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Review

The Peripersonal Space in a social world



Olena V. Bogdanova^{a,b,f,*}, Volodymyr B. Bogdanov^{a,b,e}, Audrey Dureux^{a,b},
Alessandro Farnè^{a,b,c,d} and Fadila Hadj-Bouziane^{a,b,**}

^a Integrative Multisensory Perception Action & Cognition Team (Impact), INSERM U1028, CNRS UMR5292, Lyon Neuroscience Research Center (CRNL), Lyon, France

^b University of Lyon 1, France

^c Hospices Civils de Lyon, Neuro-Immersion Platform, Lyon, France

^d Center for Mind/Brain Sciences (CIMeC), University of Trento, Italy

^e Ecole Nationale des Travaux Publics de l'Etat, Laboratoire Génie Civil et Bâtiment, Vaulx-en-Velin, France

^f INCIA, UMR 5287, CNRS, Université de Bordeaux, France

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ABSTRACT

The PeriPersonal Space (PPS) has been defined as the space surrounding the body, where physical interactions with elements of the environment take place. As our world is social in nature, recent evidence revealed the complex modulation of social factors onto PPS representation. In light of the growing interest in the field, in this review we take a close look at the experimental approaches undertaken to assess the impact of social factors onto PPS representation. Our social world also influences the personal space (PS), a concept stemming from social psychology, defined as the space we keep between us and others to avoid discomfort. Here we analytically compare PPS and PS with the aim of understanding if and how they relate to each other. At the behavioral level, the multiplicity of experimental methodologies, whether well-established or novel, lead to somewhat divergent results and interpretations. Beyond behavior, we review physiological and neural signatures of PPS representation to discuss how interoceptive signals could contribute to PPS representation, as well as how these internal signals could shape the neural responses of PPS representation. In particular, by merging exteroceptive information from the environment and internal signals that come from the body, PPS may promote an integrated representation of the self, as distinct from the environment and the others. We put forward that integrating internal and external signals in the brain for perception of proximal environmental stimuli may also provide us with a better understanding of the processes at play during social interactions. Adopting such an integrative stance may offer novel insights about PPS representation in a social world. Finally, we discuss possible links between PPS research and social cognition, a link that may contribute to the understanding of intentions and feelings of others around us and promote appropriate social interactions.

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* Corresponding author. Neuroscience Research Center, ImpAct Team, 16 Avenue Doyen Lépine 69500 Bron, France.

** Corresponding author. Neuroscience Research Center, ImpAct Team, 16 Avenue Doyen Lépine 69500 Bron, France.

E-mail addresses: olena.bogdanova@u-bordeaux.fr (O.V. Bogdanova), fadila.hadj-bouziane@inserm.fr (F. Hadj-Bouziane).

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1. Introduction: what is PeriPersonal Space?

In everyday life, humans and animals evolve in a complex environment composed of various kinds of objects with which they interact. Appropriate interactions require solving many computationally demanding sensorimotor problems, including the effective optimization of the distance between the agent's body/effector and objects in space. Even though we perceive the space surrounding us as a Cartesian continuum, our brain actually encodes for modular representations of space. This concept was introduced by Brain (Brain, 1941), following neuropsychological evaluations of hemispatial neglect, a condition that frequently follows right brain damage in which patients fail to attend to stimuli presented on the contralesional side. Brain suggested dissociation between 'a grasping' and a 'walking' distance to account for rather selective impairments of some of these patients for either one of these spatial dimensions (Làdavas, Zeloni, & Farnè, 1998; Làdavas & Farnè, 2004).

This notion was then supported by seminal electrophysiological studies, in particular by Rizzolatti, Scandolara, Matelli, and Gentilucci (1981) (Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981), who first introduced the term PeriPersonal Space (PPS) to describe this region of space near the body where physical interactions with objects in the environment take place. PPS was distinguished from the extrapersonal space that referred to the space outside the mouth/hand grasping distance. Using electrophysiological recordings in monkeys, Rizzolatti, Scandolara, Matelli, and Gentilucci (1981) first identified a set of neurons in the posterior periauricular regions, within the ventral premotor cortex, which responded more to objects presented in the peripersonal space compared to objects presented outside this sector of space. Several studies have shown that activities of single neurons in ventral premotor cortex (Graziano, Yap, & Gross, 1994; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981), the putamen (Graziano & Gross, 1993) and the parietal cortex (Colby, Duhamel, & Goldberg, 1993) were selectively modulated by the presence of objects near the hand or the face. In the parietal cortex, several subregions exhibited this selective coding, namely the ventral intraparietal area (Colby et al., 1993), the medial intraparietal area (Colby & Duhamel, 1996), and area 7b of the parietal lobe (Graziano & Cooke, 2006). Another critical feature of these neurons is that they are multisensory, they respond to visual, tactile, and auditory stimuli (Avillac, Hamed, & Duhamel, 2007; Colby et al., 1993; Duhamel, Colby, & Goldberg, 1998; Gentile, Petkova, & Ehrsson, 2011; Graziano, Hu, & Gross, 1997; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981). Neurons with responses to either tactile and visual stimuli were coded in body part-centered coordinates: for example, visual receptive fields were anchored to the tactile ones and followed the hand in space if it moved. They also display selectivity in several directions, with some neurons exhibiting preference for looming objects (Graziano et al., 1997).

Since the seminal work in monkeys, an abundant literature has accumulated to understand the characteristic of PPS coding/representation and its functions (Avillac, Ben Hamed, et al., 2007; Brozzoli, Makin, Cardinali, Holmes, & Farnè,

2012; Caggiano, Fogassi, Rizzolatti, Thier, & Casile, 2009; Cléry, Guipponi, Wardak, & Ben Hamed, 2015, 2018; di Pellegrino & Làdavas, 2015; Graziano & Cooke, 2006; Grivaz, Blanke, & Serino, 2017). These studies revealed one key feature of PPS representation, hence its flexibility. This flexibility depends on external factors, that is the characteristics of the stimulus within PPS (its nature, valence and the context), internal factors related to individual traits (physical—e.g., arm length or height; personality traits, bodily states) and exposure to different procedures such as tool use (Berti & Frassinetti, 2000; Biggio et al., 2017, 2019; Farnè, Pavani, Meneghello, & Làdavas, 2000; Maravita, Spence, Clarke, Husain, & Driver, 2000; Serino et al., 2015) or following body (Makin, Wilf, Schwartz, & Zohary, 2010) or spinal cord injuries (Scandola et al., 2020).

Ongoing, fast modulations of PPS representations following tool use (Canzoneri et al., 2013; Farnè, Iriki, & Làdavas, 2005; Serino, Bassolino, Farnè, & Làdavas, 2007) or body illusions (D'Angelo, di Pellegrino, & Frassinetti, 2019; Maister, Cardini, Zamariola, Serino, & Tsakiris, 2015; Noel, Pfeiffer, Blanke, & Serino, 2015) have also been reported during motion (Berger, Neumann, & Gail, 2019; Noel, Grivaz, et al., 2015), or in the presence of other individuals (Pellencin, Paladino, Herbelin, & Serino, 2017; Teneggi, Canzoneri, di Pellegrino, & Serino, 2013). Developmental studies also show the existence of early predisposition to stimuli processing in the PPS in newborns or in first-year infants (Drew, Meltzoff, & Marshall, 2018; Orioli, Filippetti, Gerbino, Dragovic, & Farroni, 2018). Along the same lines, multisensory integration of spatial cues, a key property of PPS representation, develops gradually across the lifespan (Bremner, Holmes, & Spence, 2008; Burr & Gori, 2012; Sorrentino et al., 2021).

Based on these properties and owing to their anatomical position at the interface with motor regions, it was suggested that PPS brain regions play a key role in visually guided actions or in more general terms facilitate the interactions with objects in our environment. In recent years, the diversity of methodologies employed to study PPS representation has had important implications for its theoretical conceptualization (de Vignemont & Iannetti, 2015), leading to different frameworks describing PPS representations in terms of a network of body-part centered representations (Hunley & Lourenco, 2018), a set of continuous action fields (Bufacchi & Iannetti, 2018) or an index of multisensory body–environment interactions (Serino et al., 2019). Closely related to the current topic, it has been suggested that PPS could contribute to the representation of the self (Noel, Pfeiffer, et al., 2015; Serino, 2019). While discussing these different theoretical accounts is beyond the scope of the present review article, we posit that they are all compatible with a role of PPS representation in social interactions. In particular, we will argue that, by merging exteroceptive information from the environment and internal signals that come from the body (that is a physiological representation of the state of the body, including somatosensory, proprioceptive, visceral afferents etc.), the PPS may indeed underlie an integrated representation of the self, as distinct from the environment and the others.

Adding to this complexity, one should also consider that the mere presence of conspecifics around us affects our behavior. This phenomenon has been long studied in social

psychology and is well documented in human and animal research (Bond & Titus, 1983; Reynaud, Guedj, Hadj-Bouziane, Meunier, & Monfardini, 2015). Indeed, another dimension of spatial perception, stemming from ethology and social psychology and that could relate to PPS representation, has been termed ‘personal space’ (Altman & Chemers, 1984; Hayduk, 1983). The notion of flight zone, later termed margin of safety, to describe the distance animals keep between themselves and other animals has first been introduced by Hediger, the director of the Zurich Zoo in 1955, and was thought to serve both communicative and survival functions. The American anthropologist Edward T. Hall adapted this concept to a comfort zone or personal space, that we keep between us and others to regulate the interpersonal distance and to avoid discomfort, or even anxiety (Hall, 1966; 2014). This distance governing social interactions is a ubiquitous entity, present with some variations across the animal kingdom and in humans (Baldwin & Baldwin, 1974; Kennedy, Gläscher, Tyszka, & Adolphs, 2009; Vestal, 1977). Graziano & Cooke (2006) were the first to relate PPS and the ethological concept of a flight zone and the psychological concept of personal space (Graziano & Cooke, 2006). Despite their different origins, both personal space and PPS representation broadly refer to the space anchored to the body. As such, they may share some commonalities.

In this review, we depart from the classical ‘action-related’ features of PPS, to rather focus on the social dimension(s) of PPS representation, which has seen an exponentially growing interest in recent years (Heed, Habets, Sebanz, & Knoblich, 2010; Patané, Farnè, & Frassinetti, 2017; Pellencin et al., 2017; Teneggi et al., 2013). First, we will review findings describing the influence on PPS of social elements depending on the context (emotional valence, moral judgment, interaction with partners, etc.) making the PPS enlarge, shrink or remap. Second, we will frame the comparison between PPS and Personal Space (PS) at both the theoretical and empirical level, aiming at clarifying these concepts. Third, we will discuss whether and how the internal states of the organism relate to PPS representation in social environments. Finally, we will consider possible mechanisms allowing for the interactions between body signals and brain networks to adapt behavioral responses according to varying social contexts. We ultimately advance that these represent important dimensions along which PPS and its relation with social behaviors will be better understood, and provide some perspectives on PPS in the field of social cognition and its role in social interactions.

2. PeriPersonal Space representation in a social world

2.1. PPS through different lenses: a variety of experimental procedures

Since Rizzolatti et al.’s findings in monkeys (Rizzolatti, Scandolara, Gentilucci, & Camarda, 1981; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981), several experimental approaches have been employed in humans to study PPS representation, to better understand and characterize its features and functions (Brozzoli, Demattè, Pavani, Frassinetti,

& Farnè, 2006; Farnè et al., 2000, 2005). Different methods focused on either perceptual abilities, action planning or defensive responses (Table 1). Most typically, participants were exposed to static or dynamic multisensory stimulations and, more recently also uni-sensory ones. What follows is a brief, non-exhaustive description of the experimental procedures used to investigate PPS representation. Regardless of the methods, a stimulus presented within PPS typically induces a modulation of the cognitive processes taking place, made observable via several measures.

In static conditions, methods typically compare the behavioral outcome in response to stimuli appearing either in close (within PPS), or far space (outside PPS). This is the case for the crossmodal congruency task, in which the difference in performance between incongruent and congruent trials, known as Cross-modal Congruency Effect (CCE), measures the amount of the cross-modal interaction (Spence, Nicholls, Gillespie, & Driver, 1998). This method revealed larger CCE for visual distractors close to (vs. far from) the stimulated hand (Spence et al., 1998, 2004). This finding extends to static conditions before an upcoming movement: merely planning to reach an object increased crossmodal congruency effects (Belardinelli, Lohmann, Farnè, & Butz, 2018; Brozzoli et al., 2009, 2010; Patané et al., 2018). Such behavioral effects may be accompanied by changes in motor cortex excitability (Job, de Fockert, & van Velzen, 2016; Wamain, Gabrielli, & Coello, 2016).

In dynamic conditions, stimuli typically move toward or away from participants and behavioral responses are probed along the spatiotemporal displacement. An influential example of such a multisensory interaction paradigm consists of a speeded tactile detection task concurrent to an irrelevant (visual or auditory) approaching stimulus (Canzoneri, Magosso, & Serino, 2012). The stimulus being delivered at different timings, being thus more or less close to the participant, this method measures multisensory boosting of touch perception by an approaching stimulus. It allows to model behavioral responses along the sagittal plane with a sigmoidal function, whose inflexion point is interpreted as the PPS ‘boundary’. The displacement of this point toward or away from participants is typically interpreted as a reduction or an enlargement of PPS extent, respectively (Canzoneri et al., 2012; Teneggi et al., 2013).

Another method leveraged the reachability judgment task (Coello et al., 2008). Here, participants view an object (either static at a certain distance, or moving toward them) and have to judge whether (or stop the object movement when) it is reachable. The reachability distance, used as a proxy of PPS representation, is also interpreted as the boundary of PPS representation, and has been assessed in different contexts, including social ones (Cartaud, Ruggiero, Ott, Iachini, & Coello, 2018; Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010; Iachini et al., 2016; Iachini, Ruggiero, Ruotolo, Schiano di Cola, & Senese, 2015; Quesque et al., 2017).

Not last, other studies probed the defensive nature of PPS, measuring the hand-blink reflex (HBR), in which an electrocutaneous stimulation of the median nerve at the wrist elicits a blink reflex (Bisio et al., 2017; Bufacchi, 2017; Sambo, Liang, Cruccu, & Iannetti, 2012). Its amplitude, as measured via the electromyographic activity recorded from orbicularis oculi

Table 1 – Experimental approaches used to probe PPS in human behavioral research.

Tasks	Main results	References
Perception and PPS representation: Detection or discrimination tasks		
Crossmodal congruency	Stronger Cross-modal Congruency Effect (CCE), with close vs. far visual stimuli.	(Aspell, Lavanchy, Lenggenhager, & Blanke, 2010; Spence et al., 2004)
Audio- or Visuo-tactile extinction	Inability to detect a visual stimuli presented in the contralesional side if presented concurrently with a competing ipsilesional event of another modality (in near space)	(Brozzoli et al., 2006; Farnè et al., 2000, 2005)
Multisensory interaction	Faster tactile stimuli detection in the presence of approaching audio or visual stimuli	(Canzoneri et al., 2012; Serino et al., 2015; Stone, Kandula, Keizer, & Dijkerman, 2018)
Line bisection	Bias to bisect lines slightly to the left close to the body and slightly to the right in the far space	(Hunley, Marker, & Lourenco, 2017; Lourenco et al., 2011)
Visual detection/discrimination	Faster response to stimuli close to the body or hand; faster target discrimination in near space (vs. in the far space)	(Blini et al., 2018; Dureux et al., 2021; Plewan & Rinkenauer, 2017; Reed, Grubb, & Steele, 2006)
Action-related PPS representation:		
A. Action planning and execution in near space with or without movement		
Reachability judgment	Modulation of the size of reachable space as a function of the stimuli.	(Iachini et al., 2014; Quesque et al., 2017; Ruggiero et al., 2017)
Spatial alignment	Facilitation of the behavioral response when the target is in a congruent position to an intended or executed grasping movement in close space	(Costantini et al., 2010; Stefani et al., 2014)
Action planning and execution	Stronger multisensory integration effects during interactive compared to non-interactive movements.	(Belardinelli et al., 2018; Brozzoli et al., 2009, 2010; Patané et al., 2018; Senna et al., 2019)
B. Defensive responses		
Hand blink reflex	Increase of HBR amplitude as a function of the position the hand and a nociceptive stimulation applied on the hand	(Bisio et al., 2017; Bufacchi, 2017; Sambo et al., 2012; Sambo & Iannetti, 2013)
Multisensory interaction	Facilitation of tactile detection with approaching stimuli with negative emotional valence; Facilitation of nociceptive detection with approaching visual stimuli; Increase of skin conductance response with approaching noxious stimuli	(De Paepe, Crombez, & Legrain, 2016; Ferri et al., 2015; Rossetti et al., 2015);
Reachability judgment	Increase of skin conductance response with approaching angry faces	Cartaud et al. (2018)
Time to collision/temporal order judgment	Privileged temporal judgements with visual stimuli in close space	(De Paepe, Crombez, Spence, & Legrain, 2014)

muscles, increases when the stimulated hand comes closer to the face, thus ‘entering’ the PPS surrounding it. This suggests that the brainstem circuits mediating the HBR are under the influence of higher-level brain regions coding space representation in relation to body parts proximity (as is PPS), likely to protect the body from potential danger in the environment.

To sum-up, PPS extent has been estimated with a variety of methods that manipulated distance as the main variable. The task conditions and the behavioral outcome may thus tap into a given property or function of the PPS construct, as the guidance of voluntary action and the enabling of self-defensive reactions. Such modulatory effects appear to occur gradually along the sagittal plane. Several studies have shown that PPS representation is shaped depending on a variety of intrinsic and environmental factors and likely result from complex computations integrating both internal and external signals. Such computations could get even more complex when we consider real-world situations with multiple layers of interactions with objects and peers. The following sections will attempt to frame this complexity.

2.2. Social modulation of PPS representation

When investigating the influence of a modulator, and in particular social factors that involve the presence of *others* (e.g., partners, conspecifics, confederates, intruders etc.), the characteristics of the latter(s) matters. One needs to consider their physical attributes, that could appear as salient features with a bottom up influence, such as their sex or emotional signals, as well as more subtle features that may involve a top-down influence, such as participants’ prior beliefs about the other (i.e., moral judgements). As summarized in Table 2, both the characteristics of the participant and his/her relationships with the other, notably their familiarity and personality traits, may also matter for PPS representation. Under the influence of social elements, depending on the context, PPS representation is affected and its boundary enlarges, shrinks or remaps in relation to the other (Fig. 1).

In studies using the visuo-tactile or audio-tactile congruency task, participants hold vibrotactile stimulators while a task irrelevant visual (or auditory) stimulus is presented at incongruent or congruent position in regard to the vibrotactile stimuli. Spence et al. (2004) showed that the CCE was stronger when the visual stimulus appeared close as compared to far from the tactile stimulation (Spence et al., 2004). Using this procedure, Heed et al. found that performing this task alone or with another person differently affected performance (Heed et al., 2010). CCE was significantly reduced in the presence of the other participant, only when he/she sat within the participant’s PPS and when the two protagonists were concurrently performing the task. No effect was found when the other stood outside the participant’s PPS, or when she/he did not perform the task, suggesting that for the effect to take place, the participant needed to know that the other was also engaged by responding to the tactile stimulus. Interestingly, the mere attribution of object ownership also affects PPS representation during both observed and executed grasping actions performed by participants facing each other as measuring using CCE (Patané, Brozzoli, Koun, Frassinetti, & Farnè, 2020). In this study, the authors manipulated the

ownership status of an object to be grasped by the participants (“is mine or other’s”) and found ownership-dependent modulation of PPS, such that this modulation only occurred when observing or executing grasping action toward objects that has been assigned to oneself. This study highlights the link between PPS and the notion of self that might also be extended with tools as previously mentioned but also with object ownership.

Studies using the multisensory interaction task showed that the mere presence of another person vs a mannequin shrinks the participant’s PPS boundary (Teneggi et al., 2013) (Table 2). By contrast, after a cooperative game with the other, the PPS boundary enlarges toward the confederate (Hobeika, Taffou, & Viaud-Delmon, 2019; Teneggi et al., 2013). A similar change, i.e., PPS enlargement, was also found when facing a moral other as compared to an immoral one (Pellencin et al., 2017). Finally, another type of PPS plasticity, termed *shared or merged* PPS, has been revealed in tasks involving either synchronous stimulation to the participants and the confederate (Maister et al., 2015) or when they both performed the same task concurrently (Teramoto, 2018) (see Fig. 1B for illustration). These settings yielded faster detection time with stimuli approaching the confederate when the two persons experienced the same condition, mimicking ‘a shift of PPS representation’ between them, beyond physical spatial proximity. Interestingly, Iachini et Ruggiero (Iachini & Ruggiero, 2021), recently revealed that the representation of one’s own and others’ PPS was affected by physical distance but also by the possibility of the protagonists to move or not their arms, suggesting that the representation of others’ PPS might be triggered by a motor simulation of one’s own PPS. In the same vein, the amplitude of the hand blink reflex was enhanced both when the stimulated hand belonged to the participant and to another person; it was also enhanced when the stimulated hand was brought close to the face of another individual and this enhancement was dependent on the participants’ empathic traits (Fossataro, Sambo, Garbarini, & Iannetti, 2016). That is, not only purely physical spatial proximity between agents modulates PPS, but their level of familiarity, social proximity and the interactions between them come into play. For instance, enhancement of touch perception in a participant, induced by the observation of a photograph depicting another person being touched in the same location, depended on the degree of familiarity or social proximity between the observer and the observe (Serino, Giovagnoli, & Ladavas, 2009). Such shared PPS representations may facilitate interactions with others via multisensory predictive coding mechanisms (Fanghella, Era, & Candidi, 2021).

Other researchers applied the reachability judgment task, as a proxy of PPS representation (Fig. 1), reporting it was shorter facing an avatar as compared to an object, or a robot (Iachini, Coello, Frassinetti, & Ruggiero, 2014). This distance increased with angry emotional faces (Cartaud et al., 2018, 2020) and avatars that were tagged with immoral statements (Iachini, Pagliaro, & Ruggiero, 2015). Another set of experiments assessed the impact of social factors onto PPS plasticity before and after tool use, thought to modify both spatial and body representation (Bassolino, Finisguerra, Canzoneri, Serino, & Pozzo, 2015; Canzoneri et al., 2013; Cardinali, Brozzoli, & Farnè, 2009). The studies consistently found that tool use affected reachability distance after a cooperation with the confederate, leading to larger reachability distance toward

Table 2 – Social modulation of PeriPersonal (PPS) and Personal Space (PS) measures.

Social manipulation	PPS	PS
	Multisensory interaction task Variable: Sigmoidal central point	Stop-distance paradigm Variable: comfort distance
Presence of the other outside PPS (Real person vs. mannequin) (Teneggi et al., 2013)	⇐ with real unfamiliar other	
Before and after non-cooperative or cooperative game (Teneggi et al., 2013)	⇒ (Faster RT in the far space) after cooperative game	
Emotional sounds (Ferri et al., 2015)	⇒ with negative sound (vs. neutral or positive sounds)	
Moral judgment (moral vs. immoral) (Pellencin et al., 2017)	⇒ with moral other	⇐ with moral other
Facial emotions of confederate (neutral, happy, fearful) (Ellena et al., 2020) ^a	Visual attention redistribution in near space with fearful faces	
After synchronous multisensory stimulation (only participants responding) (Maister et al., 2015)	Shared PPS (faster tactile detection with auditory stimuli near the other only after synchronous multisensory stimulation	
Cooperation (Hobeika et al., 2019)	⇒ right hemispace and independently of the location of the partner only when participants collaborated with a partner	
	Reachability judgment task Variable: Reachability distance	Stop-distance paradigm Variable: comfort distance
Standing still (passive) or walking toward stimuli (active) (avatar, object, robot in VR) (Iachini et al., 2014)	⇐ with avatar vs cylinder	⇐ with avatar vs cylinder
Moral judgment (moral vs. immoral) (Iachini, Pagliaro, & Ruggiero, 2015)	⇐ with moral other	⇐ with moral other
Facial expressions (neutral, happy, angry) (Ruggiero et al., 2017)	⇐ with happy other	⇐ with happy other
Facial expressions of other (positive vs negative) with point-light walkers (Cartaud et al., 2018) ^a	reachability judgments were not influenced by the facial expression	⇐ with happy or neutral other vs with angry one
Cooperative tool use (before and after) (Candini et al., 2019; Patané et al., 2017)	⇒ after vs. before	⇐ after vs. before
Individual tool use (before and after) Exp2 in (D'Angelo et al., 2017) (Patané et al., 2016)	⇒ after vs. before	⇔ after vs. before
Individual tool use (before and after) with point-light walkers (Qesque et al., 2017)	⇒ after vs. before	⇒ after vs. before
Invisible body illusion Exp1 in (D'Angelo et al., 2017)	⇔ after body illusion	⇐ after body illusion
	Hand Blink Reflex	
Presence of other inside PPS (Fossataro, Sambo, et al., 2016)	Increase of HBR amplitude when stimulated hand close to confederate's face	
	Cross congruency task	
Presence of other (Heed et al., 2010)	Reduced interference cost (CCE) with confederate inside but not outside PPS	
	Audio-(visuo-) tactile interaction task	
After joint task performance (Dell'Anna et al., 2020)	no facilitation in near space in non-cooperative condition	

(continued on next page)

Table 2 – (continued)

Social manipulation	PPS	
	Multisensory interaction task Variable: Sigmoidal central point	Stop-distance paradigm Variable: comfort distance
After joint task performance (Teramoto, 2018)	Shared PPS (faster tactile responses with visual stimuli near the confederate)	
	Spatial alignment task	
Presence of other (Saccone et al., 2018)	Shared PPS (equal affordance responses for space near self and the other)	
	Spatial encoding task	
Collaborative interactions (Rocca, Wallentin, Vesper, & Tylén, 2019)	Linguistic coding of proximal space is shifted towards the other in a collaborative condition	
⇒ Expansion, ⇐ reduction, ⇔ unchanged.		
^a Cartaud et al. (2018) and Ellena et al. (2020) reported an increase of electrodermal activity; Dureux et al. (2021) reported increase of heart rate for faces presented in close vs. far space.		

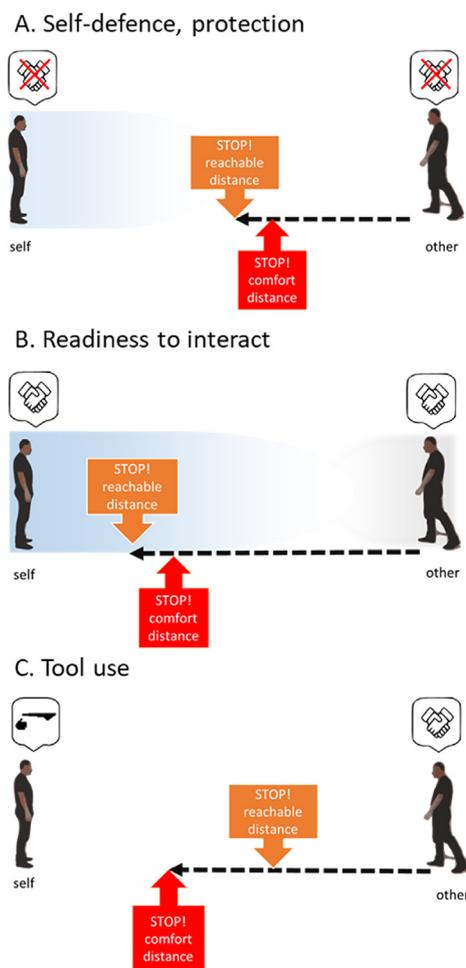
the cooperative confederate (Candini, Giuberti, Santelli, di Pellegrino, & Frassinetti, 2019; Patané et al., 2017).

Importantly, as discussed in the previous paragraphs, when considering PPS boundary, one needs to keep in mind the way this boundary is defined and measured: 1) using the central point of the sigmoid fitting the performance along the sagittal plan in multisensory interaction task or 2) measuring the reaching distance with the reachability judgement task. Note that in the former setting, the confederate was typically static and located outside participants' PPS, while participants' performance was measured with a visual probe approaching them. This implies that in such setting the social element is 'indirectly' interfering with the participant's PPS representation. By contrast, in the reachability judgement task, the confederate is typically positioned outside the participant's PPS and then moves toward the participants (in the passive version of the task, or the participant moves toward the confederate, in the active version of the task). Here, the social element is 'directly' interfering with the participant's PPS representation. With the multisensory interaction task, a positive interaction between the participants and the confederate or the presence of a social factor with a positive valence, or valued judgement (morality), elicited an enlargement of the participant's PPS. By contrast, a social factor with a negative valence, or unvalued judgement (immorality), most often elicited shrinkage of the participant's PPS. With the reachability judgement task, a social factor with a positive valence or valued judgement (morality) typically elicited shorter reachable distances while a social factor with a negative valence, or unvalued judgement (immorality), elicited larger reachable distances (Fig. 1).

This opposing direction of the effects could reflect either real differences between measures, and thus spatial representations they tackle, or may only be apparent. A PPS expansion measured by multisensory interaction might signify an inclusion of the other's PPS into one's own PPS (Teneggi et al., 2013) leading to a larger 'avenue' for potential interactions between the agents. A shrinkage of PPS, when measured by the reachability judgment task, might similarly emphasize participants are keener to 'come closer'. Perceiving what is reachable indeed activates motor representation of reaching actions, whose neural bases are reported to include motor and premotor regions (the dorsal premotor cortex, the supplementary motor area), as well as posterior parietal cortex (V6A and parietal reach region in anterior and medial intraparietal sulcus) (Filimon, 2010; Lara, Cunningham, & Churchland, 2018; Monaco et al., 2011; Pitzalis et al., 2013). As such, PPS and reachability circuitries involve partly common, but also some specific brain machinery. While this might account for some of the opposite effects measured behaviorally, recent evidence also points to genuine differences between these spatial representations (Zanini et al., 2020).

3. PeriPersonal and personal space: how do they relate to each other?

As posited earlier, despite their different origins, both PS and PPS refer to the space surrounding the body. Are they similar, but different concepts? The literature shows that in some instances, they either converge or diverge. The next section will



A. In the presence of an immoral, angry/fearful, non-cooperative confederate:

PPS: Shrinkage of PPS estimated with the multisensory interaction task (Dell'Anna et al., 2020; Pellencin et al., 2017; Teneggi et al., 2013) vs extension of reachability distance (Cartaud et al., 2018; Iachini, Pagliaro, et al., 2015; Ruggiero et al., 2017);

PS: extension of comfort distance (Cartaud et al., 2018; Iachini, Pagliaro, et al., 2015; Ruggiero et al., 2017).

B. In the presence of moral, happy, cooperative confederate:

PPS: Extension of PPS estimated with the multisensory interaction task (Hobeika et al., 2019; Pellencin et al., 2017; Teneggi et al., 2013) vs shrinkage of reachability distance (Cartaud et al., 2018; Iachini, Pagliaro, et al., 2015; Ruggiero et al., 2017);

Self-other shared or merged PPS estimated with the multisensory interaction task (Maister et al., 2015; Rocca et al., 2019; Saccone et al., 2018; Teneggi et al., 2013; Teramoto, 2018);

PS: Shrinkage of comfort distance (Cartaud et al., 2018; Iachini, Pagliaro, et al., 2015; Ruggiero et al., 2017).

C. After tool use:

PPS: Extension of reachability distance (Candini et al., 2019; Patané et al., 2017)

PS: Shrinkage of comfort distance (Candini et al., 2019; Patané et al., 2017, Candini et al., 2019; Patané et al., 2017).

Fig. 1 – Changes in PPS and PS representations measurements in different social contexts. In the examples depicted, PPS boundary was estimated with the multisensory interaction task (illustrated here as grey shadow, msi PPS) or the reachability judgement task (orange block), while PS boundary (comfort distance) was estimated with the stop distance paradigm (red block). The multiplicity of the experimental approaches leads to divergent results and interpretations.

summarize the studies that have directly compared these two spatial concepts in the same subjects (Table 2). Before, as we have exemplified above for PPS, it is important to recall how PS is measured. Typically, the reference measure considered in this field is the comfort distance, which is most frequently assessed with the ‘stop-distance paradigm’. A participant faces another person (the experimenter) walking toward her/him. In the passive version of this task, participants stay still and have to stop the approaching experimenter at the latest separating distance they feel comfortable with. In the active version, roles are reversed and the experimenter stays still while participants move towards him/her to stop at a comfortable separating distance (Shin, Song, Kim, & Biocca, 2019; Sorokowska et al., 2017). The procedure can include measures from different perspectives, egocentric (first person) or allocentric (third person view). It has been evaluated in real world situations (Hayduk, 1983), in virtual environments (Nishihara & Okubo, 2015), or even using a paper-pencil version (Duke & Kiebach, 1974). Importantly, it always includes two agents (the participant and the confederate) facing each other and, contrary to the reachability judgement where a motor representation of a reaching action toward the

confederate is prompted, with the stop-distance paradigm the emphasis is put on the participant's inner state, to avoid discomfort or anxiety (Gifford, 1982; Hayduk, 1983).

The majority of the studies that have directly compared PPS and PS have used the reachability judgment task as a proxy for PPS representation. In such a case, PS and PPS mostly overlapped. Both reachability and comfort distances strongly depended on the context (Iachini et al., 2014, 2016). When participants performed the stop distance and reachability paradigms in their passive version (being approached), both measures were larger than in the active situation (Iachini et al., 2014, 2016). Both reachability and comfort distances depended similarly on the participant's level of anxiety and her/his sex. They were also influenced by the others' attributes: their facial expressions (Cartaud et al., 2018, 2020; Ruggiero et al., 2017), the judgements that can be attributed to them such as morality (Iachini, Pagliaro, & Ruggiero, 2015), as well as age and sex (Iachini et al., 2016; Iachini, Ruggiero, et al., 2015; Ruggiero, Rapuano, & Iachini, 2019). For instance, smaller distances were typically reported for female and young person compared to male or adult person.

Yet, depending on the experimental paradigm to probe PPS representation, results may also diverge. In the study of (Iachini, Pagliaro, & Ruggiero, 2015), both reachability judgement and stop distance tasks decreased when facing a moral person. However, when PPS was estimated with the multisensory interaction task, PPS representation expanded towards a moral/cooperative agent (Teneggi et al., 2013). As anticipated above, this discrepancy may reflect true differences between PS and PPS representations, as well as merely reflect methodological differences across their measures, again underlying how experimental procedures used to evaluate PPS representation might matter.

A different, more bottom-up approach for testing PS and PPS similarities and differences has been undertaken by looking at the impact that tool-use may exert on them. In this respect, the measure of reachable and comfort distances after tool use also lead to mixed results (Candini et al., 2019; Patané et al., 2017). The use of a long tool consistently increased reachability distance estimated either alone (Bourgeois, Farnè, & Coello, 2014), or in the presence of a point-light walker (Quesque et al., 2017), a real confederate (D'Angelo, Pellegrino, & Frassinetti, 2017; Patané, Iachini, Farnè, & Frassinetti, 2016), as well as following cooperative tool use (Patané et al., 2017). These findings are in keeping with studies showing that tool use modulates PPS boundaries. However, these studies reported differences in terms of the impact of tool use on PS, as measured by the stop distance paradigm. Some researchers (D'Angelo et al., 2017; Patané et al., 2016) showed that this measure remained unchanged when facing an unfamiliar person, while it decreased after cooperative tool use in the same paradigm (Candini et al., 2019; Patané et al., 2017). By contrast, Quesque et al., 2017 reported an increase of PS towards a light-point walker after tool use (Quesque et al., 2017). It is possible that the use of a light-point walker—compared to a real person—may be responsible for this difference. Another manipulation, the illusion of having a tall body (200 cm of height) also significantly reduced interpersonal distance and enlarged reachability distance (D'Angelo et al., 2019). Interpersonal distance is typically reduced towards kids (Iachini et al., 2016), people also preferring to enter into personal space of short, but not tall others (Caplan & Goldman, 1981).

To sum-up, both spatial representations depend on other individuals and their interaction with the environment, to manipulate it or protect from it (de Vignemont & Iannetti, 2015; Graziano & Cooke, 2006). Both depend on the subjects' personality traits, for example anxiety level (Iachini, Ruggiero, et al., 2015; Sambo & Iannetti, 2013). The different effects induced by the same sensory-motor manipulation on either spatial representations may result from differences in terms of bottom-up (tool use) or top-down (sense of agency, PPS remapping) processes, or signify that they probe different aspects of the space surrounding us. Since both PPS and PS refer to spatial representations in relation to the body, they might loosely share some features but to date the empirical dissociations reported above (see also (Zanini et al., 2020) and the different experimental approaches suggest some cautions should be kept in mind when trying to delineate a unifying conceptual framework.

4. PPS, interoception and bodily self-consciousness

Interoception refers to the process by which the nervous system senses, integrates and interprets signals originating from inside the body, providing a moment-by-moment mapping of the body's internal landscape across conscious and unconscious levels (Khalsa et al., 2018). Salient stimuli in the space surrounding the body may induce changes in autonomic responses, as for example, during the observation of a noxious stimulus approaching and either touching the hand or stopping close or far from it (Rossetti, Romano, Bolognini, & Maravita, 2015). Electrodermal activity also increased in response to approaching angry faces (Cartaud et al., 2018, 2020; Ellena, Starita, Haggard, & Lådavas, 2020). Strong interoceptive signals in response to salient features, such as an angry or happy person approaching us, are likely to exert different impacts on our body, brain and behavior, likely promoting approach or avoidance reactions and fine-tuning our motor behavior. When surrounded by others, the estimation of appropriate physical distances should ideally be computed considering affective and social relationships, on top of their physical distance. This is even possibly reflected through metaphors with which we describe our relationships in many languages: 'this is my closest friend', 'a noble with its entourage', 'he is distancing himself from me' (Lakoff & Johnson, 1980). Yet, interoceptive signals are highly dependent on the subjects and interoceptive sensitivity can provide some insights about these inter-individual differences. For instance, in the study by Ferri, Ardizzi, Ambrosecchia, & Gallese, 2013 (Ferri et al., 2013), only people with high interoceptive sensitivity showed higher autonomic response in a social situation (observation of the experimenter's hand performing a caress-like movements at different distances from their own hand, as compared to a similarly moving metal stick), particularly when the experimenter's hand was moving at shorter distances. Higher interoceptive accuracy, measured with the heartbeat perception task, has also been related to sharper PPS boundary, as computed by the central point of sigmoid curve in audio-tactile multisensory task, in subjects with high self-consciousness (Ardizzi & Ferri, 2018). In addition, participants who were able to improve their interoceptive accuracy show more pronounced changes in sigmoid curve slope in the visual-tactile task and changes in their subjective experience of the self in space assessed by means of questionnaires (Noel, Park, et al., 2018). Interoceptive awareness, based on the perception of inner state of the body may thus be related to PPS representation (Ardizzi & Ferri, 2018; Cartaud et al., 2018; Noel, Park, et al., 2018; Noel, Pfeiffer, et al., 2015; Rabellino, Frewen, McKinnon, & Lanius, 2020; Rossetti et al., 2015; Scandola et al., 2020).

Interestingly, it has recently been suggested that the multisensory mechanism of PPS representation contributes to a representation of the self as distinct from the environment and the others and contributes to Bodily Self-Consciousness (Blanke, Slater, & Serino, 2015; Noel, Bertoni, et al., 2020; Noel, Failla, et al., 2020; Noel, Lytle, Cascio, & Wallace, 2018; Scandola et al., 2020; Serino, 2019). As quoted from Serino (Serino, 2019), page 150): the notion of "Bodily Self-

Consciousness reflects the experience of the self as a subject of the experience grounded into a body that is felt as one's own (self-identification), which occupies a specific location in space (self-location) and which faces the world from a specific perspective (first-person perspective).” It is tempting to suggest that the first two ‘selves’, namely self-identification and self-location, may reflect sensorimotor and spatial aspects of the relationship between the body (my body) and the external world (Jeannerod, 2006). As such, illusory or real changes in body dimensions, or body position in space may change PPS representation (Berger et al., 2019; Cardini, Fatemi-Ghomi, Gajewska-Knapik, Gooch, & Aspell, 2019; D'Angelo et al., 2017; Noel, Grivaz, et al., 2015; Pfeiffer, Noel, Serino, & Blanke, 2018). The full-body illusion, induced with virtual reality, indeed shifted the self-PPS boundary towards VR avatars (Ehrsson, 2007; Lenggenhager, Tadi, Metzinger, & Blanke, 2007; Noel, Pfeiffer, et al., 2015).

Thus, these relationships seem to be mainly determined by the constraints between the environment and the body. Instead, interoceptive signals beyond proprioceptive and vestibular inputs might have a more prominent influence on one's first-person perspective. By this, we do not imply that these are three different entities; we rather suggest that multiple influences from outside and inside the body are complementarily contributing to PPS representation of oneself and that such influences may dynamically shape our interactions with the environment. For instance, hand amputees display a sort of neglect for the space closely surrounding their missing limb (Makin et al., 2010). Even the mere temporary immobilization of one upper limb has proven to shrink PPS around that limb (Bassolino et al., 2015). In spinal cord injured patients, PPS is selectively reduced around the body parts below the lesion level, while it remained preserved around the body parts above the lesion level (Scandola et al., 2016, 2020). Passive movement induced by the experimenter partly restored PPS representation. Note that recovery induced by another person, thus with social components, need to be more deeply investigated as promising direction for future research. In addition, an evaluation of interoceptive awareness through questionnaires suggested that in subjects with incomplete lesion, greater interoceptive sensibility was associated with a better representation of PPS. When explicitly asked, the participants were able to accurately identify the presence of movement (even though it was not visible), again pointing toward a link between interoception and PPS representation. In autistic patients, altered bodily self-consciousness and disrupted integration of exteroceptive and interoceptive signaling are observed in addition to abnormalities in PPS representation, and both processes seem to be related to deficits in multisensory integration (Mul et al., 2019). These deficits might account for some of the social interactions difficulties encountered in these patients (Rabellino et al., 2020).

The handful of studies that measured physiological signals when stimuli enters PPS, support the idea that these stimuli—and more so those socially connoted—not only change overt behavioral responses, but also body responses. For instance, a recent study revealed that facial emotions displayed in the PPS enhance the observers' heart rate and

facilitate their perceptual discrimination compared to facial emotions displayed outside the PPS (Dureux et al., 2021). As such, PPS coding might result from interactions at a more complex level than previously thought, including not only external, but also internal signals. Keeping in mind that bodily signals may impact social cognition through interoception (Gao, Ping, & Chen, 2019) and that PPS representations contribute to bodily self-consciousness (Serino, 2019), the role of PPS representation in social interactions may be more important than previously thought. It is for instance possible that the intrinsic sense of discomfort which delineates personal space and strongly depends on the personality of the intruder may depend on interactions between PPS and interoception. Recent evidence in support to this possibility comes from a study showing enhanced skin conductance response in participants when a confederate approached compared to when he moved farther away in the stop distance paradigm (Candini, Battaglia, Benassi, di Pellegrino, & Frassinetti, 2021). However future investigations are needed to explore that question by measuring interoceptive signals in protocols probing PPS and PS.

Indeed, very few studies have so far included interoceptive measures when assessing changes of PPS representation depending on the context. These signals might help better understanding the direction of the effects measured, their dependency from context, and more so when involving social factors (Cartaud et al., 2018). As a direct measure of sympathetic or parasympathetic nervous system activation following psychological or physiological arousal (Baig & Kavakli, 2019; Taylor & Epstein, 1967), they could inform us about the inner state of the subjects facing diverse contexts. They might track the impact of the proximity of others, whether the emphasis is put on the participant's inner state (to avoid discomfort or anxiety, as it is typically measured with the stop-distance paradigm) or whether instead the emphasis is on perception of surrounding stimuli, or the reachable space.

In other words, protecting our body, as well as interacting with stimuli in the environment, starts from and within the body. Needs, goals and concurrent bodily states may thus contribute to define bodily self and self-PPS, which likely govern the complex interplay between social and visuomotor processes within our social world. Multisensory processing may be one of the underlying mechanisms for this interplay between internal and external signals. A few available evidences indeed suggest a link between bodily signals and PPS representation. In addition, accumulating evidence suggest that personality traits (anxiety, claustrophobia) also contribute defining one's own PPS representation and personality traits are highly related to our inner state and responses to stressful situations (Iachini, Ruggiero, et al., 2015; Lourenco, Longo, & Pathman, 2011; Sambo & Iannetti, 2013) see also (Lebert, Chaby, Garnot, & Vergilino-Perez, 2020). Adding measures of internal physiological states in the future might help gathering a deeper understanding of PPS, its relationships with PS and possibly reconciling the discrepancies between different studies/methodologies. We thus suggest that by merging exteroceptive information from the environment and internal signals that come from the body, PPS may promote an integrated representation of the self, as distinct

from the environment and the others to provide us with a better understanding of the processes at play during social interactions.

5. PPS representation and brain–body interactions

In humans, neuroimaging studies revealed that PPS network includes frontoparietal regions and the putamen (Brozzoli et al., 2011, 2012, 2014; Bremmer et al., 2001; Cléry et al., 2015; Gentile et al., 2011; Grivaz et al., 2017; Sereno & Huang, 2006) and is thought to represent a putative homologue of the premotor-parietal PPS network described in monkeys. More recently, neuroimaging studies have provided some insights on how PPS network may be modulated by social factors. Holt et al. (2014) revealed a selective brain activation in response to approaching vs. receding faces (compared to spheres) in PPS network, namely the dorsal intraparietal sulcus and ventral premotor cortex (Holt et al., 2014). A greater coupling between those PPS regions was correlated with a higher self-estimated social activity and shorter comfort distance between the participant and the experimenter, measured outside the scanner.

How could approaching social stimuli specifically shape PPS network activation? A constant reciprocal adjustment of brain-body interactions is essential to adapt behavioral responses during such interaction. One possible pathway through which PPS coding could be modulated is via the adrenal medulla that has direct links with the motor cortex (Dum, Levinthal, & Strick, 2016). In addition, ascending interoceptive signals are relayed to several brainstem nuclei, including the nucleus of the solitary tract (NTS), parabrachial nucleus (PB), and periaqueductal gray matter (PAG), that in turns regulate neuromodulatory inputs to subcortical and cortical brain regions (Azzalini, Rebollo, & Tallon-Baudry, 2019; Critchley & Harrison, 2013). For instance, an approaching threat induces an increased activation of the PAG, likely preparing the body to protect itself and possibly escape from a potential danger (Mobbs et al., 2007). Ascending interoceptive signals are also sent to subcortical regions involved in autonomic regulation, such as the hypothalamus, amygdala, striatum, and cerebellum (Azzalini et al., 2019; Critchley & Harrison, 2013). These signals are thus in a position to modulate directly or indirectly the activity of PPS network. For instance, the default mode and salience networks support interoception and allostasis and continuously interact with other networks underlying different cognitive functions (Khalsa et al., 2018; Kleckner et al., 2017).

Approaching faces also induced activation of the insula (Schienle, Wabnegger, Leitner, & Leutgeb, 2017). The insula can be considered as a hub integrating exteroceptive sensory inputs and interoceptive signals (Uddin, Nomi, Hébert-Seropian, Ghaziri, & Boucher, 2017), and linking external and internal experiences. This structure regulates functions of the autonomic system and participates in forming bodily self-awareness, sense of agency and body ownership (Seghezzi, Giannini, & Zapparoli, 2019; Uddin et al., 2017). In a study leveraging intracranial EEG recordings, multisensory neurons sensitive to both audio and tactile stimuli were found in the

insular region (Bernasconi et al., 2018). The activity of these neurons was modulated by the distance of the stimulus from the body; their activation was observed during very early stages (~50 ms); while later (~200 ms) distance-related responses were recorded in precentral and postcentral gyri (Bernasconi et al., 2018). Moreover, activation of the insula was uncovered using functional magnetic resonance imaging during observation of a moving object close to the hand (Schaefer, Heinze, & Rotte, 2012) and electric stimulation of insular regions induced both social approach or withdrawal reactions (Caruana, Jezzini, Sbriscia-Fioretti, Rizzolatti, & Gallese, 2011). Importantly, the insula is functionally and anatomically connected with the amygdala (Mufson, Mesulam, & Pandya, 1981; Uddin et al., 2017), a region playing a critical role in regulating distances during social interactions (Kennedy et al., 2009; Schienle, Wabnegger, Schöngassner, & Leutgeb, 2015; Vieira, Tavares, Marsh, & Mitchell, 2017). Patients with bilateral amygdala lesions show a marked reduction of interpersonal distance (Kennedy et al., 2009). These patients also exhibited deficits in retrieving socially relevant knowledge from unfamiliar faces and tended to judge unfamiliar faces as more approachable and more trustworthy than did control subjects (Adolphs, Tranel, & Damasio, 1998). Theta burst stimulation of regions of the PPS network, the inferior parietal lobule and the ventral premotor cortex affected amygdala responses to neutral vs negative emotional stimuli (Engelen, Zhan, Sack, & de Gelder, 2018). Such interactions might lead for example to the expansion of PPS representation with social negative sounds (Ferri, Tajadura-Jiménez, Väljamäe, Vastano, & Costantini, 2015). Not surprisingly, the amygdala activity is enhanced with looming stimuli invading near space (Coker-Appiah et al., 2013). Similarly, atypical amygdala activity (Lough et al., 2015) in autistic subjects has also been related to abnormal decrease of interpersonal distance (Kennedy & Adolphs, 2014; Massaccesi et al., 2021). A recent study found increased functional connectivity from the amygdala to the dorsal intraparietal sulcus and the fusiform gyrus (FFA), a region selective for face perception and recognition, in autistic patients compared to controls (Massaccesi et al., 2021). In this pathology, atypical interoception and bodily self-consciousness have also been documented (Mul et al., 2019; Quadt, Critchley, & Garfinkel, 2018); and may lead to altered PPS and/or PS representation (Mul et al., 2019; Noel, Cascio, Wallace, & Park, 2017) but see (Candini et al., 2019). In schizophrenic patients, Holt et al. (2015) found an increase of the dorsal intraparietal sulcus activity in response to approaching faces that was correlated with larger interpersonal distance. Interestingly, they also reported a reduction of the functional coupling between the dorsal intraparietal sulcus and FFA in these patients. This suggests that an abnormal dialogue between the regions processing face recognition and the region processing PPS representation might lead to difficulties in the interaction with elements, including peers, in the close surrounding space (Di Cosmo et al., 2017).

In sum, PPS network might integrate external and internal information to promote our interactions with the surrounding space within spatial and temporal frames (Belardinelli et al., 2018; Cléry et al., 2020; Serino, 2019). From that perspective, PPS may serve to estimate the probability of interaction with

the surrounding three-dimensional environment (Kandula, Hofman, & Dijkerman, 2015), guide our behavior depending on the context (Dijkerman & Farnè, 2015), and adjust behavior even during movement (Senna, Cardinali, Farnè, & Brozzoli, 2019), which is extremely important in social relations. In terms of PPS representation, the integration of multisensory information coming from the outside with bodily signals, including vestibular signals might not only contribute to self-consciousness (Noel, Park, et al., 2018), but also to distinguish self from others, as indicated by studies with bodily illusions and studies with pathological embodiment in neurological patients (Fossataro, Gindri, Mezzanato, Pia, & Garbarini, 2016; Makin, Holmes, & Ehrsson, 2008; Noel, Pfeiffer, et al., 2015).

6. PPS and social interactions

Beyond its sensitivity to the intrusion of objects and agents into one own's space, PPS representation is also sensitive to the intrusion of objects into the near space of others; this vicarious response was found in both human and animal studies (Brozzoli, Ehrsson, & Farnè, 2014; Brozzoli, Gentile, Bergouignan, & Ehrsson, 2013; Fossataro, Sambo, et al., 2016; Iachini & Ruggiero, 2021; Ishida, Nakajima, Inase, & Murata, 2010; Patané et al., 2020; Schaefer et al., 2012). When surrounded by others, the estimation of distance can be affected not only by the physical depth, but also by the relationships or the interactions we share with these individuals. These factors also influence our inner states. The fact that the degree of such vicarious PPS responses (Fossataro, Sambo, et al., 2016) was related to the perceived proximity between individuals beyond the physical distance, might suggest that PPS contributes to intention reading and action understanding (Kilner, Vargas, Duval, Blakemore, & Sirigu, 2004), essential for appropriate social interactions (Hunnius & Bekkering, 2014; Woodward, Sommerville, Gerson, Henderson, & Buresh, 2009). Iachini and Ruggiero (2021) found that sharing a partner's perspective influences the estimation of an object location within one own's PPS (Iachini & Ruggiero, 2021). Furthermore, manipulating the ownership status of an object ("whose object this is") also revealed a modulation of PPS in relation to this notion of ownership (Patané et al., 2020). Thus, PPS could have been exapted to map, and to maybe "understand" the ownership status of others' actions. It is possible that by integrating both external and internal signals to promote an integrated representation of the self, as distinct from the environment and the others, PPS might be equipped to face these challenging computational situations we encounter in our social world.

The phenomenon of shared PPS representation in the presence of others (Costantini, Ambrosini, Scorolli, & Borghi, 2011; Pellencin et al., 2017; Saccone, Szpak, Churches, & Nicholls, 2018) also opens questions on how PPS may be related to the development and regulation of various kinds of social relationships, including interaction, self-others coordination, and cooperation (Fanghella et al., 2021). The need to interact and cooperate with others modifies low-level perceptive mechanisms in PPS task (Hobeika et al., 2019), participating in what one could call 'supraindividual' representation of space. Emotional faces in the near space modulate our perceptual abilities and bodily signals (Dureux et al., 2021; Ellena et al., 2020). It is thus possible that self-PPS activation may contribute to shared, or joint attention during

performance of the same task (cooperative action) (Mundy, 2018) which strongly depends on synchronization between partners (Fabbri, Frisoni, Martoni, Tonetti, & Natale, 2017). It is also possible that shared PPS may play a role in learning processes, as modelled in (Juett & Kuipers, 2019). Being close to cooperative vs non-cooperative partners modulates responses in multisensory tasks, enlarging or merging PPS boundary between the cooperative individuals or shrinking of PPS in non-cooperative case (Dell'Anna et al., 2020; Teneggi et al., 2013).

Greater self-other overlap is related to increased sensorimotor responses to others' sensations (Riečanský, Lengersdorff, Pfabigan, & Lamm, 2020) and enlarges self-PPS towards the partner (Pellencin et al., 2017). In that sense, self-PPS activation may contribute to the prediction and understanding of others' feelings. Notably, individuals' empathic responses are modulated by the physical distance with others (Lomoriello, Meconi, Rinaldi, & Sessa, 2018; Mahayana et al., 2014; Mencl & May, 2009). In addition, only individuals with high empathic traits develop significant vicarious defensive PPS response with approaching threats (Fossataro, Sambo, et al., 2016).

The level of self-other overlap and the intention to interact with a stranger affects the multisensory representations of the space between oneself and the other (Pellencin et al., 2017). The level of self-other overlap is defined by two related factors, 'feeling close' and 'behaving close' (Myers & Hodges, 2012). Therefore, perceived social proximity may be dependent on the 'closeness' between another (stranger) subject's behavior and one's own pre-existing implicit expectations. Via mechanism of shared representations, self-PPS may participate in perspective taking, impression and judgments about others, e.g., "if you behave, act and react as myself", you are more similar, closer to me, and "I understand you better". In this way, self PPS may contribute to gaining social, temporal and physical proximity with the others around us in addition to the regulation of social distances (Parkinson, Liu, & Wheatley, 2014; Ruggiero et al., 2019; Sorokowska et al., 2017). At this stage of our knowledge, it is difficult to precisely delineate the extent to which PPS might play a role in social cognition. Yet, in light of the growing studies interested in the influence of social factors on PPS, here we hope that future studies will provide insights on the exciting issue.

7. Concluding remarks

Since the discovery of the PPS, its definition and functional roles have been continuously expanding (Bufacchi & Iannetti, 2018; Hunley & Lourenco, 2018) and re-conceptualizing (Serino, 2019). To date, an increasing consensus exists on some basic functional roles of PPS: it may allow a subject to rapidly and flexibly interact with 3D environment, and to optimize behavioral responses towards both inanimate and animate objects around and avoid threatening and harmful elements. Yet, recent years have seen an ever-growing interest into higher level, contextual dependent modulations of these functions that seem to propel PPS roles well beyond its basic, though critical functions for survival (Ardizzi & Ferri, 2018; Rabellino et al., 2020; Salomon et al., 2017). While these expanding possibilities are in keeping with the idea that this spatial representation is susceptible to both bottom-up and top-down modulations (Coello, Quesque, Gigliotti, Ott, &

Bruyelle, 2018), the study of the social dimension of PPS may face novel challenges, notably because the role of PPS representation in the domain of social interactions may require the PPS processing to involve predictive abilities and sensory remapping to efficiently help understanding other people's actions and intentions.

We believe a critical aspect for future investigations of PPS social role is to account for its dependency on subjects' individual personalities and interoceptive states. So far, the impact of social factors produced somewhat contradictory outcomes. We argue that one possible reason for that relates to the use of 'classical' available methodologies, typically used so far to probe PPS basic sensorimotor functions. The recent development in PPS literature in relation to social elements has opened new avenues for investigators, combining physiological and psychological aspects of PPS space and its relation to other measurements of social interaction, such as interpersonal distance.

New dimensions of modern research relate PPS and self-body perception, putting the emphasis on the participation of interoceptive inputs into perception of proximal environmental stimuli. We advance that both novel and well-established methodologies should be coupled with physiological indexes, to fully embrace the view that interoceptive signals may contribute critical insights on how the PPS network works. Gathering brain and body activity while interacting with (or in the mere presence of) conspecifics, may help understanding how social PPS processing shapes our behavior.

CRedit author statement

Olena V. BOGDANOVA: Conceptualization; Writing - Original Draft.

Volodymyr B. BOGDANOV: Visualization; Writing - Review & Editing.

Audrey DUREUX: Writing - Review & Editing.

Alessandro FARNE: Writing - Review & Editing.

Fadila HADJ-BOUZIANE: Funding acquisition; Project administration; Supervision; Conceptualization; Writing - Review & Editing.

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