



Special section: Editorial

The body and cognition: The relation between body representations and higher level cognitive and social processes

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The relation between the body and higher-order mental functions has been a topic of discussion for many decades, if not centuries, in philosophy as well as psychology, and has more recently been widely discussed in cognitive neuroscience, robotics, and artificial intelligence. In philosophy, the so-called mind-body problem has a long tradition. This discussion traces back to ancient Greek philosophers, but the debate was renewed by René Descartes' radical statement that the mind "is entirely and truly distinct from the body [and the brain] and may exist without it" (Descartes, 1975). While most contemporary philosophers reject his idea of a substance dualism, the role of the body in shaping conscious experience continues to be controversial (Gallagher, 2005). Influential philosophers directly opposed his mind-body dualism by stressing the importance of bodily experience (e.g., James, 1890; Merleau-Ponty, 1945), and recent theories have been progressively converging their emphasis on the high relevance of bodily processes (i.e., the nonconceptual representations and processing of body-related information) in cognitive processes and self-consciousness (e.g., Bermúdez, 1998; Damasio, 1994; Gallagher, 2000, 2005; Varela, Thompson, & Rosch, 1991). Indeed, the idea of embodied cognition has gained increasing influence in psychology and neuroscience in recent decades (see e.g., Barsalou, 2008 for an extensive review). This notion is based on the embodiment thesis, which states that "many features of cognition are embodied in that they are deeply dependent upon characteristics of the physical body of an agent, such that the agent's beyond-the-brain body plays a significant causal role, or a physically constitutive role, in that agent's cognitive processing" (Wilson & Foglia, 2011). Empirical examples have been substantiated in a wide range of cognitive functions, including

numerical processing, visual attention, social cognition, memory, and language (Barsalou, 2008; Fischer, 2012). While embodied cognition initially emphasizes the relation between the physical body and cognitive function, it has also become increasingly clear that the sense of the body is plastic and is not only dependent on incoming sensory information but also on internal representations of our body, some of which are highly cognitive in nature. Body representations and the underlying neural mechanisms have received increasing attention in cognitive neuroscience over the last few decades. There has been a lively debate about the functional architecture of body representations and various theoretical models have been proposed (e.g., Berlucchi & Aglioti, 1997; Longo, Azañón, & Haggard, 2010; Moseley, Gallace, & Spence, 2011; Paillard, 1999; de Vignemont, 2010). While many of these models were built on clinical data from disorders of the bodily self, the development of new paradigms to alter bodily experiences has refined and extended such models. These paradigms typically confront healthy participants with ambiguous multisensory information about their body, during which bottom-up signals from unimodal sensory systems are integrated and decoded by higher, multisensory levels of the hierarchy to construct an updated body representation (Botvinick & Cohen, 1998; Ehrsson, 2007; Kammers, de Vignemont, Verhagen, & Dijkerman, 2009; Lackner, 1988; Lenggenhager, Tadi, Metzinger, & Blanke, 2007; Stratton, 1899; Tsakiris & Haggard, 2005). Bodily awareness can be quite easily manipulated in healthy participants, and such paradigms thus provide an interesting tool to study the link between body representations and cognition beyond the research classically performed in the embodied cognition domain. Several studies have demonstrated that illusory

changes in body awareness influence a broad variety of higher-level cognition processes. For example, experimentally altered body perception can affect the perception of the size and distance of external stimuli (Banakou, Groten, & Slater, 2013; van der Hoort, Guterstam, & Ehrsson, 2011) and even episodic memory (Bergouignan, Nyberg, & Ehrsson, 2014). These experimental body manipulation paradigms can also modulate social cognition, such as social distance perception (Mazzurega, Pavani, Paladino, & Schubert, 2011) or implicit biases (Maister, Sebanz, Knoblich, & Tsakiris, 2013; Peck, Seinfeld, Aglioti, & Slater, 2013) (for a recent review) see Maister, Slater, Sanchez-Vives, and Tsakiris (2015). Similarly, patient studies have evinced that longer-term alterations in body awareness also affect cognitive processes, such as perspective-taking (Besharati et al., 2016), and that peripheral alteration of bodily signaling due to physical loss of a body part can also influence visual spatial perception (Makin, Wilf, Schwartz, & Zohary, 2010). These studies therefore suggest that, in order to understand how the body influences cognition and vice versa, one needs to investigate the relation between three different components: peripheral sensorimotor signals, higher order body representations, and cognitive function.

This special issue provides a state of the art overview of the current investigations and topics on the body and cognition. It assimilates interdisciplinary findings from neuropsychology, neurology, neuroimaging, and cognitive psychology, and covers the relation between body awareness and various cognitive functions in the motor and social domain. This is exemplified by the two reviews in this special issue. In an attempt to integrate and newly structure the large body of literature on the bodily self in philosophy, developmental psychology, and neuroscience, Riva, 2018 proposes a new theoretical model of body representations. He stresses the importance of both an online integration of incoming intero- and exteroceptive signals, as well as stored representations of the body (body memory), and proposes unique body representations that emerge during distinct developmental periods. While the most basic representation, the minimal selfhood, is present from birth, other representations emerge later. After the initial sensorimotor experience and agency (i.e., classical body schema) has been established, more cognitive schemata, linked to body ownership, social function, and allocentric representations, begin to emerge. These multimodal representations are integrated into what Riva labels a “body matrix”: a supramodal multisensory representation of the body and the space surrounding the body, which serves to protect and extend the individual’s body on both homeostatic and psychological levels. Riva then describes potential disorders of the body matrix in various clinical conditions and how these can be remedied using modern technologies.

The second review by Porciello et al., 2018 focuses on one particular experimental setup, which uses conflicting multisensory signals to alter face representation, the enfacement illusion. The authors argue that this illusion is especially relevant for studying the interaction between body representations, identity, and social aspects, as the face, more than other body parts, is crucial both for identification and social communication. The authors review current evidence for the role of exteroceptive and interoceptive signals in building

body representations and self-awareness. Moreover, they discuss the neural network implicated in plastic changes of the self and link it to the predictive coding framework. This predictive coding framework is also featured in the review by Riva, 2018, who proposes its involvement in creating a supramodal body matrix, activated by central top-down attentional processing. Both reviews advocate that a combination of bottom-up multisensory signals and top-down cognitive processes constitute important components for both the stable sense of a bodily self as well as for its plasticity. Indeed, the empirical papers in this special issue have focused mostly on the role of either peripheral sensory signals or top-down representations. Overall, the empirical contributions of this special issue can roughly be subdivided into three different topics: a) sensory input, multisensory integration and aspects of body representation; b) the relation between motor function and body representations; and c) the link between body perception and cognitive function.

1. Multisensory integration and body cognition

Studies investigating the role of sensory input in relation to bodily cognition have focused on different modalities. Fossataro et al., 2018 used asynchronous visuo-tactile stimulation in a rubber hand illusion-like setup to restore the sense of ownership over the disowned own hand in stroke patients. Asynchronous stroking of the visible rubber hand and the invisible own hand is generally used as a control condition in the rubber hand illusion, since the mismatch between the bottom-up and top-down multisensory signaling typically prevents the generation of an altered sense of ownership. Previous studies have demonstrated that asynchronous tactile stroking differs from both the synchronous touch and visual only conditions in that it prevents visuo-proprioceptive integration and thus proprioceptive drift in healthy participants (Rohde, Di Luca, & Ernst, 2011). Other studies using the rubber hand or related illusions to study body ownership report a generally enhanced illusion in patients suffering from clinical disorders of corporeal awareness (Lenggenhager, Hilti, & Brugger, 2015), and demonstrate that an integration of the rubber hand into their own body representation is possible even under asynchronous stroking conditions (van Stralen, van Zandvoort, Kappelle, & Dijkerman, 2013). The group of E+ patients studied by Fossataro et al., pathologically embody the (foreign) hand of the experimenter when placed in front of them in a congruent position (Garbarini et al., 2013; but see also Gerstmann 1942). When the experimenter moved this hand, the patient claimed he moved the hand himself; when this foreign hand was touched, the patient claimed he felt the touch. Interestingly, Fossataro et al., 2018 showed that asynchronous stroking of the visible experimenter’s hand and the invisible own hand in E+ patients with residual tactile sensibility resulted in a temporary reduction of pathological embodiment of the experimenter’s hand. These findings suggest that a conflict between visual and tactile input influences body ownership and thus that the effects of asynchrony are bidirectional. It further sheds light on how multisensory

stimulation paradigms could potentially be used in therapeutic settings. While the described manipulation only resulted in a transient reduction, which is typical for this field, future studies should investigate how longer-term stimulation might affect body cognition in these patients.

Crucianelli, Krah, Jenkinson, & Fotopoulou, 2018 focused on a different sensory modality that more recently entered the research field of body representations: interoception. They investigated interoceptive (cardiac and affective touch) signals using the archetypical body ownership illusion, i.e., the rubber hand illusion (Botvinick & Cohen, 1998). First, they examined the link between two different aspects of interoceptive perception: cardiac awareness (heartbeat counting task) and affective touch experience during stroking of the arm at velocities that optimally activate the c-tactile system, but found that cardiac awareness did not predict pleasantness ratings of c-tactile optimal touch. This may suggest that interoceptive perception is not a unitary trait, but rather, and similar to the exteroceptive modality, is different for various interoceptive signals. In their second experiment, Crucianelli et al. related interoceptive perception to body ownership as assessed by the rubber hand illusion. They replicated the finding that c-tactile optimal stroking enhanced the illusion, confirming the importance of this type of interoceptive signal for body ownership (see also Crucianelli, Metcalf, Fotopoulou, & Jenkinson, 2013; Lloyd, Gillis, Lewis, Farrell, & Morrison, 2013; van Stralen et al., 2014). In contrast to previous studies (Suzuki, Garfinkel, Critchley, & Seth, 2013; Tsakiris, Tajadura-Jiménez, & Costantini, 2011), however, cardiac sensitivity, as measured by the heartbeat detection task, was not related to the strength of the illusion. Overall, the results of this study confirm the importance of interoceptive signals for body ownership, but only partially. The authors suggest that this could depend on the attentional weighting that individuals give to interoceptive signals, which may be influenced by multisensory and contextual factors. Carefully disentangling the different facets of interoceptive cues and their influence on body cognition will be important for the field, especially since most research has typically focused on cardiac sensitivity and to a lesser extent on c-tactile touch when examining interoception, while other potentially influential signals, such as respiratory and gastrointestinal cues, have been almost completely ignored. The contradicting findings of this article to previous research highlights the importance of reporting both positive and negative findings to more accurately discern the role of interoceptive signaling in corporeal awareness.

Another often neglected sensory modality that has recently received increasing attention in body representation research is the vestibular system (Ferrè & Haggard, 2016; Lenggenhager & Lopez, 2015; Pfeiffer, Serino, & Blanke, 2014). While previous studies investigated the contribution of vestibular cues on body ownership using artificial vestibular stimulation during altered embodiment (Ronchi et al., 2012; Salvato et al., 2016), Lopez & Elzi, 2018 studied altered body cognition in a large sample of patients with vestibular disturbances. They reported that out-of-body experiences (OBEs) occurred significantly more often in patients with dizziness (14%) than in the controls (5%). OBEs were related to

peripheral vestibular dysfunction in particular, but also to depersonalization-derealization, depression, and migraines. The authors concluded that the presence of OBEs in dizziness patients may be related to a problem in multisensory integration (conflicting information between vestibular and other bodily signals) combined with psychological and neurological factors. The study also underlines the importance of introducing a more systematic assessment of alterations in body perception in clinical populations affected by peripheral sensory disturbances.

Overall, these three studies show that multisensory integration and disintegration of different modalities are crucial for various aspects of bodily experience. As demonstrated by all the articles, it is important to consider a broad range of bodily signals but also a broad range of methods. The three above mentioned studies cover the cohorts that have been investigated most in this field, i.e., healthy participants, patients with brain lesions in areas of higher-order body representations, as well as patients with alterations in sensory input due to peripheral disturbances.

2. Motor aspects of body cognition

In addition to its key role in the integration of multisensory cues, the motor system is also crucial for our sense of a body (Bottini et al., 2009; Burin et al., 2015; Maravita & Iriki, 2004). Two papers in this special issue focused on the mutual interaction between motor functions and body representations in two groups of patients with alterations in peripheral bodily signals. Saetta et al. (2018) showed that the characteristics of a phantom perception following limb loss influences bodily movement perception, while Reid et al., 2018 reported that complex regional pain syndrome (CRPS) affects spatially defined motor function. In this latter study, patients with unilateral CRPS of the upper limb were asked to perform two motor tasks: a circle drawing task and a button pressing task to examine motor accuracy and motor coordination, respectively. Performance was found to be impaired on both tasks with the affected hand; but more importantly, performance was also poor when the tasks were completed with the healthy hand on the afflicted side of their body midline. These findings underscore the bidirectional and interdependent relationship between spatial and bodily representations in patients with unilateral CRPS and exemplify how a body-related spatial bias can affect motor performance.

Saetta et al. (2018) studied amputees who experienced the presence of a phantom limb. In particular, they investigated how solidity constraints of the phantom influence the perception of an apparent limb motion illusion. When a physical object occupies the same space as the phantom limb, the phantom disappears (obstacle shunning) in some amputees, whereas the phantom limb and object may co-exist (obstacle tolerance) in others. The apparent motion illusion consists of two pictures with a limb positioned on either side of an object. These pictures are shown with different stimulus onset asynchronies (SOAs). When the SOA is short, the limb appears to move through the object, while longer SOAs result in the limb apparently moving around the object. Interestingly, amputees who experience obstacle shunning of the

phantom, perceived the limb mainly as moving through the object, while amputees with object tolerance mainly experienced the limb as moving around the object. The authors explained this in terms of intuitive physics; that is, for amputees who experience obstacle shunning, apparent motion perception of the limbs is not constrained by the laws of impenetrability. Instead, they perceive their limb as moving through the physical object due to the disappearance of the phantom. In contrast, people who experience obstacle tolerance have stronger constraints for apparent motion of the limb, perhaps because they must avoid co-location of the phantom with physical objects.

Overall, both studies show that changes in bodily experience following peripheral damage affect higher-order motor-related body representations and suggest complex and interdependent interactions between the two.

3. The relation between body perception and higher cognitive function

In line with the main focus of the special issue, several studies directly investigated the link between body representations and other cognitive functions. [Azevedo, Badoud, & Tsakiris \(2018\)](#) linked cardiac signaling to attentional engagement to fearful faces. [Van Stralen et al., 2018](#) observed a relation between body awareness deficits following stroke and left-right orientation problems, whereas [Pellencin, Paola, Herbelin, & Serino, 2018](#) showed that social perception of others can influence peripersonal space.

The study of [Azevedo et al., 2018](#) represents an illustrative example of how body-related processing influences higher-order cognition. They found that during the systolic component, when cardiac signals to the brain are maximal, attentional engagement to fearful facial stimuli is enhanced specifically for low frequency, but not for high frequency or broadband facial stimuli. Low frequency stimuli are considered to be relevant for the fast detection of emotional facial expressions and are supported by a subcortical pathway involving the superior colliculus, pulvinar, and amygdala ([Mendez-Bertolo et al., 2016](#); [Vuilleumier et al., 2003](#)). These findings suggest that cardiac signals enhance processing of visual threat stimuli and, in particular, facilitate the fast extraction and attentional engagement to threat cues. While this result is in line with increasing evidence that interoception might influence cognitive processes ([Tsakiris & Critchley, 2016](#)), it also uses an elegant paradigm to overcome some of the methodological problems associated with current research on interoception and cognition ([Brener & Ring, 2016](#)).

[Van Stralen et al., 2018](#) focused on a different aspect of higher-order cognition: spatial judgements. They studied the relation between somatosensory and body awareness deficits, and the ability to distinguish the left and right side of the body in a group of subacute stroke patients. This left-right orientation is considered to be an aspect of the structural body representation, together with more segmental aspects such as the ability to identify and distinguish between fingers ([Dijkerman & de Haan, 2007](#)). They observed that deficits in left-right orientation can be selectively impaired for pictures

shown from a first and third person perspective, respectively. More importantly, neglect and finger agnosia predicted impairments in overall left-right orientation performance, while self-reported body awareness problems and finger agnosia predicted deficits in distinguishing left and right from a third person perspective. Finally, problems in left-right orientation were consistently associated with damage to the right anterior insular cortex, an area also considered to be involved in body awareness. Overall, this study demonstrates that body awareness problems are related to deficits in other aspects of body cognition, such as structural body representation.

In the final study of this special issue, [Pellencin, Paola, Herbelin, and Serino \(2018\)](#) investigated the effect of information about the social identity of another person on the representation of the space surrounding our body, i.e., the peripersonal space. Previous studies have shown that peripersonal space is body part centered and mediated by neural areas that largely overlap with those also involved in body representations ([Blanke, Slater, & Serino, 2015](#)). Using a novel augmented reality set-up and the well-established visuo-tactile stimulation paradigm to assess peripersonal space boundaries ([Canzoneri, Magosso, & Serino, 2012](#)), the authors showed that information about another person's moral identity can influence the boundaries of peripersonal space. When the other person was judged to be moral, the peripersonal space was larger than when this person was considered to be immoral. Moreover, this extension of peripersonal space was specifically linked to social cues from human participants, as it did not occur when an object was presented. The authors suggested that the extension of peripersonal space may have ensued from action-related mechanisms; that is, participants were more willing to interact with a moral compared to an immoral person and therefore extended their action space. While this study did not directly assess body representations, it did demonstrate that higher-order social perceptions about another person can modulate representations closely related and anchored to the body. Furthermore, it is in line with recent studies that measured body representations more directly, showing that social perception might influence bodily illusions ([Bufalari et al. 2014](#)). It thus confirms a *mutual* interaction between body-related and social cognition; an aspect that has often been neglected in current literature.

4. Integration

Consistent with its aim, the studies in the current special issue cover a diverse range of topics and methodology. The picture that emerges is that body representation constitutes a complex multimodal system, comprised of sensory mechanisms that bidirectionally interact with higher-order representations to continuously update and modulate corporeal awareness and cognition. Bodily representation, motor performance, and cognition are notably interdependent processes. Reviews on body representations suggest the involvement of a complex network of cortical and subcortical areas ([Berlucchi & Aglioti, 1997](#); [Moseley et al., 2011](#); [Porciello et al., 2018](#); [Riva, 2018](#)). This is exemplified in the review by Riva in this special issue, which provides a general and extensive body representations framework appropriate to many of the empirical studies and

clinical reports. The studies investigating the role of sensory input for bodily experience are in line with the general idea that our bodily experience is mediated by online internal (vestibular, interoceptive, proprioceptive) and external (tactile) information (see Figures 1 and 3 Riva, 2018). These studies demonstrate the complexity in which peripheral signals contribute to the bodily experience, both in healthy participants and in patients (Crucianelli et al., 2018; Fossataro et al., 2018; Lopez & Elzi, 2018; Reid et al., 2018). An important mechanism to consider is predictive multisensory integration, which has also been emphasized in the review by Porciello et al., 2018. Importantly, Riva additionally provides a framework for the different higher-order body representations, including their development (“body memory” in Riva’s terms, see Figures 2 and 3 Riva, 2018). Several of the body representations he describes have been investigated in the empirical studies in this special issue. The two studies assessing the correlation between body representations and motor representations would relate to the Active Body, in Riva terms (Reid et al., 2018; Saetta et al. 2018). An aspect of this representation also involves “movement of the body in space”, which fits in well with the spatial component of motor deficits in complex regional pain syndrome (Reid et al., 2018), as well as the effects of object phantom limb interactions on body part movement perception in the study of Saetta et al. (2018). Van Stralen et al., 2018 reported a link between structural body representations (left-right orientation) and body ownership, both of which seem to be part of the Personal body in Riva’s description. The observation that the anterior insula is important for both body ownership and left-right orientation may therefore not be so surprising. While these studies nicely fit some aspect of Riva’s model (2018), other potentially relevant aspects, such as ontogenetic development, are not covered in this special issue, but will be important to address in future empirical study.

It has long been assumed that the bodily self is also a social phenomenon (Schilder, 1935). Interactions between the Self and others were investigated in the studies of Azevedo et al., 2018 and Pellencin et al., 2018. These are featured less in the Riva review, but more prominently in the review by Porciello et al., 2018, where particular attention is paid to the face, our most socially relevant body part. Both the studies of Azevedo and Pellencin demonstrate how socioemotional processing is coupled to bodily processing. While the study of Pellencin et al., 2018 shows that social information affects personal space, the study of Azevedo et al., 2018 shows the reverse influence: bodily signals (i.e., cardiac signals) influence attention to emotionally salient and therefore socially relevant stimuli. This interaction between body representation and processing of social information is clearly bidirectional; an aspect that has often been neglected in studies on body representations and should be considered, or controlled for, more carefully in future studies. Especially during the enfacement illusion but also in other studies, such social aspects might influence plasticity of the bodily self.

5. Conclusion

As mentioned in the introduction, the question of how body (representations) and mind relate to each other has a long

history. The renewed interest in body representations in cognitive neuroscience and neuropsychology during the last few decades has provided new paradigms to study this question, resulting in considerable advances in both the theoretical models and aspects studied. It is clear that, in order to understand how body and cognition are related, one needs to assess peripheral sensorimotor processes, higher-order body representations, as well as cognitive functions. The papers of this special issue have covered and extended these aspects. Several studies focused on the relation between sensory input or motor function and body representation. Furthermore, both the reviews and various empirical papers provide further evidence for how body representations and higher-order functions, such as attention, spatial cognition, and social cognition are intrinsically linked. We are confident that these papers and future empirical studies both in healthy participants and in patients will further advance this field. This is important not only for understanding the fundamental mechanisms of embodied cognition and for developing treatment for patients with body representation disorders, but potentially also for a broad range of applied sciences dealing with altered body representations, such as robotics or virtual reality (Keizer, van Elburg, Helms, & Dijkerman, 2016; Perez-Marcos et al., 2012; Riva, Baños, Botella, Mantovani, & Gaggioli, 2016).

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REFERENCES

- Azevedo, R. T., Badoud, D., & Tsakiris, M. (2018). Afferent cardiac signals modulate attentional engagement to low spatial frequency fearful faces. *Cortex*, 104, 232–240. <https://doi.org/10.1016/j.cortex.2017.06.016>.
- Banakou, D., Groten, R., & Slater, M. (2013). Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences of the United States of America*, 110(31), 12846–12851. <https://doi.org/10.1073/pnas.1306779110>.
- Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, 59(1), 617–645. <https://doi.org/10.1146/annurev.psych.59.103006.093639>.
- Bergouignan, L., Nyberg, L., & Ehrsson, H. H. (2014). Out-of-body-induced hippocampal amnesia. *Proceedings of the National Academy of Sciences of the United States of America*, 111, 4421–4426. <https://doi.org/10.1073/pnas.1318801111>.
- Berlucchi, G., & Aglioti, S. (1997). The body in the brain: Neural bases of corporeal awareness. *Trends in Neurosciences*, 20(12), 560–564.
- Bermúdez, J. L. (1998). *The paradox of self-consciousness*. MIT Press.
- Besharati, S., Forkel, S. J., Kopelman, M., Solms, M., Jenkinson, P. M., & Fotopoulou, A. (2016). Mentalizing the body: Spatial and social cognition in anosognosia for hemiplegia. *Brain*. <https://doi.org/10.1093/brain/awv390> (2015), awv390.
- Blanke, O., Slater, M., & Serino, A. (2015). Behavioral, neural, and computational principles of bodily self-consciousness. *Neuron*, 88(1), 145–166. <https://doi.org/10.1016/j.neuron.2015.09.029>.

- Bottini, G., Sedda, A., Ferrè, E. R., Invernizzi, P., Gandola, M., & Paulsen, E. (2009). Productive symptoms in right brain damage. *Current Opinion in Neurology*, 22(6), 589–593. <https://doi.org/10.1097/wco.0b013e328332c71d>.
- Botvinick, M., & Cohen, J. (1998). Rubber hands “feel” touch that eyes see. *Nature*, 391(6669), 756.
- Brener, J., & Ring, C. (2016). Towards a psychophysics of interoceptive processes: The measurement of heartbeat detection. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1708), 20160015. <https://doi.org/10.1098/rstb.2016.0015>.
- Burin, D., Livelli, A., Garbarini, F., Fossataro, C., Folegatti, A., Gindri, P., et al. (2015). Are movements necessary for the sense of body Ownership? Evidence from the rubber hand illusion in pure hemiplegic patients. *Plos One*, 10(3), e0117155. <https://doi.org/10.1371/journal.pone.0117155>.
- Canzoneri, E., Magosso, E., & Serino, A. (2012). Dynamic sounds capture the boundaries of peripersonal space representation in humans. *Plos One*, 7(9), e44306. <https://doi.org/10.1371/journal.pone.0044306>.
- Crucianelli, L., Krahé, C., Jenkinson, P. M., & Fotopoulou, A. (2018). Interoceptive ingredients of body ownership: Affective touch and cardiac awareness in the rubber hand illusion. *Cortex*, 1–13. <https://doi.org/10.1016/j.cortex.2017.04.018>.
- Crucianelli, L., Metcalf, N. K., Fotopoulou, A., & Jenkinson, P. M. (2013). Bodily pleasure matters: Velocity of touch modulates body ownership during the rubber hand illusion. *Frontiers in Psychology*, 4(OCT), 1–7. <https://doi.org/10.3389/fpsyg.2013.00703>.
- Damasio, A. R. (1994). *Descartes' error. Emotion, reason and the human brain*. New York: Avon Book.
- de Vignemont, F. (2010). Body schema and body image—pros and cons. *Neuropsychologia*, 48(3), 669–680. <https://doi.org/10.1016/j.neuropsychologia.2009.09.022>.
- Descartes, R. (1975). *A discourse on method, meditation and principles*. London: (Everyman's Library, Ed.).
- Dijkerman, H. C., & de Haan, E. H. (2007). Somatosensory processing subserving perception and action: Dissociations, interactions, and integration. *The Behavioral and Brain Sciences*, 30(2), 224–230.
- Ehrsson, H. H. (2007). The experimental induction of out-of-body experiences. *Science*, 317(5841), 1048. <https://doi.org/10.1126/science.1142175>.
- Ferrè, E. R., & Haggard, P. (2016). The vestibular body: Vestibular contributions to bodily representations. *Cognitive Neuropsychology*, 33(1–2), 67–81. <https://doi.org/10.1080/02643294.2016.1168390>.
- Fischer, M. H. (2012). A hierarchical view of grounded, embodied, and situated numerical cognition. *Cognitive Processing*, 13(S1), 161–164. <https://doi.org/10.1007/s10339-012-0477-5>.
- Fossataro, C., Bruno, V., Gindri, P., Pia, L., Berti, A., & Garbarini, F. (2018). Feeling touch on the own hand restores the capacity to visually discriminate it from someone else' hand: Pathological embodiment receding in brain-damaged patients. *Cortex*, 104, 209–219. <https://doi.org/10.1016/j.cortex.2017.06.004>.
- Gallagher, S. (2000). Philosophical conceptions of the self: Implications for cognitive science. *Trends in Cognitive Sciences*, 4(1), 14–21.
- Gallagher, S. (2005). *How the body shapes the mind*. Oxford: Oxford University Press.
- James, W. (1890). *The principles of psychology*. New York: Henry Holt and company.
- Kammers, M. P. M., de Vignemont, F., Verhagen, L., & Dijkerman, H. C. (2009). The rubber hand illusion in action. *Neuropsychologia*, 47(1), 204–211. <https://doi.org/10.1016/j.neuropsychologia.2008.07.028>.
- Keizer, A., van Elburg, A., Helms, R., & Dijkerman, H. C. (2016). A virtual reality full body illusion improves body image disturbance in anorexia nervosa. *Plos One*, 11(10), e0163921. <https://doi.org/10.1371/journal.pone.0163921>.
- Lackner, J. R. (1988). Some proprioceptive influences on the perceptual representation of body shape and orientation. *Brain*, 111, 281–297.
- Lenggenhager, B., Hilti, L., & Brugger, P. (2015). Disturbed body integrity and the rubber foot illusion. *Neuropsychology*, 29(2), 205–211. <https://doi.org/10.1037/neu0000143>.
- Lenggenhager, B., & Lopez, C. (2015). Vestibular contributions to the sense of body, self, and others. In T. Metzinger, & J. M. Windt (Eds.), *Open MIND*. Frankfurt am Main: MIND Group. <https://doi.org/10.15502/9783958570023>.
- Lenggenhager, B., Tadi, T., Metzinger, T., & Blanke, O. (2007). Video ergo sum: Manipulating bodily self-consciousness. *Science*, 317(5841), 1096–1099. <https://doi.org/10.1126/science.1143439>.
- Lloyd, D. M., Gillis, V., Lewis, E., Farrell, M. J., & Morrison, I. (2013). Pleasant touch moderates the subjective but not objective aspects of body perception. *Frontiers in Behavioral Neuroscience*, 7(DEC), 207. <https://doi.org/10.3389/fnbeh.2013.00207>.
- Longo, M. R., Azanon, E., Haggard, P., Azañón, E., & Haggard, P. (2010). More than skin deep: Body representation beyond primary somatosensory cortex. *Neuropsychologia*, 48(3), 655–668. <https://doi.org/10.1016/j.neuropsychologia.2009.08.022>.
- Lopez, C., & Elzi, M. (2018). Out-of-body experience in vestibular disorders – A prospective study of 210 patients with dizziness. *Cortex*, 104, 193–206. <https://doi.org/10.1016/j.cortex.2017.05.026>.
- Maister, L., Sebanz, N., Knoblich, G., & Tsakiris, M. (2013). Experiencing ownership over a dark-skinned body reduces implicit racial bias. *Cognition*, 128(2), 170–178. <https://doi.org/10.1016/j.cognition.2013.04.002>.
- Maister, L., Slater, M., Sanchez-Vives, M. V., & Tsakiris, M. (2015). Changing bodies changes minds: Owning another body affects social cognition. *Trends in Cognitive Sciences*, 19(1), 6–12. <https://doi.org/10.1016/j.tics.2014.11.001>.
- Makin, T. R., Wilf, M., Schwartz, I., & Zohary, E. (2010). Amputees “neglect” the space near their missing hand. *Psychological Science*, 21(1), 55–57.
- Maravita, A., & Iriki, A. (2004). Tools for the body (schema). *Trends in Cognitive Sciences*, 8(2), 79–86. <http://doi.org/S1364661303003450> [pii]10.1016/j.tics.2003.12.008.
- Mazzurega, M., Pavani, F., Paladino, M. P., & Schubert, T. W. (2011). Self-other bodily merging in the context of synchronous but arbitrary-related multisensory inputs. *Experimental Brain Research*, 213(2–3), 213–221. <https://doi.org/10.1007/s00221-011-2744-6>.
- Merleau-Ponty, M. (1945). *Phénoménologie de la perception*. Paris: Gallimard.
- Moseley, G. L., Gallace, A., & Spence, C. (2011). Bodily illusions in health and disease: Physiological and clinical perspectives and the concept of a cortical “body matrix”. *Neuroscience and Biobehavioral Reviews*, 36(1), 34–46. <https://doi.org/10.1016/j.neubiorev.2011.03.013>.
- Paillard, J. (1999). Body schema and body image - a double dissociation in deafferented patients. G. N. Gantchev, S. Mori, & J. Massion (Eds.). *Motor control, today and tomorrow*, 198–214.
- Peck, T. C., Seinfeld, S., Aglioti, S. M., & Slater, M. (2013). Putting yourself in the skin of a black avatar reduces implicit racial bias. *Consciousness and Cognition*, 22(3), 779–787. <https://doi.org/10.1016/j.concog.2013.04.016>.
- Pellencin, E., Paola, M., Herbelin, B., & Serino, A. (2018). Social perception of others shapes one's own multisensory peripersonal space. *Cortex*, 104, 163–179. <https://doi.org/10.1016/j.cortex.2017.08.033>.

- Perez-Marcos, D., Solazzi, M., Steptoe, W., Oyekoya, O., Frisoli, A., Weyrich, T., et al. (2012). A fully immersive set-up for remote interaction and neurorehabilitation based on virtual body ownership. *Frontiers in Neurology*, 3, 110. <https://doi.org/10.3389/fneur.2012.00110>.
- Pfeiffer, C., Serino, A., & Blanke, O. (2014). The vestibular system: A spatial reference for bodily self-consciousness. *Frontiers in Integrative Neuroscience*, 8, 31. <https://doi.org/10.3389/fnint.2014.00031>.
- Porciello, G., Bufalari, I., Minio-paluello, I., Di, E., Maria, S., Fondazione, I., et al. (2018). The ‘enfacement’ illusion: A window on the plasticity of the self. *Cortex*, 104, 261–275. <https://doi.org/10.1016/j.cortex.2018.01.007>.
- Reid, E. J., Braithwaite, F. A., Wallwork, S. B., Harvie, D., Chalmers, K. J., Spence, C., et al. (2018). Spatially-defined motor deficits in people with unilateral complex regional pain syndrome. *Cortex*, 104, 154–162. <https://doi.org/10.1016/j.cortex.2017.06.024>.
- Riva, G. (2018). The neuroscience of body memory: From the self through the space to the others. *Cortex*, 104, 241–260. <https://doi.org/10.1016/j.cortex.2017.07.013>.
- Riva, G., Baños, R. M., Botella, C., Mantovani, F., & Gaggioli, A. (2016). Transforming Experience: The potential of augmented reality and virtual reality for enhancing personal and clinical change. *Frontiers in Psychiatry*, 7, 164. <https://doi.org/10.3389/fpsy.2016.00164>.
- Rohde, M., Di Luca, M., Ernst, M. O., Luca, M., & Ernst, M. O. (2011). The rubber hand illusion: Feeling of ownership and proprioceptive drift Do not go hand in hand. *Plos One*, 6(6), e21659. <https://doi.org/10.1371/journal.pone.0021659>.
- Ronchi, R., Rode, G., Cotton, F., Farnè, A., Rossetti, Y., & Jacquin-Courtois, S. (2012). Remission of anosognosia for right hemiplegia and neglect after caloric vestibular stimulation. *Restorative Neurology and Neuroscience*, 1–6. <https://doi.org/10.3233/RNN-120236>.
- Saetta, G., Grond, I., Brugger, P., Lenggenhager, B., Tsay, A., & Giummarra, M. J. (2018). Apparent motion perception in lower limb amputees with phantom sensations: “Obstacle shunning” and “obstacle tolerance”. *Cortex*, 104, 220–231.
- Salvato, G., Gandola, M., Veronelli, L., Agostoni, E. C., Sberna, M., Corbo, M., et al. (2016). The spatial side of somatoparaphrenia: A case study. *Neurocase*, 22(2), 154–160. <https://doi.org/10.1080/13554794.2015.1077257>.
- Schilder, P. (1935). *The image and appearance of the human body*. London: Kegan Paul.
- Stratton, G. M. (1899). The spatial harmony of touch and sight. *Mind*, 8(4), 492–505. <https://doi.org/10.1093/mind/VIII.4.492>.
- Suzuki, K., Garfinkel, S. N., Critchley, H. D., & Seth, A. K. (2013). Multisensory integration across exteroceptive and interoceptive domains modulates self-experience in the rubber-hand illusion. *Neuropsychologia*, 51(13), 2909–2917. <https://doi.org/10.1016/j.neuropsychologia.2013.08.014>.
- Tsakiris, M., & Critchley, H. (2016). Interoception beyond homeostasis: Affect, cognition and mental health. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1708), 20160002. <https://doi.org/10.1098/rstb.2016.0002>.
- Tsakiris, M., & Haggard, P. (2005). The rubber hand illusion revisited: Visuotactile integration and self-attribution. *Journal of Experimental Psychology. Human Perception and Performance*, 31(1), 80–91. <https://doi.org/10.1037/0096-1523.31.1.80>.
- Tsakiris, M., Tajadura-Jiménez, A., & Costantini, M. (2011). Just a heartbeat away from one's body: Interoceptive sensitivity predicts malleability of body-representations. *Proceedings. Biological Sciences/The Royal Society*, 278(1717), 2470–2476. <https://doi.org/10.1098/rspb.2010.2547>.
- van der Hoort, B., Guterstam, A., & Ehrsson, H. H. (2011). Being barbie: The size of one's own body determines the perceived size of the world. *Plos One*, 6(5), e20195. <https://doi.org/10.1371/journal.pone.0020195>.
- van Stralen, H. E., Dijkerman, H. C., Biesbroek, J. M., Kuijff, H. J., van Gemert, H. M. A., Sluiter, D., et al. (2018). Body representation disorders predict left right orientation impairments after stroke: A voxel-based lesion symptom mapping study. *Cortex*, 104, 140–153. <https://doi.org/10.1016/j.cortex.2017.05.025>.
- van Stralen, H. E., van Zandvoort, M. J. E., Kappelle, L. J., & Dijkerman, H. C. (2013). The Rubber Hand Illusion in a patient with hand disownership. *Perception*, 42(9), 991–993.
- van Stralen, H. E., van Zandvoort, M. J. E., Vissers, L. M. G. L. M. G., Hoppenbrouwers, S. S., Kappelle, L. J., Dijkerman, H. C., et al. (2014). Affective touch modulates the rubber hand illusion. *Cognition*, 131(1), 147–158. <https://doi.org/10.1016/j.cognition.2013.11.020>.
- Varela, F. J., Thompson, E., & Rosch, E. (1991). *The embodied Mind: Cognitive science and human experience*. Cambridge, MA: MIT Press.
- Wilson, R. A., & Foglia, L. (2011). Embodied cognition. In N. Zalta (Ed.), *The stanford encyclopedia of philosophy (fall 2011)*.