Region-of-interest analysis approaches in neuroimaging studies of body ownership: An activation likelihood estimation meta-analysis

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Abstract
How do we feel that we own our body? By manipulating the integration of multisensory signals and creating the illusory experience of owning external body parts and entire bodies, researchers have investigated the neurofunctional correlates of body ownership. Recent attempts to synthesize the neuroimaging literature of body ownership through meta-analysis have shown partly inconsistent results. A large proportion of functional magnetic resonance imaging (fMRI) findings on body ownership include analyses based on regions of interest (ROIs). This approach can produce inflated findings when results are synthesized in meta-analyses. We conducted a systematic search of the fMRI literature of ownership of body parts and entire bodies. Three activation likelihood estimation (ALE) meta-analyses were conducted, testing the impact of including ROI-based findings. When both whole-brain and ROI-based results were included, frontal and posterior parietal multisensory areas were associated with body ownership. When only ROI-based results were included, larger areas of the frontal and posterior parietal cortices and the middle occipital gyrus were associated with body ownership. A whole-brain meta-analysis, excluding ROI-based results, found no significant convergence of activation across the brain. These findings highlight the difficulty of quantitatively synthesizing a neuroimaging field where a large part of the literature is based on findings from ROI-based analyses. We discuss these findings in the light of current practices within this field of research and highlight current problems of meta-analytic approaches of body ownership. We recommend the

Abbreviations: ALE, activation likelihood estimation; BA, Brodmann area; BOLD, blood-oxygen-level-dependent; BSI, body-swap illusion; CluB, clustering the brain; EFI, enfacement illusion; FBI, full-body illusion; fMRI, functional magnetic resonance imaging; FSL, FMRIB Software Library; FWE, familywise error; L, left; Mango, multi-image analysis GUI; MKDA, multilevel kernel density analysis; MNI, Montreal Neurological Institute; R, right; RFI, rubber foot illusion; RHI, rubber hand illusion; ROI, region of interest; SPM, Statistical Parametric Mapping; SVC, small-volume correction.

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sharing of unthresholded data as a means to facilitate future meta-analyses of the neuroimaging literature of body ownership.

**KEYWORDS**
ALE meta-analysis, fMRI, multisensory integration, ownership, region of interest

## 1 | INTRODUCTION

Body ownership is the non-conceptual, ever-present sense that our body and body parts belong to us. It is the sense that I experience this body as ‘my’ body. Over the past decades, body ownership has been studied through perceptual illusion paradigms that alter the sense of ownership over individual body parts, in particular utilizing the rubber hand illusion (RHI) paradigm (Botvinick & Cohen, 1998). A number of extensions of this paradigm have been developed, such as the out-of-body illusion (Ehrsson, 2007), the full-body illusion (Lenggenhager et al., 2007), the body-swap illusion (Petkova & Ehrsson, 2008), the enfacement illusion (Tsakiris, 2008) as well as other body parts such as the rubber foot illusion (Crea et al., 2015; Lenggenhager et al., 2015).

Current theories of body ownership emphasize the role of multisensory integration in the experience of body ownership. Typically, visual and somatic input is manipulated to induce illusory body ownership (e.g., through synchronous visuotactile stimulation). Accordingly, it has been hypothesized that cortical regions that perform this integration of sensory stimuli from the body are involved in generating the body ownership sensation (Blanke, 2012; Ehrsson, 2012; Graziano & Botvinick, 2002).

The first neuroimaging study of the RHI using functional magnetic resonance imaging (fMRI) by Ehrsson et al. (2004) found increased activity in premotor and intraparietal areas. These areas are known for their multisensory properties (Gentile et al., 2011; Graziano & Botvinick, 2002; Stein & Stanford, 2008) and therefore ideal candidates for the integrative processes underpinning the RHI and body ownership more generally. Later studies have corroborated this finding (Brozzoli et al., 2012; Guterstam et al., 2015; Petkova et al., 2011), while others have not (Limanowski et al., 2014). Other areas activated in neuroimaging studies of body ownership include the insula (Apps et al., 2015; Tsakiris et al., 2007), the lateral occipital cortex (Guterstam et al., 2015), the parietal operculum (Gentile et al., 2013), the putamen (Petkova et al., 2011) and the cerebellum (Ehrsson et al., 2005; Preston & Ehrsson, 2016). Among these, the premotor–parietal and the insular activations received particular attention in theories of body ownership (Blanke, 2012; Ehrsson, 2012; Tsakiris, 2010).

Recently, three separate coordinate-based meta-analyses have been conducted on neuroimaging studies of body ownership (Grivaz et al., 2017; Salvato et al., 2020; Seghezzi et al., 2019). The three meta-analyses compared the neurofunctional correlates of body ownership, resulting from separate meta-analyses, with the neurofunctional correlates of peripersonal space (Grivaz et al., 2017), sense of agency (Seghezzi et al., 2019) and interoception (Salvato et al., 2020).

Grivaz et al. (2017) conducted an activation likelihood estimation (ALE) meta-analysis of 17 functional imaging studies of body ownership. They found converging activation patterns within four clusters (Grivaz et al., 2017), two located in bilateral intraparietal regions, one in the right ventral premotor cortex and one in the left anterior insula (Grivaz et al., 2017).

Seghezzi et al. (2019) combined ALE with a method based on an optimized hierarchical cluster algorithm: clustering the brain (CluB; Cattinelli et al., 2013). Seventeen studies were included in the analysis. They found two clusters in the left hemisphere associated with body ownership, one located in the inferior parietal lobule and one in the left anterior insula (Grivaz et al., 2017).

Salvato et al. (2020) conducted a meta-analysis of 16 functional imaging studies of body ownership using multilevel kernel density analysis (MKDA). They found convergence of activation in six clusters, two located bilaterally in inferior temporal–occipital regions, one in the left inferior parietal lobe, one in the right precentral gyrus, one in the left fusiform gyrus and one in the right cerebellar tonsil (Salvato et al., 2020).

Despite some common findings, the three meta-analyses demonstrated different activation patterns. A convergence of activation was found in intraparietal areas in all three meta-analyses, although bilaterally in Grivaz et al. (2017). Additionally, Seghezzi et al. (2019) found no premotor clusters, only Grivaz et al. (2017) found activity in the insula, and Salvato et al. (2020) indicated a more extensive network of occipitotemporal, parietal, prefrontal and cerebellar areas associated with body ownership. These discrepancies have important implications for current theories of body ownership, including...
whether the insula is involved in body ownership (Karnath & Baier, 2010; Tsakiris et al., 2007).

The selection of inclusion criteria and analytical flexibility can impact the results of a meta-analysis (e.g., Lakens et al., 2016; Palpacuer et al., 2019). For example, two of the previously mentioned meta-analyses selected to include all available neuroimaging results (Grivaz et al., 2017; Seghezzi et al., 2019), while one meta-analysis only included findings resulting from whole-brain analysis, excluding ROI-based findings (Salvato et al., 2020). Interestingly, the latter study found no significant convergence of activation in the insula (Salvato et al., 2020).

In fMRI analysis, a statistical map is created where voxels exceeding a particular statistical threshold are considered activated. In a whole-brain (univariate voxel-wise) analysis, hypothesis testing is conducted simultaneously for each voxel in the brain and then corrected for multiple comparisons. A ubiquitous approach within fMRI research, including among neuroimaging studies of body ownership, is to investigate further certain regions of interest (ROIs) (e.g., Bekrater-Bodmann et al., 2014; Brozzoli et al., 2012; Ehrsson et al., 2004; Ehrsson et al., 2005; Guterstam et al., 2015; Limanowski et al., 2014; Limanowski & Blankenburg, 2016a; Petkova et al., 2011). ROIs can be defined based on anatomy, previous literature or a separate localizer scan and are considered justified only when a strong a priori hypothesis exists (Duncan et al., 2009; Poldrack, 2007). ROIs can help limit the severity of correcting for multiple comparisons, a fundamental problem in neuroimaging. This can be achieved either by averaging across voxels in the predefined area of interest or, alternatively, by limiting the search for significance to those voxels inside the ROI, known as a small-volume correction (SVC) (Worsley et al., 1996). The SVC effectively lowers the threshold necessary to reach a statistical significance compared with whole-brain analysis and can thereby provide increased statistical power (Cremers et al., 2017; Saxe et al., 2006).

Brain structures linked to multisensory integration (Stein & Stanford, 2008), such as the ventral premotor cortex, intraparietal cortex or insula, have often been selected as ROIs in individual neuroimaging studies of body ownership. These ROIs are often selected based on hypotheses stemming from existing theoretical frameworks (e.g., Blanke, 2012; Ehrsson, 2012) and single-cell recordings of bimodal neurons within these areas (e.g., Graziano & Botvinick, 2002). These structures provide a plausible neuronal substrate for the processes assumed to underlie body illusions (e.g., Gentile et al., 2011); therefore, selecting these structures as ROIs can be considered appropriate. However, on a meta-analytic level, ROI-based studies present a problem.

Coordinate-based meta-analyses such as ALE and MKDA test for convergence across experiments against a null hypothesis of random spatial associations across the entire brain, which assumes that each voxel a priori has the same probability of being activated (Albajes-Eizaguirre & Radua, 2018; Eickhoff et al., 2012). Because the threshold for reaching significance is lowered in ROI (including SVC) approaches, the inclusion of these results in a meta-analysis violates the assumption of equal activation probability. Thus, it can bias the meta-analytical results towards these regions (Müller et al., 2018). For this reason, best-practice guidelines for neuroimaging meta-analysis are to exclude results from these analysis approaches (Müller et al., 2018). The impact of ROI-based results on coordinate-based meta-analyses has recently been investigated in phobia research. Here, it has been demonstrated that the inclusion of ROI-based results inflates group differences and thus influences the interpretation of the neurobiological processes underlying phobias (Gentili et al., 2019). Taken together, this introduces the possibility that previous meta-analytical results, such as the convergence in the premotor–parietal or insular areas, resulted from this ROI-induced bias.

Whereas the previous meta-analyses focused on the overlap of the ownership network with other networks, we here aimed to quantitatively synthesize the fMRI literature on the sense of body ownership. We additionally aimed to investigate the use of ROI-based approaches and assess how these methods might affect current meta-analytical findings within the field. For this purpose, we conducted a systematic literature search for fMRI experiments utilizing body ownership illusions and three separate ALE meta-analyses. The primary meta-analysis included results based on ROI and whole-brain analyses. Two additional meta-analyses were conducted: a whole-brain meta-analysis, in which results from ROI-based methods were excluded, and an ROI-only meta-analysis where only results from ROI-based methods were included. We hypothesized that the choice of inclusion criteria, in the form of inclusion or exclusion of results based on whole-brain or ROI analyses, would impact the meta-analytic results.

## 2 | METHOD AND MATERIALS

### 2.1 | Selection of studies and inclusion criteria

A literature search was conducted to identify fMRI experiments investigating the neurofunctional correlates related to the sense of ownership of a body part or the whole body in healthy participants. PubMed, Web of
Science and Scopus were searched for relevant articles during February 2020, using the following search terms: ‘fmri’ OR ‘functional magnetic resonance imaging’ AND ‘ownership’ OR ‘self-identification’ OR ‘rubber-hand illusion’ OR ‘full-body illusion’ OR ‘body-swap illusion’. The search was restricted to articles published before 19 February 2020. Relevant titles and abstracts were evaluated for full-text screening. Full-text articles were then evaluated for inclusion based on predefined inclusion criteria (see below). Furthermore, additional references were obtained from two recent meta-analyses on the topic (Grivaz et al., 2017; Seghezzi et al., 2019) by evaluating articles that the authors identified for inclusion.

Experiments were included in the meta-analysis based on the following inclusion criteria:

1. It used fMRI.
2. It contained at least one contrast comparing body ownership to a control condition in a within-subject design.
3. The field of view contained the whole brain.
4. Results were reported as coordinates in a standard stereotaxic reference space, either Montreal Neurological Institute (MNI) or Talairach. Statistical Parametric Mapping (SPM) and FMRIB Software Library (FSL) use MNI as their standard templates. Therefore, coordinates from studies using these programmes, and which did not report a transformation from MNI to Talairach, were treated as MNI coordinates unless the use of a different template was explicitly stated ($n = 1$).
5. All participants were adults and of a non-clinical population.
6. The articles were written in English and published in a peer-reviewed journal.

### 2.2 Data extraction

We manually extracted information on activation foci (peak coordinates), sample size, stereotaxic coordinate space (i.e., MNI or Talairach), type of illusion, statistical contrasts and statistical significance thresholds (see Table 1 and Supporting Information). For articles that included more than one relevant contrast for the same group of subjects (e.g., Limanowski & Blankenburg, 2015), the coordinates from each contrast were pooled together into a single set of coordinates and treated as one experiment. In other words, only one set of coordinates was used for each experiment to minimize the possibility that the meta-analytic results were influenced by within-group effects (Müller et al., 2018; Turkeltaub et al., 2012). Petkova et al. (2011) included three separate experiments and was therefore not pooled together. Thus, each subject-group was treated as one individual experiment (Turkeltaub et al., 2012).

### 2.3 ALE meta-analysis

The primary meta-analysis was conducted on all the activation foci resulting from the systematic search (ROI included). Two additional meta-analyses were conducted to assess the potential impact of the inclusion of ROI-based results. ROI analyses include techniques where one or several candidate regions are used to limit the number of statistical tests, such as by averaging across the ROI or limiting the number of tests to the voxels inside the ROI (SVC). For the whole-brain meta-analysis, foci resulting from ROI analyses were excluded. For the ROI-only meta-analysis, only foci resulting from ROI analyses were included. Three foci survived both whole-brain correction and ROI analysis, and these were included in the whole-brain meta-analysis. The results of a second, post hoc ROI meta-analysis, where these three peaks were excluded in the ROI-only meta-analysis, can be seen in the Supporting Information.

Each meta-analysis was conducted using the coordinate-based meta-analytical method ALE (Eickhoff et al., 2009, 2012; Turkeltaub et al., 2012), as implemented in the GingerALE software version 3.0.2 (Brainmap, n.d.). All processing steps were confined to the more conservative grey matter mask (Eickhoff et al., 2009).

ALE treats activation foci as the centre of a 3D Gaussian probability distribution to account for each focus’s spatial uncertainty, with larger samples receiving a tighter distribution (Eickhoff et al., 2009). First, activation maps were created for the individual experiments by taking for each voxel the maximum probability associated with any one activation focus reported by that experiment (Turkeltaub et al., 2012). Then, by taking the union of the modelled activation maps, an ALE map was calculated. The ALE map consists of voxel-wise ALE scores that describe the convergence of results at each location of the grey matter of the brain (Eickhoff et al., 2009).

Non-parametric $p$ values were obtained through an analytically derived null distribution that reflects a random spatial association between experiments (Eickhoff et al., 2012). These $p$ values were initially thresholded using a cluster-forming threshold of $p < .001$ to define clusters of interest. The size of the clusters that survived this threshold was then compared with a null distribution of cluster sizes, which was estimated with 1,000 Monte Carlo simulations, storing the largest cluster of each iteration (Acar et al., 2017; Eickhoff et al., 2012). Clusters
achieving a family-wise error (FWE) corrected significance of \( p < .05 \) were considered significant, reflecting current recommendations for best practices (Eickhoff et al., 2016; Müller et al., 2018).

Visualization of the resulting activation clusters was overlaid on an MNI template using the Multi-image Analysis GUI (Mango; Mango, n.d.). For labelling (volume based and local maxima), coordinates were transformed into Talairach space using icbm2tal (Lancaster et al., 2007), and results were labelled using Talairach Daemon (nearest grey matter; Lancaster et al., 2000), which is implemented automatically in the GingerALE software.

To provide additional information about the significant clusters identified in the ALE meta-analyses, we identified which individual experiments reported activation foci within, and thereby contributed to, each cluster. Two specific characteristics were of interest. First, for the primary meta-analysis, we examined how many of the individual experiments reported results based on ROI analysis. If several of these experiments reported results based on ROI analyses of the regions in the clusters, it

| TABLE 1 | Functional magnetic resonance imaging (fMRI) studies included in the primary meta-analysis |
|-----------------|---------------------------------|-----------------|
| Author and year | Sample size | Illusion | Contrasting description |
| Ehrsson et al. (2004) | 18 | RHI | (Sync cong – async cong) – (Sync incong – async incong) |
| Ehrsson et al. (2005) | 15 | RHI | (Illusion – asynchronous) + (illusion – incongruent) |
| Petkova et al. (2011) | 26 | BSI | Study 1: (body synch – body Asynch) – (wood synch – wood asynch) |
| | | | Study 2: (1PP synch – 1PP Asynch) – (3PP synch – 3PP asynch) |
| | | | Study 3: (attached hand synch – attached hand asynch) – (detached hand synch – detached hand asynch) |
| Ionta et al. (2011) | 22 | FBI | Body by stroking interaction |
| Brozzoli et al. (2012) | 16 | RHI | (Synch first – synch second) – (async first – async second) |
| Gentile et al. (2013) | 15 | RHI | (Congr match – TimeIncong match) – (congr mismatch – TimeIncong mismatch) |
| Guterstam et al. (2013) | 14 | RHI | Synchronous vs. asynchronous inclusively masked with a synchronous vs. incongruent condition |
| Limanowski et al. (2014) | 20 | RHI | Congruent vs. incongruent spatial stimulation for RHI vs. control object |
| Bekrater-Bodmann et al. (2014) | 25 | RHI | Sync vs. async |
| Apps et al. (2015) | 15 | EFI | Congruency \times\ synch interaction |
| Gentile et al. (2015) | 16 | FBI | Average decoding maps for synch vs. async |
| Guterstam et al. (2015) | 15 | BSI | Sync vs. async across positions |
| Limanowski and Blankenburg (2015) | 20 | RHI | Congruent vs. incongruent (arm) |
| | | & Congruent vs. incongruent (across touch locations) |
| Limanowski and Blankenburg (2016a) | 19 | RHI | Congruent vs. incongruent |
| Limanowski and Blankenburg (2016b) | 13 | RHI | Real > fake synch > fake mixed > fake async |
| Preston and Ehrsson (2016) | 32 | BSI | Synchronous vs. asynchronous across body type |
| Matsumoto et al. (2020) | 28 | RFI | Synch after > synch before (across both feet) |

Note: Nineteen fMRI experiments were included in the primary meta-analysis. Bekrater-Bodmann et al. (2014) were not included in the whole-brain meta-analysis. Guterstam et al. (2013), Ionta et al. (2011), Matsumoto et al. (2020) and Preston and Ehrsson (2016) were excluded from the ROI meta-analysis. See the Supporting Information for a detailed description of which peak coordinates from each experiment were included in each meta-analysis. Abbreviations: BSI, body-swap illusion; EFI, enfacement illusion; FBI, full-body illusion; RFI, rubber foot illusion; RHI, rubber hand illusion.

*aThe two contrasts were pooled together.*
would further indicate that ROI experiments drove the meta-analytical results. Next, we further identified the types of illusions used in the individual studies that contributed to each significant cluster. As this analysis was conducted after inspecting the results of the ALE meta-analyses, it should be considered exploratory.

The data that support the findings of this study are openly available in OSF (https://osf.io/kzyf5/?view_only=4f95d280736f4923a4dcfe6141972736).

3 | RESULTS

3.1 | Selection and inclusion of studies

The database search yielded a total of 271 articles, and the previous meta-analyses yielded an additional 34 articles, for a total of 305 articles. After the removal of duplicates, a total of 158 articles remained, and their abstracts were screened. Thirty-seven articles were identified as relevant, and the full texts of these articles were further assessed based on the inclusion criteria (see Figure 1 for a PRISMA flow chart (Moher et al., 2009).

The literature search yielded a total of 19 fMRI experiments (from 17 articles; Table 1), with a total of 369 subjects and 217 activation foci, for inclusion in the primary meta-analysis. We performed three different meta-analyses: First, in the primary meta-analysis, we included all available data sets. This meta-analysis largely replicates previous meta-analyses. Second, a whole-brain meta-analysis excluded foci resulting from ROI analyses and excluded one article (Bekrater-Bodmann et al., 2014). Eighteen fMRI experiments (from 16 articles), with a total of 344 subjects and 163 activation foci, were included in this second meta-analysis. Third, an ROI-only meta-analysis, where all non-ROI foci were excluded, resulted in 15 fMRI experiments (from 13 articles), with 273 subjects and 56 activation foci. For a detailed list of the included studies and foci, see Supporting Information.

3.2 | Characteristics of included studies

Eleven of the included experiments investigated the activations of ownership over a hand, six over a whole body, one over another face and one over a foot. Different variations of the RHI (Botvinick & Cohen, 1998) were used for the experiments investigating ownership over a hand. The whole-body ownership studies used variations of the full-body illusion (Lenggenhager et al., 2007) or the body-swap illusion (Petkova & Ehrsson, 2008). In addition, one study utilized the enfacement illusion (Tsakiris, 2008), and one utilized the rubber foot illusion (Crea et al., 2015). The illusion conditions were generally compared with a control condition, for example, in the form of asynchronous stroking (Ehrsson et al., 2004), stroking in an incongruent position (Gentile et al., 2013; Limanowski & Blankenburg, 2015), with the arm detached from the body (Petkova et al., 2011) or to the blood-oxygen-level-dependent (BOLD) response before the induction of the illusion (Matsumoto et al., 2020).

The activation foci resulted from contrasts comparing the factor of interest and a control condition, such as [synchronous stroking condition > asynchronous stroking condition], as well as from interaction effects, such as [synchronous congruent condition > asynchronous congruent condition] versus [synchronous incongruent condition > asynchronous incongruent condition].

3.3 | ALE meta-analysis

3.3.1 | Primary meta-analysis

The meta-analysis of all identified fMRI experiments included 19 experiments. The minimum cluster size was 688 mm³. Significant convergence was found in three clusters. Two clusters were located in bilateral posterior parietal areas. The left cluster was mainly located in the inferior parietal lobule, extending to the superior parietal lobule. The right posterior parietal cluster was mainly located in the superior parietal lobule, spanning the precuneus and the inferior parietal lobule. The third cluster was located in the right frontal lobe, primarily in the precentral gyrus, spanning the inferior and middle frontal gyri. Peak activation magnitudes for these three clusters were located in the left inferior parietal lobule, the right superior parietal lobule and the right precentral gyrus (Table 2, Figure 2a).

3.3.2 | Whole-brain meta-analysis

The meta-analysis of whole-brain results, where all ROI-based results were excluded, included 18 experiments. The minimum cluster size was 736 mm³. This analysis identified no significant clusters (Table 2).

3.3.3 | ROI-only meta-analysis

The meta-analysis of only ROI-based results included 15 experiments. The minimum cluster size was 656 mm³. Significant convergence was found in five clusters. Two clusters were located in bilateral parietal areas, with
the left cluster located primarily in the inferior parietal lobule and extending into the superior parietal lobule and the right cluster located primarily in the superior parietal lobule and the precuneus. Two clusters were located in bilateral frontal areas. Both clusters were located mainly in the precentral gyri and extending into the inferior and middle frontal gyri. The final cluster was located in the left occipital–temporal lobules, located primarily in the middle temporal gyrus, extending into inferior temporal and middle occipital gyri. Peak activation magnitudes for these five clusters were located in the left superior and inferior parietal lobule, the left inferior frontal gyrus, the right precentral gyrus and the middle occipital gyrus (Table 2, Figure 2b). The peaks of three of these clusters spatially coincide with the clusters of the primary meta-analysis: inferior parietal lobule \((-38, -48, 56\) vs. \(-38, -48, 56\)), precentral gyrus \((48, 8, 32\) vs. \(50, 6, 34\)) and superior parietal lobule \((34, -56, 54\) vs. \(-32, -56, 52\)).

### 3.3.4 Post hoc analysis

In line with best practice recommendations, we report the individual experiments contributing to each of the three significant clusters (Müller et al., 2018).

For the primary meta-analysis, five experiments contributed to the left inferior parietal cluster (Gentile et al., 2013; Guterstam et al., 2015; Limanowski & Blankenburg, 2015; Petkova et al., 2011). Each of these experiments reported results based on ROI analyses in parietal areas. Two experiments investigated the neurofunctional correlates of ownership of a hand and three of an entire body (body-swap illusion).

Four experiments contributed to the right precentral gyrus cluster (Apps et al., 2015; Ehrsson et al., 2005; Gentile et al., 2013; Petkova et al., 2011). One of these experiments reported results based on whole-brain correction (Apps et al., 2015), while the other three
experiments reported results based on ROI analyses in precentral areas. Two experiments investigated ownership of a hand, one of a body (body-swap illusion) and one of another face (enfacement illusion).

Five experiments contributed to the right superior parietal cluster (Apps et al., 2015; Ehrsson et al., 2005; Gentile et al., 2013; Guterstam et al., 2013, 2015). Once again, only one experiment reported results based on whole-brain correction (Apps et al., 2015), while the other four reported results based on ROI analyses. Three experiments investigated ownership of a hand, one of a body (body-swap illusion), and one of another face (enfacement illusion).

For the ROI-only meta-analysis, eight experiments contributed to the left inferior parietal cluster, five investigating ownership of a hand and three of a body (body-swap illusion) (Bekrater-Bodmann et al., 2014; Ehrsson et al., 2005; Gentile et al., 2013; Guterstam et al., 2015; Limanowski & Blankenburg, 2015; Petkova et al., 2011).

No grey matter found
—
40
70
2
0.009
L middle occipital gyrus
BA 19
50
74
4
0.008

Whole-brain analysis

No significant clusters

Note: Cluster coordinates (weighted centre) are reported in MNI space. Clusters were thresholded at a cluster-forming threshold of \( p < .01 \) uncorrected, and an FWE corrected cluster-level threshold of \( p < .05 \). Labelled using Talairach Daemon.

Abbreviations: ALE, activation likelihood estimation; BA, Brodmann area; L, left; R, right.

Four experiments contributed to the right precentral gyrus cluster, three investigating ownership of a hand and one of a body (body-swap illusion) (Brozzoli et al., 2012; Ehrsson et al., 2005; Gentile et al., 2013; Petkova et al., 2011).

Three experiments contributed to the right superior parietal cluster, one investigating ownership of a hand, one of a body (body-swap illusion) and one of a face (enfacement illusion) (Apps et al., 2015; Gentile et al., 2013; Guterstam et al., 2015).

Finally, four experiments contributed to the left middle occipital gyrus cluster, three investigating ownership of a hand and one of a body (full-body illusion) (Gentile et al., 2015; Limanowski & Blankenburg, 2015, 2016a, 2016b).

Additionally, we performed a modified version of the ROI-only meta-analysis. When inspecting the individual study results, we identified three SVC peaks from two studies (Apps et al., 2015; Limanowski & Blankenburg, 2015), which also survived whole-brain correction. Here, 14 studies with 53 peaks were included. When removing these peaks, we found clusters in the precentral and posterior parietal cortex, with similar coordinates to the previous results. Notably, the right
FIGURE 2  Neurofunctional correlates of body ownership. Results of the ALE meta-analyses were overlaid on a standard MNI template (Colin27_T1_seg_MNI.nii). Clusters were thresholded at a cluster-forming threshold of $p < .01$ uncorrected, and an FWE corrected cluster-level threshold of $p < .05$. Colour intensities correspond to ALE scores, ranging from red (lower) to white (higher). Panel (a): The primary meta-analysis showed significant convergence of activation centred in the left inferior parietal lobule, right precentral gyrus, and right superior parietal lobule. Panel (b): The ROI-only meta-analysis showed significant convergence of activation centred in the left inferior parietal lobule, left inferior frontal gyrus, right precentral gyrus, right superior parietal lobule and middle occipital gyrus. The whole-brain meta-analysis showed no significant convergence of activation and is not shown. ALE, activation likelihood estimation; FWE, family-wise error; MNI, Montreal Neurological Institute; ROI, region of interest.
parietal and occipital clusters were not significant in this modified ROI-only analysis. We consider these results exploratory. For a further discussion of these results, see the Supporting Information.

4 | DISCUSSION

Previous meta-analyses of the neurofunctional correlates of body ownership have shown partly conflicting results (Grivaz et al., 2017; Salvato et al., 2020; Seghezzi et al., 2019). We conducted an ALE meta-analysis of fMRI experiments of body illusion paradigms. Two additional meta-analyses were conducted to assess the impact of including experiments based on ROI analyses: one excluding ROI-based results and one excluding whole-brain results. The primary meta-analysis showed convergence of activation in three clusters situated in bilateral posterior parietal and right frontal regions. These results are similar to those presented in Grivaz et al. (2017), except we found no convergence in the insula. The whole-brain meta-analysis yielded no significant clusters of activation. These results differ markedly from a previous whole-brain meta-analysis of body ownership, where a convergence of activation was found in six clusters (Salvato et al., 2020). The ROI-only meta-analysis showed convergence of activation in five clusters situated in bilateral posterior parietal regions, bilateral frontal regions and left occipital–temporal regions. The clusters in the inferior parietal, superior parietal and precentral gyrus spatially coincide with the respective clusters found in the primary meta-analysis. Together with the null results of the whole-brain meta-analysis and the post hoc analysis showing that all but one of the studies contributing to the significant clusters utilized ROI analysis, these results provide indirect evidence that the inclusion of activation foci based on ROI analyses influenced the results of the primary meta-analysis.

Our primary analysis largely corroborated the activation of premotor and parietal areas in body ownership, as has been demonstrated in individual studies of body ownership (Ehrsson et al., 2004; Petkova et al., 2011) and previous meta-analyses (Grivaz et al., 2017; Salvato et al., 2020). Of note, although our meta-analysis showed bilateral parietal activity, several studies reported unilateral activity (Bekrater-Bodmann et al., 2014; Brozzoli et al., 2012; Ehrsson et al., 2004, 2005; Petkova et al., 2011), in line with two previous meta-analyses (Salvato et al., 2020; Seghezzi et al., 2019). The convergence of activation in frontoparietal regions may support a model in which the integration of exteroceptive (i.e., visual and tactile) multisensory stimuli is a critical step in the formation of body ownership illusions (Ehrsson, 2012; Kalckert & Ehrsson, 2014).

Contrary to Grivaz et al. (2017), but in line with Salvato et al. (2020), no significant clusters were found in the temporoparietal junction or the insula. The insular region has been implicated in body ownership (Karnath & Baier, 2010; Tsakiris et al., 2007) and is at the centre of theories highlighting the role of interoception in body ownership or self-awareness (Crucianelli et al., 2018; Seth, 2013; Tsakiris, 2017). Thus, our results cannot confirm the involvement of the insula in ownership illusions, even when different parts of the insula region have shown elevated activity in several ownership studies (e.g., Brozzoli et al., 2012; Limanowski et al., 2014; Tsakiris et al., 2007). Moreover, Salvato et al. (2020) found an overlap of activations in inferior parietal regions for both body ownership and interoception and suggested that these areas could mediate and integrate input from different modalities, including interoceptive cues.

The results obtained by the three meta-analyses conducted here show that differences can emerge depending on whether or not results based on ROI analyses are included. Almost every experiment contributing to the significant clusters in the premotor and parietal cortices reported results based on ROI analyses. As two of the previous meta-analyses included ROI-based findings (Grivaz et al., 2017; Seghezzi et al., 2019), those analyses were likely influenced by this factor. It should be noted that out of the 19 experiments identified in the systematic search, only five experiments were completely free from any ROI-based approach (Apps et al., 2015; Guterstam et al., 2013; Ionta et al., 2011; Matsumoto et al., 2020; Preston & Ehrsson, 2016). Here, 10 out of 14 studies utilizing an ROI-based approach used coordinates from the seminal study by Ehrsson et al. (2004) focusing on the premotor and intraparietal cortex, either directly (e.g., Bekrater-Bodmann et al., 2014; Ehrsson et al., 2005; Petkova et al., 2011) or indirectly (e.g., Brozzoli et al., 2012; Gentile et al., 2013, 2015; Guterstam et al., 2015; Limanowski & Blankenburg, 2015). Albeit we do not refute the validity of these assumptions nor the usage of ROI-based methods in these individual neuroimaging studies, it demonstrates a tendency within this field of research to rely on a priori defined candidate regions for body ownership and a scarcity of whole-brain analysis results.

When a large portion of the literature consists of results based on ROI analysis, it becomes difficult to synthesize the literature through meta-analysis. It leaves us with the choice of either including ROI-based findings, which is against best practice guidelines for neuroimaging meta-analysis because it leads to inflated significance for those regions (Gentili et al., 2019, 2021; Müller et al., 2018), or including the only whole-brain results,
which instead leads to a large number of findings being excluded. As individual neuroimaging studies, in general, tend to suffer from low statistical power (Button et al., 2013; Carp, 2012b), low reproducibility (e.g., Botvinik-Nezer et al., 2020; Carp, 2012a) and increased false-positive rates (Eklund et al., 2016; Wager et al., 2007), meta-analysis provides an approach for overcoming these limitations, facilitates cumulative science (Lakens et al., 2016) and is an important tool for resolving conflicting results within the neuroimaging literature (Müller et al., 2018). Small sample sizes and, thereby, low statistical power are common in the fMRI literature of body ownership, with an average of 19.4 subjects per experiment in our sample (range 13–32).

Unlike classical effect-size meta-analyses in clinical and behavioural sciences, or image-based meta-analyses (Salimi-Khorshidi et al., 2009), ALE does not focus on the presence or absence, nor the strength, of an effect at any given location. ALE instead identifies the spatial convergence across data, which means that the null findings of the whole-brain meta-analysis do not indicate the lack of an effect in whole-brain body ownership experiments, rather a lack of convergent findings across these experiments. This lack of convergence indicates high levels of heterogeneity.

In any meta-analysis, there is a trade-off between the number of experiments included and the amount of heterogeneity (Müller et al., 2018). For example, our primary meta-analysis included different types of illusions (e.g., RHI and body-swap illusion) conducted on different body parts (e.g., hand, foot, face and abdomen). In addition, different laboratories use different experimental setups, methods for induction (e.g., different stroking patterns), measures of the effect (e.g., different questionnaire statements) and experimental designs, which can influence the behavioural measures of body ownership (Kalckert et al., 2019; Reader et al., 2021; Riemer et al., 2019). This heterogeneity likely impacts our meta-analytic results and the results of previous meta-analyses of body ownership.

Despite an increase in neuroimaging studies on body ownership in recent years, the number of studies remains modest in terms of meta-analyses. It is recommended that at least 17–20 experiments are included in an ALE meta-analysis to achieve sufficient statistical power and minimize the risk that a single experiment largely drives results (Eickhoff et al., 2016; Müller et al., 2018). The number of experiments included in the primary meta-analysis (19: 369 subjects), the whole-brain meta-analysis (18: 344 subjects), and the ROI-only meta-analysis (15: 273 subjects) is relatively modest. Although these numbers are similar to previous meta-analyses within the field (Grivaz et al., 2017; Salvato et al., 2020; Seghezzi et al., 2019), the present results would benefit from future confirmation that relies on more extensive datasets, and the ROI-only meta-analysis should be viewed with particular caution. Furthermore, our relatively low number of studies excluded the possibility of performing further subgroup analyses to identify potential sources of heterogeneity, as investigating heterogeneity across a small number of experiments is of questionable value. Interestingly, heterogeneity within an ALE meta-analysis could indicate functional subdomains (Ngo et al., 2019).

The existence of subdomains within body ownership has been proposed. A distinction has been made regarding partial ownership, such as limb ownership studied in the RHI and global ownership, such as in full-body illusions (Blanke & Metzinger, 2009; Gentile et al., 2015). It has been argued that global ownership, often called self-identification, can only be studied using full-body illusions (Blanke & Metzinger, 2009). Following this logic, including limb-ownership experiments and full-body ownership experiments in the same meta-analysis, under the assumption that they study the same phenomenon, can be considered problematic. Although premotor and posterior parietal regions have been implicated in both limb-ownership (Ehrsson et al., 2004) and full-body ownership (Petkova et al., 2011), multivoxel pattern analysis has indicated a more fine-grained distinction between body part ownership and full-body ownership within these brain regions (Gentile et al., 2015). Similarly, it has been argued that the perception of one’s face is different from the perception of body-parts and thus involving additional and specific processes at the psychological and neuronal level (Tsakiris, 2008; Tsao & Livingstone, 2008).

A way to facilitate future coordinate-based meta-analyses on body ownership could be for researchers always to include uncorrected whole-brain results. More importantly, online repositories such as OpenfMRI (Poldrack et al., 2013), NeuroVault (Gorgolewski et al., 2015) or ANIMA (Reid et al., 2016) can be used to provide researchers with the opportunity to access unthresholded and original data, thereby facilitating image-based meta-analyses, which do not have to rely on coordinates of statistical significance (Salimi-Khorshidi et al., 2009). In turn, these meta-analyses can significantly contribute to our understanding of body ownership by (1) reliably reproduce the neurofunctional correlates of body ownership (and compare them to other constructs), (2) including findings from studies using both ROI-based and whole-brain analyses without biasing the results, (3) providing coordinates for ROI-based analyses in future neuroimaging studies, in line with best practice recommendations (Gentili et al., 2021; Müller et al., 2018), and (4) investigating potential subdomains within body ownership.
5 | CONCLUSIONS

The present meta-analyses indicate inconsistencies across the results of fMRI studies of body ownership. When results from all individual experiments identified in our systematic search were included in the meta-analysis, frontoparietal multisensory areas are involved in the sense of body ownership. However, a second, whole-brain meta-analysis, without ROI-based results, showed no significant convergence across experiments. A third, ROI-only meta-analysis indicated that larger areas of the frontal and posterior parietal cortices and the middle occipital gyrus were associated with body ownership. These findings highlight reproducibility issues on a meta-analytical level within the field of body ownership and the difficulty of quantitatively synthesizing neuroimaging literature where a large proportion of findings are based on ROI analysis. We recommend more studies presenting whole-brain results, data sharing and replication studies with large sample sizes to facilitate better future syntheses of the neuroimaging literature of body ownership, including the investigation of potential sources of heterogeneity such as subdomains of body ownership.

AUTHOR CONTRIBUTIONS

MN and AK designed the study. MN and AK conducted the systematic search. MN analysed the data. MN and AK discussed the results and wrote the manuscript.

CONFLICT OF INTEREST

The authors state no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

All analysis files and supplementary materials used in this study are made publicly available online (https://osf.io/kzyf5/?view_only=4f95d280736f4923a4dcfe6141972736).

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REFERENCES

Acar, F., Seurinck, R., Eickhoff, S. B., & Moerkerke, B. (2017). Assessing robustness against potential publication bias in coordinate based fMRI meta-analyses using the Fail-Safe N. BioRxiv, 1, 1–23. https://doi.org/10.1101/189001
Albajes-Eizaguirre, A., & Radua, J. (2018). What do results from coordinate-based meta-analyses tell us? NeuroImage, 176, 550–553. https://doi.org/10.1016/j.neuroimage.2018.04.065
Apps, M. A. J., Tajadura-Jiménez, A., Sereno, M., Blanke, O., & Tsakiris, M. (2015). Plasticity in unimodal and multimodal brain areas reflects multisensory changes in self-face identification. Cerebral Cortex, 25(1), 46–55. https://doi.org/10.1093/cercor/bht199
Bekrater-Bodmann, R., Foell, J., Diers, M., Kamping, S., Rance, M., Kirsch, P., Trojan, J., Fuchs, X., Bach, P., Çakmak, H. K., Maaß, H., & Flor, H. (2014). The importance of synchrony and temporal order of visual and tactile input for illusory limb ownership experiences—An fMRI study applying virtual reality. In PLoS ONE, 9(1), e87013. https://doi.org/10.1371/journal.pone.0087013
Blanke, O. (2012). Multisensory brain mechanisms of bodily self-consciousness. Nature Reviews Neuroscience, 13(8), 556–571. https://doi.org/10.1038/nrn3292
Blanke, O., & Metzinger, T. (2009). Full-body illusions and minimal phenomenal selfhood. Trends in Cognitive Sciences, 13(1), 7–13. https://doi.org/10.1016/j.tics.2008.10.003
Botvinick, M., & Cohen, J. (1998). Rubber hands ‘feel’ touch that eyes see. Nature, 391(6669), 756–756. https://doi.org/10.1038/35784
Botvinik-Nezer, R., Holzmeister, F., Camerer, C. F., Dreber, A., Huber, J., Johannesson, M., Kirchler, M., Iwanir, R., Mumford, J. A., Adcock, R. A., Avesani, P., Baczkowski, B. M., Bajracharya, A., Bakst, L., Ball, S., Barilari, M., Bault, N., Beaton, D., Beitner, J., … Schonberg, T. (2020). Variability in the analysis of a single neuroimaging dataset by many teams. Nature, 582(7810), 84–88. https://doi.org/10.1038/s41586-020-2314-9
Brozzoli, C., Gentile, G., & Henrik Ehrsson, H. (2012). That’s near my hand! Parietal and premotor coding of hand-centered space contributes to localization and self-attribute of the hand. Journal of Neuroscience, 32(42), 14573–14582. https://doi.org/10.1523/JNEUROSCI.2660-12.2012
Button, K. S., Ioannidis, J. P. A., Mokrysz, C., Nosek, B. A., Flint, J., Robinson, E. S. J., & Munafò, M. R. (2013). Power failure: Why small sample size undermines the reliability of neuroscience. Nature Reviews Neuroscience, 14(5), 365–376. https://doi.org/10.1038/nrn3475
Carp, J. (2012a). On the plurality of (methodological) worlds: Estimating the analytic flexibility of fmri experiments. Frontiers in Neuroscience, 6, 149. https://doi.org/10.3389/fnins.2012.00149
Carp, J. (2012b). The secret lives of experiments: Methods reporting in the FMRI literature. NeuroImage, 63(1), 289–300. https://doi.org/10.1016/j.neuroimage.2012.07.004
Cattinelli, I., Valentini, G., Paulesu, E., & Borghese, N. A. (2013). A novel approach to the problem of non-uniqueness of the solution in hierarchical clustering. IEEE Transactions on Neural Networks and Learning Systems, 24(7), 1166–1173. https://doi.org/10.1109/tnnls.2013.2247058
Crea, S., D’Alonzo, M., Vitiello, N., & Cipriani, C. (2015). The rubber foot illusion. Journal of Neuroengineering and Rehabilitation, 12(1), 1–6. https://doi.org/10.1186/s12984-015-0069-6
Cremers, H. R., Wager, T. D., & Yarkoni, T. (2017). The relation between statistical power and inference in fMRI. PLoS ONE, 12(11), 1–20. https://doi.org/10.1371/journal.pone.0184923
Cruceanu, L., Krahe, C., Jenkinson, P. M., & Fotopoulos, A. K. (2018). Interceptive ingredients of body ownership: Affective touch and cardiac awareness in the rubber hand illusion. Cortex, 104, 180–192. https://doi.org/10.1016/j.cortex.2017.04.018
Duncan, K. J., Pattamadilok, C., Knierim, L., & Devlin, J. T. (2009). Consistency and variability in functional localisers. *NeuroImage*, 46(4), 1018–1026. https://doi.org/10.1016/j.neuroimage.2009.03.014

Ehrsson, H. H. (2007). The experimental induction of out-of-body experiences. *Science*, 317(5841), 1048. https://doi.org/10.1126/science.1142175

Ehrsson, H. H. (2012). The concept of body ownership and its relation to multisensory integration. In B. H. Stein (Ed.), *The new handbook of multisensory processes* (pp. 775–792). http://mitpress.mit.edu/catalog/item/default.asp?tt=2&sid=12794

Ehrsson, H. H., Holmes, N. P., & Passingham, R. E. (2005). Touching a rubber hand: Feeling of body ownership is associated with activity in multisensory brain areas. *Journal of Neuroscience*, 25(45), 10564–10573. https://doi.org/10.1523/JNEUROSCI.0800-05.2005

Ehrsson, H. H., Spence, C., & Passingham, R. E. (2004). That hand! Activity in premotor cortex reflects feeling of ownership of a limb. *Science*, 305(5685), 875–877. https://doi.org/10.1126/science.1097011

Eickhoff, S. B., Bzdok, D., Laird, A. R., Kurth, F., & Fox, P. T. (2012). Activation likelihood estimation revisited. *NeuroImage*, 59(3), 2349–2361. https://doi.org/10.1016/j.neuroimage.2011.09.017.Activation

Eickhoff, S. B., Laird, A. R., Grefkes, C., Wang, L. E., Zilles, K., & Fox, P. T. (2009). Coordinate-based activation likelihood estimation meta-analysis of neuroimaging data: A random-effects approach based on empirical estimates of spatial uncertainty. *Human Brain Mapping*, 30(9), 2907–2926. https://doi.org/10.1002/hbm.20718

Eickhoff, S. B., Nichols, T. E., Laird, A. R., Hoffstaedter, F., Amunts, K., Fox, P. T., Bzdok, D., & Eickhoff, C. R. (2016). Behavior, sensitivity, and power of activation likelihood estimation characterized by massive empirical simulation. *NeuroImage*, 70–85, 70–85. https://doi.org/10.1016/j.neuroimage.2016.04.072

Ekholm, A., Nichols, T. E., & Knutsson, H. (2016). Cluster failure: Why fMRI inferences for spatial extent have inflated false-positive rates. *Proceedings of the National Academy of Sciences*, 113(28), 7900–7905. https://doi.org/10.1073/pnas.1602413113

Gentili, C., Cecchetti, L., Handjarias, G., Lettieri, G., & Cristea, I. A. (2021). The case for preregistering all region of interest (ROI) analyses in neuroimaging research. *European Journal of Neuroscience*, 53(2), 357–361. https://doi.org/10.1111/ejn.14954

Graziano, M. S. A., & Botvinick, M. (2002). How the brain represents the body: insights from neurophysiology and psychology. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action: Attention and performance XIX* (pp. 136–157). Oxford University Press.

Gutierrez, M., & USA, O. (2017). Common and distinct brain regions processing multisensory bodily signals for personal space and body ownership. *NeuroImage*, 147 (December 2016), 602–618. https://doi.org/10.1016/j.neuroimage.2016.12.052

Guterstam, A., Björnsdotter, M., Gentile, G., & Ehrsson, H. H. (2015). Posterior cingulate cortex integrates the senses of self-location and body ownership. *Current Biology*, 25(11), 1416–1425. https://doi.org/10.1016/j.cub.2015.03.059

Guterstam, A., Gentile, G., & Ehrsson, H. H. (2013). The invisible hand illusion: Multisensory integration leads to the embodiment of a discrete volume of empty space. *Journal of Cognitive Neuroscience*, 25(7), 1078–1099. https://doi.org/10.1162/jocn_00393

Ionta, S., Heydrich, L., Lenggenhager, B., Mouthon, M., Fornari, E., Chapuis, D., Gassert, R., & Blanke, O. (2011). Multisensory mechanisms in temporo-parietal cortex support self-location and first-person perspective. *Neuron*, 70(2), 363–374. https://doi.org/10.1016/j.neuron.2011.03.009

Kalckert, A., Bico, I., & Fong, J. X. (2019). Illusions with hands, but not with balloons—Comparing ownership and referral of touch for a corporal and noncorporal object after visuotactile stimulation. *Perception*, 48(5), 447–455. https://doi.org/10.1177/0301006619839286

Kalckert, A., & Ehrsson, H. H. (2014). The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership. *Consciousness and Cognition*, 26(1), 117–132. https://doi.org/10.1016/j.concog.2014.02.003

Karnath, H. O., & Baier, B. (2010). Right insula for our sense of limb ownership and self-awareness of actions. *Brain Structure & Function*, 214(5–6), 411–417. https://doi.org/10.1007/s00429-010-0250-4

Lakens, D., Hilgard, J., & Staaks, J. (2016). On the reproducibility of meta-analyses: Six practical recommendations. *BMC Psychology*, 4(1), 24. https://doi.org/10.1186/s40359-016-0126-3

Lancaster, J. L., Tordesillas-Gutiérrez, D., Martinez, M., Salinas, F., Evans, A., Zilles, K., Mazziotta, J. C., & Fox, P. T. (2007). Bias analyses in neuroimaging research. *The new handbook of multisensory processes* (3), 2349–2536, 10564–10573. https://doi.org/10.1111/ejn.14954

Graziano, M. S. A., Botvinick, M. (2019). How the brain represents the body: insights from neurophysiology and psychology. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action: Attention and performance XIX* (pp. 136–157). Oxford University Press.
Nerative activity underlying the illusionary self-attribute of a dummy arm. Human Brain Mapping, 36(6), 2284–2304. https://doi.org/10.1002/hbm.22770

Limanowski, J., Lutti, A., & Blankenburg, F. (2016b). That body area is involved in illusory limb ownership. Frontiers in Neuroscience, 10.1038/s41398-015.2016

Limanowski, J., & Blankenburg, F. (2015). Network activity underlying the illusion of body swapping. PLoS ONE, 33. https://doi.org/10.1371/journal.pone.003832

Poldrack, R. A. (2007). Region of interest analysis for fMRI. Social Cognitive and Affective Neuroscience, 2(1), 67–70. https://doi.org/10.1093 SCAN/NSM006

Poldrack, R. A., Barch, D. M., Mitchell, J. P., Wagner, T. D., Wagner, A. D., Devlin, J. T., Cumba, C., Koyejo, O., & Milham, M. P. (2013). Towards open sharing of task-based fMRI data: The OpenfMRI project. Frontiers in Neuroinformatics, 7(JUNE), 1–12. https://doi.org/10.3389/fninf.2013.00012

Preston, C., & Ehrsson, H. H. (2016). Illusory obesity triggers body dissatisfaction responses in the insula and anterior cingulate cortex. Cerebral Cortex, 26(12), 4450–4460. https://doi.org/10.1093/cercor/bhw313

Reader, A. T., Trifonova, V. S., & Ehrsson, H. H. (2021). The relationship between referral of touch and the feeling of ownership in the rubber hand illusion. Frontiers in Psychology, 12(FEBRUARY), 1–10. https://doi.org/10.3389/fpsyg.2021.629590

Reid, A. T., Bzdok, D., Genon, S., Langner, R., Müller, V. I., Eickhoff, C. R., Hoffstaetter, F., Cieslik, E. C., Fox, P. T., Laird, A. R., Amunts, K., Caspers, S., & Eickhoff, S. B. (2016). ANIMA: A data-sharing initiative for neuroimaging meta-analyses. NeuroImage, 124, 1245–1253. https://doi.org/10.1016/j.neuroimage.2015.07.060

Riemer, M., Trojan, J., Beauchamp, M., & Fuchs, X. (2019). The rubber hand universe: On the impact of methodological differences in the rubber hand illusion. Neuroscience and Biobehavioral Reviews, 104(JANUARY), 268–280. https://doi.org/10.1016/j.neubiorev.2019.07.008

Salimi-Khorshidi, G., Smith, S. M., Keltner, J. R., Wager, T. D., & Nichols, T. E. (2009). Meta-analysis of neuroimaging data: A comparison of image-based and coordinate-based pooling of studies. NeuroImage, 45(3), 810–823. https://doi.org/10.1016/j.neuroimage.2008.12.039

Salvato, G., Richter, F., Sedeño, L., Bottini, G., & Paulesu, E. (2020). Building the bodily self-awareness: Evidence for the convergence between interoceptive and exteroceptive information in a multilevel kernel density analysis study. Human Brain Mapping, 41(2), 401–418. https://doi.org/10.1002/hbm.24810

Saxe, R., Brett, M., & Kanwisher, N. (2006). Divide and conquer: A defense of functional localizers. NeuroImage, 30, 1088–1096. https://doi.org/10.1016/j.neuroimage.2005.12.062

Seghezzi, S., Giannini, G., & Zapparoli, L. (2019). Neurofunctional correlates of body-ownership and sense of agency: A metaanalytical account of self-consciousness. Cortex, 121, 169–178. https://doi.org/10.1016/j.cortex.2019.08.018

Seth, A. K. (2013). Interoceptive inference, emotion, and the embodied self. Trends in Cognitive Sciences, 17(11), 565–573. https://doi.org/10.1016/j.tics.2013.09.007

Stein, B. E., & Stanford, T. R. (2008). Multisensory integration: Current issues from the perspective of the single neuron. Nature Reviews Neuroscience, 9(4), 255–266. https://doi.org/10.1038/nrn2331

Tsakiris, M. (2008). Looking for myself: Current multisensory input alters self-face recognition. PLoS ONE, 3(12), e4040. https://doi.org/10.1371/journal.pone.0004040
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