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**The Neuroscience of Body Memory: from the Self through the Space to the Others**

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Running Title: The Neuroscience of Body Memory

## The Neuroscience of Body Memory: from the Self through the Space to the Others (REVISION 2)

**Abstract.** Our experience of the body is not direct; rather, it is mediated by perceptual information, influenced by internal information, and recalibrated through stored implicit and explicit body representation (body memory). This paper presents an overview of the current investigations related to body memory by bringing together recent studies from neuropsychology, neuroscience, and evolutionary and cognitive psychology. To do so, in the paper, we explore the origin of representations of human body to elucidate their developmental process and, in particular, their relationship with more explicit concepts of self. First, it is suggested that our bodily experience is constructed from early development through the continuous integration of sensory and cultural data from six different representations of the body, i.e., the Sentient Body (Minimal Selfhood), the Spatial Body (Self Location), the Active Body (Agency), the Personal Body (Whole Body Ownership – Me); the Objectified Body (Objectified Self – Mine), and the Social Body (Body Satisfaction – Ideal Me). Then, it is suggested that these six representations can be combined in a coherent supramodal representation, i.e. the “body matrix”, through a predictive, multisensory processing activated by central, top-down, attentional processes. From an evolutionary perspective, the main goal of the body matrix is to allow the self to protect and extend its boundaries at both the homeostatic and psychological levels. From one perspective, the self extends its boundaries (peripersonal space) through the enactment and recognition of motor schemas. From another perspective, the body matrix, by defining the boundaries of the body, also defines where the self is present, i.e., in the body that is processed by the body matrix as the most likely to be its one and in the space surrounding it. In the paper we also introduced and discusses the concept of “embodied medicine”: the use of advanced technology for altering the body matrix with the goal of improving our health and well-being.

## The Neuroscience of Body Memory: from the Self through the Space to the Others (REVISION 2)

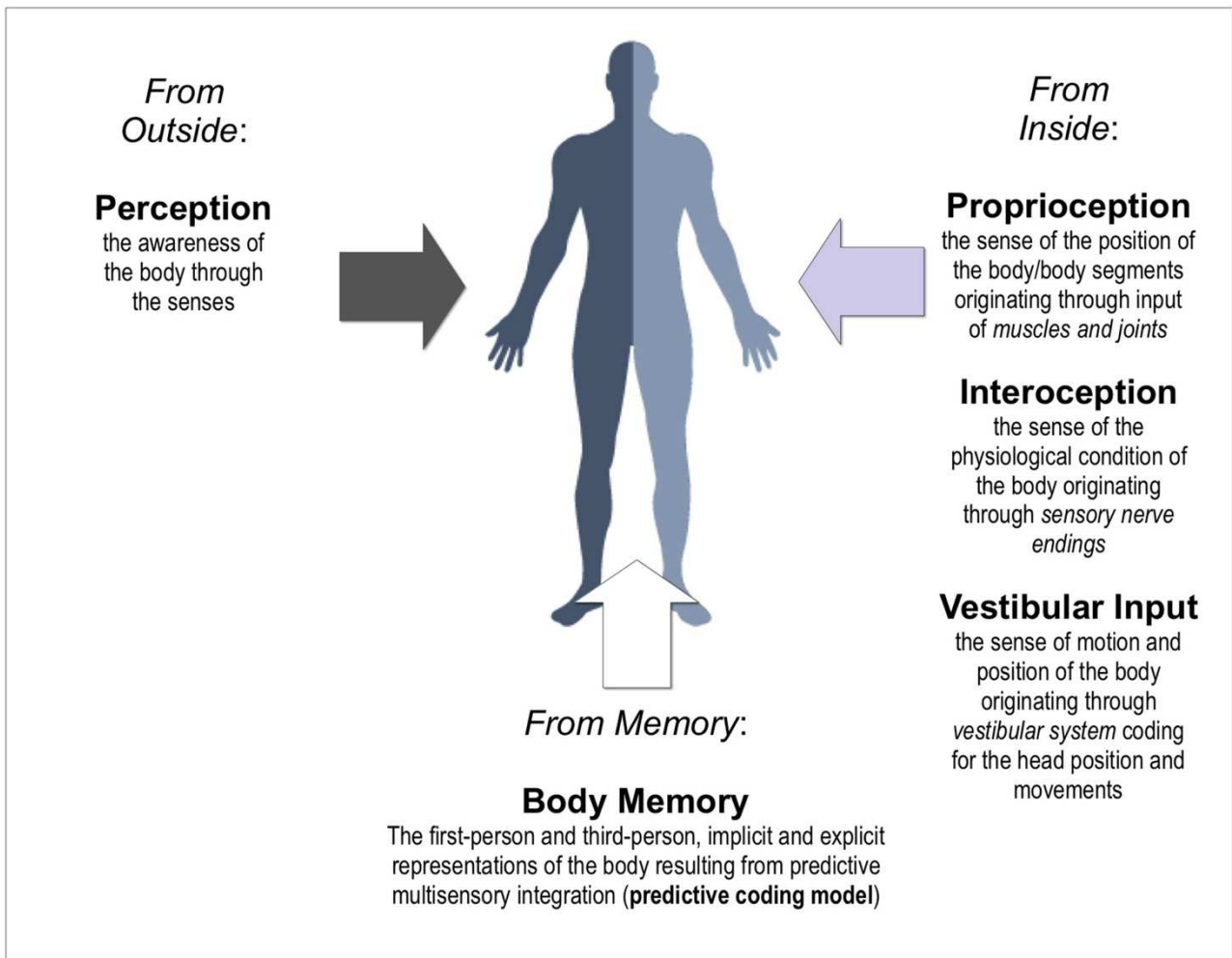
### 1. Introduction

The body is an object of perception, just like any other object in the world. Yet, at the same time, the body is different (Aspell, Lenggenhager, & Blanke, 2012). From one perspective, it provides the background conditions that enable perception and action (cognitive approach); from another perspective, it is associated closely with our sense of self and its intentionality (volitional approach).

For these reasons, different researchers have identified the experience of the body as the possible starting point for the development of a comprehensive scientific model of self-consciousness (Ananthaswamy, 2015; Craig, 2009, 2010; Damasio, 2010; Lenggenhager, Tadi, Metzinger, & Blanke, 2007; Tsakiris, 2012, 2017).

However, to study the experience of the body is not an easy task. As noted by Olaf Blanke (2012), the body is the most multi-sensory “object” in the world; it requires the processing and integration of different bodily signals in the premotor, temporoparietal, posterior parietal, and extrastriate cortices. In addition, our experience of the body is not direct (Figure 1), but it is (Blanke, Slater, & Serino, 2015; Pazzaglia & Zantedeschi, 2016; Riva, 2016b):

- mediated by perceptual information;
- influenced by internal information: Interoception, the sense of the physiological condition of the body; Proprioception, the sense of the position of the body/body segments; and Vestibular Input, the sense of motion of the body;
- recalibrated through stored implicit and explicit body representation (body memory).



**Figure 1. The experience of the body**

Recent research has focused on the investigation of how perceptual information and internal information influence our experience of the body. First, the study of multisensory processing has shown that it is possible to alter Bodily Self-Consciousness (BSC - the non-conceptual and pre-reflective processing and representation of body-related information) and its contents (Blanke, Faivre, & Dieguez, 2016; Costantini, 2014b; Macaуда et al., 2015) by modifying somatosensory and visual bodily signals, i.e., during a rubber-hand illusion (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005) or a body-swapping experience (Guterstam, Abdulkarim, & Ehrsson, 2015; Petkova & Ehrsson, 2008; Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2009). A second line of research underlined the possibility of using signals from the inside of the body (e.g., visceral signals) to

modify our BSC (Aspell et al., 2013; Park et al., 2016; Suzuki, Garfinkel, Critchley, & Seth, 2013). A final research line explored the link between BSC and cognition and identified a direct link between interoception, proprioception, vestibular input, and higher cognitive processes, such as attention, perception, decision-making, and emotional processing (Azevedo, Ainley, & Tsakiris, 2016; Maister, Slater, Sanchez-Vives, & Tsakiris, 2015; Mast, Preuss, Hartmann, & Grabherr, 2014; Muller et al., 2002; Tajadura-Jimenez, Grehl, & Tsakiris, 2012).

Even if neuroscience historically has differentiated between two different multimodal body representations, i.e., the body schema, working at the sub-personal level and a conscious and semantic body image, there has been widespread confusion about their nature and their characteristics (de Vignemont, 2010; Gallagher, 1986, 2005). As underlined by De Vignemont (2010), “There needs to be more than one mental representation of the body. But how many? Two? Three? Four? Although there is a growing consensus that there are at least two distinct types of body representation, the body schema and the body image, there is still little agreement beyond that. Some may conclude that we would be better off without these notions.” (p. 670).

In the past, neurology and psychiatry identified different bodily disorders that were used to develop different taxonomies of body representations (de Vignemont, 2010; Giummarra, Gibson, Georgiou-Karistianis, & Bradshaw, 2008). However, it is quite complex to organize and integrate syndromes that express different deficits, distortions, abnormal beliefs, and experiences of the body. More, as underlined by Bartolomeo (2011), complex cognitive functions are the result of large-scale networks linking distant cortical regions, rather than emerging from the activity of single cortical areas.

In this paper, starting from the original reflections offered by Merleau-Ponty in his book “Phenomenology of perception”, I will introduce the concept of “Body Memory” presenting an

overview of the current investigations of body memory, bringing together the recent studies from neuropsychology, neuroscience, and cognitive psychology.

The objective is to advance our understanding of the bodily experience of the self and to offer a convergent view of how it might be related to body memory.

## **2. Body Memory**

Neuroscience has recently explored the experience of the body focussing on the concept of body representations, i.e., cognitive structures that function to track the state of the body and encode it (de Vignemont, 2016). However, less attention has been focused on the role of body memory. Merleau-Ponty (1945/1962) stated, “Our body comprises as it were two distinct layers, that of the habit-body [body memory] and that of the body at this moment [body representations]... Correspondingly, my body must be apprehended not only in an experience which is instantaneous, peculiar to itself and complete in itself but also in some general aspect and in the light of an impersonal being.” (p. 95). As Fuchs (2012) underlined, “This implicit memory is based on the habitual structure of the lived body, which connects us to the world through its operative intentionality.” (p. 9).

In fact, Merleau-Ponty argued in favor of a sensorimotor view of bodily awareness in which the body memory provides to the self the bodily know-how, i.e. the knowledge of how to act with or towards a part of one's body. Following Gallese and Sinigaglia we can envisage the body memory “as a manifold of action possibilities” allowing the “practical attunement of the body to its environment” (Bermúdez, Marcel, & Eilan, 1995).

The best arguments in favor of the concept of body memory (“long term body image”) were proposed by O’Shaughnessy in his classical book entitled “Consciousness and the world” (O’Shaughnessy, 2000). According to O’Shaughnessy, the dynamic nature of proprioception, i.e., it can easily change according to the postural/ bodily sensations experienced by the subject,

suggests the existence of a long-term memory that provides a common spatial content. In O'Shaughnessy's words (2000), "The justification for positing a long-term body image (I, as I call it) begins with the fact that a common content C exists in all short-term body images (the i's, as I call them) over an extended period. This justification is immeasurably strengthened by the consideration that, while the content of proprioception is spatial and while postural and other sensations cause proprioception, postural sensations cannot be the *original bearer* of spatial content in proprioception" (p. 651, italic font in the original). The experience of phantom limbs in individuals who are congenitally limb-deficient (Brugger et al., 2000) or who suffer the amputation of a limb (Melzack, Israel, Lacroix, & Schultz, 1997) at an early age provides a clear support to this claim.

Under this scenario, our body memory - that is largely innately determined, but exhibits a malleability at the hands of protracted coordinated experience - allows the construction of different short-term body images providing the real time information about the posture and location of the body (O'Shaughnessy, 2000).

Even if this vision is quite popular outside the field of Neuroscience, its appeal within this discipline is quite limited.

A first key issue is that our memory of the body is multimodal and includes different, but tightly-bound representations, with perceptive, affective and cognitive contents (Antonios Dakanalis et al., 2016; de Vignemont, 2014; Gaudio & Quattrocchi, 2012). In addition, these representations develop in discrete stages, and the process of their development reflects the effects of the steps of neural maturation that bring about the transition from one stage to the next (Schoore, 2016). In fact, 70% of the final DNA in the human cerebral cortex is added after birth (Howard, 1973).

The communicative and social roles of our bodies have a key influences on body memory. In fact, our bodies' memories are the result of our direct bodily experiences, and they also include our



experiences of how others perceive and represent our bodies (Riva, 2014; M. J. Rochat, Serra, Fadiga, & Gallese, 2008; Slaughter & Brownell, 2012).

For these reasons, in this paper, the origin of the memory of the human body memory is explored to elucidate the process by which it was developed and, in particular, its relationship with more explicit concepts of self. First, it is suggested that our bodily experience is constructed from early development through the continuous integration of sensory and cultural data from six different representations of the body (Figure 2), i.e., the Sentient Body (Minimal Selfhood), the Spatial Body (Self Location), the Active Body (Agency), the Personal Body (Whole Body Ownership – Me), the Objectified Body (Objectified Self – Mine), and the Social Body (Body Satisfaction – Ideal Me). Then, it is suggested that these six representations are combined in a coherent supramodal representation - the “body matrix” – through a predictive, multisensory processing activated by central, top–down, attentional processes. The paper also introduces and discusses the concept of “embodied medicine,” i.e., the use of advanced technology for altering the body matrix with the goal of improving people’s health and well-being.

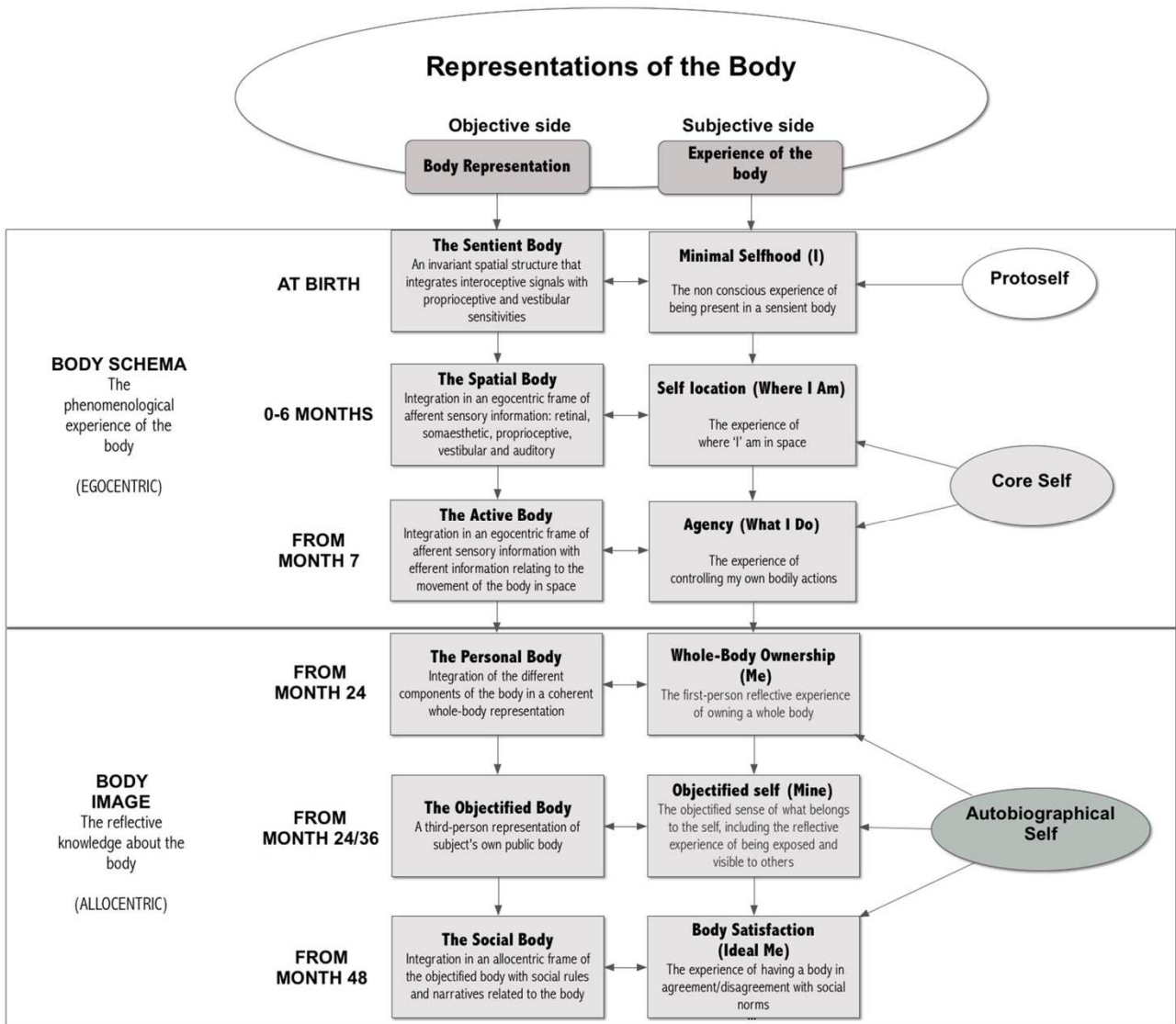


Figure 2. Ontogenetic development of body representations

### 3. The ontogenetic development of body memory

The analysis of the development of body representation systems in childhood is crucial for understanding the role of body memory in different cognitive functions (Bahrck, 2013; Gallagher, in press), from the development of a sense of self and identity to the control of action and intentionality. In addition, its analysis also underlines the complexity and the duration of the process (Cowie, Sterling, & Bremner, 2016; Nardini, Begus, & Mareschal, 2013), i.e.,

representations develop slowly and in a fragmented manner, reaching maturity only at the age of 10 to 11 .

### **3.1 The experience of the body in infants: from the protoself to the core self**

According to psychotherapists and neuroscientists, people's first memory of their bodies is related to the experience of birth. For example, Otto Rank (1929) underlined how the physical event of birth, in which the infant experiences for the first time the feeling of separation from the mother, can be considered the most significant event in the history of the individual. In Rank's view, the memory of that event continues to produce effects for a considerable length of time after birth, creating what he defined as the "nucleus of the unconscious" (p. xxiii). As noted by Damasio (1999), at birth, the body becomes the very first focus of the infant's attention through the inescapable experience of processing her/his sensory impressions. Specifically, the body is experienced through primordial feelings that express some variations of pleasure/pain and relaxation/tension, i.e., the individual is contained within a sentient body.

These processes support the idea that newborns possess an invariant spatial structure that is topologically defined (i.e., "The Sentient Body") and, beginning prenatally, integrates the signals of the interoceptive homeostatic system with proprioceptive and vestibular sensitivities (Azañón et al., 2016; Bahrick, 2013; Gallagher, 2005; Meltzoff & Moore, 1997; P. Rochat, 2012). Phenomenologically, this representation allows infants to separate themselves from the outside world, giving rise to the non-conscious experience of being bounded within a sentient body, which is the most basic self experience, i.e., that of *minimal phenomenal selfhood* (Blanke & Metzinger, 2009) or *protoself* (Damasio, 1999). As discussed earlier, a strong support to the first part for this claim is provided by aplasic patients with congenital limb deficiency (Brugger et al., 2000). They experience a phantom limb even though they have never had any sensory experience of such a

limb, suggesting that the existence of an innate, long-term representation encoding of the general structure of the body irrespective of one's actual physical body (de Vignemont, 2014).

A recent review by Badoud and Tsakiris (Badoud & Tsakiris, 2017), in which they assessed recent behavioural and neuroimaging evidence from non-clinical and clinical populations, suggested the existence of a link between the interoceptive homeostatic system and this invariant spatial structure mediated by the somatosensory cortices. Specifically, as noted by Khalsa and colleagues in a lesioned patient (Khalsa, Rudrauf, Feinstein, & Tranel, 2009), interoception also involves afferent information from the skin provided by a cortical network, which implicates the primary somatosensory cortex in the post-central gyrus.

Experientially, the protoself becomes aware of the external world through the body; every time an object touches the body, the protoself knows where the object is touching. The main outcome of this process is the creation of different somatotopic maps (Marshall & Meltzoff, 2015). As noted by Damasio (1999), “[They] are based on changes that occur in the body and brain during the physical interaction of an object with the body. Signals sent by sensors located throughout the body construct neural patterns that map the organism's interaction with the object. The neural patterns are formed transiently in the varied sensory and motor regions of the brain that normally receive signals coming from specific body regions.” (p. 60).

Before infants begin to manipulate objects and move in space, they have little obvious need for integrating these body maps. However, in the first months of life, different mechanisms of multi-sensory integration are activated between the body senses (somatosensation, proprioception, and kinaesthesia) and the distal senses (vision and audition). How these maps are integrated has been of significant interest, and different authors have suggested that this is achieved through multisensory neurons or groups of neurons that are influenced by inputs from more than one sensory modality (Allman, Keniston, & Meredith, 2009; Meredith, Nemitz, & Stein, 1987; Meredith

& Stein, 1996), i.e., unimodal neurons that have responses that are modulated by a different sensory modality, i.e., bimodal sensors that are activated by two different sensorial modalities and trimodal sensors that are activated by three different sensory modalities.

It is important to remember that these maps represent more than the internal structure, state, position, and motion of the body (interoceptive, proprioceptive and vestibular maps); they also represent the world that surrounds the body (exteroceptive maps). As emphasized by Damasio (1999), “The body and the surrounding environment interact with each other, and the changes caused in the body by that interaction are mapped in the brain. It is certainly true that the mind learns of the outside world via the brain, but it is equally true that the brain can be informed only via the body.” (p. 74).

In particular, both neuroscience and clinical psychology emphasize that another distinctive feature of the mind is its ability to identify other human bodies in the external world. For example, infants are able to recognize their mothers’ voices at birth (Burnham, 1993; Decasper & Fifer, 1980), and they are able to copy simple behaviours from other humans, e.g., tongue protrusion and mouth opening – in the first days of their lives (Meltzoff, 2007; Meltzoff & Brooks, 2001). As demonstrated by Saby and colleagues (2013) in their study of a sample of 14-month-old infants, when the infants observed someone else using a particular body part, the observation activated the corresponding areas of the infants’ own sensorimotor cortices.

How is this achieved? Again, a possible answer comes from a peculiar group of multimodal neurons, i.e., mirror neurons. These neurons, originally found in the ventral premotor cortex and inferior parietal lobule of monkeys’ brains (Bonini et al., 2010; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996; Rizzolatti, Fogassi, & Gallese, 2000), are able to match observed and executed actions by transforming sensory information into a motor format.

Several authors have suggested that this process is the result of associative learning's linking temporal regions that visually code for others' actions (e.g., the observation of lip protrusion) with parietal regions that are involved in executing actions (e.g., the execution of lip protrusion) (Brass & Muhle-Karbe, 2014; Catmur, Press, Cook, Bird, & Heyes, 2014; Cook, Bird, Catmur, Press, & Heyes, 2014). In this view, the infant's interactions with the mother and other relevant people, sustain this learning process and have a critical role in the postnatal maturation of brain structures that will regulate adult socioemotional functioning (Schore, 2016). An elegant way to explain this process is offered by the ideomotor theory. Herbart and Butz (Herbart & Butz, 2012) provided the following summary of this theory: "Whenever a movement is executed, the (mental representation of the) movement gets associated with (the mental representation of) its effects. This association between movement and effect is bidirectional. If the organism later wants to reach a goal state, the mere *anticipation* of this state may be sufficient to *directly* trigger the appropriate movement." (The words in italic font were presented this way in the original document.)

In other words, through the involvement of the ventral sensory stream, the learning process produces an additional ideomotor representation i.e., the to-be-produced sensory consequences of the action (Cassidy, Jones, & Shaver, 2013; Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1890; Massen & Prinz, 2009).

These representations have three main properties (Brass & Muhle-Karbe, 2014; Hommel et al., 2001; James, 1890). First, if conflicting representations are not available, ideomotor representations are able to elicit the actions with which they are associated. For example, the view of a person protruding her/his lips strongly overlaps with the representation used by the infant to control lip protrusion. So, its availability, if conflicting representations are absent, can directly activate the lip-protruding motor program. Second, their content is subject

independent, so using them alone does not allow differentiation between externally-triggered and internally-triggered motor representations. Third, they also are used to control motor functions by comparing their contents with the sensory consequences of actions.

The characteristics of ideomotor representations force the infant to develop new body representations to solve two critical problems, i.e., 1) Do the representations come from my body or not (spatial contingency – self location)? and 2) Do the representations activate the movement of my body or not (spatio-temporal contingency - agency)? As noted by Jeannerod and Pacherie (Jeannerod & Pacherie, 2004), “This [premotor] cortical network provides the basis for the conscious experience of goal-directedness – the primary awareness of intentions – but does not, by itself, provide us with a conscious experience of Self or Other-agency. By the same token, we can be aware of an intention without being aware of whose intention it is, i.e., something more than the sole awareness of a naked intention is needed to determine its author.” (p. 140).

Gergely and Watson (1999) suggested that infants are able to solve these problems using a complex perceptual detection module that can identify contingent relations (temporal correlations) between their responses and external stimulus events (Parise & Ernst, 2016). First, this module identifies spatial correspondence through visual spatial reliance, i.e., by representing body parts in their typical locations (Bremner, Holmes, & Spence, 2008). Then, it identifies the spatio-temporal correspondences through postural remapping, i.e., by dynamically remapping the representation of the position of the limbs in response to changes in postural information obtained from proprioception and vision (Bremner et al., 2008). Various authors have suggested that this process is controlled by the cerebellum through the acquisition and maintenance of internal models that simulate the mapping between a set of causes and effects (Cullen & Brooks, 2015; Ito, 2008; Wolpert, Miall, & Kawato, 1998).

The detection of spatial contingency allows infants, during their first six months of life, to solve the problem of self location. In addition, by using this technique, they are able to develop a new body map - “the spatial body” – that integrates the contents of “the Sentient Body” with first-person and third-person afferent sensory information (retinal, somesthetic, proprioceptive, vestibular, and auditory information) in an egocentric frame of reference (Giummarra et al., 2008; Antonella Maselli, 2015; Riva, 2014; Slaughter & Brownell, 2012). This ability was demonstrated experimentally by Bahrick and Watson (1985). In their study, a sample of infants was shown contingent (live) and non-contingent (pre-recorded) first-person videos of their bodies from the waist down. Their results clearly showed that infants as young as five 5 months of age were capable of discriminating between live and recorded images of their own movements.

The problem of agency is addressed in the next six months of life, through the detection of spatio-temporal contingencies. In this way, infants develop a third body map - “the active body” (Kammers, de Vignemont, Verhagen, & Dijkerman, 2009; Riva, 2014; Shibuya, Unenaka, & Ohki, 2017; Zwicker, Moore, & Povinelli, 2012) – that integrates the previous maps with efferent information related to the movement of the body in space (visuo-motor synchrony). This new body map allows toddlers to perceive visual and proprioceptive sensations as an integrated experience due to the perfect temporal correlation between proprioceptive (first-person) and perceptual (third-person) information (Zwicker et al., 2012). An experimental demonstration of the evolution of this ability was conducted by Hiraki (2006), who explored the ability of 5-month-old and 7-month-old infants to detect proprioceptive-visual intermodal contingency using live and delayed (two seconds) videos of the infants’ own leg movements. The results showed that only the 7-month-old infants demonstrated temporal sensitivity for contingency detection by looking at the delayed view for a significantly longer time. The 5-month-old infants showed no preference for either view.



Through the ability to recognize and actuate spatio-temporal contingencies through the body, the self evolves to its next level, i.e., the core self, which is able to connect itself with the events in which it is involved (Damasio, 1999). As emphasized by Damasio (1999), “The core self, then, is created by linking the modified protoself to the object that caused the modification. Timing is likely to play a role here, too, when the causative object begins to be processed and changes in the protoself begin to occur. These steps take place in close temporal proximity, in the form of a narrative sequence imposed by real-time occurrences.” (p. 155).

From an experiential perspective, the self is now able to use the body maps to recognize and actuate motor intentions (self location) and proximal intentions (agency) (Decety & Sommerville, 2003). In other words, the mapping of a hand moving on a 30-degree trajectory at a rate of 15 centimetres per second towards a ball is a lot more for the self than a collection of surfaces (Sommerville, Blumenthal, Venema, & Sage, 2012). It reveals an actor (the other toddler trying to take the ball) and its proximal intention (taking the ball), and it can be a window for the understanding of her/his future intention (playing with the ball).

The ventro-dorsal stream, the network between the ventral premotor cortex and the inferior parietal cortex, has an important role in these processes (Berlucchi & Aglioti, 1997; Murata, Wen, & Asama, 2016). In addition, this stream shares common neural substrates with the “who” system described by Jeannerod (2003), allowing the distinction between self-intended actions and actions executed or intended by others. In this view, the parieto-premotor network, by developing these two new maps and connecting them to the bodies of others, allows a direct link between higher-order cognitive functions and sensory-motor control (Murata et al., 2016).

### **3.2 Entering a social world: from the reflective experience of the body to the autobiographical self**

Beginning in the period from 12-18 months, toddlers are able to identify body parts. However, they do not have a reflective experience of their whole body and others' whole bodies until the end of their second year of life (Brownell et al., 2012). As explained by Brownell and colleagues (2012), "Our data suggest that children first become aware of their individual body parts in isolation from one another, then begin to represent their body as an obstacle in relation to other things in the world, then become able to consider their own body size explicitly, which is followed by representing how their body parts are arranged in relation to one another" (pp. 38–39).

Why? A first issue is the maturation of the brain. It is well known that, before the second year of life, infants experience infantile amnesia (Travaglia, Bisaz, Sweet, Blitzer, & Alberini, 2016), i.e., they rapidly forget episodic memories formed during the first postnatal period. Travaglia and colleagues (2016) recently suggested that this is the result of the immature development of the hippocampus, making it unable to reinstate context-specific memories, including the body-related memories. In addition, Gilga and Southgate (2012) suggested the infants' difficulty in learning and reflecting a human's full-body appearance also may be the result of an attentional bias, i.e., infants are more interested in recognizing and actuating intentions than in learning and identifying the structural properties of the body.

In this view, toddlers' acquisition of the reflective experience of their own body and others' bodies is a process that depends on two parallel processes, i.e., 1) the maturation of the hippocampus and the development of allocentric spatial memory abilities (Ribordy, Jabes, Lavenex, & Lavenex, 2013; Travaglia et al., 2016) and 2) the emergence and development of mirror recognition (P. Rochat & Zahavi, 2011) and true imitation, i.e., the ability to mimic the body movements of others (Jones & Yoshida, 2012). In fact, true imitation requires the knowledge of two critical activities (Jones & Yoshida, 2012), i.e., 1) a detailed, first-person representation of the body parts and the actions they make possible and 2) the mapping of this representation onto a third-person

representation of body parts and the actions of others. This process is even more complex for mirror recognition, because the mirror image is left-right reversed, i.e., the right side of the body is visible in the right side of the mirror. For this reason the body in the mirror has a special status for the subject (Jenkinson & Preston, 2015; Vogeley & Fink, 2003) because, different from other distant objects, viewing one's body in the mirror activates representations of peripersonal space despite the fact that the image appears in extrapersonal space. This enables the objectified view of the body experienced in a mirror to be processed as part of the self (Jenkinson & Preston, 2015, 2017).

Through these processes, which occur between 24 and 48 months after birth, infants develop two new body representations, i.e., 1) integrated and reflective knowledge of their own body parts and actions ("The personal body" – the first-person reflective experience of the body), and 2) the map of this knowledge onto their knowledge of the body parts and actions of others ("the objectified body" - mine). It is important to emphasize that "the objectified body" is not a representation of others' bodies. Instead, it is the infant's visible body, a third-person representation of the infant's own public body (Riva, 2014; P. Rochat, 2010), i.e., the body that others see and, more importantly, the body that they evaluate and judge.

The development of a reflective experience of the body is, according to Damasio (1999), a precursor of the appearance of a more advanced self, i.e., the autobiographical self. In fact, this advanced self emerges only when, to quote the book's title, self comes to mind. In other words, the appearance of the autobiographical self is the outcome of the ability to intersect past events with the representational maps of the whole-body sensory experience. Using autobiographical memories characterized by temporal, spatial, and self-referential features, toddlers are able to relate WHAT happened and WHERE and WHEN it happened, such as recalling playing soccer at the

park yesterday (Scarf, Gross, Colombo, & Hayne, 2013; Souchay, Guillery-Girard, Pauly-Takacs, Wojcik, & Eustache, 2013).

From the subjective perspective, the main experiential results of these new maps are the reflective experience of owning a whole body – “Whole Body Ownership” (Me) - and the “Objectified Self” (Mine) - the objectified sense of what belongs to the self, including the reflective experience of being exposed and visible to others (P. Rochat, 2010, 2012). As emphasized by Rochat and Zahavi (2011), “...what is at stake here is the realization that I exist in an intersubjective space. I am exposed and visible to others. When seeing myself in the mirror, I am seeing myself as others see me. I am confronted with the appearance I present to others. In fact, not only am I seeing myself as others see me, I am also seeing myself as if I was an other, i.e., I am adopting an alienating perspective on myself.” (p. 209).

The emergence of the Me and of the Mine emphasizes a critical point underlined in the introduction to this paragraph (Riva, 2014), and that is that culture has a central role in shaping our bodily experience as we construct and revise our own experience of the body through a variety of social inputs.

Even if viewing and touching other bodies influences our body, real-life encounters are not mandatory. In particular, language and cultural practices also have a direct influence on our bodily experience by providing identities to which we must conform and providing rituals to perform (Brugger, Lenggenhager, & Giummarra, 2013; Mauss, 1973).

In this view, the final step in the developmental process of experiencing and remembering the body is the comparison of “the objectified body” with an ideal cultural body produced by institutional norms and values (Calogero, 2012; A. Dakanalis & Riva, 2013; Thompson, Heinberg, Altabe, & Tantleff-Dunn, 1999). For example, Fredrickson and Roberts (1997) suggested that

Western culture teaches women to evaluate themselves as objects to be looked at and evaluated on the basis of physical appearance.

The main outcome of this process is a new representation of the body, i.e., the “social body.” This representation integrates and compares the objectified representation of the body with the ideal cultural body (the Ideal Me), transforming the body into a symbolic project and guiding the actions of the self. As emphasized by Shilling (2012), “treating the body as a project... involves practical recognition of the significance of bodies as both personal resources and social symbols... Bodies become malleable entities to be shaped and honed by the hard work of their owners.” (p. 7).

### **3.3 The evolutive role of body representations**

The tight link between the development of the self and the development of the body representations suggests that the memory of the body is much more than a series of interconnected maps. I have suggested that the development of more advanced body maps allows the self to enact and understand a more advanced level of intentionality (Riva, Waterworth, & Waterworth, 2004; Riva, Waterworth, Waterworth, & Mantovani, 2011; Waterworth & Riva, 2014; Waterworth, Waterworth, Mantovani, & Riva, 2010).

Recently, Mylopoulos and Pacherie (in press) suggested that the link between these intentions and the different body representations is achieved through motor schemas. Specifically, prior intentions include executable action concepts that describe the organization and structure of the action (motor schema) using a set of predefined parameters related to the body and the world around it (Jeannerod, 1997); these parameters can be defined and updated using Bayesian inference and modelling (Braun, Mehring, & Wolpert, 2010). In this view, motor schemas are the result of a process of inductive generalization from sets of motor representations or from sets of already extant motor schemas. Empirical evidence that supports the existence of a link between

motor schemas and intentions is the activation of motor representations during the processing of linguistic items pertaining to action (Buccino, Colago, Gobbis, & Bonaccorso, 2016; Kemmerer, 2015; Repetto, Colombo, Cipresso, & Riva, 2013; Vanhoutte et al., 2015). In addition, the link between the anticipatory images of action-effects and motor schemas also suggests a critical role of intentions in shaping peripersonal space.

Rizzolatti and colleagues defined “peripersonal space” as the space immediately around our bodies (Rizzolatti et al., 1996), and later studies demonstrated both its role in monitoring the position of objects in space in relation to the body, and its plasticity after both short-term and long-term learning and practice of a tool (Holmes & Spence, 2004). Additional more recent studies, however, have provided a more complex picture of the role of peripersonal space, i.e., 1) the affording features of an object evoke a motor response in the observer’s brain even when it is out of her/his reach, provided that it is reachable by another individual (Cardellicchio, Sinigaglia, & Costantini, 2013; Fini, Costantini, & Committeri, 2014); 2) the plasticity in peripersonal space after the use of a tool does not depend strictly on the active use of the tool itself, but it is triggered by anticipatory images of its action-effects (Galli, Noel, Canzoneri, Blanke, & Serino, 2015); 3) the plasticity in peripersonal space is affected by the psychological properties of objects, i.e., affective valence and knowledge about their functions (Valdes-Conroy, Roman, Hinojosa, & Shorkey, 2012).

Taken together these studies suggest that intentions, through the peripersonal space, gate the representation of the potential motor acts afforded by visible objects allowing their identification as potential targets for one's own actions or others' actions (Maranesi, Bonini, & Fogassi, 2014).

#### **4. The Body Matrix: Controlling the Body Experience**

The framework offered here highlights the critical role of ontogenic development and social interactions in defining the characteristics of the memory of our body. If early representations

(The Sentient Body, The Spatial Body, The Active Body) have a critical role in shaping our phenomenological experience of the body (“online – body schema”), the reflective knowledge about the body (“offline – body image”) requires the introduction of new representations (The Personal Body, The Objectified Body, and The Social Body) that are closely related to our social experience.

At this point, however, there are different critical questions to be answered, i.e., 1) Is there a need for more than the two classical mental representations of the body, i.e., body schema and body image, to explain body memory? 2) If yes, do they develop into different, separable systems? 3) Are they interdependent of one another? 4) If so, how do they interact?

Recently, in a review, Blanke and colleagues (2015) assessed the neurophysiological, neuroimaging and behavioral studies that have explored the characteristics of bodily self-consciousness. According to their analysis, distinct body signals and neural processes are required for self-identification, self-location and body-part ownership. For example, neurological patients who have damage to the temporo-parietal junction, experience an altered self-location (Ionta et al., 2011). In addition, if we apply the neuropsychological principle of dissociation as a possible way of developing a taxonomy of body memory (de Vignemont, 2010), it is possible to identify a bodily disorder for each of the six body representations included in the framework, in which one is impaired while the others are not (Riva, 2014), i.e., phantom limb (Sentient Body), unilateral hemi-neglect (Spatial Body), alien hand syndrome (Active Body), autoscopic phenomena (Personal Body), xenomelia (Objectified Body), and body dysmorphia (Social Body). These examples suggest that the different representations develop independently, following the progressive maturation of the brain. Cowie and colleagues (2016) demonstrated that, when rubber hand illusions were induced in children of different ages, “the multisensory foundations of the bodily self undergo a

protracted period of development through early and mid-childhood, reaching an adult state by 10 to 11 years.” (p. 230).

But are they independent of one another?

Different studies of congenitally-blind subjects and subjects who became blind later (Ley, Bottari, Shenoy, Kekunnaya, & Roder, 2013; Nava, Steiger, & Roder, 2014) have suggested that damage to an “early” system at a young age might impair the development of later representations. For example, Ley and colleagues showed that the remapping of tactile inputs into an external reference frame was related to early visual input during the first 24 months of life and that individuals who were blind for their first two years of life do not recover this ability (Ley et al., 2013). In addition, the lack of this remapping ability prevents congenitally-blind individuals from experiencing a somatosensory version of the rubber hand illusion (Nava et al., 2014).

In this view, our bodily representations are organized hierarchically (Seth, 2014), i.e., if lower level representations map sensory signals from inside and outside the body within an egocentric frame of reference (first-person), the higher level representations map more abstract (multi-modal, amodal, and contextual) aspects of our sensorimotor experience within an allocentric frame of reference (third-person). Also, they progressively integrate the content of the first innate representation, i.e., the Sentient Body, with new multi-sensory bodily stimuli from both themselves and other people, allowing the production and understanding of more and more advanced, goal-directed actions. This point is addressed in more detail in the next paragraphs.

A final key question for the presented framework is how these different body representations are integrated in a coherent and single experience of the body. Different authors have suggested that the multisensory brain mechanism has a critical role in the ability to integrate bodily signals (Blanke et al., 2015; Ehrsson, Spence, & Passingham, 2004; A. Maselli, Kilteni, Lopez-Moliner, & Slater, 2016; Petkova et al., 2011).



According to Moseley and colleagues, body representations are integrated in a coarse supramodal multi-sensory representation of the body and the space around it, i.e., the “body matrix,” the evolutive goal of which is to allow the individual to protect and extend her/his boundaries at both the homeostatic and psychological levels (Gallace & Spence, 2014; Moseley, Gallace, & Spence, 2012; Sedda, Tonin, Salvato, Gandola, & Bottini, 2016).

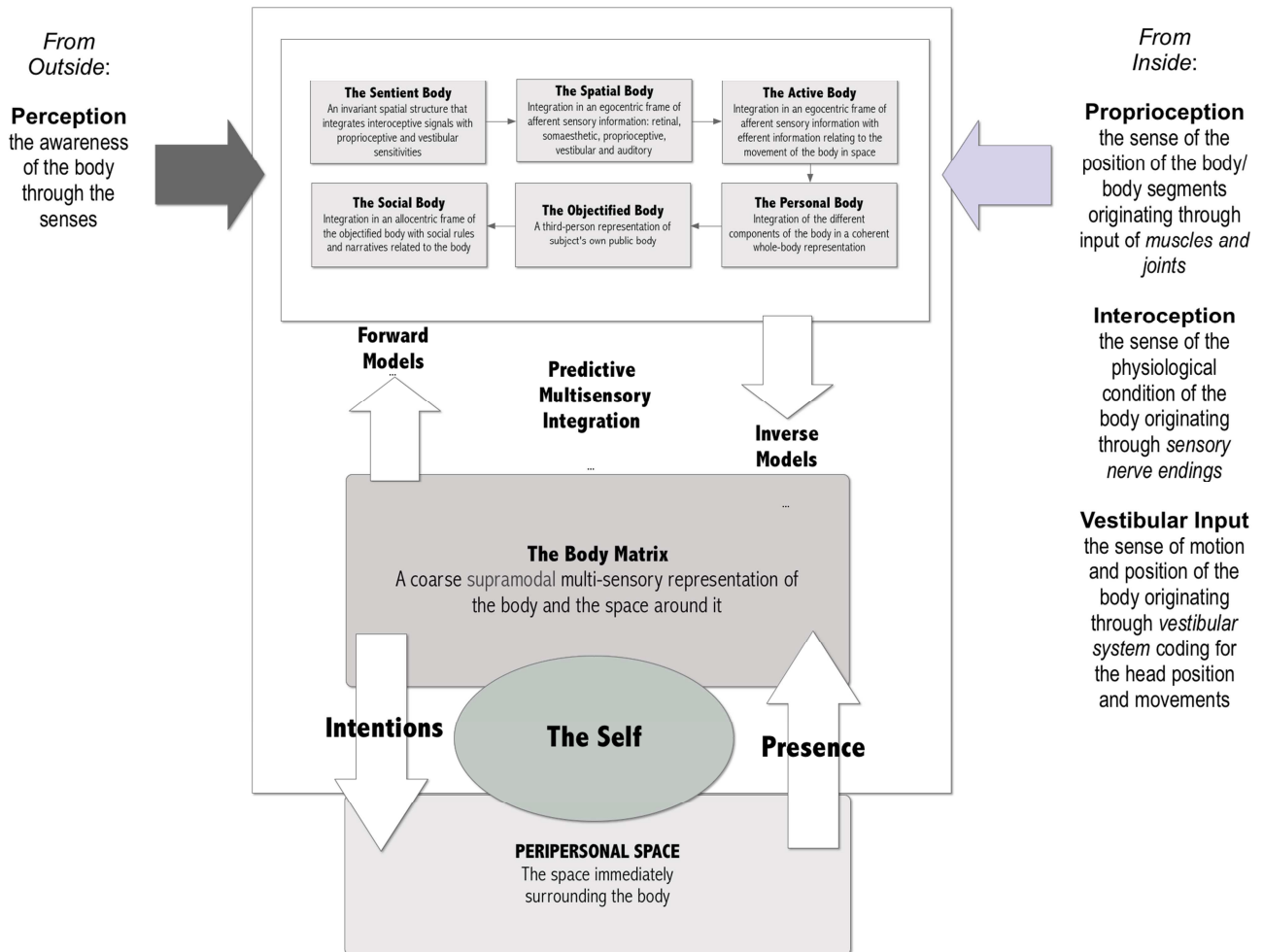
The body matrix emerges from the flow of information across large-scale networks that link various regions of the brain (Bolognini, Convento, Rossetti, & Merabet, 2013; Gallace & Spence, 2014; Moseley, Gallace, & Spence, 2012). Specifically, through the connections between the posterior parietal cortex and the insular cortex, the body matrix integrates somatotopic and peripersonal sensory data with body-centred spatial sensory data and an object-centred body image from vision and memory. As noted by the authors (Moseley, Gallace, & Spence, 2012) “the body matrix integrates these constructs by proposing a direct inter-relationship between cognitive representations, such as ownership over a body part, and homeostatic function, such as thermoregulation.” (p. 43).

In this view, the body matrix allows the resolution of potential conflicts between the body representations by producing coherent short-term representations of the body and the space around it on the basis of their contents and three general laws, i.e., bodily signals are integrated more strongly according both to their spatial and temporal proximity (the nearer the signals are, the more they are integrated) and to the weakness of a single signal (the weaker the signal is, the more it is integrated) (Blanke et al., 2015). Computational models have shown that different bodily inputs can be combined using maximum-likelihood estimation models that minimize errors and allow multisensory integration with a perceptual precision greater than that of the individual inputs (Blanke et al., 2015; Prsa, Jimenez-Rezende, & Blanke, 2015). This is achieved through the predictive, multi-sensory integration (multisensory binding) that is activated by central top-down

attentional processes (Clark, 2016a; de Vignemont, 2014; Feldman & Friston, 2010; Samad, Chung, & Shams, 2015; Talsma, 2015; Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). In agreement with the predictive coding framework (Clark, 2013; Friston, 2010, 2012), the body matrix actively maintains a mental model of the body and the space around it (peripersonal space), which provides predictions about the expected sensory input and tries to minimize the amount of free energy (or ‘surprise’).

I have not offered an in-depth discussion of these concepts in this article, because authoritative and thorough accounts have been provided elsewhere (Clark, 2013, 2016b; Friston, 2010, 2012; Hohwy, 2013; Talsma, 2015). Herein, I will extend beyond their work to explore the link between the body matrix, the self, and the body experience.

According to the predictive coding model, a critical goal of the body matrix is to minimize the average of surprise (the disparity between intentions and the effects of enacting them) across the different representations and to learn how best to model and predict incoming contents. In other words, the contents of the body matrix are adjusted on the basis of the (dis)agreement (Talsma, 2015) between the perceived sensory activity, and the activity predicted through the integration of the contents of the different representations that define the satisfaction conditions of the intentions of the self (Figure 3).



**Figure 3. The interaction between the Self, the Body Matrix and the different body representations**

This process is bi-directional (Friston, Daunizeau, Kilner, & Kiebel, 2010), i.e., the body matrix can be changed to accommodate unexpected sensory signals (perceptual inference and learning), and actions are performed to confirm the sensory predictions made by the body matrix according to the intentions of the self (active inference). Specifically, the contents of the body matrix are defined by top-down predictive signals, integrating the generative models of the causes of sensory signals defined by the different body representations (Friston et al., 2010). The different models are ranked and included in the body matrix according to their relevance for the intentions of the self (selective attention). A classical demonstration of the effect of this selection process in the

space around the body matrix is the phenomenon of inattentive blindness in which unexpected objects fail to capture one's attention if they are not relevant to the satisfaction predictions of the enacted intention (Simons, 2000; Simons & Chabris, 1999). At the same time, the content and the priority of the different generative models are modified continually by bottom-up prediction errors that signal mismatches between predicted and actual content of the different body representations (Friston, 2009). For example, in the rubber hand illusion, the mismatch between the predicted and the actual position of the perceived hand modifies both the content of the body matrix, i.e., reduces the motor excitability of the corticospinal hand circuits, (Della Gatta et al., 2016) accompanied by modulation of the temperature of the skin (Moseley et al., 2008; Rohde, Wold, Karnath, & Ernst, 2013) - and its sensory predictions – i.e., the haptic sensory predictions associated with motor commands (Aymerich-Franch, Petit, Kheddar, & Ganesh, 2016).

This also is true for higher-level body representations (Maister et al., 2015). Bodily illusions that induce ownership over a body of a different race produce a change in low-level body representations. These changes create errors further up in the processing hierarchy and also update attitudes and beliefs held about one's self mapped in high-level body representations (Peck, Seinfeld, Aglioti, & Slater, 2013).

In this view, by defining the boundaries of the body, the body matrix also defines where the self is present. This concept is not new. Damasio (2003) stated, "If the readers of Nature were asked to define the concept of 'self,' I imagine that the answers would cluster around two principal meanings. One would be refreshingly precise, i.e., "what the immune system identifies as belonging to the body" (p. 223). However, this concept also suggests that, for the self, the phenomenal experience of the body is determined by the brain's estimation of the most likely interpretation of the content of the body matrix, computed according to Bayesian principles (Apps & Tsakiris, 2014; Tsakiris, 2017). In simpler words, the body matrix also defines where the self is

present, i.e., in the body that is processed by the body matrix as the most likely to be its one (Apps & Tsakiris, 2014) (Holmes & Spence, 2004). As noted by Apps and Tsakiris, “The mental representation of the physical properties of one’s self are, therefore, also probabilistic. That is, one’s own body is the one that has the highest probability of being ‘me,’ since other objects are probabilistically less likely to evoke the same sensory inputs. In short, the notion that there is a ‘self’ is the most parsimonious and accurate explanation for sensory inputs. In mathematical terms, this parsimonious accuracy is exactly the quantity that is optimised when minimising free energy or prediction error.” (p. 88).

In the following paragraphs, two possible corollaries of this vision are introduced and discussed, i.e., 1) presence, the feeling of being present in the body matrix and in the space around it, which has a critical, evolutive role in that it allows the control of action and drives psychological selection and 2) damaged, malfunctioning, or altered feedback from and toward the body matrix has a direct effect on the bodily experience of the self and may be involved in the aetiology of different neurological and psychiatric disturbances.

#### **4.1 Presence and Flow: The feeling of being inside the body matrix**

According to Friston and colleagues, all biological systems follow the principle of free-energy minimisation (Friston, 2010; Friston & Stephan, 2007), i.e., they act on the environment and sample it to avoid irreversible alterations of their boundaries. In other words, this principle has a clear evolutive goal (Friston & Stephan, 2007), which is the survival of the biological system. “Systems that fail to maintain a low free-energy will encounter surprising environmental conditions, in which the probability of finding them (i.e., their surviving) is low. Put simply, systems with a lower free energy will be selected over systems with a higher free energy.” (p. 451)

If low free-energy states are so important for survival, their detection should be a critical goal for any biological system, including humans. So, the human brain should learn to model and predict incoming sensory input to minimize the average of surprise across the different the body representations. I suggest that the feeling of “presence,” i.e., the feeling of being in the body matrix and in the space surrounding it (peripersonal space), is the experiential tool used to achieve this goal (Riva, Waterworth, & Murray, 2014; Riva et al., 2011). According to Sanchez-Vives & Slater (2005) “presence” can be defined as the feeling to be in an environment, be it real or virtual. However, as seen previously, different studies suggest a critical link between the body and the space it is in: the “peripersonal space” is the space immediately surrounding our bodies, and the “extrapersonal space” is the space beyond our bodies (Dijkerman & Farne, 2015; Holmes & Spence, 2004). In this view, being present in the body matrix also locates the individual in the space around it. In addition, the strict link between the body matrix and peripersonal space was addressed in a recent study by Kandula and colleagues (2015). Their study demonstrated that information from an approaching visual stimulus in peripersonal space could be used to make judgments about the location and time of impending tactile contact (Kandula et al., 2015). In other words, by viewing an object entering peripersonal space, we are able to extract implicit information about the time and location of where the body will be touched. This also suggests that peripersonal space is important for the maintenance of bodily integrity by predicting the negative consequences of a bodily contact (de Haan, Smit, Van der Stigchel, & Dijkerman, 2016).

In this view, through the pre-reflexive monitoring of the feeling of presence (Riva & Waterworth, 2014), the self tries to overcome any threat or breakdown in its activity (break in presence), and it searches for engaging and rewarding activities (optimal experiences).

According to Winograd and Flores (1986), a breakdown is a disruption in the flow of presence, i.e., a breakdown occurs when the self, during an intentional action, is forced to shift its attention from

the prior intention to the object/environment to cope with it, e.g., when we stumble on a tree root. If we use the framework discussed here, the breakdown experienced by stumbling on the root is the result of the mismatch between the predicted and the actual position of the legs, which does not allow the minimization of free energy.

However, the self preferentially engages in activities associated with a positive, complex, and intrinsically-rewarding state (Seligman & Csikszentmihalyi, 2000). Csikszentmihalyi (1975, 1990) defined these activities as “optimal experiences” or “flow.” During these activities, the self experiences absorption, a full sense of control and experiential immersion. Specifically, the use of the term “flow” underlines the experience of continuity and fluidity during the actions, which characterizes them. I suggest that what makes an activity optimal is free energy minimization, i.e., having correctly predicted the outcome of its prior intention, the self can use the body to enact it prereflexively. In this view, the minimization of free energy and the feeling of presence have key roles in the process of “psychological selection,” and they drive the attention of the self towards experiences that are associated with flow, thereby facilitating their replication (Csikszentmihalyi & Massimini, 1985; Massimini & Delle Fave, 2000). Thus, flow triggers the direct investment of the self in the practice and cultivation of the intrinsically rewarding experiences.

As noted by Delle Fave and colleagues (Delle Fave, Massimini, & Bassi, 2011), “Optimal experience can be considered as the “psychic compass” supporting the developmental trajectory each individual autonomously builds and follows throughout life... Throughout their lives, they thus build a personal life theme that is a set of interests and goals they uniquely cultivate and pursue” (p. 48).

#### **4.2 Embodied Medicine: Altering the body matrix to improve health and well-being**

In the previous paragraphs, we have seen how the contents of the body matrix are modified by bottom-up prediction errors that signal mismatches between predicted and actual content of the different body representations. An important effect of this process is the top-down modulation induced by multi-sensory conflicts over the contents of the different body representations, starting from the first one, i.e., The Sentient Body, which has direct access to the interoceptive homeostatic systems (Blanke et al., 2016; Tsakiris, 2017). I suggest that the body matrix is able to modulate basic physiological mechanisms, such as thermoregulatory control (Tieri, Gioia, Scandola, Pavone, & Aglioti, 2017) and pain thresholds (Martini, Perez-Marcos, & Sanchez-Vives, 2014), through access to this low-level body representation. As suggested by Moseley and colleagues (2012), “The body matrix integrates these constructs by proposing a direct inter-relationship between cognitive representations such as ownership over a body part and homeostatic function such as thermoregulation.” (p. 40). A recent study by Finotti and Costantini (2016) further expanded this vision, highlighting the existence of biochemical mechanisms that link the body matrix to the immune system (Costantini, 2014a) with important “implications for a range of neurological, psychiatric, and immunological conditions in which alterations of multisensory integration, body representation and dysfunction of the immune system co-exist.” (p. 1).

In this view, damage, malfunctioning, or altered feedback from and toward the body matrix might be involved in the aetiology of different disturbances (Riva, 2016a), from neurological disorders, such as chronic pain (Di Lernia, Serino, & Riva, 2016; Tsay, Allen, Proske, & Giummarra, 2015) and neglect (Bolognini et al., 2016; Lenggenhager et al., 2012), to psychiatric disorders, such as depression (Barrett, Quigley, & Hamilton, 2016; Wheatley et al., 2007), schizophrenia (Ferri et al., 2014; Klaver & Dijkerman, 2016; Postmes et al., 2014), eating and weight disorders (Keizer et al., 2013; Keizer, Smeets, Dijkerman, van Elburg, & Postma, 2012; Riva, 2014; Scarpina et al., 2016;



Serino, Dakanalis, et al., 2016), and depersonalization/derealization disorder (Jauregui Renaud, 2015; Simeon et al., 2000).

How does this occur? I suggest the following two possibilities, i.e., 1) through an impairment in the ability of correctly linking bodily signals to their potential pleasant (or aversive) consequences and 2) through an impairment in the ability of updating the body matrix with new contents from real-time perception-driven inputs.

Various studies suggested a direct link between altered interoception and different disturbances. For example, altered interoceptive awareness is present in anxiety disorders (Pollatos, Traut-Mattausch, Schroeder, & Schandry, 2007), poorer interoceptive accuracy and higher interoceptive sensibility in autism (Garfinkel et al., 2016), altered somatic signaling and interoception in depression (Harshaw, 2015), and overactive monitoring of internal bodily signals in obsessive-compulsive disorder (Yoris et al., 2017).

According to Paulus & Stein (2010), a brain circuit that involves the medial prefrontal cortex, the dorsolateral prefrontal cortex, and the anterior cingulate evaluates anticipatory interoceptive signals using self-relevant and belief-based processes to identify those that are relevant. If this process is impaired, the individual no longer can correctly identify the relevant interoceptive signals that predict potential pleasant (or aversive) consequences. In this view, the different diseases are related to the degree to which these wrong interoceptive prediction schemas evolve (Paulus & Stein, 2010). For example in depression, when the relationship between arousal and interoceptive accuracy decrease, anhedonia symptoms increase in severity, (Dunn et al., 2010). However, in anxiety, an increased interoceptive sensitivity associated with a decreased interoceptive accuracy produces an augmented detection of a prospective aversive body state (Paulus & Stein, 2010).

A second way the body matrix may be involved in the etiology of neurological and psychiatric disorders is through an impairment in the ability to update its contents (Riva, 2012). As we have seen previously, a critical goal of the body matrix is the integration of multisensory bodily signals. In particular, lower level sensory signals within an egocentric frame of reference must be integrated with higher level abstract bodily information within an allocentric frame of reference.

A recent hypothesis is that these different bodily representations are integrated within an amodal spatial representational format, based on a three-dimensional coordinate system (spatial image), shared by both perceptual and linguistic knowledge (Kelly & Avraamides, 2011; Loomis, Klatzky, Avraamides, Lippa, & Golledge, 2007; Wolbers, Klatzky, Loomis, Wutte, & Giudice, 2011). Loomis and colleagues also suggested (Giudice, Klatzky, Bennett, & Loomis, 2013; Loomis, Klatzky, & Giudice, 2013) that this amodal representation format is available in spatial working memory and allows the development of a composite representation of space derived from both perception (egocentric) and long-term memory (allocentric).

The use of an amodal spatial representation has two key advantages (Giudice et al., 2013). First, it allows the active imagination of spatial layouts (mental travel) and the possibility of performing mental transformations. Second, it allows the control of actions, even when the source stimulus is no longer available, through a direct link between what is being perceived from the external world and the available internal model what is being perceived (Loomis, 1992). However, a continuous translation process is required between the different reference frames.

According to a prominent neural model of spatial memory and imagery (Byrne & Becker, 2008; Byrne, Becker, & Burgess, 2007), the translation between egocentric and allocentric representations involves the retrosplenial cortex, with the support of place and grid cells. In their own words: “Both encoding and retrieval/imagery require translation between egocentric and

allocentric representations, which are mediated by posterior parietal and retrosplenial areas and the use of head direction representations in Papez's circuit" (p. 340).

Recently, I suggested that different factors (Gaudio & Riva, 2013; Riva, 2014, 2016b) – from stress, to functional connectivity alterations, to an altered monoamine neural modulation – may impair this process, locking the individual to an old memory of the body that cannot be updated. This mechanism may be involved in different disturbances, ranging from eating and weight disorders (A. Dakanalis, Carrà, Clerici, & G., 2015; Antonios Dakanalis et al., 2016; Serino, Scarpina, et al., 2016) to Alzheimer's disease (Serino & Riva, 2014, 2017).

So our challenge is to determine how we can use technology to modify the contents of the body matrix. Following the discussion above, two possible ways to correct a dysfunctional body matrix are: 1) the use of technologies to facilitate the integration of external and inner body signals (Azevedo et al., 2016; Azevedo et al., 2017; Suzuki et al., 2013) and, 2) the use of technologies to induce a controlled mismatch between the predicted/dysfunctional content and the actual sensory input thereby improving the body representations (Keizer, van Elburg, Helms, & Dijkerman, 2016; Serino & Dakanalis, 2016; Serino, Pedroli, et al., 2016).

The emerging fields of interoceptive feedback (Schoenberg & David, 2014; Suzuki et al., 2013), sonoception, i.e, the use of sound and vibration to modify inner body signals (Azevedo et al., 2017; Riva, Serino, Di Lernia, Pavone, & Dakanalis, 2017) - and body illusion techniques (Costantini, 2014b), may offer practical tools for the above strategies.

An example of the first approach is the study by Suzuki and colleagues (2013). The authors created a "cardiac rubber hand illusion" in which a computer-generated, augmented-reality providing a real-time feedback of interoceptive (cardiac) information, thereby facilitating the online integration of exteroceptive and interoceptive signals. This approach may be replicated in patients with anxiety to improve their interoceptive accuracy.

An example of the second approach is described in the paper by Azevedo and colleagues (2017), in which a wearable device was used to deliver discrete, on-demand, heartbeat-like vibrations on the wrist to modulate levels of arousal and calmness. This approach produced significant calming effects on physiological arousal and subjective experience in the experimental sample (using a single-blind design) during their anticipation of making a public speech.

An example of the third approach is detailed in the paper by Serino and colleagues (2016). Their research provided evidence that an illusion of body ownership over a body different from the current one can change body percept and affect (i.e., reduce body size distortions and body dissatisfaction) and motivate initiation and maintenance of healthy eating behaviours, even in non-operable, extremely-obese patients (i.e., body mass index  $> 60 \text{ kg/m}^2$ ).

These studies provided the basis for a new trans-disciplinary research field that I propose to call “Embodied Medicine” (Riva, 2016a; Riva et al., 2017), the main goal of which is the use of advanced technology for altering the body matrix with the goal of improving people’s health and well-being.

## **5 Conclusions**

The aim of this paper was to provide a new theoretical perspective on human body memory in order to account for previous findings and offer a novel framework for future research in neuroscience. Recent research in this area explored the experience of the body and the self by using two different, but converging, views i.e., the cognitive perspective and the volitional perspective. Cognitive studies analyse how the body is experienced and used in response to environmental conditions, while volitional studies analyse how the self uses the body to achieve its needs and goals.

In this paper, I have suggested that the notion of body memory, i.e., the cognitive structure that enables and defines the operative intentionality of the body, (Merleau-Ponty, 1945/1962) may be the missing link between these two approaches because it directly connects the experience of the body with the development of the self. First, I described the ontogenic process behind human body representations and attempted to describe their developmental process and their relationship with the evolution of the self. Specifically, I suggested that our bodily experience is constructed from early development through the continuous integration of sensory and cultural data from the following six different representations of the body (Figure 2) (Riva, 2014):

- 1) *The Sentient Body*: An invariant spatial structure topologically defined that, beginning prenatally, integrates the signals of the interoceptive homeostatic system with proprioceptive and vestibular sensitivities. The experiential outcome of this representation is *minimal phenomenal selfhood*, the non-conscious experience of being present in a sentient body;
- 2) *The Spatial Body*: The Integration in an egocentric frame of afferent sensory information, i.e., retinal, somaesthetic, proprioceptive, vestibular, and auditory information. The experiential outcome of this representation is *self location*, i.e., the experience of where 'I' am in space;
- 3) *The Active Body*: The integration in an egocentric frame of afferent sensory information with efferent information relating to the movement of the body in space. The experiential outcome of this representation is *agency*, the experience of controlling bodily actions.
- 4) *The Personal Body*: The Integration of the different components of the body in a coherent whole-body representation. The experiential outcome of this representation is *whole-body ownership (Me)*, the reflective experience of owning a whole body.
- 5) *The Objectified Body*: A third-person representation of a subject's own public body. The experiential outcome of this representation is the *objectified self (Mine)*, the objectified sense of what belongs to the self, including the reflective experience of being exposed and visible to others

6) *The Social Body*: The Integration in an allocentric frame of the objectified body with social rules and narratives related to the body. The experiential outcome of this representation is the *body satisfaction/dissatisfaction* generated by the reflective experience of having a body in agreement/disagreement with social norms (Ideal Me).

The framework offered here highlights the critical roles of ontogenic development and social interactions in defining the characteristics of our body memory. If early representations (The Sentient Body, The Spatial Body, The Active Body) have a critical role in shaping our phenomenological experience of the body (“online – body schema”), reflective knowledge about the body (“offline – body image”) requires the introduction of new representations (The Personal Body, The Objectified Body, and The Social Body) that are closely related to our social experience. These latter representations also share a critical feature in that they map the body using a different frame of reference, i.e., allocentric.

Then, I suggested that these six representations are integrated in a coherent supramodal representation, i.e., the “body matrix,” the evolutive goal of which is to allow the individual to protect and extend her/his boundaries at both the homeostatic and psychological levels (Gallace & Spence, 2014; Moseley, Gallace, & Spence, 2012). In this view, the body matrix allows the resolution of potential conflicts between the body representations by producing a coherent representation of the world and the body on the basis of their contents. This is achieved through the predictive, multi-sensory integration activated by central top–down attentional processes (Clark, 2016a; Feldman & Friston, 2010; Samad et al., 2015; Talsma, 2015; Talsma et al., 2010).

In addition, the development and integration of different body representations in the body matrix allow the self to extend its boundaries. Specifically, the peripersonal space gates the representation of the potential motor acts afforded by visible objects allowing their identification as potential targets for one's own actions or the actions of others (Maranesi et al., 2014).

By defining the boundaries of the body and the space around it, the body matrix also define where the self is present, i.e., the self is present in the body that is processed by the body matrix as the most likely to be its one (Apps & Tsakiris, 2014) and in the space surrounding it. I also discussed two possible corollaries of this vision. The first was presence, i.e., the feeling of the self's being present in the body matrix, which has a critical evolutive role. By monitoring presence prereflexively (Riva & Waterworth, 2014) the self tries to overcome any breakdown in its activity (break in presence) and searches for engaging and rewarding activities (optimal experiences). Second, damaged, malfunctioning, or altered feedback from and toward the body matrix has a direct effect on the bodily experience of the self and may be involved in the aetiology of different neurological and psychiatric disturbances. I have suggested the following two mechanisms, i.e., 1) through an impairment in the ability of correctly linking bodily signals to their potential pleasant (or aversive) consequences and 2) through an impairment in the ability of updating the body matrix with new contents from real-time perception-driven inputs. In the paper, I also introduced and discussed the concept of "embodied medicine," i.e., the use of advanced technology for altering the body matrix with the goal of improving people's health and well-being.

This framework has significant explanatory value, because body memory explicitly links the body matrix to the self, to the space in which the self is located, to the evolution of the self, and to the homeostatic mechanisms that regulate people's physical bodies. However, there are some caveats that must be considered. Perhaps the most important caveat is that, even though predictive coding models now have significant influence on research in neuroscience, direct empirical support is yet to come. As suggested by Apps and Tsakiris (2014) the use of behavioural tasks in conjunction with computational models derived from predictive coding can help to verify whether the body matrix truly integrates the different body representations in a probabilistic and Bayesian way.

In addition, the precise mechanisms that allow this integration certainly must be investigated further. Even though Moseley and colleagues (2012) suggested a direct involvement of the parietal cortex and the insular cortex, more work, including neuroimaging studies, is required to clarify the process and to elucidate the mediating circuits underlying the body matrix.

Although this paper offers a rich theoretical framework in which the available research data from different disciplines can be integrated and understood, it also is true that, to date, these data neither largely support nor refute its contents. In conclusion, even if important questions remain unanswered, the framework that I have provided offers an extensive set of predictions that can be tested experimentally. In particular, as emphasized by Dijkerman in relation to body representations (2015), “a model of how different components relate to each other would be crucial to be able to test their interactions systematically.” (p. 427). This is exactly what I tried to do in this paper. I hope that future experimental studies will generate novel findings that better elucidate the neural and psychological bases of body memory and its relation with the self.

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