The results of the current study suggest that this may not

only be the case for events occurring to the other's body, but also for events *close* to the other's body.

These results also have implications for our understanding of close social relationships. Closely affiliated individuals, such as friends or romantic partners, may be more likely to share sensory experiences, during shared activities such as eating or walking together. Furthermore, affiliated individuals tend to show increased mimicry of each other's movements and postures (e.g. Bourgeois & Hess, 2008; Stel, van Baaren, Blascovich, van Dijk, McCall, Pollman, van Leeuwen, Mastop & Vonk, 2010) which may lead to further shared sensory and motor experiences. Thus, a remapping of a partner's PPS after such a shared experience may not only serve to optimise our own defensive behaviours, but may facilitate behaviours aimed to protect our partner from harm. A rapid, intuitive first-person understanding of sensory events approaching a close social partner could play an important role in empathic behaviours, protection and altruistic helping. What is important now is to elucidate the functional distinction between an extension and a remapping of the representation of PPS, and what social interactions elicit these separable changes in spatial representations.

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