Common and distinct brain regions processing multisensory bodily signals for peripersonal space and body ownership

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ABSTRACT

We take the feeling that our body belongs to us for granted. However, recent research has shown that it is possible to alter the subjective sensation of body ownership (BO) by manipulating multisensory bodily inputs. Several frontal and parietal regions are known to specifically process multisensory cues presented close to the body, i.e., within the peripersonal space (PPS). It has been proposed that these PPS fronto-parietal regions also underlie BO. However, most previous studies investigated the brain mechanisms of either BO or of PPS processing separately and by using a variety of paradigms. Here, we conducted an extensive meta-analysis of functional neuroimaging studies to investigate PPS and BO processing in humans in order to: a) assess quantitatively where each one of these functions was individually processed in the brain; b) identify whether and where these processes shared common or engaged distinct brain mechanisms; c) characterize these areas in terms of whole-brain co-activation networks and functions, respectively. We identified (i) a bilateral PPS network including superior parietal, temporo-parietal and ventral premotor regions and (ii) a BO network including posterior parietal cortex, IPS; (right intraparietal sulcus, IPS; and left IPS and superior parietal lobule, SPL), right ventral premotor cortex, and the left anterior insula. Co-activation maps related to both PPS and BO encompassed largely overlapping fronto-parietal networks, but whereas the PPS network was more frequently associated with sensorimotor tasks, the BO network was rather associated with attention and awareness tasks. Finally, the conjunction analysis showed that (iii) PPS and BO tasks anatomically overlapped only in two clusters located in the left parietal cortex (dorsally at the intersection between the SPL, the IPS and area 2 and ventrally between areas 2 and IPS). Distinct activations were located for PPS at the temporo-parietal junction and for BO in the anterior insula. These results in PPS and BO and provide evidence-based insight about the overlap of the two processes in the IPS region and the extensive connectivity between the two associated co-activation networks. They also show significant dissociations, with PPS fronto-parietal areas located more proximal to the central sulcus than BO areas. Such anatomical distinction may also reflect the different functions of the two processes, whereby PPS areas underlie a multisensory-motor interface for body-objects interaction and BO areas being involved in bodily awareness and self-consciousness.

Introduction

The sense that our body belongs to us, body ownership (BO), is argued to be one of the cardinal features of subjective experience (Blanke and Metzinger, 2009; Gallagher, 2000). Recently, multisensory bodily illusion paradigms have been developed to study BO in the laboratory, describing the detailed behavioral mechanisms underlying the sensation of ownership for the hand (Botvinick and Cohen, 1998), the face (Sforza et al., 2010; Tsakiris, 2008) and the entire body

(Ehrsson, 2007; Lenggenhager et al., 2007; Petkova and Ehrsson, 2008). These illusions have demonstrated that by manipulating multisensory cues it is possible to induce ownership over fake or virtual body parts or whole bodies. For example, to induce the rubber hand illusion, Botvinick and Cohen (1998) stroked with a brush both a realistic-looking rubber hand (in view of the participant) and the real hand of the participant (occluded from view) using stroking patterns in spatio-temporal synchrony. Participants felt stronger illusory ownership over the rubber hand in the synchronous (illusion) than the asynchronous

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(control) visuo-tactile stroking condition. Similar paradigms applied synchronous visuo-tactile stimuli between the trunk of a participant and a virtual body to achieve ownership over a body (full-body illusion, out-of-body illusion or body-swap illusion; Ehrsson, 2007; Lenggenhager et al., 2007; Petkova and Ehrsson, 2008), or between the participant's and another person's face to manipulate face ownership (enfacement illusion; Sforza et al., 2010; Tsakiris, 2008). These results, as well as converging evidence from subsequent variations of these experiments, have led to a growing consensus that ownership over hands, faces, and bodies crucially relies on the integration of multiple bodily signals in the brain (Blanke, 2012; Blanke et al., 2015; Ehrsson, 2012; Ehrsson et al., 2004; Makin et al., 2008; Serino et al., 2013; Tsakiris, 2010).

Research in non-human primates has shown that multisensory cues, in particular those involving the body, are processed and integrated by a specialized neural system mapping the space around the body, i.e. the peripersonal space (PPS) (Cléry et al., 2015; di Pellegrino and Làdavas, 2015; Graziano and Cooke, 2006; Ladavas and Serino, 2008; Rizzolatti et al., 1997). Specific populations of multisensory neurons, originally described in a fronto-parietal network of the macaque brain, integrate tactile information on the body with visual (or auditory) stimuli occurring close to the body, i.e. within the PPS (Graziano and Cooke, 2006; Rizzolatti et al., 1981a, 1981b; Duhamel et al., 1998; Fogassi et al., 1996; Graziano et al., 1994). Similar multisensory integration mechanisms have been also described in the human brain, in frontal and parietal areas, homologous to those macaque regions where PPS neurons have been identified (Bremmer et al., 2001; Serino et al., 2011, for reviews, see Cléry et al., 2015; di Pellegrino and Làdavas, 2015).

Importantly, recent accounts have proposed a direct link between the neural mechanism underlying BO and multisensory PPS processing (Blanke, 2012; Blanke et al., 2015; Ehrsson, 2012; T. R. Makin et al., 2008). Under normal circumstances, the extent of PPS is defined by the size of the multisensory receptive fields of PPS neurons. Synchronous visuo-tactile stimulation implemented to induce the different bodily illusions (altering BO) may lead to changes in the spatial characteristics of multisensory receptive fields of PPS neurons in such a way that the boundaries of PPS extend to include the virtual body part or whole body for which participants experience ownership (for a discussion, see Blanke et al., 2015). Behavioral support of this prediction has been provided in both the context of the rubber hand illusion (Pavani et al., 2000; Zopf et al., 2010; Guterstam et al., 2016), the enfacement illusion (Maister et al., 2015) and the full body illusion (Aspell et al., 2009; Noel et al., 2015). These studies showed that after synchronous visuo-tactile stimulation, visual or auditory stimuli presented close to the artificial body for which participants experience ownership were integrated with tactile information on their body, as normally only occurred for stimuli presented close to their physical body (i.e. within PPS; see Serino et al., 2015).

Neuroimaging experiments have recently started unraveling the brain mechanisms associated with encoding of sensory events within the hand, face and trunk PPS (e.g., Makin et al., 2007, Bremmer et al., 2001; Huang et al., 2012). Although activations have most often been reported in premotor and posterior parietal areas (e.g. Makin et al., 2007), they also encompassed a larger network of regions, including the parietal operculum (e.g. Tyll et al., 2013), the insula (e.g. Schaefer et al., 2012), the cingulate cortex (e.g. Holt et al., 2014), the lateral occipital cortex (e.g. Gentile et al., 2013), the putamen (e.g. Gentile et al., 2011) and the cerebellar cortex (e.g. Brozzoli et al., 2011).

Concerning BO, neuroimaging studies have recently engaged in assessing the neural correlates of ownership over a hand, a face, or a whole body (e.g. Apps et al., 2013; Ehrsson et al., 2004; Petkova et al., 2011). The vast majority of these studies highlighted again similar fronto-parietal regions, but also involved the parietal operculum (e.g. Gentile et al., 2013), the insula (e.g. Apps et al., 2013), the cingulate

cortex (e.g. Tsakiris et al., 2007), the lateral occipital cortex (e.g. Guterstam et al., 2015), the putamen (e.g. Petkova et al., 2011), and the cerebellar cortex (e.g. Ehrsson et al., 2005). Importantly, the clusters reported in the fronto-parietal regions were neither always present (Limanowski et al., 2014), nor were they necessarily always the most prominent (Apps et al., 2013).

Despite numerous qualitative reviews discussing the neural mechanisms of PPS (Blanke et al., 2015; Cléry et al., 2015; di Pellegrino and Làdavas, 2015) or BO in humans (Blanke, 2012; Ehrsson, 2012; Serino et al., 2013; Tsakiris, 2010), no quantitative assessment of the available data from the literature has, to date, been conducted for PPS or BO. However, this will be important to reveal the key neural structures selectively involved in integrating multisensory stimuli in PPS and for BO. Furthermore, despite the above-mentioned behavioral evidence linking PPS and ownership and reviews suggesting a possible overlap of common neural mechanisms (Blanke, 2012; Blanke et al., 2015; Ehrsson, 2012; Makin et al., 2008), it is currently unknown whether or to what extent they exploit the same or distinct brain regions (but see Brozzoli et al., 2012; Gentile et al., 2013). For instance, the premotor cortex, that has been associated with PPS and BO (see e.g., Brozzoli et al., 2011; Ehrsson et al., 2005, respectively), covers a considerable portion of the frontal lobe and its anatomical delineation in humans is still a matter of debate (Mayka et al., 2006). Therefore, activity reported in ventral and dorsal premotor cortex regions by previous studies on BO or PPS could potentially refer to spatially distinct sub-regions within the premotor cortex. Thus, although the behavioral human and the electrophysiological monkey data suggest a close link between multisensory integrative brain mechanisms within PPS and BO, the evidence in humans remains sparse and has involved, in addition, many areas outside the classical fronto-parietal network.

In order to determine the key neural structures for PPS, for BO, and their potential common structures in humans, we carried out a systematic quantitative coordinate-based meta-analysis on human functional neuroimaging studies (Eickhoff et al., 2009, 2012; Turkeltaub et al., 2002). We investigated which brain regions (i) consistently process unisensory and multisensory events occurring within PPS, (ii) are associated with the subjective sensation of BO, and (iii) whether PPS and BO share common neural substrates. Finally, we characterized these regions in terms of functions and co-activation networks against a database of general neuro-imaging experiments.

Methods

Selection of studies and inclusion criteria

We investigated common neural correlates of PPS and BO. To do so, we searched for the relevant neuroimaging experiments using the Pubmed (www.pubmed.com) and the Web of Knowledge (www.webofknowledge.com) internet portals using domain-general ("fMRI" or "PET") and domain-specific (PPS: "peripersonal space" or "multisensory integration"; BO: "ownership" or "self-identification" or "rubber-hand illusion" or "full-body illusion" or "body-swap illusion") search terms. Further references were obtained from recent reviews on these topics (Blanke et al., 2015; Cléry et al., 2015; di Pellegrino and Làdavas, 2015) as well as reference-tracing. Included in the current meta-analysis were PET or fMRI studies performed in groups of healthy subjects reporting results either in standardized Montreal Neurological Institute (MNI) or Talairach (TAL) coordinates. All TAL coordinates were transformed into MNI using a linear transformation (Lancaster et al., 2007) and subsequently all the analyses were performed in MNI space. Studies reporting activation clusters obtained using a small-volume correction or lower thresholds based on a-priori hypotheses were included in the analysis only in the case where a satisfying justification for doing so was provided by the authors. For PPS, the use of small-volume correction based on a-