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Article

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Montirosso, R and McGlone, FP (2020) The body comes first. Embodied reparation and the co-creation of infant bodily-self. Neuroscience & Biobehavioural Reviews, 113. pp. 77-87. ISSN 0149-7634

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The body comes first Embodied reparation and the co-creation of infant bodily-self.

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Highlights

- Infant bodily-self emerges in early embodied interactions with mother
- Embodied interactions typically fluctuate between attuned and misattuned states
- Embodied reparation is achieved through tactile contact and maternal interoceptive sensitivity
- These elements contribute to co-create the infant bodily-self

Introduction

The bodily-self is a compelling certitude which supports the ability to perceive our body as separate from other entities and provides the basis of self-perception. This in turn is crucial for engaging in social interactions, interpreting and predicting the thoughts, actions and behaviors of others (Meltzoff, 2017). Bodily-self is a concept that involves not only neural representation and modulation of physiological homeostasis, but also the perception of body ownership (Seth, 2013). In adults, information regarding the state of the bodily-self depends upon exteroceptive somatosensory, visual, and vestibular signals, as well as those originating interoceptively, which provide inputs and sensations about the state of one’s own body, such as pain, temperature, itch, respiration, cardiac signals, hunger etc., which are integrated to generate bodily-self representation (Riva, 2017). While there are no conclusive findings about the exact timing, developmentally, of the emergence of the sense of a bodily-self (Slaughter and Brownell, 2011), recent studies indicate that processing of information from the body begins during the first year of life and more likely a process that starts *in-utero* (Zieber et al., 2015). Studies on the ontogeny of human body perception in infants suggest that a pre-reflective, non-conceptual form of bodily self-awareness, a primitive sense of self (i.e., 'minimal self'), is already present in the first months of life (Gallagher, 2000; Damasio, 2010).

The formation of bodily-self is hypothesized to be driven and progressively refined by learning about sensorimotor contingencies via interactions between brain-body-environment (Georgie et al., 2019) and self-generated actions (i.e., self-exploration, Di Mercurio et al., 2018). Interestingly, it has been suggested by Marshall and Meltzoff (2015) that sensory/perceptual experience of one's own body involves relational and emotional exchanges. For example, research on the mµ rhythm, recorded electroencephalography (EEG), suggests that infants are provided with a mirror mechanism that enables them to generate, at the cortical level, a bidirectional representation of both other-action perception and their own-action execution (Caspers et al., 2010), and that they can activate sensorimotor correspondences between their own body parts and the body parts of others (Meltzoff et al., 2018). Interestingly, alterations in early interpersonal experience, such as preterm birth, might contribute to deficits in the bidirectional sensorimotor representation of both other-action perception and an infant's own-action execution (Montirosso et al., 2019). This evidence suggests that during infancy the bodily-self is not an entity dependent solely on inherited neuro-maturational processes (e.g., brain-body interactions), rather it is dependent upon relational experiences of body-to-body interactions (i.e., embodied interactions) which provide the basis for the constitution of the minimal-self, a necessary and vital precursor of subsequent 'self-other' distinctions (Fotopoulou and Tsakiris, 2017; Ciaunica and Crucianelli, 2019).

From birth, an infant is engaged in body-to-body interactions with their mother, most of which are part of routines such as having a nappy changed, being fed, playful exchanges etc. During these embodied interactions, by countless multimodal reciprocal exchanges, mother and infant need to coordinate their behaviors and bodies, and both contribute to interpersonal rhythmic cycles of co-regulation (an interpersonal process variously termed ‘synchrony’, ‘mutual regulation’, or ‘attunement’; Tronick, 2004; DiCorcia and Tronick, 2011). Within these cycles of mutual regulation, face-to-face exchanges, physical proximity and tactile interactions have a key role for supporting bio-behavioral synchrony (Atzi and Gendron, 2017), that is the coordination of physiological, neuroendocrine and behavioral exchanges which that are known to be important for the building of the infant's social development (Feldman, 2012; Feldman et al., 2014). Indeed, accumulating evidence has documented that during the first year of life an infant experiences implicit synchrony between its own bodily activities and the mother’s, as evidenced by EEG activity, heart rhythm, and neuroendocrine responses (Winberg, 2005; Leong et al., 2017; Van Puyvelde et al., 2019). While a number of studies suggest that the dyad’s ability of co-regulation is important for the development of well-functioning stress regulation (DiCorcia and Tronick, 2011; Feldman et al., 2012; Welch, 2016), more recent views hypothesize that this interpersonal process, which unfolds during early interactions, might support the infant’s bodily-self perception (Ciaunica and Crucianelli, 2019).

Recognizing the centrality of a bio-behavioral synchrony perspective being embedded in early embodied interactions leads, at least in part, to a couple of critical questions. First, although mothers and infants are able to reciprocally adjust their own physiological activities (Van Puyvelde et al., 2015), above all when they are in close body contact, it should be recognized that a constant bio-behavioral synchrony is a rather improbable phenomenon. In agreement with evidence from research on early social-interaction dynamics (Tronick, 2004), it is reasonable to assume that during embodied interactions co-regulation states (referred to as attunement) and non co-regulation states (misattunement), alternate. This poses the question: how does each partner’s bodily activity, dynamically and continuously, make possible the shift from misattunement to attunement? Second, if the cycles of mutual regulation are a process which develops during embodied interactions, then we need to consider the role played by the mother's body and not only focus on the infant's body. Specifically, it would be of interest to understand if, and to which extent, the mother's body contributes to how parents interpret and respond to their infant's bodily signals (so-called, maternal sensitivity). Indeed, it remains unclear how infants and their mothers reach bio-behavioral synchrony and what is the contribution of the maternal body in this process. Here, we discuss recent evidence which allows the examination of bio-behavioral synchrony in early interactions indicating that mothers' interact with infants using: i) tactile contact behaviors (e.g., skin-to-skin, touch) and ii) interoceptive sensitivity (i.e., ability to perceive internal input about the state of one's own body). We propose that, along with other interactive processes (Markova et al., 2019), bio-behavioral synchrony is achieved between the dyad through tactile contact behaviors as much as it may be induced by maternal interoceptive sensitivity, which supports moment-by-moment adaptation of the mother to interactive demands and the infant's needs. Although these elements are likely interwoven, the focus here is not to analyze their potential links, rather to describe how they might contribute to bio-behavioral synchrony. We conclude by presenting the hypothesis that embodied interactions promote not only interpersonal synchrony, but also co-creates the infant bodily-self.

Tactile interactions between parent and infant are pervasive, playing a central role for an infant's developing social, emotional, and physical needs (Moszkowski et al., 2009; Jean, Stack, and Fogel, 2009; Stack and Jean, 2011). For example, recent work has documented that touch during the neonatal period is associated with improved physiological and behavioral indices of emotional reactivity in infants of depressed mothers (Sharp et al., 2012). Interestingly, immediate post-natal tactile stimulation and physical contact reduce newborns' crying and distress and support newborn adaption to life outside of the womb (Winberg, 2005). A recent study found that mothers' touching behaviors in the first minutes to an hour after birth were predictive of a mother's touching behaviors 3-months later (Mercuri et al., 2019). In this latter, the frequency of immediate post-natal maternal touch was associated with more soothing, regulating maternal touch observed after an age-appropriate experimental stress induction procedure, the Face-to-Face Still-Face paradigm, (i.e. stress resulting from a temporary parent's unresponsiveness; Tronick et al., 1978). Furthermore, recent evidence suggests epigenetic mechanisms influencing stress response are associated with tactile contact experience in full-term infants (Lester et al., 2018; Murgatroyd et al., 2015), while adverse stress-related experience, which also implies an altered maternal contact-related experience during the early stage of life (e.g., prematurity), can have in impact on the DNA methylation, stress response and endocrine regulation, short- (Montirosso et al., 2016; Provenzi et al., 2016) and long-term (Provenzi et al., 2019).

Nevertheless, the importance of maternal touch to an infant's developing needs goes well beyond these aspects. Touch is a multidimensional and dynamic system and has a unique role on perception of body ownership in adults (Tsakiris, 2017). Specifically, touch could enhance the early subjective feelings of body ownership, supporting multisensory integration (Crucianelli et al., 2018). Indeed, there is now evidence for multimodal integration related to body perception in the early period of life. Recent research finds newborns are able to detect multisensory integration of body-related information both for the temporal (Filippetti et al., 2013) and spatial properties (Filippetti et al., 2015) of visual-tactile stimulation. At 4 months of age infants are sensitive to tactile-auditory spatio-temporal correspondences (Thomas et al., 2017). Even more remarkably, 5 month old infants looked longer at an animated character that was moving in asynchrony with their own cardiac rhythm, suggesting that even at this early age, infants showed an implicit sensitivity to interoceptive signals, and an ability to integrate these interoceptive signals with external visual-auditory stimuli (Maister et al., 2017). However, the infant's brain is not mature enough for a complete multisensory integration, and recent studies suggest development of this process is not predetermined (Burr and Gori, 2012; Stein, Stanford and Rowland, 2014), rather it improves and becomes increasingly more specialized with experience (Lewkowicz and Bremner, 2020) and social interaction with physical contact would facilitate multisensory integration. In a study, 8-months-old infants heard pseudo-words both while they were tickled (multimodal audio−tactile condition) and not tickled (unimodal audio condition). After this phase, brain activity (i.e., EEG) was measured during the perception of the same words. Compared to the audio condition, the audio−tactile condition was associated with higher brain activity within the left temporal regions (Tanaka, Kanakogi, Kawasaki and Myowa, 2018). Authors suggest that their findings provide neural evidence that the integration of audio-tactile information in infant's brain is facilitated by social interaction involving physical contact with others. Thus, along with other processes involved in brain maturation, interpersonal tactile stimulation could be implicated in integrating information between modalities, which in turn would support the development of bodily self-perception in the infant (Fotopoulou and Tsakiris, 2017; Crucianelli and Filippetti, 2018).

While accumulating evidence supports the fundamental role of gentle touch during parent-infant interactions, little is known about the role of parental interoception. However, how interoception is defined and quantified remains a matter of debate (Garfinkel et al., 2015). From a general point of view interoception refers to the ability to perceive physiological changes, especially from internal organs such as the viscera, heart, lungs, and skin (Craig 2002). While its importance for survival is evident, an increasing number of studies suggest that, along with many different external and bodily sensory inputs, interoception might be crucial for the development and function of perception, higher-order cognitive processes and affect (Allen and Tsakiris, 2019). For example, interoceptive accuracy (i.e., the extent to which one can correctly detect one's own interoceptive signals) has been found to be associated with ability in decision-making (Dunn et al.

2010) and self-regulation (Herbert et al. 2007). Even more important for the aims of the current paper, interoceptive accuracy has been found to be associated with the ability to recognize emotion (i.e., empathy; Fukushima et al., 2011) and to contribute to the perception of the self (Fotopoulou and Tsakiris, 2017). These findings are in line with an embodied cognition theoretical view, which suggests that higher-order cognitive processes are situated in bodily systems, highlighting a putative role of interoception in both self- and other-perception (Gallese, 2007; Tsakiris, 2017). In the light of this evidence, it is reasonable to assume that parental interoception might play a crucial implicit role in 'mother sensitivity'. In fact, to 'read' infant's bodily signals and to link these cues with specific emotional meanings and appropriate responses, mothers need to have awareness (even if in an implicit way) of their own body experiences (see: Tylka, Lumeng, and Eneli, 2015; for a similar proposition in relation to the development of intuitive eating behaviors).

To analyze this view, we will first discuss the emergence of bodily-self in infants and the links with neuroanatomical and neurophysiological pathways of tactile stimulation. We will also present the role of affectionate touch in mother-infant exchanges. Moreover, beside affectionate touch, early exchanges are mediated by embodied interactions, in which both the mother's and infant's body dynamically changes their own interoceptive states. We will argue that the mother's state of interoceptive sensitivity serves as a foundation for responsiveness to her infant's body signals. According to this perspective, an infant's subjective experience of bodily-self may not only be localized within the infant (Ciaunica and Crucianelli, 2019), but could rather be conceived as a process of shared inter-corporeality in which the mother plays a critical role in co-creating the infant's bodily-self.

The emergence of a bodily-self in infants

The newborn's body is a highly multisensorial 'entity' continuously sensing a cacophony of tactile, visual, auditory, vestibular, olfactory, gustatory, proprioceptive and motor signals (André et al., 2018). Bodily sensations, of interoceptive and exteroceptive origin, are associated with the need of regulating homeostasis and the behavioral drives that are necessary to maintain the integrity of the body (Craig, 2002). Previous studies have suggested the mechanisms through which visual, vestibular, proprioceptive and tactile inputs are integrated in different levels of body awareness (Gentsch et al., 2016; Fotopoulou and Tsakiris, 2017). The mechanisms underpinning somatosensory integration with other external environmental signals are thought to support a non-conceptual and basic form of bodily-self (Ehrsson, Holmes and Passingham, 2005; Ionta et al., 2011; Tsakiris, 2010), likely associated with a sense of agency and body ownership (Riva, 2017; Seth and Tsakiris, 2018).

Human newborns have a basic sense of self (Filippetti et al., 2015) and a rudimentary distinction between representations of their bodies and those of other people (Rochat, 2003). Through self-exploration and perception of contingent sensorimotor information infants learn what belongs to their body (Gergely and Watson, 1999; Filippetti et al., 2013). In fact, synchronous visual-proprioceptive and visual-tactile stimulation is uniquely 'self-specifying'. The infant can use such contingencies to identify self-performed actions very early in life. For example, in the first hours of life infants look longer at a video of another newborn's face if it is stroked by a brush when their own face is brushed synchronously, rather than asynchronously (Filippetti et al., 2013). Importantly, this preference disappeared in both synchronous and asynchronous tactile stimulation when the newborns look at an infant's face in an inverted presentation, suggesting that they may have a predisposition for specific naturalistic body patterns (Filippetti et al., 2013). Likewise, 7- and 9-month-old infants prefer to look at a video of a doll's legs being stroked synchronously, rather than asynchronously, with their own legs (Zmyj et al., 2011). The difference is in the temporal synchrony or spatial congruency between proprioceptive input (where infants feel the body to be) and visual stimulation (where the infants see the body to be), suggesting that they behave differently towards sensations that originate from their own body versus those that are caused by the external stimulation. Other evidence shows that visual-tactile contingencies may have a specific role in an infants' perception of their own body. Using magnetoencephalography (MEG), Meltzoff and colleagues (2018) investigated the neural representation of body parts in 7-month-old infants. Somatosensory cortex was activated when their own body was touched, but also when infants visually perceived touch to someone else's body. The authors suggest that cortical representations of body parts may underlie connections between self and other. Overall, these findings imply that an infants' multisensory integration of body-related information, including the integration of tactile stimuli with vision and proprioception, could provide the basis for establishing an early distinction between one's body and that of others (Cascio et al., 2012).

Bodily self-perception and interoception: The role of the insula

Although the integration of exteroceptive signals (i.e., proprioceptive and kinesthetic input informing about the movement of the body in space) plays a critical role in generating our sense of self, recent studies suggest the integration of interoceptive signals (i.e., neural mapping of multiple body states) is also crucial for bodily self-perception (Craig, 2009). Interoception involves the detection and processing of multiple signals from the body such as temperature, itch, pain, cardiac signals, respiration, hunger, thirst and touch – both discriminative and affective. Importantly, interoception has been associated with the generation of subjective feelings and self-perception (Damasio, 2010), in connection with insular cortex activation (Craig, 2002; Seth, 2013). In fact, it has been hypothesized that the anterior insula integrates sensorimotor signals and body schema networks (which involve different cerebral area such as parietal and frontal regions) creating a neural representation of the body into an embodied form of self-awareness (Namkung et al., 2017; Atzil et al., 2018). The insular cortex has a number of significant features. First, it is amongst the earliest cortical regions to develop and differentiate and is at an advanced maturational stage from 27 weeks of gestation (Afif et al., 2007). This indicates that the insular cortex has an early involvement in the elaboration of somatosensory stimulation – again at an early maturational level from ~ 12 weeks gestational age, to which the fetus and the newborn are exposed. Second, insula neurons (as with cingulate neurons) have a specific cytoarchitecture: in contrast with pyramidal neurons which have a series of small basal dendrites that stretch from the cell body, these nerve cells, called spindle, or Von Economo neurons, are bipolar with only one bigger basal dendrite (Allman et al., 2005). Von Economo neurons are found in 4- month-old infants, increasing in number until four years of age and, interestingly, have also been identified in those mammals (such as big apes, some cetaceans and elephants) that use inter-individual contact to maintain affiliative behaviors. They are hypothesized to be implicated in body self-perception (Reiss and Marino, 2001; de Waal et al., 2005; Plotnik et al., 2006; Hakeem et al., 2009). Third, insula activity is central for affective and socio-cognitive information processing involving the self and others (Namkun et al., 2017). Lastly, this brain region is strongly involved in the regulation of homeostasis, in the elaboration of interoceptive inputs and in somatosensory perception with respect to pleasant tactile stimulations (Olausson et al, 2002; Björnsdotter et al., 2009). Moreover, while the anterior insular cortex has been implicated in the integration of autonomic and visceral signals into emotional and cognitive processes, the dorsal posterior insula supports primary cortical representations of ascending interoceptive pathways, reporting inputs (e.g., mechanical, thermal or chemical) from the skin, muscles, joints and internal organs (Craig, 2002). Importantly, the roles of the insular lobe for body-awareness in general (Craig, 2002, 2009), and of the right posterior insula in particular for the subjective experience of body-ownership has been well-established (Tsakiris, Schutz-Bosbach and Gallagher, 2007).

For the aim of this review it is critical to understand the development of insula functioning. Although the research is at the very beginning, recent neuroimaging studies targeting the insular and somatosensory cortices in 2-month old babies report that slow stroking compared to fast stroking touch activated insular cortex, suggesting that this brain structure is functional at very early stages of postnatal life (Jönsson et al., 2018; Tuulari et al., 2019). Thus, since the first period of life the insula might integrate bodily and environmental information, providing a neural representation of bodily-self as a sentient entity (Namkun et al., 2017). In turn, this may constitute a basis for the elaboration of the distinction between the "inside" and the "outside" of the body, between "self" and "other" (Björnsdotter et al., 2009; Craig, 2009; Miguel et al., 2019). Nurturing touch could play a special role in this process. In fact, despite the exteroceptive origins of affectionate touch it has the capacity to simultaneously convey information about the "inner" body and the external world (Fotopoulou and Tsakiris, 2017).

The role of affectionate touch in infancy

When we are touched, or we touch something/somebody, the stimulus is processed in terms of its exteroceptive, discriminatory information content via fast conducting myelinated peripheral nerve pathways projecting to primary somatosensory cortical areas (McGlone and Reilly, 2010). However, an increasing body of evidence is establishing that there is a specialized sub-modality of touch sensing and processing its affective (i.e., rewarding, pleasant) properties (Essick et al., 2010; Morrison et al., 2010; Olausson et al., 2010). Recent neurophysiological studies have documented the existence of a dual-touch system consisting of two parallel neural pathways, one subserving discriminative touch and the other affective touch (McGlone et al., 2007; McGlone et al., 2014). The latter is encoded and processed by a recently characterized (in humans) population of mechanosensitive unmyelinated C-fibers that respond optimally to the gentle caressing touch, typical of nurturing care. These nerves, called C-tactile afferents (CT) project primarily to the dorsal posterior insula (Olausson et al., 2002; McGlone et al., 2014), and to brain networks involved in social perception processing (see below). CTs have only been found in the hairy skin of the body and not in glabrous skin, such as the palmar skin of the hand. Despite this dual tactile transmission, the response to pleasant touch clearly assumes a particular valence in interpersonal relationships (the so-called 'social touch hypothesis', Olausson et al., 2002; Morrison et al., 2010). The preferred stimulus for CTs could not have been more appropriately evolved as they are tuned to respond to the specific velocities, forces and temperatures experienced by an infant during skin-to-skin nurturing care (Löken et al., 2009; Morrison, 2011; Ackerley et al., 2014; McGlone et al., 2014). CTs optimal firing response to gentle skin stroking, when recorded during microneurography studies (Löken et al 2009), is between 1-10 cm/s, corresponding to self-reported pleasant perception of touch as measured psychophysically (Essick et al., 2010), leading to the hypothesis that CTs have evolved in all social mammals to encode the socio-affective and rewarding dimensions of touch (Morrison et al., 2011). Interestingly, a recent lesion study which has investigated deficits in the perceived affectivity of CT optimal touch has found that posterior and anterior right insula lesions reduce pleasantness sensitivity in perceiving CT-optimal touch (Kirsch et al., 2020). Cutaneous afferent C-fibers are a diverse population of unmyelinated, slowly conducting nerves that evolved primarily to provide a basic function of protection by detecting and transmitting information to the brain of negatively hedonic (i.e., nociceptive, pruriceptive) events from the skin of the body or viscera, or of positively hedonic (affiliative touch) events. C-fibers mature early in development: nociceptive stimuli evoke neural responses already at 25 weeks of gestation (Slater et al., 2006), and at 35-37 weeks, EEG brain responses are similar to those observed in adults (Fabrizi et al., 2011).

In adults, affective touch leads to widespread activation of a network of brain regions which comprise areas involved in social perception and social cognition, including the posterior insula, posterior superior temporal sulcus, medial prefrontal cortex, and dorsal anterior cingulate cortex (Bjornsdotter et al., 2014; Gordon et al., 2013; Olausson et al., 2002), amygdala and orbitofrontal cortex (McGlone et al., 2007; Nees et al., 2019). Nevertheless, the emergence of this network in infancy is only partially understood. Research which has investigated infant brain response to affective touch during the first year of life leads to controversial findings. For example, using functional Near Infrared Spectroscopy (fNIRS) no increased responses for affective versus non-affective touch in posterior superior temporal sulcus and in prefrontal cortex regions were found in 5-month-old infants (Pirazzoli et al., 2019). On the other hand, while a few fNIRS studies indicate that the brain response to affective tactile stimuli emerges between 10 and 12 months of age (Miguel, Gonçalves, Cruz, and Sampaio, 2019; Miguel, Lisboa, Gonçalves and Sampaio, 2019; Miguel, Gonçalves and Sampaio, 2020), other neuroimaging research suggests that the affective touch system could be active very early in ontogeny (Jönsson et al., 2018; Tuulari et al., 2017). Notably, in children aged 5, maternal touch was predictive of resting activity in insula and in right posterior superior temporal sulcus, regions associated with the developing social brain and social perception (Brauer et al., 2016). Overall, these findings suggest that CT fibers could be crucial to convey socio-affective tactile information in the very early stages of development. Indeed, there are reasons to believe that affective touch is already being detected and processed during the early months of life. An infant's body is able to discriminate general tactile stimulation from pleasant tactile stimulation during development as they prefer tactile stimulations compatible with CT activation (Croy et al., 2019). A recent study reports that in young infants, sensitivity to pleasant touch is described by an inverted U-shaped function, similar to that observed in the adult, suggesting that a dual touch system might be potentially active in utero (Zieber et al., 2015), and the first months of life (Fairhurst et al., 2014). Particularly, 9-month-old infants displayed lower heart rate and greater behavioral engagement to body stimulation when they were stroked at a stroking velocity similar to the one that in adults activates CT fibers (Fairhurst et al., 2014). Furthermore, there is evidence that the optimal range for activating C-T fibers supports increasing attention to contingent social information in 4-month-old infants (Della Longa et al., 2019). Moreover, compared to a non-stroking touch condition, during and after maternal stroking touch, the parasympatho-inhibitory regulation of infants increased while, intuitively, mothers stroked their infants at a CT afferent optimal velocity (Van Puyvelde et al., 2019). Thus, infants do not treat interpersonal touch as a purely mechanosensory event and, even more relevant, the infants' response to interpersonal touch is dependent on the source of the touch (Aguirre et al., 2019). In their study, Aguirre and colleagues (2019) found that infants' heart rate decreased more in response to stroking touch when their mother, rather than a stranger, was the source of the touch and, even more importantly, this effect was found only for CT-fiber-related tactile stimulation.

Importantly, unmyelinated CT afferents take a distinct ascending pathway from the periphery via spinal pathways to a different part of the thalamus than myelinated low threshold mechanoreceptors, projecting to dorsal posterior insular cortex (Olausson et al., 2002; Morrison et al. 2011; McGlone et al, 2014; Marshall et al., 2019). The signals conveyed via such affectionate touch provide, at the same time, bottom-up information about one's own body, as well as top-down information about the social contact and context. In other words, it simultaneously integrates information about 'the self' and about the external human environment. Thus, affective touch is here posited to be important not only in maintaining infant wellbeing and serving as a protective function by promoting affiliative behaviors (McGlone et al., 2014), but also in mediating the connection between self and other and developing bodily self-perception. In one study, using a preferential looking task, 5-month-old infants displayed a preference for the body-related visual–tactile synchrony when they were stroked at slow velocity, suggesting that affective CT-optimal touch might play a crucial role in the early development of bodily self-perception (Della Longa et al., 2020). Although CT affective touch might facilitate the process of discriminating the body boundaries of self (Fotopoulou and Tsakiris, 2017), early parent-infant embodied interactions might also contribute to the experience of infant bodily-self through a key aspect of human caregiving, that is, interoceptive sensitivity, which in turn contributes to modulate self-other boundaries (Tajadura-Jiménez and Tsakiris, 2014).

Beyond a conventional view of maternal sensitivity

Implicit neurobehavioral sensitivity to interoceptive signals emerges in early infancy and it appears sensitive to emotional processing (Maister et al., 2017). Thus, it is highly plausible that, at least partially, in early infancy interoception is affected by interpersonal exchanges. A recent retrospective study found that young adults classified as demonstrating signs of avoidant attachment, based on attachment theory (Bowlby, 1969), reported lower interoceptive awareness, suggesting that the quality of early interpersonal relationships might be associated with later interoceptive functioning (Oldroyd et al., 2019). While research has mainly focused on the infant's interoceptive functioning it would not be surprising to find that a mother's interoceptive functioning could also play a role in the early exchanges with their infant. Indeed, while the mother may not always be aware of her own body signals, it is highly unlikely that embodied interactions with the infant would not impact their own bodily experiences, which imply an array of bodily tension, heart-beats, breathing and tactile pleasantness links to these sensations. Importantly, although interoceptive sensitivity does not imply full consciousness and the need for verbal expressions, the ability to represent one's own internal body state has been found to be associated with social attitudes (Ferri et al., 2013). Likewise, one could expect ventral-ventral parent-infant contact (e.g., skin-to-skin contact) and others embodied interactions involve activation of the mother's bodily sensations (see below), with possible modifications of interoceptive sensitivity which supports moment-by-moment adaptation to interactive demands and infant' needs. The focus on parental interoceptive functioning during early interactions sheds a different light on parental sensitivity. Over the past decades a mothers' sensitivity has been considered a crucial aspect of the mother-infant relationship. Research in this field has devoted much attention to maternal sensitivity as the ability to respond promptly and in an active, warm, acceptant, appropriate and flexible way to the infant's signals (Kivijärvi et al., 2001). Furthermore, there is evidence that maternal sensitivity, at least partially, relies on perceptual processing of infants' body. For example, a recent study has explored the association between maternal sensitivity and the refinement of maternal visuo-perceptual processes in perceiving infants' body (Montirosso et al., 2016). Authors found that a more refined maternal perception of own infant's body cues was associated with higher maternal sensitivity.

Although traditional measures of maternal sensitivity implies higher-order social cognitive skills such as mentalization, recent studies highlight that parenting heavily relies on nonverbal, bodily based and biological co-regulation that have been referred to as *parental embodied mentalization* (PEM, i.e., the parental capacity to comprehend the infant's mental states from their body movement and adjust their own kinesthetic patterns accordingly (Shai and Belsky, 2011). Notably, infants of mothers displaying greater PEM during a mother–infant free-play at 6 months showed secure attachment at both 15 and 36 months; and at 54 months displayed greater social competence, fewer behavioral problems and greater cognitive functioning (Shai and Belsky, 2011). Interestingly, this prediction held even after accounting for traditional measures of maternal sensitivity. It should be noted that a high-order maternal sensitivity concept based on mentalization might be only partially paralleled and mimicked by the low-order and bodily based parenting level. Indeed, some recent findings suggested that maternal non-attuned mind-related comments were associated with touch behaviors that were not contingent with the infant's emotions (Crucianelli et al., 2018). Consistently, while traditional measures of maternal sensitivity did not significantly predict infant attachment security, affectionate touch during infant feeding at 3 months of age was associated with more secure attachment to their mother at 1 year of age

(Weiss et al., 2000). Interestingly, in their study the authors found that mother’s felt security regarding their own tactile experience as a child, increased her infant’s chances of having a secure attachment. A variety of maternal behaviors associated with providing a secure base provision, such as being available for connection, allowing infant physical proximity, providing emotional regulation through soothing physical contact assessed at 4.5 months significantly predicted infant attachment at 12 months, with an effect size 8 times larger than maternal sensitivity (Woodhouse et al., 2020). Collectively, these findings provide initial evidence for a conceptual shift in our understanding of maternal caregiving which goes beyond the conventional view of maternal sensitivity and is more closely associated with the embodied interaction view (Botero et al., 2019).

From this perspective, while appropriate parenting requires coordination of multiple systems, including both behavioral and physiological components, to read infant signals and respond sensitively (Barrett and Fleming, 2011; Welch, 2016), the mother's ability to perceive her own internal signals might further support the responsivity to her infant’s cues. This view is corroborated by evidence suggesting that interoceptive sensitivity is not only crucial for the processing of emotional experience and self-regulation (Herbert and Pollatos, 2012), but most importantly it is associated with the ability to understand emotion in others (i.e., empathy; Fukushima et al., 2011). Moreover, a recent study found that activation of the parent's anterior insula (i.e., the cerebral hub which supports interoceptive sensitivity) in response to a video of self-interacting with his/her own infant predicted lower somatic problems in the child six years later, and this link was mediated by the parent's sensitive behavior at age four (Abraham et al., 2019). Remarkably, intuitive maternal stroking is not only tuned to the stimulation of CT fibers in infants aged 4 to 54 weeks, but stroking velocities were significantly correlated to maternal interoception, as measured by heart rate, suggesting that maternal affectionate touch behavior might be moderated by some aspects of maternal interoception (Bytomski et al., 2020).

Interestingly, mothers' interoceptive knowledge (i.e., parent knowledge of their own and other people's interoceptive sensations) about their own emotions has been found to be associated with social affective skills (i.e., emotion regulation, social initiative, cooperation, self-control) in middle childhood (MacCormack et al., 2019). Thus, if maternal sensitivity were, at least partially, associated with the accuracy with which mothers perceive their own bodily signals, then maternal interoceptive sensitivity might facilitate parental inferences about infant's physiological and emotional states and infant's ability to form accurate perceptions of bodily sensations. Mothers could be able to teach infants interoceptive cues which could help them differentiate bodily states (i.e., distress, hunger, tiredness, etc.). Furthermore, as suggested by studies which have documented a link between interoception and empathy (Fukushima et al., 2011), interoceptive sensitivity might support a mothers' ability to attune to her infant's bodily states, for managing these own bodily cues when infant experiences emotion and interacts with others, thereby modeling her emotion regulation and social skills.

Embodied reparation: A putative process subserving experiences of embodied interactions

Based on existing evidence from developmental research, it stands to argue that in the early embodied interactions, the cycles of mutual regulation should imply both body attunement and body misattunement between mother and infant.

A number of studies suggest that during the first months of life, mothers and infants are able to reciprocally adjust their own physiological activities , above all when they are in close body contact, a sort of physiological body-to-body synchrony (i.e., bodily attunements or co-regulation; Neu et al., 2009; Atzil and Gendron, 2017). For example, a study documented thermal synchrony during skin-to-skin holding of twins (Ludington-Hoe et al., 2006). Notably, given that twins were held at the same time in skin-to-skin contact, each maternal breast temperature reacted to the thermal needs of the infant on that breast. Maternal-infant heart rate variability attunement was reported during the first months of postnatal life (Feldman et al., 2011). Remarkably, during simple continuous skin-to-skin contact (i.e., the mothers were asked to hold their infants' hand or foot) 2-months-old infants adjust their heart rate to fluctuations of their mothers' cardiorespiratory activity (Van Puyvelde et al., 2015). Collectively, these findings indicate that mother-infant bodily attunements are established in various forms in the first months of life.

While it has been largely documented that bodily attunement is crucial for mother-infant interactions (Shai and Belsky, 2011), the potential role of misattunement conditions of psychobiological states have received less attention. Nevertheless, early adverse experiences (e.g., prematurity) or mother/infant characteristics (e.g., presence of at-risk conditions) might lead to bodily misattunement between partners. Some interesting results comes from studies using the Face-to-Face Still-Face paradigm (DiCorcia and Tronick, 2011), which allows for accurate measurement of infants' and mothers' reactions highlighting the impact of a misattunement process. For example, Ham and Tronick (2006) found that reciprocal regulatory effects of infant and mother heart rate variability were affected during the still-face episode in which the mother is temporarily unresponsive. A recent study has documented a complex pattern of coordination of hypothalamic-pituitary-adrenal (HPA) axis between infants and their mothers while facing a social stress associated maternal unavailability (Provenzi et al., 2019). Before the onset of the stressful condition the two partners presented coupled salivary cortisol concentration. Soon after the experimental manipulation of maternal behavior and the occurrence of a socio-emotional stress condition, non-significant cortisol coupling was found between mothers and infants suggesting that the dyad, like a system, was facing a perturbation and facing a challenge in their previously observed biological coordination. Importantly, this pattern of coordination of HPA axis was altered between preterm infants and their mothers, suggesting that in at-risk development conditions, partners were less able to dynamically coordinate HPA axis regulation (Provenzi et al., 2019).

At this point, one could wonder how infants and their mothers might reach bio-behavioral synchrony. Although it remains largely unclear how infants and their caregivers synchronize, based on infant behavioral research, we propose that there is a putative process (i.e., *embodied reparation* see below) which could serve a similar function in facilitating body-to-body synchrony. In the Mutual Regulation Model (MRM), Tronick (2004) suggests that in typical interactions mothers and their infants fluctuate between attuned and misattuned states and recovery attunement states by a process called 'reparation'. Indeed, mother–infant interactions during the first months of life are characterized by frequent misattunements (so called, interactive ruptures). Because misattunements are the rule rather than the exception (Tronick and Cohn, 1989), dyadic reparations needed to gain new dyadic states of attunements after normally occurring interactive ruptures (Tronick, 2004). Behavioral data suggest that, during face-to-face interactions, mother and infant are in misattunement states for almost 70% of time (Tronick and Cohn, 1989). Thus, dyadic reparation is critical for the development of infants' self-regulatory capacities and scaffolding an implicit inner sense of self-efficacy in regulating the stress elicited by socially challenging conditions (DiCorcia and Tronick, 2011). For example, Provenzi et al. (2015) reported that 4-month-old infants who experience more frequent dyadic reparation within the interaction with their mother were more prone to the vagal reactivity (i.e., the vagal brake) in response to a social disruption condition (i.e., temporary maternal unavailability during the still-face paradigm), which is thought to reflect an adaptive parasympathetic functioning and effective stress regulation (Porges, 2007).

While, based on existing evidence, bodily attunements is through enhanced social connectedness, effective communication and interpersonal regulation (Atzil et al., 2018), there is a lack of theoretical ground and conceptual framework guiding the body-to-body perspective of mother-infant interaction which takes into account early forms of bodily misattunement and reparation. Critically, it is necessary to recognize that the maintenance of a constant bodily attunement between two partners is rather improbable, but also if it were so it would prevent any possibility of bodily misattunement, thus leading the infant to never experience a reparatory step. As mentioned, bodily attunements and bodily misattunement processes, separately considered, could be not sufficient to delineate how mothers and infants reciprocally adjust their own physiological activities. Here, we propose that inevitable bodily misattunement may be followed by a reparatory step, the process which focuses on the phase of transforming bodily misattunement states into bodily attunements. The construct of *embodied reparation* describes the process by which each partner modifies their own bodily states thereby making possible the shifting from bodily misattunement to bodily attunements (Fogel, 2011). It is likely that this process occurs, dynamically and continuously, at multiple bio-behavioral levels including the micro-temporal level where the mother regulates the infant's neurophysiological processes.

Of course, the shift from bodily misattunement to bodily attunement could be more evident when the infant experiences moments of discomfort, or tension or distress during which the infant's interoceptive system is strongly dysregulated (Welch, 2016). Recent neuroscience models suggest that interoceptive experience might reflect predictions about the expected state of the body (Barrett and Simmons, 2015). In infants and in mothers moment-by-moment prediction anticipates inputs related to sensory information from exteroceptive and interoceptive information and which would be the best potential action to manage this information (Atzil et al., 2018). Any discrepancy from the expected state of the body is a prediction error which generates a physiological unbalance in the infant's body (for instance, infant experiences low skin temperature). While infants have self-regulation ability to cope with distress (e.g., non-nutritive sucking), their resources are limited. As a consequence, the manifestation of such physiological changes emerges as bodily, behavioral and emotional signals which convey to the mother the infant's state. Although a mother uses several behaviors to comfort her infant (i.e., voice, eye contact) and to restore emotional connection and physiological co-regulation (Atzil et al., 2018), we speculate physical proximity (e.g., affectionate/nurturing touch) and maternal interoceptive sensitivity play a key role in *embodied reparation* process. Indeed, physical proximity and maternal interoceptive sensitivity would support a sort of data processing strategy in which discrepancies between psychobiological states of partners can be minimized, either by performing actions (i.e., affectionate touch) to modify the partner bodily states to fit the own bodily states or by changing the own bodily states to fit the partner bodily states (Seth and Tsakiris, 2018). By interoceptive sensitivity a mother can implicitly adapt to her infant's body state by, for example, adjusting her own skin temperature to that of the infant (Ludington-Hoe et al., 2006). In other words, *embodied reparation* allows the infant to reduce the discrepancies within the interoceptive system using the mother's body. Thus, interoceptive information of the infant's body is gradually associated with inputs from the mother (Atzil et al., 2018) suggesting that an efficient *embodied reparation* allowing the infant to recover a stable interoceptive experience, which, in turn, would support positive experience of the own bodily-self.

As for physical proximity, while no infant study has researched this topic, there is indirect evidence from an adult study in which affectionate touch during pain administration increased bodily attunement. Specifically, during pain administration, partner touch increased interpersonal respiration coupling (Goldstein et al., 2017) and interpersonal neural synchronization in brain networks associated with analgesia (Goldstein et al., 2018). Overall, this evidence indicates that social touch not only increases interpersonal physiological and brain-to-brain coupling, but promotes affiliative bonding and a positive subjective self-experience (Krahé et al., 2016; Krahé et al., 2018).

Furthermore, although it is quite possible that each partner contributes to the *embodied reparation* process, the infant has limited and immature regulatory, behavioral, and attentional capacities to repair the misattunements, so that most *embodied reparations* could be managed by the parent. The mother's ability to quickly perceive and respond to the infant's bodily signals depends on a subtle balance between the awareness of her own body signals and those of the infant's (Abraham et al., 2019). As a consequence, maternal interoceptive sensitivity is an essential component to adjust own bodily sensations to support infants' regulatory capacities and to restore physiological co-regulation.

Importantly, early adverse experiences, such as premature birth, can have a negative impact on dyadic co-regulation, affecting the *embodied reparation* process and therefore have an impact on the development of the infant bodily-self. For instance, along with other stressful experiences, preterm infants experience physical restraint which limits the possibility of contact with the peripersonal space (e.g., clothes, sheets) as well as of self-contact (Durier et al., 2015). Moreover, whereas their tactile and proprioceptive systems receive minimal input, preterm infants are exposed to atypical procedural handling routines, altered stimulations and multiple stressful procedural interventions which are associated with long-term changes in somatosensory function or pain response (Walker et al., 2018). Preterm birth is also a stressful event for mothers and may affect the mother–preterm infant relationship (Korja et al., 2012). In fact, preterm birth is associated not only with a less-than-optimal maternal bonding (Provenzi et al., 2017), but also can affect the mother‘s ability to perceive her infants' bodily cues. For example, mothers of preterm infants are less efficient in perception of their infants' bodily cues (Butti et al., 2018). Collectively, these conditions could limit opportunities for successful repair of bodily misattunements between mother and infant. As a consequence, the extent to which *embodied reparations* are disrupted, preterm infants could develop a distorted sense of interoception, which in turn could have an impact on the development of the bodily-self. Notably, a recent study has documented that preterm birth might interfere with the development of body representations. Specifically, school-aged children born preterm without neurological sequelae exhibited an impairment of body representation assessed by a visual body recognition task (Butti et al., 2020).

In short, bodily attunements, bodily misattunements and *embodied reparation* provide much more than the infant's behavior regulation. To some extent they sculpt the infant's bodily-self. Empirical assessment of the relationship between these processes and problematic interoception and bodily perception is warranted

Concluding remarks and future perspectives

Infants have the capacity to perceive their own body, for example using sensorimotor contingencies or by self-contact. However, these capacities are unlikely to depend only on a single process but rather are integrated by inter-corporeal connections. The development of an infant's bodily-self is an interactive phenomenon and interpersonal nurturing touch, as processed by CTs and by the brain areas they project to, is here posited to lead to increased interpersonal bodily attunement, which in turn supports the representation of the infant bodily-self (Filippetti et al., 2013; Bremner and Spence, 2017). Moreover, it has been hypothesized that an altered processing in CT stimulation (McGlone et al., 2014) and in social brain network including insula (Allman et al., 2005) might underpin neurodevelopmental conditions currently grouped under the classification of autism spectrum disorders which are characterized by an atypical sense of self (Lombardo et al., 2009). Thus, it seems conceivable that the infant is not only able to synchronize with external stimuli (Provasi et al., 2014), but, during embodied interactions with their mother, is able to encode maternal affectionate touch, specifically through CTs (Aguirre et al., 2019) and to coordinate with maternal somatic inputs (i.e., cardiorespiratory patterns, body temperature, etc.) (e.g., Van Puyvelde et al., 2019). Importantly, it is plausible that affective touch and close physical proximity allow the dyad to attune both during pleasant exchanges and, even more importantly, after a bodily misattunement (i.e., *embodied reparation*). The renewed bodily attunement would regulate the infant's interoceptive states (e.g., decreases heart rate) and support bodily states which facilitate the interoceptive sensitivity and therefore the infant's bodily-self-perception.

Maternal interoceptive sensitivity may be another way for mothers to support bodily attunement into their embodied interactions with infants. There is now neuroimaging evidence suggesting that interoceptive awareness significantly enhances neural activity during empathy in bilateral anterior insula (Ernst et al., 2013). Thus, we speculate that maternal interoceptive sensitivity expands a mother's ability to perceive their infant's body, which in turn would affect the mother's social engagement and emotional responsiveness. Therefore, the focus on parental interoceptive sensitivity in early interactions offers the theoretical framework as well as one practical access of research to investigate the contribution of the mother's body in infant bodily-self-development.

Additionally, while relational repairs by a sensitive mother are crucial for socio-emotional development (Tronick, 2004), *embodied reparations* are here posited to be critical for building a representation of the infant bodily-self. In this perspective, less embodied reparations would impair the infant's ability to form accurate representations of bodily sensations. Thus, naturally occurring variations in *embodied reparations* during exchanges with the mother's body would contribute to both infant bodily self-perception and interactive embodied meaningful patterns. Therefore, individual differences in tactile biography may determine not only how an infant will respond to touch, but also, at least partially, how the infant will perceive its own bodily-self. In other words, specific patterns both of embodied interactions (e.g., *how*, *when*, *how much* and *where* the mothers touch their infants) and *embodied reparations* (i.e., *how*, *when*, *how much* and in *which circumstances* dyad actively shifts from bodily misattunement to bodily attunement) could become more and more a part of the workings of the dyadic interactive processes which sculpt the sense of infant bodily-self. This framework has implications about the role of, specifically, CT touch both in clinical research in children with atypical development (Provenzi et al., 2020) and for promoting the use of affective touch in early parental interventions (Botero et al., 2019). For instance, video-feedback intervention in which mothers watch videos of their interaction with their at-risk infants, helps them not only to become more aware of their infants' signals and to interpret these signals more accurately, but also makes them aware of the impact of misattunement states on the interaction (Giusti et al., 2018).

The opinions suggested here have implications for research in developmental neuroscience and future research is necessary to examine the implications related to our hypothesis. A first point of interest involves affective touch as a factor supporting infant's bodily-self perception. How much affectionate touch would be appropriated? Do adverse experiences affect the affectionate touch processing? For example, currently we are studying the brain responses to gentle skin stroking, a type of tactile stimulus associated with affective touch, in the postcentral gyrus and posterior insular cortex - two cerebral regions known to process this kind of tactile stimulation – in preterm infants. Second, if maternal interoceptive sensitivity could have a critical role to adjust own bodily sensations to support infants' regulatory capacities and to restore physiological co-regulation, then we need further evidence in order to corroborate that mothers' interoceptive sensitivity is related to infant's bodily-self perception. Finally, despite the above insights, embodied interaction has remained generally understood to be a unidirectional process (i.e., from mother to infant), this assumption is however challenged by evidence that even the mother's body is affected by the inter-corporal connections with her own infant (Matthiesen et al., 2001), and parents experience the kinetics and intensity of body sensations through the proximity of affective touch mechanisms. How does the infant's touch affect the mother's bodily-self perception? How does this inter-corporality process modify maternal interoceptive sensitivity? Furthermore, future research is needed to investigate mother and infant interoception during the first period of life. Given the evidence that infants have an implicit neurobehavioral sensitivity to interoceptive signals (Maister et al., 2017), it would be important to examine how individual differences in interoception can develop in connection with maternal interoceptive sensitivity. More in general, in order to investigate the role of *embodied reparations*, research involving behavioral, physiological and neural approach should be performed at various ages and conditions to establish the dynamics of the interplay between maternal touch, maternal interoceptive sensitivity and infant's bodily-self perception.

In recent years, there has been an increasing interest in the pre-reflective bodily foundations of the self, which are thought to be grounded in our embodied experience of being a separate entity (Damasio, 2000), providing a rudimental awareness of ourselves (Gallagher, 2000; Allen and Tsakiris, 2019). Therefore, the "self starts with body" (Baumeister, 1999) and the bodily experience is ubiquitous in everyday experience, above all for an infant. However, given the primacy of the embodied interactions at the very first stages of human life, this view should be integrated with a further consideration: an infant's bodily self-perception emerges from the dynamic interplay between signals arising from both (a) inside the body and (b) interpersonal affective exchanges with mother. The latter is a very critical point given that, as Ciaunica (2019) highlighted, before an infant "meets" mother's mind, the infant "meets" mother's body, a process that critically depends on affective touch, as mediated by CTs. Moreover, to some extent, the contrary is equally true, before mother "meets" infant's mind, mother "meets" infant's body. Thus, bodies come first and along with several other interactive processes, *embodied reparations* make embodied meaning within and between individuals, which increase the coherence and complexity of each infant's and, likely parent's sense of bodily-self establishing reciprocal awareness.

Declarations of interest: none.

Funding: This study was partially supported by Italian Ministry of Health (Ricerca Finalizzata RF-2016-02361884 and Ricerca Corrente 2018-2019-2020) to RM.

Acknowledgments.
The first author is deeply indebted with Ed Tronick, whom scientific work on early mother-infant relationship has inspired the view discussed in the current review. We would like to thank Eleonora Mascheroni, Eleonora Visintin, Elisa Rosa, Niccolò Butti and Elena Guida for their valuable support at *0-3 Center for the at-Risk Infant,* Scientific Institute IRCCS Eugenio Medea, Bosisio Parini (Lecco), Italy. The authors are grateful to anonymous reviewers for helpful comments.

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