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INVESTIGATING THE RELATIONSHIP BETWEEN SENSE OF OWNERSHIP AND SENSE OF AGENCY THROUGH SKIN TEMPERATURE MEASUREMENT DURING A DECISION-MAKING TASK

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SUMMARY

ABSTRACT

Bodily self-awareness is a multidimensional construct with *Sense of Ownership* (SoO) and *Sense of Agency* (SoA) as its two main levels. SoO and SoA are tightly interconnected in our everyday lives, so much that our actions could be a prominent source of information to recognize the self. Thermoregulation has been proven to be pivotal in participating to a coherent sense of ownership, with alterations in limb temperature following modulation of limbs ownership, although with some controversial results. Our aim was to investigate whether manipulations of SoA could induce changes in SoO, reflected implicitly by variations in skin temperature of the effectors of the actions (i.e. hands). In a within-subject design, we administered N = 27 healthy young volunteers a decision-making task in three different conditions ("free-choice", "forced-choice" and "mixed-choice"), in order to manipulate their SoA. Every condition consisted of 6 blocks of 5 choices each, for a total of 30 choices per condition. At the beginning of the task and after each block, we took pictures of the participants' hands with a thermal camera. Moreover, we administered them questionnaires to assess their explicit perception of SoO and SoA. We hypothesized decreased SoO and SoA in the "forced-choice" and in the "mixed-choice" conditions compared to the "free-choice" one, both at the explicit and the implicit level. Results showed that SoO and SoA, measured explicitly, decreased strongly in both the "forced-choice" condition and in the "mixed-choice" condition as compared with the "free-choice condition", as expected. However, no significant result was found concerning the hand temperature. Our study supports relationship between SoO and SoA only at the explicit level, but further research is needed to better understand their implicit relation and the potential thermoregulatory changes associated with them.

Keywords: bodily self-awareness, decision-making, sense of agency, sense of ownership, skin temperature, delay discounting

1. INTRODUCTION

The importance of having a coherent, unique, and global sense of one's own body is often taken for granted, but it immediately becomes evident when alterations of it arise, not only in pathological conditions but also in experimental manipulations and paradigms. In this context, *Sense of Ownership* (SoO) and *Sense of Agency* (SoA) are the two main components of bodily self-awareness, a multidimensional construct which has been identified to describe the awareness of one's own body, both in terms of recognizing that specific body as one's own (namely, *SoO*) and of feeling agents of one's own actions (i.e. *SoA*). SoO and SoA are profoundly interconnected in our everyday lives, influencing one another even in our simplest activities. No meaningful and purposeful action, decision, or thought would be possible without feeling in control of the self and of those actions, decisions, and thoughts.

It is noteworthy to consider that this awareness of one's own body is not something that only lies at a cognitive level, but it's also physiologically rooted in oneself. Indeed, any kind of change that happens in self-awareness has been proven to also bring with it some alterations in internally generated parameters such as skin conductance, magnitude of motor evoked potentials and, importantly, skin temperature, and vice versa, with changes in the latter related to alterations in the former. Skin temperature alterations in relation to body awareness have been long at the center of a big debate because of the controversial results obtained in experimental paradigms and studies. Research showed that, in both pathological and experimental setups, reduction in skin temperature could be observed in those body districts towards which the subjects reported to have decreased feelings of ownership. For instance, a very famous experimental paradigm, the *Rubber Hand Illusion (RHI),* shows how inducing SoO towards a fake (i.e. "rubber") limb can significantly reduce the SoO felt towards one's own limb and, consequently, its real skin temperature.

Another important point lies in the tight and demonstrated relationship between SoO and SoA, which are related at a level where actions are considered a prominent source of information to recognize the self. Bodily self-awareness arises, indeed, from the integration of a lot of different kinds of information, along which there are the interoceptive ones, namely those coming from the inside of our body, such as thermoregulation, heartbeat, and visceral ones, the proprioceptive ones, that are related to the position of our limbs in space, and the exteroceptive ones, namely the ones coming from the external environment, which in turn can also derive from actions. It is, though, a natural consequence of this relationship to consider

SoO and SoA as profoundly intertwined and to recognize their bidirectional interaction, so that alterations of SoO cause changes in SoA, and vice versa.

Since their deep complexity, SoO and SoA can be seen from different points of view. In particular, SoA can also be considered as the feeling of being agents not simply of one's own actions, but also, more widely, of the *decisions* that bring to actions. This is why we explored the relationship between agency and the decision-making field – also the latter is something that is constantly and unconsciously present in every moment of our everyday lives, since we are continuously faced with the need to make decisions between different options. No other study until now, though, had tried to delve deeper into this relationship, in particular managing to alter subjects' SoA by manipulating their possibility to exert decisions as they prefer with the aim of measuring changes in physiological parameters.

Thus, this study implemented a decision-making task (i.e. intertemporal choices between smaller, immediately available rewards, and larger rewards that are though reachable after a longer period of time) to investigate the consequences of free and forced choices on participants' SoA, and, consequently, on their SoO and on the skin temperature of participants' hands, since the latter are the effectors of the decisions.

Our results showed a dissociation: at the explicit level (i.e. ratings and questionnaires), participants reported alterations of their perceived SoO and SoA across the free and the forced-choice conditions, with the highest ratings for the former and the lowest for the latter, in line with our hypothesis. At the implicit level (skin temperature measurement), however, we did not observe the expected same trend of results for participants' hands temperature, which did not significantly differ across the decision-making task conditions.

In the first chapter of this work, a general theoretical background on self-awareness will be given. In particular, it will be shown the importance of having representation(s) of our body at many levels; it will be then explained the concept of *bodily self-awareness* differentiating and defining its main components based on the principal theoretical conceptualizations in the field, briefly describing then some pathological alterations of it and their consequences. More attention will be then paid to the main sources of information used to build a coherent sense of the self, evidencing also their neural correlates.

A considerable part of this chapter will be then dedicated to the description, explanation and theoretical conceptualizations of SoO and SoA, which will be the main focus of this research work. A brief excursus on their neural correlates will be provided, followed by the philosophical and neuroscientific perspectives on their profound relationship. The last part will be focused on the debated relationship between SoO and skin temperature, providing evidence for studies both supporting and disconfirming their link.

The second theoretical chapter will be centered on a concise description of the decision-making field, in particular of intertemporal choices. A quick look at the main models proposed to describe the general behavior of subjects will be given, with a focus on the hyperbolic discount function – the one we referred to in this work –, followed by a deeper understanding of the main neurocognitive models proposed to describe the neural bases of intertemporal choices. The chapter will end with a brief description of some studies showing both functional and lesional studies to support the main hypothesis on the neural correlates of this fundamental cognitive activity.

The fourth chapter will be the first one entirely dedicated to this research work, focusing on its rationale and main hypotheses underlying it.

An accurate description of our sample of participants will be given in the fifth chapter, followed by the detailed procedure of our experimental paradigm. All the tasks will be explained, starting from the explicit SoO and SoA questionnaires, then the three conditions of the Delay Discounting Task (i.e. "free-choice", "forced-choice", and "mixed-choice" ones); the precise explanation of the methodology adopted to collect hands skin temperature measurements will be then given, followed by the description of the other questionnaires administered after the decision-making task. At the end of this chapter, the main analyses that we planned to perform on our data will be presented.

In the sixth chapter, the main results will be shown, starting from the descriptive statistics of the sample (i.e. scorings obtained at the questionnaires) and the explicit measures for SoO and SoA obtained via the administration of the ad-hoc questionnaire; then, before presenting some exploratory analyses performed to better understand our data, the results of the implicit measurement for SoO will be shown.

In the last chapter we will discuss our main results, focusing in particular on the explicit measures for SoO and SoA and on the analyses on hands temperature, trying to position them into the broader context of literature in the field. The main limitations of the study will be discussed, followed by some suggestions for necessary future studies.

2. BODILY SELF-AWARENESS

Our ability to interact with the external environment, to interface with the reality and to live our everyday lives is fundamentally based on our body and on the awareness of it as being a tridimensional object that we recognize as ours – and, as it follows, on the mental representation that we have of it (Haggard & Wolpert, 2005).

This representation has a pivotal role in every aspect of our lives, starting from the most basic daily-life activities to more high-level social interactions with other people, as it helps in building the sense of the self. For instance, having a representation of our body allows us to perceive the boundaries between us and the external objects, thus enabling us to move around the environment, to know our position in space, to reach objects; in the same way, at higher levels the representation we have of our body (e.g., the way in which we see ourselves) can profoundly influence our mood and emotions, and consequently the way in which we relate with others; all the non-verbal aspect of communication can also be influenced by the representation of the body, in which gestures, facial expressions, posture, are all instruments that can share significant messages during social interactions; again, in social and cultural interactions we *build* corporeal representations that profoundly change based on the context, and that can impact on the perception of the self and on social interactions (something that is considered acceptable in terms of physical aspect can change both across and within societies, and people tend to adhere to these norms).

The importance of body representation is reflected by the multiple different forms in which it unfolds in the brain (Gallace & Papagno, 2014). One could highlight the point-to-point representations where it is possible to find a precise correspondence between the involved brain area and its neural underpinnings, but also the highest-level, multisensory, and multimodal ones, in which this type of coincidence is harder to be detected. For instance, one could find the somatotopic map in the primary somatosensory cortex (*SI)*, which contains a precise mapping of the specific body districts (*sensory homunculus*), whose cortical extension reflects the density of the somatosensory receptors located there (Penfield & Rasmussen, 1950); or less-specific but multisensory, more complex representations as in the secondary somatosensory cortex (*SII*); or the supramodal, higher-order cognitive ones, deeply rooted in the social and cultural context and extremely plastic and malleable that subserve a constant and coherent feeling of the self.

The unequivocable importance of experiencing the feeling that conscious experiences are bound to the self and are experiences of a unitary entity has been named *bodily self-awareness* (Berlucchi & Aglioti, 2010; Blanke et al., 2015; Salvato et al., 2020), a multidimensional concept that has been considered to involve many different aspects, such as the experience of owning a body, the perception of visceral signals from that body and of the body in space, and feeling the agency over actions (Berlucchi & Aglioti, 2010; Blanke, 2012; Salvato et al., 2020). It is a mental construct that comprises the sense impressions, perceptions, and ideas about one's own and others' body in its dynamic organization and its relations to others (Critchley, 1979; Berlucchi & Aglioti, 1997).

Many theoretical speculations have been proposed in order to define the main components of the construct of *bodily self-awareness* and to comprehensively describe this concept. The first distinction to be drawn in this regard comes from the neurologists Henry Head and Gordon Holmes (1911) who identified (a) a *postural schema* as a combined standard against which all subsequent changes of posture are measured; (b) a *superficial schema,* as a central mapping of somatotopic information derived from the tactile inputs; and (c) a *body image* as the internal representation in the conscious experience of visual, tactile and motor information coming from the body. Schilder (1935) then, claiming to be in accordance with this view, has though equated the postural model – namely, the *body schema* – with the final, conscious sensation of position, meaning that he equated the *body schema* with the *body image*, that is the image or representation of "our own body which we form in our mind" (Schilder, 1935, p. 11).

From that moment on, as many authors have highlighted (e.g., Gallagher, 1986; Paillard, 1999; Berlucchi & Aglioti, 2010), the interchangeable use of these terms in neurological and psychological studies has led to terminological confusion and conceptual difficulties, despite the need for a clear distinction between these two concepts[1].

[1] In 2005, in his book "How the body shapes the mind", Gallagher claimed that "although these concepts [namely, the body image and body schema] have long been used in psychological studies of embodiment, they have also been criticized for being too ambiguous and even obscurant. Without denying that there is some *de facto* truth to this criticism, it is also the case that many of the problems with these concepts are due to the fact that researchers almost always fail to employ a systematic conceptual distinction between body image and body schema. I will argue that if the clear and proper distinction is made, these concepts carve up the conceptual space in a way that leads to a productive understanding of embodied consciousness. Along the way, this distinction will help to clarify not only perceptual experience and action, but also a variety of specific phenomena such as neonate imitation, phantom limbs, deafferentation, unilateral neglect, and the linguistic nature of gesture." (p. 5).

Those who advocate the need for a dichotomous distinction between body image and body schema[2] (e.g., Gallagher, 1986, 2005; Paillard, 1999; Haggard & Wolpert, 2005) attempted to support their view by referring to neural bases individuated starting from more general neurocognitive dichotomies (Berlucchi & Aglioti, 2010). For instance, both Paillard (1999) and Gallagher (2005) had referred to two anatomo-functional dichotomies, namely the what-where dichotomy of Ungerleider and Mishkin (1982), specific for the distinction between perception of objects and spatial localization, and the vision-for-perception and vision-for-action division operated by Milner and Goodale (2006). It followed the conceptualization of the *body image* as a sort of pictorial description of the body mainly based on visual inputs (Paillard, 1999) and of a system of perceptions, but also attitudes and beliefs relative to the body (Gallagher, 2005) – and, importantly, present to consciousness –, and of the *body schema* as a sensorimotor map of the body space based primarily on proprioception (Paillard, 1999), providing the material perspective on the outside world (Gallagher, 2005) – which is, instead, generally for unconscious actions.

Gallagher (1986; 2000), as one of the prominent researchers in the field, postulated then that in the *body image* there is a perceptual, cognitive, or emotional awareness of the body, which appears as owned, abstract and disintegrated – "something in-itself" –, while the *body schema* operates in a non-conscious manner, being unowned or anonymous and functioning holistically, and being "not in-itself apart from its environment".

More recently, Haggard and Wolpert (2005) have extended these definitions by proposing that if *body image* refers to the conscious and mainly visual representation that concerns the canonical way in which the body appears from the outside – a definition fundamentally in line with the everyday use of this expression –, the *body schema* is the neural representation of the body used for spatial sensorimotor processing; it is a sort of postural representation, mainly based on tactile and proprioceptive information and constantly, automatically and unconsciously updated following every movement that is accomplished. It is by virtue of this type of representation that we are able to execute movements and to deal with the external environment and the world, by means of seven fundamental properties of the body schema (Haggard and Wolpert, 2005): (a) *spatial coding,* which is the representation of the position and

[2] Many authors (e.g., Sirigu et al., 1991; Coslett et al., 2002; Schwoebel & Coslett, 2005) suggest, instead, the existence of a *multicomponent* organization of body knowledge, rather than a dichotomous distinction. For instance, Schwoebel and Coslett (2005) propose a representation of the body that includes (i) a body schema, as the dynamic internal representation of bodily parts based both on interoception and on motor information; (ii) a body structural description, mainly based on visual information, and (iii) a body image representing semantic and lexical information about the body.

configuration of the body as a volumetric object in space, supported by the integration of tactile and proprioceptive information from, in turn, the body surface and the configuration of the limbs in space; (b) *modularity*, for which the different body parts are stored in different neural modules, with the resulting modular network representing all the different postures and the spatial and categorical relationships between the segments; (c) *update with movement,* to represent the automatic and continuous tracking of the position of the body parts together with the motion; (d) *adaptability,* because of the capacity of the body schema to adapt to allow for gradual changes in the spatial properties of the body (e.g., during development our body undergoes significant and drastic changes); (e) *supramodality*, as all the different sources of information (i.e., visual, tactile, proprioceptive, and interoceptive) are integrated; (f) *coherence,* for the coherent spatial organization of the body schema that the brain maintains across both space and time, providing for the resolution of possible inter-sensory discrepancies and ensuring a continuity of the experience of the self; (g) *interpersonality*, that is the property of using a common body scheme in order to represent not only one own's, but also others' body.

As already mentioned, the importance of having a plastic, malleable and adaptable representation of one own's body is reflected in the possibility of experiencing a *sense of self* that is continuous and coherent: it is indeed possible to find cases in which this doesn't happen because of the disruption of specific neural mechanisms or brain lesions (Berlucchi & Aglioti, 1997) and/or alterations of some of the properties of the body schema. Thus, the mechanisms of this representation exhibit both stability, since some brain regions seem permanently committed to representing the specific and correspondent body parts in conscious awareness, and plasticity, because of the fast adaptability and reactivity to changes in the body itself (Berlucchi & Aglioti, 1997).

For instance, following the amputation of a limb, it frequently happens that the patient reports to feel the presence of the amputated part of the body (Ramachandran & Hirstein, 1999) and, often, a severe pain associated to it (Chahine & Kanazi, 2007), the so-called *Phantom Limb Syndrome,* first described by the work of Silas Mitchell (1872). Although no comprehensive and precise explanation of this complex phenomenon has been found yet, it is possible to trace back this experience, at least in part, to some alterations in different kinds of representations of the body: (i) the somatotopic representation of the body – and, in particular, of the amputated limb – in *SI,* which leads to a *reorganisation* of the cortical representation of the homunculus' areas near the involved missing part (Pons et al., 1991); and (ii) higher-level properties of body representations arising from the memory that we have of it, derived from the *interpersonal* nature of the body schema: this memory could be built based on the proprioceptive and tactile information coming from the periphery of one own's body, together with inputs coming from the observation and knowledge of other people's bodies (Berlucchi & Aglioti, 1997; Papagno & Gallace, 2014).[3,4]

Another example could be the alteration of the *adaptability* property of the body schema that can be found in the so-called *Rubber Hand Illusion (RHI)*. It is a peculiar experimental paradigm in which a healthy subject is induced to experience the sensation of ownership towards a fake limb (i.e., the rubber hand), together with a diminished sense of belonging of one own's, real limb involved in the stimulation (Botvinick & Cohen, 1998). In the classic experiment, the subject is presented with the rubber hand in an anatomically compatible position with his own hand, the latter being hidden from sight; both the real and the rubber hands are stimulated with two paintbrushes and, if done *synchronously,* the majority of the participants report the tactile sensations as coming not from the real hand, but from the rubber one. This illusion is thought to rely, along with many other processes, also on the integration of three types of information, namely vision, touch, and proprioception. During the induction of the *RHI*, the mental representation of the body tends to adapt to the ongoing stimulation and to the integration – in this case erroneous – of the main sources of inputs.

2.1 DISORDERS OF BODY AWARENESS

As already mentioned, there are some patients with acquired brain damage who exhibit selective impairments in body awareness, thus providing information regarding not only the nature of conscious processes, but also their neural substrates and the physiological processes associated to it (Bottini et al., 2018).

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[3] Sticking to another theoretical conceptualization (Carruthers, 2008a, 2008b), the traditional schema/image contraposition – the traditional conscious/non-conscious issue – is avoided, assuming that all the representations of the body are available to consciousness. In this way, the distinction becomes between *online (synchronic)* body representations, about the current state of the body and constructed from sensory inputs with explicitly conscious contents, and *offline* representations, relatively stable and reflecting the body as it usually looks like based in part from present sensory inputs and in part from stored memories, thus being available to explicit consciousness both immediately and after memory retrieval. Thus, the *Phantom Limb* phenomenon could be explained by referring to a failure to record the amputated limb into the *offline* body representation (Berlucchi & Aglioti, 2010), with the possibility of temporarily suppress this pathological phenomenon by updating the offline representation – for example the use of mirrors for relieving phantom pain (Ramachandran & Altschuler, 2009).

[4] Melzack (1990) talks about a *neuromatrix* to describe the distributed neural network, largely prewired by genetics but at the same time open to shaping influences from the environment and experiences, that underlies the body schema. This neuromatrix includes the somatosensory system, reticular afferents to the limbic system and cortical regions for self-recognition and recognition of external objects. According to this view, then, phantom phenomena would be caused by the persisting activity of the neuromatrix components that have been deprived of their normal inputs because of the loss of that body part, and also by the brain's interpretation of this activity as originating from the missing part (Berlucchi & Aglioti, 1997).

For instance, one of the main pathologies of interest is *Anosognosia for Hemiplegia (AHP)*, a condition in which patients deny the presence of their contralesional motor deficit (Babinski, 1914), being it for upper or lower limbs only, or happening in a modality-specific fashion, meaning that it can concern either motor or sensory impairments (patients could have deficits only in motor aspects, thus not being able anymore to move that part of the body, but still be able to feel sensations there, or vice versa). It is the existence of these specific dissociations that suggests the possibility of having conscious processes *selectively affected,* and not a general and global impairment in awareness. For example, motor denial in these patients can manifest in various ways, such as claiming to have performed a movement with their paralyzed limb, despite clear demonstrations that no movements have occurred, or becoming aware that they aren't able to do that (Bottini et al., 2018). In the first case, the denial for the paralysis of their limb can be considered as embedded into the neural systems that subserve the comparison between the intended and performed movements (Frith et al., 2000), so that they cannot efficiently link the two aspects. In the second case, it can be detected a dissociation between the semantic knowledge that the body segments can move (which is clearly wrong) and the memory of being able to move prior to the occurrence of the brain lesion (Marcel et al., 2004) – this being spared. Also, there can be different levels of awareness within the same patients between *implicit* and *explicit* awareness: subjects with AHP may have implicit knowledge of the deficit, but explicitly deny it (e.g., Marcel et al., 2004). But it's plausible that the explanation goes further than the simple discretization of the anatomical substrates underlying the different manifestations: some authors (e.g., Fotopoulou et al., 2010; Moro et al., 2011) have suggested a more complex picture in which AHP appears as a multi-component disorder caused by the lesion of distributed cortical and subcortical anatomical networks (Bottini et al., 2018).

Another extremely representative example is *somatoparaphrenia (SP)*, a psychiatric disorder characterized by the delusion that the paralyzed limb does not belong to oneself (Gerstmann, 1942). Generally, SP and AHP occur together, in particular most of the patients affected by SP also manifest forms of AHP – but it's not always true the inverse relationship –, even though rare cases of SP without AHP have been described (e.g., Invernizzi et al., 2012; Moro et al., 2016). In particular, if AHP is associated with impairments in consciousness regarding body functions – namely, moving the body part generally – SP is related to the sense of belonging of that part of the body: this could be explained, sticking to one conceptualization that will be slightly explored later in this work, by referring to a model of body representation as being composed of independent aspects (Tsakiris et al., 2006).

2.2 BUILDING BODILY SELF-AWARENESS: EXTEROCEPTIVE, PROPRIOCEPTIVE AND INTEROCEPTIVE SIGNALS

Self-consciousness is fundamentally driven by multisensory bodily signals and by their integrated neural representations (Tsakiris, 2010; Park & Tallon-Baudry, 2014; Blanke et al., 2015; Park & Blanke, 2019). Via the process of multisensory integration, one is able to create sensorial unity that guides behavior and performance, mediating human-environment interactions (Noel et al., 2018). This process is not only about the convergence and unification between the external environment and the body of the observer, but also between the perceiver of the environment and the agent that executes actions in the world (Serino et al., 2013). In particular, exteroceptive, proprioceptive, and interoceptive[5] information has been largely proven to be essential for the sense of the self (e.g., Tsakiris, 2010; Blanke, 2012; Critchley & Harrison, 2013; Park & Blanke, 2019; Salvato et al., 2020). This is because the body, in addition to receiving information from the external objects, is also continuously sent signals from the inside, such as the proprioceptive, vestibular, and interoceptive ones (Noel et al., 2018). Thus, although the specific sensory inputs that the body receives can vary, they still respect the spatio-temporal principles of multisensory integration (Blanke et al., 2015; Noel et al., 2018).[6] Basically, the simplest and most parsimonious explanation of the spatio-temporally congruent information – sensorimotor, visual, tactile, auditory, proprioceptive, and vestibular – must necessarily be that all these sources of information are related to the same entity, that is one own's body.

This kind of reasoning is further supported by what happens when dealing with bodily illusions, which demonstrate that introducing multisensory conflicts can easily alter some aspects of bodily self-awareness, such as the feeling of belonging of the body or of one part of it (Tsakiris, 2017). For instance, the above-mentioned *RHI* paradigm reflects a three-way

[5] Sherrington (1906, from Sherrington (1952)), one of the first ones to talk about, and to define, interoception, describes it as the body-to-brain axis of sensations originating from the internal body and its visceral organs that signal their physiological state, such as thirst, "air hunger", dyspnea, itch, warmth, exercise, heartbeat, distension of the bladder, stomach and other internal organs. The main four systems from which interoception originates are the cardiovascular, respiratory, gastrointestinal and urogenital ones (Tsakiris, 2017).

[6] When in 1980s and 1990s, with seminal recordings in the feline Superior Colliculus (SC), researchers established the field of multisensory integration by demonstrating the existence of neurons that responded indiscriminately to information from different senses and that also integrated that information (e.g., Meredith et al., 1987; Wallace & Stein, 1997), it was also possible to lay out the governing rules of such multisensory integration processes (Noel et al., 2018), namely the *spatial, temporal* and *inverse effectiveness* principles. The *spatial* and *temporal* principles state that the closer, respectively, in space or time two unisensory stimuli are from one another, the more readily they will be integrated or bound into a unitary multisensory percept; the *inverse effectiveness* one states that multisensory gain is the greatest when unisensory stimuli evoke weak neural responses.

interaction between vision, touch, and proprioception[7], and it can be explained by referring to a visuotactile multisensory conflict (Salvato et al., 2020) generated when both the real and the rubber hand are synchronously stimulated, thus leading the subject to experience a feeling of ownership towards the fake hand (Botvinick & Cohen, 1998). This demonstrates that multisensory processing aims at the integration of sensory signals and the resolution of potential conflicts, with the final goal of generating a coherent representation of the world and of the body that is based on the available sensory evidence (Tsakiris, 2017). This type of mismatch between visual and tactile inputs has been also proved to be effective in the case of faces (Sforza et al., 2010) and of the whole body (Ehrsson, 2007; Leggenhager et al., 2007).

Exteroceptive bodily signals are mainly originating from the so-called *peripersonal space,* that is, from the immediate space surrounding one's own body and aligned with positional changes in the body in space, thus including all the sensory inputs such as tactile, visual, and auditory ones (Park & Blanke, 2019). They are basically afferent sensory signals that involve vision, audition, gustation, olfaction, and touch and that – being *bodily* signals – involve a human body or body parts. Proprioceptive[8] information refers to both the sense of movement of the limbs and of the body parts and their position in space, and in relation to one another. Interoceptive bodily signals are, instead, those that bring afferences from the inner organs, and they include information such as the cardiac, respiratory, vestibular, and intestinal one (Park & Blanke, 2019).

Whereas for exteroception and proprioception it was already strongly supported their role in building a sense of the self, the same cannot be said for interoception until quite recently: especially with the work of Damasio (1999; 2003a; 2003b; 2010), interoceptive signals have started to be considered not only for emotions, but also for self-consciousness and, even more in particular, for *bodily* self-consciousness.

It is still not clear the precise interaction between the different sources of information, but a lot of findings have shown the existence of essential forms of integration between interoceptive, proprioceptive, and exteroceptive signals (Salvato et al., 2020). From a behavioral point of view, illusion paradigms such as the one already mentioned (*RHI*), but also the *mirror box*

[7] More recently, although some discordant results, *interoception* has also been considered fundamental also in this kind of bodily illusions, as it will be shown later in this work.

[8] The term "proprioception" was coined by the neurophysiologist Charles Sherrington in 1906 (ed. 1952) from the Latin word *proprius,* meaning *of oneself*, and the English word *reception,* that is *perception.*

illusion[9], have proven that, when interfering with the normal processing of signals coming from and to the body, a disruption of at least one of the aspects of bodily self-awareness is inevitable. For instance, Tsakiris and colleagues (2011) have proven the modulation operated by interoception on the malleability of the sense of the self: they administered the *RHI* paradigm to a group of subjects who had different levels of *interoceptive accuracy* (meaning that were differently able to detect their internal afferences), demonstrating that this latter capacity had a strong impact on the incorporation effect of the rubber hand. This suggested that, in the absence of accurate interoceptive representations, one's model of self is predominantly exteroceptive (Tsakiris, 2017), proposing for the first time the possibility of an *antagonism* between interoceptive and exteroceptive cues in bodily self-awareness. Suzuki and colleagues (2013) also showed not only that interoceptive accuracy influences the feeling of belonging of the fake and of the rubber hand, but also that this kind of relationship is further modulated by the integration of other signals, namely the proprioceptive ones; or, again, inducing a conflict between visual and proprioceptive feedback with a mirror box – thus interfering with the multisensory integration process – caused alterations in some subcomponents of *embodiment*, as showed, for example, by Medina and colleagues (2015).

Many hypotheses have been proposed about the specificities of the relationship between exteroceptive and interoceptive information in building and structuring self-awareness (Salvato et al., 2020), one of the most intriguing ones being the theoretical framework proposed by Moseley, Gallace and Spence (2012) about the existence of a *body matrix.* This refers to a set of neural structures able to maintain the integrity of the body "at both the homeostatic and psychological levels to adapt to changes in our body structure and orientation" (Moseley et al., 2012). This concept, as the authors highlighted, contrasts with previous dichotomous distinctions between a body schema and a body image (e.g., Gallagher, 2005), but it integrates these constructs by proposing a direct relationship between cognitive representations (e.g., ownership towards a body part) and homeostatic functions (in their case, specifically thermoregulation).

[9] In the *Mirror Box Illusion,* participants place both their hands into a box separated by a mirror that occludes one hand. Participants then view a reflection of their own hand in a mirror that is in a different location than their actual, occluded hand. They are then instructed to synchronously and asynchronously tap with both hands while viewing the reflected hand in the mirror. If the illusion is successful (*synchronous* condition), participants will experience a shift in the perceived location of their hidden hand such that they report feeling it at the location of the mirror-reflected hand, often resulting in feelings of ownership of the reflected hand. In the asynchronous condition the hands tap out of phase, thus creating incongruent multisensory information (Crivelli et al., 2021; Leach & Medina, 2022).

In particular, this multisensory representation of peripersonal pace and of the space directly around the body, namely the body matrix, is likely to receive inputs from areas that code for visual, tactile, interoceptive, and proprioceptive inputs, with the specificity of being aligned with a *body-centered* frame of reference. It could be altered by abnormal feedback from other areas of the brain, just as it could happen after neurological damage, and this would explain phenomena such as the *RHI*.

2.2.1 NEURAL BASES OF THE MAIN SOURCES OF INFORMATION

Since most research on self-consciousness has, until recently, focused only on the investigation of either exteroceptive or interoceptive signals (Park & Blanke, 2019), there is quite a lot of information about the contribution of the single sources of information separately.

For instance, when it comes to exteroceptive signals, human neuroimaging studies have suggested the main involvement of a network of multisensory brain areas in the premotor cortex (PMC), intraparietal sulcus (IPS), and temporoparietal junction (TPJ) being fundamental the presence of multimodal neurons[10] able to process different sensory modalities (Ionta et al., 2011; Petkova et al., 2011; Guterstam et al., 2015) (see Figure 1). In particular, next to their sensitivity to tactile, visual, and auditory signals, these neurons also integrate proprioceptive and sometimes vestibular inputs, allowing to anchor their multisensory receptive fields to the different body parts and to maintain spatial congruency between visual, auditory, and tactile receptive fields (Blanke et al., 2015).

[10] Bimodal and multimodal neurons, mainly located in the posterior parietal cortex (PPC), posterior insula, and premotor cortex (PMC) of non-human primates, have the property of responding not only to stimuli in one modality, such as the tactile one, but also to visual, auditory, and proprioceptive signals (Blanke et al., 2015). This type of neurons can also be found in the frontal cortex more extensively, and these fronto-parietal areas, strongly interconnected, are thought to form a fronto-parietal multisensory-motor network supporting sensory-motor functions (Rizzolatti et al., 1997, 2002; Andersen, 1997).

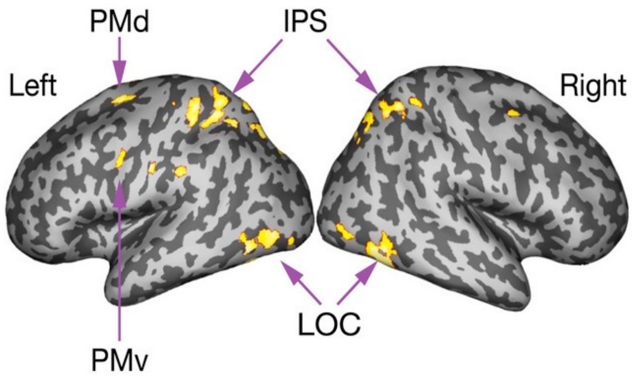

Figure 1: Activation of some of the main areas involved in the processing of efferent information. PMd = dorsal Premotor Cortex; PMv = ventral Premotor Cortex; IPS = Inferior Parietal Sulcus; LOC = Lateral Occipital Cortex. Adapted from Guterstam et al., 2015.

Instead, when it comes to afferent, interoceptive signals, the main areas involved have been proven to be the insula, the cingulate cortex, the brainstem (mainly through the nucleus of the solitary tract, and the parabrachial nucleus), and the thalamus (Park & Blanke, 2019; Liesner et al., 2021) (see Figure 2).

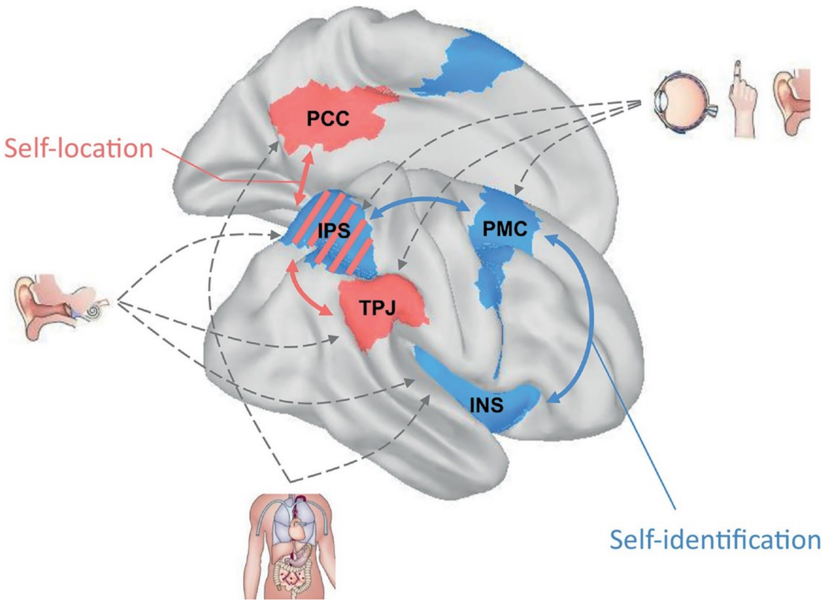

Figure 2: One of the neural Bodily-Self Consciousness models proposed. Both the exteroceptive (e-BSC) and the interoceptive (i-BSC) models are presented. PCC = Posterior Cingulate Cortex; IPS = Inferior Parietal Sulcus; PMC = Premotor Cortex; TPJ = Temporo Parietal Junction; INS = insula. Adapted from Park & Blanke, 2019.

In particular, the insula appears to be one of the most important structures involved in a variety of processes ranging from the physiological ones to some of the most high-level, cognitive ones (Craig, 2002; Park & Blanke, 2019): it is recruited by interoceptive awareness –

in particular, the anterior insula (Craig, 2002; Critchley et al., 2004) –, temperature perception (Craig et al., 2000), homeostasis more in general (Oppenheimer et al., 1992), emotions (Johnstone et al., 2006), decision making (Thielscher & Pessoa, 2007), self-recognition (Devue et al., 2007), the detection of the coincidence of the multisensory feedbacks generated by volitional movements (Berlucchi & Aglioti, 2010), and many others. The relevance of this area is currently still being unraveled, as it is the central interoceptive hub in the brain (Tsakiris, 2017): it has a fundamental role in integrating bodily and environmental information to optimize homeostatic efficiency, and also in representing the "material me" in the brain (Craig, 2009). A lot of findings[11] have basically suggested that interoception does not only participate in emotion and phenomenal consciousness, but its role for self-awareness may be much wider than this; also, the senses of *unity* and of *stability* of the self – so essential in every aspect of the everyday life – could be based on awareness of the interoceptive body, because interoception is both required for the experience of a unified, non-hollow self, and it can counteract the ever-changing influence of exteroceptive signals (Tsakiris, 2017).

The insula covers a pivotal role also in the theoretical conceptualization of the body matrix cited before (Moseley et al., 2012): the connections between the insular cortex and the posterior parietal cortex – where the processing and the integration of spatially based information happen – seem to be the most relevant ones.

2.3 SENSE OF BODY OWNERSHIP AND SENSE OF AGENCY

As it has already been mentioned, *self-awareness* is a complex mental state and a multidimensional construct that involves several dissociable experiences (Seghezzi et al., 2019). When delving deeper into this concept, it is fundamental to highlight the construct of *minimal self,* first introduced by Gallagher (2000), and to distinguish it from the *narrative self*: if the first is defined as "a consciousness of oneself as an immediate subject of experience, unextended in time", thus limited to what is accessible to *immediate* self-consciousness, the latter can be described as "a more or less coherent self-image that is constituted with a past and a future in the various stories that we and others tell about ourselves", meaning that it is extended in time (Dennett, 1991; Gallagher, 2000).

The two main levels of bodily self-awareness related to the *minimal self* are the *sense of ownership* – that is the feeling of belonging of the body, thoughts, and feelings (Frith, 1992; Gallagher, 2000; Tsakiris et al., 2007) – and the *sense of agency* – the sense that one is the

[11] To quickly get a sense of this, see Tsakiris, 2017.

initiator or the source of the action and the responsible for the consequences of those actions (Gallagher, 2000; Tsakiris et al., 2006).

A fundamental point to address is the relationship that occurs between the two and their degree of association. Many hypotheses have been proposed, even differing on the level at which one could interpret them primarily. For example, Graham and Stephens (1994), following the account of *self-referential narratives* proposed by Dennett (1987; 1991) and Flanagan (1991; 1992), claim that sense of ownership and sense of agency should be considered primarily at the level of *attribution,* on the basis of a reflective acknowledgment. In this way, they distinguish between mainly three aspects of these two phenomena: (i) attribution of ownership; (ii) reflective ascription of a certain action to myself and attribution of agency; (iii) reflective ascription that "I am the cause or author of a certain action". Thus, the sense of agency firmly depends on whether the subject succeeds in attributing a specific action or thought to themselves[12], determining that the sense of agency is indeed *generated* by a successful attribution – it is the sense that "it was in fact me who did or thought this" (Graham & Stephens, 1994b). Basically, *the sense only occurs as a result of the attribution* (de Haan & de Bruin, 2010).

In contrast, what Gallagher claims is that the senses of ownership and of agency are *first-order, phenomenological* (thus, nonconceptual) *aspects of experience,* and that they are *pre-reflectively implicit in actions* (Gallagher, 2007a, b)*,* thus providing an opposite view to Graham and Stephens, that is, *attributions reflect the senses that underlie them.* This means that the higher-order conceptually informed attributions of ownership and agency *depend* on these first-order experiences.

Thus, for Graham and Stephens at first we *attribute* a specific action or thought to ourselves, and only if we succeed in doing this, then we are able to experience the *sense* of ownership and of agency: I acknowledge that "it was *me* who did or though this" (I attribute to *me* this action or thought), and then I experience the *sense* of ownership or of agency. Instead, Gallagher claims that it is the other way around: we first *experience the senses* of ownership and of agency, and only then we *attribute* them to us. So, I do something, I think something, and I experience a sense of agency or ownership towards those experiences, but only after this I acknowledge

[12] This means that the sense of agency strictly depends on whether the subject manages to fit this action or thought in the image he has of himself, that is, if that is the sort of action or thought that he would expect himself to have, *given his picture of himself* (Graham & Stephens, 1994b). In this way, it is possible to understand how these two senses, which Gallagher attributes to his notion of *minimal self* (Gallagher, 2000), for Graham and Stephens are tightly connected to what the *narrative self* is, according to Gallagher.

that "it was *me* who did or thought this". In this regard, and to try to better disentangle the mechanisms underlying the two, many definitions have been provided for both the senses of ownership and agency.

The sense of ownership has been defined by Gallagher (2000, b; 2005; 2007a) not only in terms of experience but also in terms of *mineness* (Gallagher & Zahavi, 2020) – an experiential feature of the minimal self, constant throughout all experience and that only depends on the experience itself[13] – and in terms of *proprioception*, because it involves proprioceptive awareness, meaning that one experiences the body as perceiver and actor; this implies that the awareness of the body is of a tacit and implicit kind, resulting from the proprioceptive feedback that is omnipresent in any kind of movement.

The definition and the conceptualization of the *sense of agency* have also been reworked by Gallagher, at first being referred to the sense that one is the initiator or the source of the action (2000), but then adding layers of complexity to it by acknowledging the contribution of efferent signals, sensory afferent feedback and intentional feedback that all together have to be used in order to produce the sense of agency (Gallagher & Zahavi, 2008). In this way, it arose the necessity of distinguishing between a sense of agency as first-order experience linked to *bodily movement* itself (Gallagher 2000a, b; Farrer et al., 2003; Tsakiris & Haggard, 2005) and a sense of agency for the *intentional aspect* of an action or a goal (Farrer & Frith, 2002). Also, although claiming to criticize Graham and Stephens's perspective, Gallagher postulates the existence of a sense of agency – and, although never explicitly claiming this, of a sense of ownership – at the level of *attribution* (Gallagher & Zahavi, 2008).

Sticking to a phenomenological approach, Gallagher (2000) postulates the need for a clear and categorical distinction between sense of ownership and sense of agency when it comes to actions: the first one can be explained in terms of ecological self-awareness built into movement and perception, that is, referring to the notion of *ecological self* – the self as directly perceived with respect to the immediate physical environment (Neisser, 1988; Gallagher & Marcel, 1999), whereas the sense of agency for action is based on what precedes action and translates intention into action (Fourneret & Jeannerod, 1998; Marcel, 2003). This dependence of higher-order attributions of ownership and agency on first-order experiences led Gallagher (2000) to claim

[13] In "*The phenomenological mind: an introduction to philosophy of mind and cognitive science*" (Gallagher & Zahavi, 2008), it's claimed that "the self is conceived as the invariant dimension of first personal givenness in the multitude of changing experiences" (p. 204): this experience of *mineness* is essential for the minimal self, since it is the most primitive form of experience that is necessarily self-conscious (de Haan & de Bruin, 2010).

that these two experiences are to be considered intimately coupled and indistinguishable in the normal experience of voluntary or willed action, but when it comes to involuntary movements, automatic actions and thoughts[14] – and also unbidden thoughts and schizophrenic experiences such as thought insertion – it is in fact possible to clearly separate the two.

Instead, other authors (e.g., de Haan & de Bruin, 2010; Seghezzi et al., 2019) suggest that the distinction operated by Gallagher should be challenged: even when it comes to involuntary movements – to reflexes as well –, but also unbidden thoughts and thought insertion, agency is not totally absent: the sense of ownership and sense of agency remain profoundly related, so that distortions of the latter affect the former as well: most forms of SoO already come together with SoA. de Haan and de Bruin (2010), for instance, propose a more gradual reading of the distinction between SoO and SoA rather than a categorical distinction between the two, in particular focusing on the differences between *volitional actions* and *habitual body movements* and considering them as poles on one axis of more or less deliberate intentionality.

Nowadays, it is still unclear how and to which extent sense of ownership and sense of agency are related; what has been proved is that whereas one experiences a sense of agency only for voluntary movements (Tsakiris et al., 2007; Seghezzi et al., 2019), the feeling of ownership is continuous and omnipresent, regardless of whether the body is acting and both for voluntary and involuntary movements (van den Bos & Jeannerod, 2002; Seghezzi et al., 2019). As a consequence, it has been proposed that the sense of ownership could be a part of the sense of agency, to create which it is necessary to add the experience of voluntary control (Tsakiris et al., 2007; Longo & Haggard, 2009; Haggard, 2017). If one sticks to the distinction between the two senses at the level of higher-order consciousness, that is, at the reflective or introspective level, (Graham & Stephens, 1994a), then it could be reasonable to say that the higher-order *attributions* of agency and ownership may depend on the first-order *experiences* of them. This distinction at the pre-reflective level – meaning at the level of first-order phenomenal consciousness – has been though criticized: reports of agency and of ownership can be assumed

[14] What Feinberg (1978) claimed, analyzing the corollary discharges associated with motor commands in the CNS, and proven to alter activity in both sensory and motor pathways, was that equally legitimate could be "the proposition that the successful mechanisms of corollary discharge, required for integration and control of movement at simple levels of Central Nervous System (CNS) function, would be retained throughout evolution and play a role in the motor phenomena of conscious thought"; these corollary discharges accompanying conscious thoughts are themselves conscious, that is, they correspond to the experience of will or intention.
Sticking to this perspective, Frith (1992, ed. 2015) postulated that not only the intended and self-generated thinking is a kind of action, but that it has also to match the subject's intention for it to feel self-generated, in the same way that it happens for motor actions. Thus, it is possible to claim the existence of a sense of agency and of a sense of ownership for thought.

to be reports of pre-reflective, first-order experience of bodily states and actions, thus the sense of ownership is the pre-reflective experience or sense that one is the subject of the movement, that one is the one that is moving – voluntarily or involuntarily – or that one is experiencing a specific sensation, while the sense of agency is the pre-reflective experience or sense that one is the *cause* or author of the movement.

More recently, also neurocognitive models have been developed in order to account for the complexity of the relationship between sense of agency and sense of ownership, the three main ones being: (i) one so-called "additive" model (Tsakiris et al., 2010) that assumes that, as already mentioned, the sense of agency always contains the body ownership, plus an additional specific component that is the experience of voluntary control; this would imply the presence of a brain network shared by both the senses, but also an additional brain region specific for the sense of agency. (ii) The same authors also proposed another model, the "independence" hypothesis, that argues that agency and ownership represent distinct, qualitatively different and independent experiences, thus there should be no overlapping brain regions at the neural level. (iii) A third, more comprehensive model, so-called "interactive", was proposed by Seghezzi and colleagues (2019), that suggests that body ownership and agency can be considered as partly different experiences, but still tightly related, interdependent and interacting at the neurofunctional level: indeed, as it had already been demonstrated, the sense of agency, despite depending on the sense of ownership, is also a reliable cue to the feeling of ownership itself. At the neurocognitive level, thus, apart from the existence of brain regions specifically associated with sense of ownership and other regions related to agency, there should also be a set of brain regions shared between the two.

While the results of Tsakiris and colleagues (2010) were apparently inconsistent[15], the research group of Seghezzi (2019) provided a stronger and more reliable support for the interactive neurocognitive model. Even if body ownership and the sense of agency are grounded in part on the same multisensory integration processes, it is still possible to consider them as different experiences supported by partially distinct brain networks, exclusive for each

[15] What Tsakiris and colleagues (2010) found was an ensemble of partly contrasting results: on the one hand, neuroimaging data supported the independence model, while questionnaires were more akin to an additive one. This could be due to two main reasons: (a) the questionnaire data might reflect folk psychology for which agency is a very strong cue for ownership, thus one can experience ownership over any events or objects that one can control – in reality, the experience of ownership of actions during agency could represent a different type of ownership with respect to that felt for body parts. (b) the apparent dissociation between neural activity and introspective reports that was found could simply suggest an absence of a *one-to-one* mapping between brain activity and conscious experience.

phenomenon; thus, it could be that the senses of ownership and agency share the low-level processes of sensory integration, thus differing by higher-level, subjective processes (Pyasik et al., 2018).

2.3.1 NEURAL BASES OF SoO and SoA

Already in 1990, Melzack (1990) proposed corporeal awareness as relying upon a large neural network, with the main areas involved being the somatosensory cortex, the posterior parietal lobe and the insular cortex; he also specified the most important neural network, also called *neuromatrix*, for the body schema – with perceptual, mnemonic, and imaginative components – constituted by the somatosensory system, reticular afferents to the limbic system, and cortical regions for self-recognition and recognition of external objects and entities, all being largely prewired by generics but open to continuous shaping influences of experience (Melzack, 1990; Berlucchi & Aglioti, 1997).

When it comes to sense of ownership (SoO) and sense of agency (SoA), more specifically, there have been a lot of studies that have tried to highlight their neural bases.

In particular, for the SoO, most of them were performed by using paradigms such as the *RHI* or the *Virtual Hand Illusion (VHI)*, together with electroencephalography (EEG), functional Magnetic Resonance Imaging (fMRI), and Positron Emission Tomography (PET). The main regions that proved to be involved were the *premotor cortex* (PMC) (Rao & Kayser, 2017), bilaterally (e.g., Ehrsson et al., 2004; Petkova et al., 2011; Gentile et al., 2013); subregions of the *intraparietal sulcus* (IPS) (Ehrsson et al., 2004; Petkova & Ehrsson, 2008; Brozzoli et al., 2012; Rao & Kayser, 2017); the *extrastriate body area* (EBA) (Limanowski et al., 2014); the *putamen* (Petkova et al., 2011); and, again, the *insula* (Tsakiris et al., 2007; Limanowski et al., 2014) (see Figure 3).

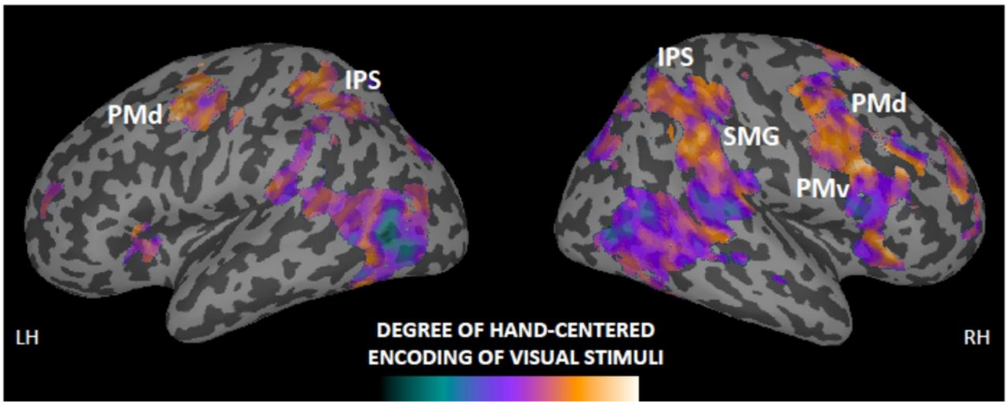

Figure 3: Example of some areas activated during perception of hand-centered stimuli (from 0 to 5, where 5 is the maximum degree of hand-centered encoding). IPS = Inferior Parietal Sulcus; PMd = dorsal PreMotor cortex; PMv = ventral PreMotor cortex; SMG = Superior Marginal Gyrus. Adapted from Brozzoli et al., 2012.

The PMC and the IPS, containing multimodal neurons, could be responsible for encoding one's own phenomenal corporeal space (Braun et al., 2018); the insula, due to its involvement in affective self-awareness and interoceptive integration (Craig, 2009), may represent one of the most important sources for SoO, thus emphasizing even more the role that interoception plays in grounding the phenomenal self (Tsakiris, 2017).

Concerning SoA, two main groups of areas have been highlighted, mainly by David and colleagues (2008) and Haggard (2017), one being composed of regions involved in the motor system, such as the *supplementary motor areas* (SMAs) (also Kühn et al., 2013), the *ventral Premotor Cortex (PMC)* and the *cerebellum,* while the other encompassing more heteromodal association cortices, such as the *posterior parietal cortex (PPC),* the *dorsolateral prefrontal cortex (dlPFC),* the *superior temporal sulcus (STS)*, and the *insula* (see Figure 4). Again, the involvement of the insula appears highly plausible due to its assumed role in bodily self-awareness (e.g., Craig, 2009). However, the way in which all these brain regions contribute to the emergence of SoA remains highly speculative (David et al., 2008; Braun et al., 2018).

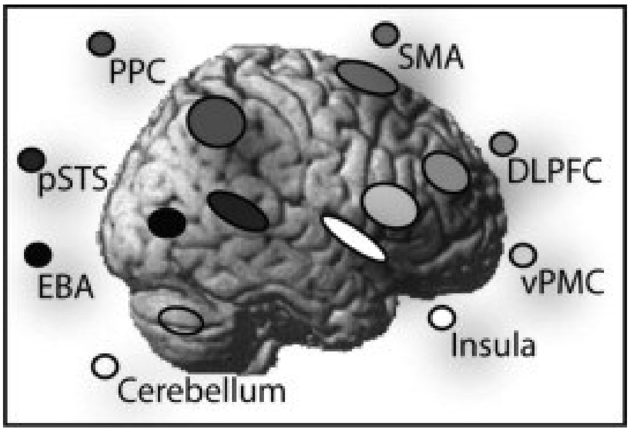

Figure 4: Main areas activated for SoA. PPC = Posterior Parietal Cortex; pSTS = posterior Superior Temporal Sulcus; EBA = Extrastriate Body Area; vPMC = ventral PreMotor Cortex; DLPFC = DorsoLateral PreFrontal Cortex; SMA = Supplementary Motor Area. Adapted from David et al., 2008

2.3.2 RELATIONSHIP BETWEEN SoO, SoA, AND OUR BODY: *EMBODIED SCIENCE*

As already pointed out, the relationship between SoA and SoO is so complex that is still debated and not completely unraveled nowadays. Data and theories are, though, now converging to one common and essential point, which is rooted in the conceptualizations that arose from the post-cognitivist[16] and connectionist[17] revolutions. First, the mind is a *situated mind* (e.g., Thelen & Smith, 1994; Port & van Gelder, 1995; Pfeifer & Scheier, 2001) – referring to the maintenance of a competency as inputs and outputs relevant to the cognitive process affecting the agent (Wilson, 2002); the mind is also an *adaptive mind* (Buller, 2006), meaning that it is able to adapt itself to the ongoing characteristics of the context that is continuously changing and capable of modify and correct itself, and it is also immersed in an *immediate* context (Ricciardelli, 2019). This mind is also, importantly, an *embodied mind,* meaning that the mind is tightly related to the body, thus every knowledge has its founding in experience (*grounded cognition*), and it proceeds on the basis of sensorial, imaginative, linguistic, affective and motivational inputs and from actions (Schubert & Semin, 2009). Cognition and behavior, thus, cannot be accounted for without considering the perceptual and motor apparatus that facilitates the agent's dealing with the external world (Calvo & Gomila, 2009). This implies that understanding cognition involves taking as unit of analysis the system embedded into its surrounding environment, and thus it implicates understanding the *coupled* system as such.

The interest in the concept of *embodiment* (e.g., Clark, 1997; Hurley, 1998; Shapiro, 2004; Gallagher, 2005; Chemero, 2009) can be ascribed to philosophy, in particular with the departure from the Cartesian framework[18] into phenomenology that has its first pioneers in Wittgenstein (1953), Heidegger[19] (1962) and Merleau-Ponty[20] (1962). Heidegger defines the entire world as the sum of all cross-references between the objects, and thus it is seen as based on *what we can do with objects and entities*: *to exist,* for him, means primarily *to carry out the possibility of*

[16] Post-cognitivism has gained momentum since the 1990s, as the vindication of embodiment for the understanding of cognition (Anderson, 2003). There are many perspectives that are part of this umbrella term, among which there are the *ecological psychology* (Gibson, 1966, 1979, ed. 2014; Turbey & Carello, 1995), *behavior-based AI* (e.g., Brooks, 1986, 1991; Pfeifer & Scheier, 2001), *embodied cognition* (Varela et al., 1991, ed. 2017; Clancey, 1997), *perceptual symbol systems* (Glenberg, 1997; Barsalou, 1999). All these approaches consider cognition and behavior in terms of the *dynamical interaction* of an embodied system that is constantly communicating with the surroundings (Calvo & Gomila, 2009).

[17] Connectionism is a perspective developed starting from the mid-20th century that relates the biological architecture of the brain with the functional architecture of the cognitive activity (Ricciardelli, 2019) and that is inspired by the neural structure of the brain.

[18] For Cartesian philosophy, the body is both necessary and unacceptable, and this ambivalence drives the mind and the body apart (Anderson, 2003).

[19] Heidegger starts from the idea that things *are present, manifest themselves, appear, without being thematically present, without being the explicit theme of a direct perception.* The relationship we have with things is called *taking care* and, in doing so, things manifest themselves as *means adapt to a specific aim.* What is primary, then, isn't knowledge – conceptualized as the mere presence of the object –, but is *taking care, the practical relationship* with objects (La Vergata & Trabattoni, 2011).

[20] One of the major themes that Merleau-Ponty analyzes is the *concreteness,* that is the fact that our mind lives a body: the mind isn't *added* to the body as something extraneous, but it creates a whole with the body, a *third substance* with respect to the traditional Cartesian dichotomy between soul and body. Our body is not just a simple *tool* for our soul, our thought, it's not a simple machine serving the mind, but it's a *living* body, full of qualities and of characteristics that we are used to reserve to the soul (La Vergata & Trabattoni, 2011).

acting, not simply to knowing objects (La Vergata & Trabattoni, 2011). On the same line, Merleau-Ponty argues that perception and representation always occur in the context of, and are therefore structured by, the embodied agent in the course of its ongoing purposeful engagement with the world: experience, which consists of ongoing inputs from many different sources, is unified into a single object of consciousness by, and in terms of, our practical orientation to the world. It follows that the subject, which controls the integration of the contents of experience, is the *body-subject in its ongoing active engagement with the world* (Calvo & Gomila, 2009).

Another extremely important contribution comes from the work of George Lakoff and Mark Johnson. They argue that the various domains of mental life are related to one another by cross-domain mappings and, in their "Philosophy in the flesh" (1999), they also claim that all cognition eventually grounds out in embodiment. Basically, their work suggests that our thinking about purposes, time, states, and change, is *rooted in our thinking about space,* and our concepts of space are *deeply tied to our bodily orientation to, and our physical movement in, the world*. They identify four main aspects of embodiment: (a) the *physiology* – the mind is inherently embodied, not just because of the instantiation of all its processes, but also because our perceptual and motor systems have a foundational role when it comes to concept definition and rational inference[21]; (b) the *evolutionary history*, which can be seen from two main perspectives: (i) one of the *sentiment,* for which perceptual and motor inference (even present in lower animals) are fundamental for abstract reason[22]; (ii) and one of the *emergence,* which relates complex behavior to the physical and evolutionary grounds of the agent; (c) the *practical activity*, because our problem-solving routines involve both cooperation between computations and internal representations, and repeated environmental interactions. The cognitive strategies that we use are shaped by the performance characteristics of our body as a whole in the given circumstances, and also by our brain's limited computational resources; and (d) *socio-cultural situatedness,* in that interactions with environment are always themselves situated in a broader social and cultural context. Action has social meaning, and agency takes place within cultural structures that are not directly under the control of the actor.

[21] For instance, even in the conceptualization of colors there is a "center-periphery" structure, with some colors being focal and others are conceptualized in terms of their focal hue.

[22] This means that the very structure of reason itself comes from the details of our embodiment, and those same neural and cognitive mechanisms that allow us to perceive and move also create our conceptual systems and modes of reason.

Specifically, what research in *embodied cognition* at the beginning departed from is the hypothesis, typical of cognitivism, that the central functions of the mind could be accounted for in terms of the *manipulation of symbols according to specific rules* and that, thus, the results of learning – and the precondition for more learning – is nothing more than the acquisition and retention of many facts about the world and how it works (Anderson, 2003).

One of the main authors in the field is claimed to be Rodney Brooks (1999), which criticizes this hypothesis proposing primarily to study intelligence not from a top-down approach, as it had been done until that moment, but from a bottom-up perspective, also emphasizing the continuity between humans and animals already highlighted before. According to his view, problem solving behavior, language, expert knowledge and application, and reason are all simple, once the essence of *being* and *reacting* are available. That "essence" is nothing else than the *ability to move around* in a *dynamic environment*, sensing the surroundings to a degree sufficient to achieve the necessary maintenance of life and reproduction.

Thus, he emphasized this continuous path from lower to higher cognition, also underlying all the different forms in which cognition appears to depend upon the physical characteristics, ability, and *situatedness* of the agent. Intelligence would, in this way, be the result not of a unique ability to perform complex, symbolic cognition *in abstraction from the environment,* but of the remarkable richness of the environment in which agents do their thinking[23].

It follows that what it is usually considered as humans' mental capacities may be properties of the wider, environmentally extended systems of which human brains are just one of the many important parts (Clark, 1997). The repeated interactions with the highly structured environment in which we are immersed are fundamental, but so it is the first-personal perspective of the agent: the agent's behavior arises only if he is aware of the socially instantiated role he is playing, and regulates his behavior taking into account both the perceived situation and role.

This concept of subjectivity has been further considered by another important researcher in the field, William Clancey (1997), who refers to it by considering the functional interactions between agent and environment which requires a special notion of *goal-drive*. In this sense, subjectivity is not realized as possessing a subset of "facts" or "misconceptions" about the

[23] It follows the importance that institutions and practices could have in supporting the possibility of high-level cognition. These structures, called *scaffolds*, occur when an epistemic action results in some more permanent cognitive aid, that is symbolic, or social-institutional (Brooks, 1999): we are able to do many complex things (e.g., language, maps, road signs), by creating larger external structures, that are both physical and social, that make us able to break down a big, complex problem into smaller and easier subproblems (Clark, 1996, ed. 1997).

world, but it is a form of feedback between how the world is perceived and how the person conceives his or her identity. Clancey claims that the "situation" within which agency must be understood, and through which cognition takes place, has both internal and external dimensions: an agent's "situation" is itself not static, but arises in the course of *dynamic* transactions between internal and external resources and structures.

Humans are essentially *embodied agents,* and advanced cognition vitally depends on a substrate of abilities for moving around in, and coping with, the world. Cognition exploits repeated interaction with the environment, not only using the world as its own best model but creating structures which advance and simplify cognitive tasks (Anderson, 2003).

Basically, what has been named *embodied science* – or *embodied cognitive science,* or in some recent conceptualizations *radical embodied cognitive science* – (Clark, 1997; Chemero, 2009) is an approach to psychology that relies on the Jamesian functionalist tradition[24] and which combines nonlinear dynamical modeling[25] with ideas about the nature of the mind from James Gibson and phenomenological philosophers cited above (Chemero, 2013). Especially with Gibson (1979, ed. 2014), it is put into evidence the organism-environment system as the central aspect of perception and cognition. Explanations for humans' behavior should not come from latent, abstract unseen entities (namely, the *mental representations*), but from an understanding of all the possible actions and of their relation to the structure of the environment in which they are embedded. Bodily skills and environmental affordances are essential to cognitive behavior, and they generally account for how the individual is capable of coordinating the behavior even when immersed in a constantly changing environment (Kiverstein & Miller, 2015). All the psychological functions are better understood only when considered at the level of the whole brain-body environment.

The most important point is that cognition and perception are not solely functions of the brain, but are also, and especially, influenced by the body and by its interactions with the environment as well as with the physical world. Mind and body are tightly interconnected, to the point that they shape our understanding of the world.

This consideration has also been largely demonstrated in neurocognitive and neuroscientific studies. Going back to the aforementioned RHI paradigm (see section 3 for a more detailed

[24] William James, as it is already known, approached psychology in the broad Darwinian tradition, focusing on the ways in which the mind adapts to the environment.

[25] Nonlinear dynamical systems are *chaotic* systems, very sensitive to their initial conditions and characterized by the impossibility of predicting long-term behavior (Wang et al., 2023).

explanation), for example, we can easily understand how even our most simple perception is constrained and limited by the body that we live in. Since we experience the feeling of “the same old body always there” (James, 1890/1891, p. 242, from Tsakiris, 2010), manipulating the *experience* of body ownership seems a viable mean to try to demonstrate what grounds the experience of our body as our own (Tsakiris, 2010). First of all, the induction of the RHI – thus, the experience of ownership of the rubber hand – has been proved to alter the physical similarity that subjects feel between their own hand and the rubber one (i.e. they perceive the two as significantly more similar with respect to those who do not experience a vivid illusion) (Longo et al., 2009). These changes cause incorporation and replacement of one’s own hand during the induction of the illusion (Tsakiris, 2010). Most importantly, as it will be more precisely explained in the next section (3.3.3), the alteration in the experience of ownership during the RHI is also accompanied by changes in the homeostatic regulation of the real body part (i.e. the hand), with the magnitude of the alteration being proportional to the strength and the vividness of the illusion (Moseley et al., 2008). This clearly demonstrates how experienced ownership towards a “new body part” (even if illusory) directly influences the real body (Tsakiris, 2010), again highlighting how *embodied* our cognition can be. Cognitive processes that disrupt the awareness of our physical self are also able to disrupt the physiological regulation of the self (Moseley et al., 2008).

Contrary to what initially hypothesized (e.g., Armel & Ramachandran, 2003), the visuo-tactile congruence is not a necessary and sufficient condition for the induction of the RHI, thus it’s not true that any kind of object, despite its shape, texture, position, can be identified as one’s own. There has been proven to be an important top-down influence exerted by non-primarily sensory representations of the body (Tsakiris, 2010): body-related percepts are correlated *and* necessarily integrated against a number of background elements and conditions that preserve the coherence of bodily experience (Graziano & Botvinick, 2001). Some conditions have necessarily to be present in order to successfully induce the experience of ownership towards an external object, and these are strictly determined by anatomical and postural constrains with respect to the real body, such as the visual form congruency between the external object and the involved body part (e.g., Haans et al., 2008), the volumetric congruency between the two (e.g., Pavani & Zampini, 2007), their postural congruency (e.g., Costantini & Haggard, 2007), and their spatial relationship (e.g., Lloyd, 2007). Again, cognitive processes, such as the experience of body ownership, are tightly related to our body, i.e. they are *embodied*[26].

This concept of embodied cognition also considers action as one of its key notions (Borghi & Cimatti, 2010), having a crucial role in determining cognition – which is constrained by the kind of body we possess (Gallese, 2008). Again, the RHI comes in help in demonstrating this: this experimental manipulation sheds light not only on how the sense of body ownership is generated during purely sensory events, but also as to how the presence of agency modulates body ownership (Tsakiris et al., 2007). In particular, the absence of any kind of movement in the classic RHI paradigm could account for an interesting finding regarding proprioceptive awareness, as already demonstrated by Tsakiris and Haggard (2005). The implicit effect of the RHI, namely the proprioceptive drift, can be only observed in the stimulated finger, whereas for the unstimulated ones it was not detectable. Visuo-tactile associations at this level operate to produce integration only at a very local level, thus one could hypothesize that the more general sense of ownership, involving the whole body, could depend on a more complex mechanism, going beyond the mere perception of the pattern of stimulation (Tsakiris et al., 2007). As pointed out by literature in the field, the different sensory and motor representations at the cortical level could give an important explanation (e.g., Blankenburg et al., 2003; Hlustik et al., 2001; Lemon, 1988): the localized effects of the RHI could arise from the activation of local and segregated representations in SI, thus during active movement of a single digit, the quantitative measures of the illusion related to it could be generalized and extended to all the other digits; this would imply that active movements, compared to passive stimulation, would induce a more global and coherent form of proprioceptive awareness (Tsakiris et al., 2007; Borghi & Cimatti, 2010) and, thus, acting with one's own body clearly participates to our cognitive processes[27].

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[26] Another example of this comes from the neurocognitive model of body ownership proposed by Tsakiris (2010). During the RHI, according to this hypothesis, there are three main critical comparisons that take place between the external information (e.g., visual form of the object, postural and anatomical features of the object involved, the current sensory input) and the information about the own body (a pre-existing body model with a reference description of the visual, anatomical and structural properties of the body; the current state of the body; and the reference frames relative to the current sensory input, respectively). The subjective experience of ownership, thus, would be the result of the incorporation of the external object updating the body model, with a subsequent physiological regulation of the body itself.

[27] These considerations could be further demonstrated for a lot of other cognitive processes, such as motor cognition, but especially language and social cognition (e.g., Borghi & Cimatti, 2010), but due to time and space constraints it is not possible to explain them in this work.

2.3.3 BODY OWNERSHIP AND TEMPERATURE

As already mentioned, one of the most crucial factors in determining the experience of owning a body is *interoception,* which consists of all those signals that are accessible to only the agent herself (Liesner et al., 2021), thus providing a very strong and, most of all, unambiguous cue of ownership.

A growing body of research has demonstrated that, among all the signals coming both from the internal models of the body and from the external environment, *temperature* might play a fundamental role (Crivelli et al., 2023).

In many pathological conditions (e.g., stroke, schizophrenia, epilepsy, anorexia nervosa, neuropathic pain) it is possible to observe both a disruption of the SoO and of temperature regulation, but the latter has always been attributed, until quite recently, to disruption of, or damage to, structures subserving autonomic control (e.g., Bruch, 1962; Lautenbacher et al., 1991; Halligan et al., 1993; Chong et al., 2004; Moseley, 2005; Holtkamp et al., 2007).

Moseley and colleagues (2008) were the first ones to propose, and to consistently demonstrate, that disruption of temperature regulation might be directly linked to disruption of body ownership. They performed six *RHI* experiments on healthy subjects and found that the illusion evoked a *limb-specific* decrease in the temperature of the participants' hands, together with a decrease in the weight given to tactile information coming from that same hand. Also, the observed decrease in temperature was associated with participants *explicitly* reporting an alteration in the SoO towards their involved limb. These results align with previous clinical observations on patients with a pathological alteration of sense of ownership already mentioned, in which a disruption of the sense of ownership was related to alterations in skin temperature. The peculiarity of these findings relies on two main points: (i) they represent the first evidence that it is possible to induce limb-specific changes in temperature regulation in *healthy* subjects*;* and (ii) that this localized effect can be evoked via a *cognitive,* psychological illusion – taking ownership of an artificial body part has consequences for the real involved body part, also physiologically speaking. The awareness of our physical self and the physiological regulation of self are closely linked in a top-down manner.

Also, this effect was interpreted in the direction for which changes in body temperature happen as a *consequence* of the disembodiment following the rubber hand paradigm. Some years later, though, for the first time another group of research hypothesized that the effect of temperature modulation was *bidirectional* (Kammers et al., 2011): they demonstrated that cooling down the participant's hand increased the strength of the *RHI*, and warming it up decreased the illusion.

Evidence of the specific thermoregulatory response related to variations in the sense of body ownership can also be found in brain-damaged patients: for instance, in somatoparaphrenia the sense of disownership felt towards the paralyzed contralesional hand is tightly related to a cooling of that very same hand in response to the administration of the *RHI* paradigm (Van Stralen et al., 2014). A *bilateral* involvement, though, has been found in a single case study in which a somatoparaphrenic patient underwent a *Caloric Vestibular Stimulation (CSV)* and temporarily regained the sense of body part ownership, concomitantly to an increase in body temperature (Salvato et al., 2018). Another study performed on participants with *Body Integrity Dysphoria (BID)*, who show a pervasive desire for the amputation of an intact and functional limb that is perceived as non-belonging to oneself (e.g., Brugger et al., 2013; Gandola et al., 2021; Salvato et al., 2022), showed that the effect of temperature modulation happened bilaterally (the legs here were the involved part) independently of the direction of attention (participants were asked to direct their attentional focus only towards the unwanted limb or towards the accepted contralateral homologue) (Salvato et al., 2022).

One debated and controversial point concerns as to whether temperature modulation can be observed only in the stimulated and involved limb, or if it is more of a bilateral and general effect. For instance, the study of Moseley and colleagues already mentioned (2008) found a unilateral effect, with changes in temperature observable only on the limb involved in the *RHI* (not in the unstimulated hand, nor even in the ipsilateral foot). This thermoregulatory response to the sense of disownership can be also induced when using a *virtual* body (Salomon et al., 2013) or limb (Tieri et al., 2017). In some cases, though, despite inducing the illusion unilaterally, the temperature modulation was observed on both limbs, as in the case of Tieri and colleagues (2017), or in the case of Crivelli and colleagues (2021) who, using a *mirror-box illusion paradigm*[28], found a *bilateral* cooling of the hands skin temperature, in particular in the synchronous condition. Contrary to Moseley and colleagues (2008), in this case this alteration in hands' temperature correlated with the *implicit* measure of the illusion (i.e., *proprioceptive drift*).

[28] The use of this paradigm, instead of the *RHI,* lies on some methodological aspects: (i) the illusion here is *actively* induced by the subject themselves, and not by the experimenter; (ii) whereas in the *RHI* the visuo-tactile stimulation is applied unilaterally, in the *MBI both* hands actively touch the mirror; (iii) both in the synchronous and the asynchronous conditions, the tapping hand movements were constant (Crivelli et al., 2021; Crivelli et al., 2023).

This conflicting evidence prompts researchers to seek new ways to test the possible direct relationship between the sense of body ownership and limb temperature. For instance, Crivelli and colleagues (2023) started from some studies on the sense of ownership, which suggested the possibility that the dominant hand is less susceptible than the non-dominant hand to alterations of bodily self-awareness, being them caused by a multisensory illusion or a brain damage. They hypothesized that the same kind of asymmetrical pattern of body ownership could be visible in skin temperature variations accompanying these variations of self-awareness. Using a *MBI* paradigm on a group of healthy dextral subjects, they explored whether the laterality of the stimulation would influence the cooling effect of the hands: specifically targeting the right or the left hand was associated with changes in skin temperature and proprioceptive drift (an indirect way to test the strength of the illusion), but not with the judgement of ownership. In particular, a *bilateral* decrease in hand skin temperature was only measured when the *MBI* was applied to the *left* hand (thus, being the participants dextral, confirming the hypothesized asymmetry). This result could suggest a fundamental point: the hand for which there is a motor preference (in this case, the right hand) is less affected by ownership modulation not only because it's the most used, but also because it represents the most important tool to perform actions, which in turn underlies all the decision-making processes of our everyday lives.

However, the relationship between body temperature and body ownership has been longed questioned: many studies have been performed, some replicating (e.g., Kammers et al., 2011; Tsakiris et al., 2011; Van Stralen et al., 2014) and others disconfirming (e.g., Rohde et al., 2013; David et al., 2014; De Haan et al., 2017) this hypothesis. Those who confirmed the existence and the strength of this relationship have primarily hypothesized that these modulations of temperature related to body ownership may be mediated by the *insular cortex.* The insula, as already mentioned, has been shown to be a key region in a variety of processes and aspects of our body, such as the feeling of body ownership (e.g., Tsakiris, 2010; Blanke, 2012), as well as the discrimination of thermal sensations (e.g., Craig et al., 2000) and of introspective information more in general (e.g., Craig, 2009). Thus, the insula could be that pivotal neural substrate that mediates the influence of temperature on interoceptive processes. More in detail, the cooling of skin temperature during this kind of bodily illusions has been suggested to relate to a modulation of the homeostatic activity that arises from a change in the body representation (Salomon et al., 2013), with the latter inducing a "disownership" of the real body part involved in the illusion, leading to a modulation of many physiological, behavioral, and tactile aspects (e.g., skin temperature[29], but also tactile processing (Moseley et al., 2008), pain thresholds (Hänsel et al., 2011), or histamine reactivity (Barnsley et al., 2011)).

[29] The variation in skin temperature, although considered significant in many studies, is still very small when it comes to absolute measures: for instance, in the original experiment by Moseley and colleagues (2008) we can talk about changes of about 0.24°C, while in other studies this difference is even smaller, in a range of 0.006-0.014°C (e.g., Salomon et al., 2013).

3. DECISION-MAKING AND INTERTEMPORAL CHOICES

In our everyday lives, we are faced with the constant need to make decisions between different options. Decision-making refers to the cognitive process that underlies our choices and that involves the evaluation of incentives, goal, and outcomes of alternative actions.

One of the most frequent types of decisions that we have to face is represented by the so-called *intertemporal choices,* thus those choices between smaller rewards, that are immediately available, and larger rewards that are though reachable after a longer period of time (Sellitto et al., 2011). This kind of decisions covers a broad range of situations, such as choosing whether to stay at home studying to prepare an incoming exam or postponing it and going out for a walk to enjoy the sunny day, or deciding whether to spend money on immediate gratification items like a luxury dinner that night or to save it for a future road trip.

Making these decisions involves a more or less conscious acknowledgment and balance of the benefits and costs that come with each option, and more specifically they require tradeoff between one outcome that comes temporally proximal with another outcome that is more distant in time (Frederick et al., 2002; Sellitto et al., 2010).

Attention to intertemporal choices can be traced back early in the history of economic conceptualizations, but the starting point for modern theories and models can be identified in the *Discounted-Utility (DU)* model proposed by Paul Samuelson (1937). It was a generalized model for intertemporal choices that could be applied in various and different circumstances and time periods, considering that the tradeoffs performed by people when making choices required a measure of *utility* [30](Ainslie, 1975; Frederick et al., 2002).

This concept of utility has been largely studied in all frameworks of decision making under risk, and in particular it represents the center of the *Expected Utility Theory (EUT),* whom foundations were laid by Bernoulli with the principle of *marginal utility* and that was further developed and extended until quite recently (Von Neumann & Morgenstern, 1944)[31]. Basically,

[30] The term "utility" is generally used in economics, and it represents a measure of relative satisfaction or gratification, for both concrete and abstract benefits (e.g., for both monetary gains and engaging in pleasurable activities) (Kalenscher & Pennartz, 2008).

[31] In particular, Von Neumann and Morgenstern (1944) were the ones who formulated the *four main axioms* of this theory useful to define a *rational decision maker:* (1) *completeness*: an individual has well defined preferences and can always decide between any of two alternatives (given the options A and B, the individual can prefer A to B, B to A or is indifferent between the two); (2) *transitivity*: as an individual makes a decision and has preferences, these are ordered hierarchically; (3) *independence of irrelevant alternatives*: two gambles mixed with an irrelevant third one will maintain the same order of preference as when the two are presented independently of the third one; and (4) *continuity:* there exists some probability such that the individual is indifferent between the most preferred and the least preferred outcome (Von Neumann & Morgenstern, 1944).

what EUT postulates is that, when a decision-maker faces a risky choice, they will decide based on the utility of the final asset positions, pointing to the option that seems to have the highest expected utility[32].

Thus, the *DU* model is the equivalent of the *EUT*, but in the framework of time: it assumes that individuals choose between options based on a *weighted sum* of utilities, with the weighting being represented by temporal discount factors (Kalenscher & Pennartz, 2008). Thus, in order to reach the most rewarding outcome, people balance the utility of the temporally proximal outcome against the one for the temporally distant option (Sellitto et al., 2011).

A large body of research has suggested that, provided that the costs for all the options are identical, the preference for an immediate or temporally remote outcome can be described as a function of the value of the respective outcomes and their delays (e.g., McDiarmid & Rilling, 1965; Ainslie, 1975; Green et al., 1994, 1997; Evenden & Ryan, 1996; Friederick et al., 2002; Reynolds et al., 2002): a reward given after a long delay appears to most people as less attractive than the same reward delivered after a short period of time (Kalenscher & Pennartz, 2008), a process known as *delay* or *temporal discounting* (Samuelson, 1937; Ainslie, 1975). In other words, the value of a future reward decreases with increasing length of time to its receipt (Kagel & Green., 1995; Myerson & Green, 1995), so that the subjective value is weakened (*discounted*) as a function of time (e.g., Cardinal et al., 2001; Sellitto et al., 2011).

Many researchers hypothesized that the delay involved in intertemporal decisions affects behavior in a similar way to what probability does in the context of risky choices (e.g., Kagel et al., 1986; Kacelnik & Bateson, 1996; Green & Myerson, 1996; Frederick et al., 2002): a temporally proximal reward may be preferred to a temporally distant one in the same way in which a more likely reward is chosen over a less likely one (Kalenscher & Pennartz, 2008).

The DU model, moreover, has provided an account for which all the disparate motives that drive individuals' intertemporal choices can be ascribed to a single parameter, that is the *discount rate* (Frederick et al., 2002). This gives a more detailed description of *how* the subjective value of a reward decreases as time passes: in particular, it diminishes by a fixed percentage for each unit of time that those goods are delayed (Samuelson, 1937; Luhmann, 2009).

[32] An important consideration is that here the expected utility is based on the weighted sum of the expected *subjective* values of all the possible outcomes, which do not necessarily coincide with the corresponding *objective* values, because the former are based on factors such as current wealth, biases, individual preferences, and environmental and social aspects (Kalenscher & Pennartz, 2008).

The first conceptualization of the DU model operated by Samuelson (1937) postulated that the trend of the discount rate can be described with a curve represented by an *exponential* function, such as:

$$V = Ae^{-kD},$$

where V is the subjective value of a future reward now; A corresponds to its amount; D is the delay to its receipt, and k a constant parameter representing an individually different discount rate.

One of the main axioms of the DU model is *stationarity,* which predicts that the ranking of preferences between several future outcomes should be maintained when the same choice outcomes are postponed by a fixed interval. If I prefer 30 euros today rather than 40 euros in one month, I should continue to choose the first option even when both the delays are postponed by three months (i.e. 30 euros in three months and 40 euros in four months). This subsequently implies that there should be some sort of neutral attitude towards time delay, an assumption known as *constant discounting*: a given delay should have the same relative impact on utility, thus it should lead to the same degree of discounting, regardless of when it occurs (Kalenscher & Pennartz, 2008; Lowenstein et al., 2008; Sellitto et al., 2011). But this is not what happens in real contexts: subjects tend to prefer a small, short-delayed reward over a large, long-delayed reward but, when the delays to both rewards are advanced by the same time interval, their preference reverses, choosing the larger one instead of the smaller one (Green et al., 1994).

Intertemporal behavior is not so linear, and an exponential function is not able to fully capture the complexity of the reasoning and balancing behind the choices (Frederick et al., 2002). A lot of research (e.g., Ainslie, 1975; Mazur, 1984, 1988; Myerson & Green, 1995) has shown that, since rewards delivered with short delays are more steeply discounted than rewards with longer delays, a *hyperbolic model* could best fit the commonly observed empirical data:

$$V = \frac{A}{1 + kD}$$

where, again, V is the subjective value of the future reward now, A the amount of the future reward, D the delay of availability of the future reward, and k the discount rate, i.e. the parameter governing the rate of decrease in value (Kalenscher & Pennartz, 2008).

Fit to the same data, the hyperbola will follow a specific shape compared to the exponential function: at short delays it will decrease faster, but at long delays it will decrease more slowly.

Also, the hyperbolic model allows to predict the so-called *indifference points,* i.e. those points in which, hypothetically, for the subject would be indifferent to choose one option instead of the other, and the curves with which these points fit best (Mazur, 2009).

There is also to consider an important aspect: discount rates vary across individuals and contexts (Luhmann, 2009). In general, delay discounting in intertemporal choices has been largely related to *impulsivity* and to a number of personality traits (e.g., Takahashi, 2005; Johnson et al., 2010) and internal state features, such as stress or level of hunger, but also to the type of reward offered (e.g., Kirby, 2009).

In particular, higher levels of delay discounting have been proved to be associated with higher levels of impulsivity (Takahashi, 2005), which could lead subjects to have impaired self-control. Thus, they would immediately crave rewards and would not be able to wait for them. Also, large discount rates in adults seem to correlate to extraversion (Ostaszewski, 1996), or a sense of powerlessness over the future (Johnson et al., 2010).

Various populations have been studied in their approach to intertemporal choices, such as children (e.g., Scheres et al., 2006), alcohol addicted (e.g., Petry, 2001), smokers (Reynolds et al., 2004), compulsive gamblers (Holt et al., 2003), and obese people (Sellitto & di Pellegrino, 2014, 2016), who all discount at a faster rate compared to healthy adults, exhibiting an inability to wait for future rewards.

It has also been found a difference between the so-called *primary* and *secondary* rewards (Frederick et al., 2002): *primary rewards,* identified as foods, drugs, or alcohol, highly depend on personal internal states and desires (e.g., Catania, 1998), such as hunger or stress; they can also rapidly bring to satiety, and they are also highly perishable, thus they have been proven to be discounted at a higher rate than secondary rewards. The latter, such as money, seem to have less power in eliciting desire for an immediate reward, especially because they do not expire and they can be exchanged with other rewards (e.g., Odum & Rainaud, 2003).

3.1 NEURAL CORRELATES OF INTERTEMPORAL CHOICES

A huge corpus of research has been conducted to attempt at unravelling the neural bases of intertemporal choices and delay discounting, both in terms of *functional* studies and *lesional* studies.

There are three main neurocognitive models that have been proposed to disentangle the complexity of intertemporal decision making in humans. One of them is the so-called β-δ model, proposed by McClure and colleagues (2004, 2007), which postulates that discounting behavior reflects the differential activation of two distinguishable neural systems: one responsible for *impatient choices,* driven by the desire for present and immediate outcomes, and the other accounting for *prudent choices,* emphasizing more the consequences of choosing delayed outcomes. The first one is the β system, also called the *limbic* one, whereas the other one is the δ system, a *cognitive, prefrontal-cortex-based* one. In particular, the interplay between the activation of these two systems is responsible for the impulsivity or the patience exhibited by people during intertemporal choices (e.g., Loewenstein, 1996; Peters & Büchel, 2011). In particular, the neural bases for the β system are thought to be the ventral striatum, the medial orbitofrontal cortex (*mOFC*) and the medial prefrontal cortex (*mPFC*); the δ system, instead, is thought to be composed by the lateral prefrontal cortex (*lPFC*) and the posterior parietal cortex (*PPC*). They are structured in such a way that when the β system is engaged, it favors the *immediate* option, whereas when the δ system is more active, a *delayed* option is favored (McClure et al., 2004).

An alternative model encompasses, instead, the presence of a *unitary* system, and it was proposed by Kable and Glimcher (2007, 2010) and further extended by Peters and Büchel (2009). In particular, Kable and Glimcher (2007) found that subjective preferences were mirrored in the pattern of activity in three main regions, that are the *ventral striatum, medial prefrontal cortex (mPFC), and posterior cingulate cortex (PCC)*, which are thought to not value immediate rewards only, but also represent the subjective value of delayed rewards. What they found subsequently (2010) confirmed their previous results: the activity in those same regions tracked the subjective value of *both* immediate and delayed rewards, thus showing that these areas do carry a value signal for delayed rewards, instead of an *impulsive* signal for immediate rewards. This led them to postulate the existence of a unitary system for intertemporal choices encompassing mPFC, PCC, and ventral striatum (Peters & Büchel, 2010; Sellitto et al., 2011).

The *self-control* model (Hare et al., 2009; Figner et al., 2010), then, proposed instead two hypotheses about the neurobiology of self-control: (i) goal-directed decisions are based upon a common value signal that is encoded in the ventromedial prefrontal cortex (*vmPFC*), but also that (ii) in the modulation of this signal while exercising self-control there is the involvement of the dorsolateral prefrontal cortex (*dlPFC*). In particular, both this model and the β-δ one predict that *reduced impulsivity in intertemporal choice would involve prefrontal cortex regions* implicated in *cognitive control,* such as the lateral PFC or the ACC (Peters & Büchel, 2010) (see Figure 5).

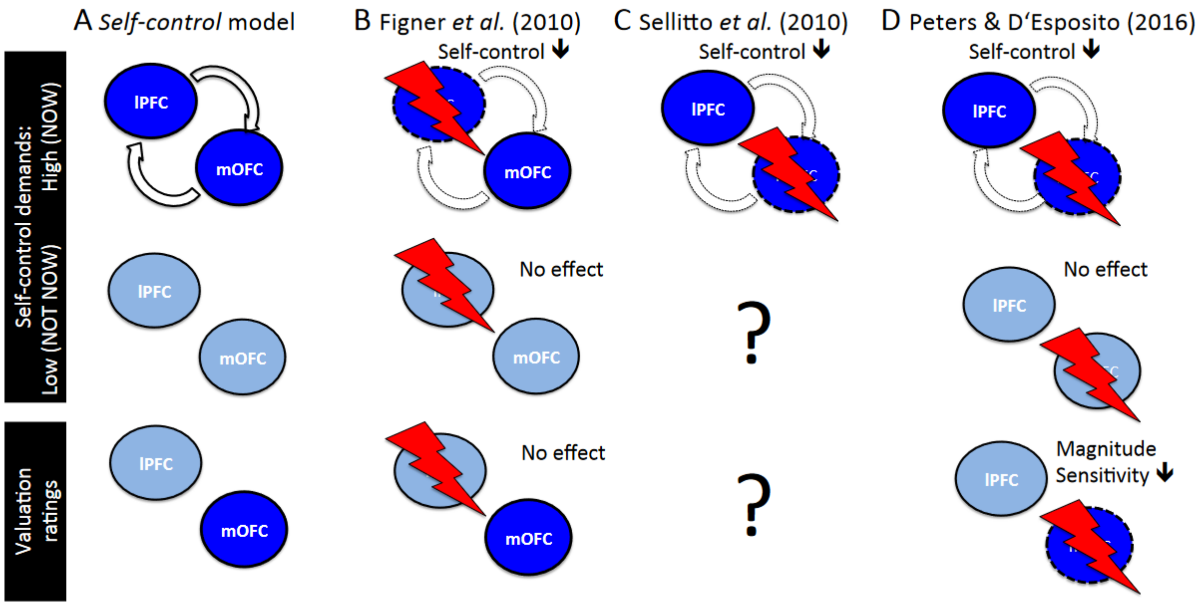

Figure 5: Self-control model (A) and empirical support for the model from other studies (B-D). Adapted from Peters & D'Esposito, 2016.

3.1.1 FUNCTIONAL STUDIES

Cognitive neuroscience has recently drawn particular attention to reward-based decision-making, considering it the result of complex emotional and cognitive processes (Loewenstein et al., 2008; Sellitto et al., 2011), and many functional neuroimaging studies have been performed in order to understand how the subjective value of different rewards is computed in the brain.

Since one of the most important characteristics of the options of these choices is the fact that they are rewards, there has been growing evidence of the involvement of a network of frontocortical and subcortical brain regions (e.g., Luhmann, 2009), specifically the areas belonging to the reward circuit: the orbitofrontal cortex (*OFC*) (e.g., Schoenbaum et al., 1998, 1999; Rangel et al., 2008), the medial orbitofrontal cortex (*mOFC*) (e.g., Kringelbach & Rolls, 2004), the ventral striatum – including the nucleus accumbens NA – the amygdala and the substantia nigra (Haber & Knutson, 2010) all play a fundamental role in this context (Figure 6 shows the key structures of the pathway). In particular, OFC and mOFC are thought to be involved during anticipation of expected rewards to code their value (e.g., Damasio, 1994; Rolls et al., 1999), and to monitor the value of different reinforcers, with the mOFC specifically being sensitive to benefits and positive outcomes and the lateral OFC more influenced by costs such as losses or punishments (Sellitto et al., 2011). Also, these two regions are involved when individuals weight delayed rewards against immediately available rewards (e.g., McClure et al., 2004, 2007; Ballard & Knutson, 2009).

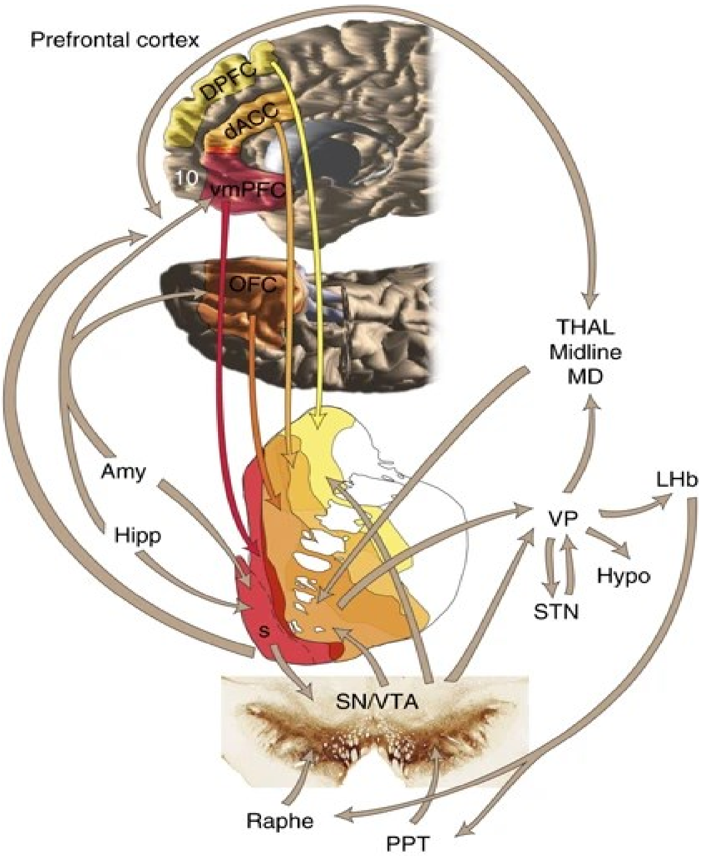

Figure 6: Key areas involved in the reward circuit, and thus implicated in decision-making. Amy = amygdala; dACC=dorsal anterior cingulate cortex; dPFC=dorsal prefrontal cortex; Hipp=hippocampus; OFC=orbital frontal cortex; STN=subthalamic nucleus; Thal=thalamus; vmPFC=ventral medial prefrontal cortex. Adapted from Haber & Knutson, 2010.

As we know, an intertemporal decision is determined by the values of the different outcomes, and the delay until the outcomes can be realized: both these constituents, i.e., reward amount and time, are represented in the brain (Kalenscher & Pennartz, 2008). Some studies attempted to analyze these two aspects. For instance, Ballard and Knutson (2009) showed the involvement of the mesolimbic and lateral brain regions in future rewards evaluation, but in this case differentially according to magnitude and delay of the rewards. What they found was that activity in the nucleus accumbens, mPFC, and PCC positively correlated with the *magnitude* of future rewards, while that in the dlPFC, TPJ, and PCC negatively correlated with the *delay* of future rewards. Basically, more impulsive subjects showed a reduced activation of the nucleus accumbens with respect to the magnitude of the rewards, while increased deactivation of the dlPFC and parietal cortices in relation to more distant rewards in time[33].

Some research work (Tanaka et al., 2004) on reward-based learning showed also a sort of *delay-related gradient* from anterior to posterior insular cortex: when learning about making sequences of actions to acquire rewards (in that case, money), these two regions appeared to be differentially involved in producing reward-prediction error signals: the ventroanterior regions were predominantly active for short delays (*immediate* condition), whereas dorsoposterior regions were more involved in long delays. Subsequent studies extended this work, for instance Wittman and colleagues (2007) found that, in case of delayed rewards, there was the activation of regions such as the bilateral *posterior* insular cortex, the left posterior cingulate, as well as temporal and parietal regions – whereas no region showed an increased activity in case of immediate options.

A similar kind of graded signal can be also identified in the subjective value of various rewards. Some studies (e.g., Rahman et al., 2001; Kable & Glimcher, 2007) highlighted the fundamental role of the ventral striatum, mPFC, and PCC in computing the subjective value attributed to each delayed reward for each subject. Thus, there could be a striatal-cortical circuit which guides our evaluation of rewards (Edwards, 1954; Kable & Glimcher, 2007), over both short and long timescales (Kable & Glimcher, 2007; Peters & Büchel, 2009).

3.1.2 LESIONAL STUDIES

Functional studies have been fundamental in order to address the specific role of some neural areas in intertemporal choices, and in particular the importance of mPFC in the evaluation of different rewards, but what they were not able to provide is the demonstration of a causal role for this region in delay discounting: studies on subjects with lesions in this and other brain areas have overcome this limitation.

At the beginning, a lot of lesion studies were performed on animals. For instance, Cardinal and colleagues (2001) studied the consequences of a lesion in the core part of the Nucleus Accumbens (NAc) of rats on a delay discounting task. They compared lesions in the NAc, in the mPFC and in the ACC, finding that only damage to the first brain area resulted in a reduced delay tolerance and increased impulsiveness: there was a profound

[33] This dissociation could seem in line with the dual-system model of McClure and colleagues (2004, 2007) already cited before. At the same time, though, the finding that mPFC and PCC were activated for both immediate and delayed rewards (Ballard & Knutson, 2009) could better fit the unitary model proposed by Kable and Glimcher (2007, 2010) (Sellitto et al., 2011).

and lasting deficit in rats' ability to choose the delayed reinforcer, leading them to more impulsive choices, thus suggesting a role of delays in reducing the value of reinforcers over time[34].

The amygdala has also been an important region to be investigated. In particular, several studies have shown that its basolateral portion (BLA), and its connection with the OFC, is necessary to flexibly update and adapt the representation of changing reward values based on the present condition (e.g., Baxter et al., 2000). Thus, these amygdala-OFC interactions may be important for mediating intertemporal decisions.

Results from animal studies have, though, been ambiguous: regions of the rat BLA actually increased preference for the short-term rewards, but lesions of the OFC and the STN in some cases decreased impulsive choices in some studies (e.g., Winstanley et al., 2004, 2005), but in others (e.g., Mobini et al., 2002) increased them[35].

However, it is clear that all these regions, namely, the NAc, BLA, STN, and OFC, all have a pivotal role in impulsive choice behavior. What some authors suggested (Winstanley et al., 2006) is that NAc and BLA might be involved in representing and maintaining the *subjective* value of the different rewards across the diverse delays, STN in making associations, and OFC in monitoring and updating representations of expected rewards, but also in directly affecting choice behavior.

Most of these results on animals were further confirmed in several human studies, at first starting from the observation of patients with, for example, ADHD, drug addiction, or frontal lobe syndrome, that present symptoms of abnormally disadvantageous delay discounting, such as future-blindness or exaggerated impulsiveness (e.g., Bechara et al., 1996, 1998). Indeed, these manifestations could be explained by referring to a pathological modulation of frontal lobe function.

The prefrontal cortex (PFC) is generally considered a bridge between perception and action, thus being the mediator of all the action-reward contingencies over time (Quintana & Fuster, 1999), and those frontal regions are generally considered the main structures to control delay discounting and impulsiveness.

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[34] This points also towards a special role of the ventral striatum, which contains the NAc, in producing time preference (Kalenscher & Pennartz, 2008).

[35] These discrepant results in the OFC lesion studies, though, could also be explained by subtle differences in task requirements or the spatial extent of the lesion (Kalenscher & Pennartz, 2008).

For instance, patients with lesions in the vmPFC tend to strongly discount or neglect the future consequences of their decision (e.g., Bechara et al., 1996, 1998); also, damage to the mOFC in humans has a consequence in motivational, emotional, affective, and behavioral domains, with manifestations such as dysregulated social behavior (Damasio et al., 1991; Damasio & Anderson, 1993), inability to inhibit simple responses, short-term goals preference over long-term ones, but also inability to make advantageous decisions, or diminished and altered physiological responses in anticipation of punishment (Sellitto et al., 2011).

The first authors to perform a temporal discounting study on patients with prefrontal lesions were Fellows and Farah (2005), but they found no significant deficit as those in animal research. They compared performance of vmPFC patients, dlPFC patients (with spared vmPFC), non-frontal patients, and healthy controls, finding that vmPFC patients showed discount rates comparable to those of the other three groups[36].

More recently, Sellitto and colleagues (2010) investigated patients with lesions in the mOFC in three different intertemporal choice tasks differing for the nature of the hypothetically offered reward (i.e. money, food, and discount vouchers), comparing them to a group of patients with lesions outside the frontal lobe, and to another group of healthy individuals. What they found was that damage to the mOFC *increased* significantly the preference for small-immediate over larger-delayed rewards, resulting in steeper TD of future rewards. Importantly, all subjects, including mOFC patients, were more willing to wait for delayed *money* and discount vouchers than for delayed food, suggesting that impatient choices were not due merely to poor motor impulse control or consideration of the goods at stake.

These results are consistent with the one of Chib and colleagues (2009), who performed a study in which participants had to make real purchasing decisions among different categories of goods (i.e. food, nonfood consumables, and monetary gambles). They found that activity in vmPFC (which includes the mOFC and the mPFC) correlated with the subjective value for all the different types of rewards, thus there could be a common neural circuit based on mOFC that underlies the evaluation of different categories of goods. That region could hold a representation of value regardless of the type of reward presented.

[36] The only remarkable difference was that, when concerning "future time perspective", vmPFC patients showed shortened personal future time perspective compared to healthy controls.

These findings, with respect to the three models explained above (see section 4.1), seem to support the existence of a *unitary model* (Kable & Glimcher, 2007, 2010; Peters & Büchel, 2009), according to which the mOFC and mPFC, together with the ventral striatum and PCC, represent the subjective value of both immediate and future rewards, all under the top-down modulation of the lateral PFC (Sellitto et al., 2011).

The mechanisms through which the mOFC might influence valuation and preference over future rewards are still not clearly understood, but two main hypotheses have been formulated (Sellitto et al., 2010; Ciaramelli & di Pellegrino, 2011): (i) since during intertemporal choices there is the need to anticipate the future experiences associated with rewards (e.g., if I am offered 20 euros today or 40 in two days, I will have to imagine how would I feel and what would happen in both cases), the prefrontal cortex regions (including mOFC) could be involved in the ability to shift the perspective to different alternatives (so-called *self-projection*); (ii) the lateral PFC, sending top-down signals to control behavior and to promote a more rational approach to choices, could have the mOFC as a target region, making it fundamental to override immediate gratifications (e.g., Hare et al., 2009; Figner et al., 2010). Damage to the mOFC, therefore, would prevent these lateral prefrontal signals from modulating the value attributed to the different options, thus making subjects unable to self-control during intertemporal decisions[37].

Notably, also hippocampal damage can affect decision-making (Peters & Büchel, 2010). Disadvantageous choice behavior has been documented in patients suffering from amnesia due to hippocampal lesions (e.g., Gupta et al., 2009)[38], being highly plausible that hippocampus and parahippocampal cortex play a crucial role in the formation of vivid event representations (Schacter & Addis, 2009). The hippocampus may thus contribute to decision-making through its role in self-projection into the future (Bar, 2009; Schacter et al., 2007), allowing an organism to evaluate future payoffs through mental simulation (Johnson & Redish, 2007; Johnson et al., 2007).

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[37] This conceptualization could also be in line with a previously proposed theory of impulse control (Bechara, 2005), for which regions in the vmPFC – which includes the mOFC – weight the long-term consequences of decisions. The vmPFC, thus, would link two systems together: one for representing patterns of emotional and affective states related, in this case, to the choice options (mainly involving the insula and the somatosensory cortices), and the other critical for memory and imagination (predominantly guided by the dlPFC and the hippocampus) (Damasio, 1994; Bechara, 2004, 2005).

[38] Also, rats with hippocampal damage show increased delay discounting (e.g., Cheung & Cardinal, 2005; Mariano et al., 2009).

4. RESEARCH HYPOTHESES AND RATIONALE

Based on the observation that SoA pertains to the experience of perceiving oneself as *agent* of one's own actions and, thus, of one's own decisions, analyzing it in a decision-making context could shed new lights not only on sense of agency itself, but also on its relationship with the SoO. As outlined in the previous chapters, SoO and SoA are indeed tightly intertwined, especially in cases of voluntary actions: a comprehensive awareness of the body would arise from the integration of afferent signals (proprioceptive and sensory ones, thus strongly related to SoO) and efferent information, which comes from actions. In this sense, action would be a medium that allows the body to distinguish itself from the external objects and that participates to building a more coherent sense of self.

Here, we aimed at manipulating participants' SoA during decision-making tasks to investigate whether this could have in turn an effect on their SoO. Specifically, we aimed at clarifying whether potential alterations in SoO could be reflected in the modulation of the temperature of the effectors used to make decisions (i.e. the hands, through which participants executed the actions to carry out their choices).

We tested this relationship by creating an experimental paradigm with a delay discounting task in three different conditions (see section 6.2.1 for details): (i) a "free choice" condition, in which the subjects could choose the option they preferred between the two proposed ones; (ii) a "forced choice" condition, in which the computer indicated to the participants the option they had to choose; and (iii) a "mixed choice" condition, with the participants being sometimes free to select their preferred option, and other times forced to choose the one indicated by the computer. In the meantime, we measured the hands temperature with a thermal camera in specific moments during each condition. We also administered participants a questionnaire on their perceived experience of SoO and SoA during the three experimental tasks, in order to have an explicit measure of the hypothesized effect.

We expected skin temperature to decrease in contexts of reduced SoA and, thus, of SoO. Specifically, we hypothesized that in the "forced choice" condition, where we expected reduced SoA and SoO since the subject was not free to make decisions, the skin temperature would be significantly lower than in the "free choice" condition where, instead, participants could exert their will and express their preferences. Concerning the "mixed choice" condition, we expected it to be placed in an intermediate position between the "free choice" and the "forced choice" ones in terms of decrease in temperature. As it concerns the explicit measures of SoO and SoA, we expected participants to report significantly higher scores (thus significantly higher perceived experience) in the “free choice” condition compared to the “forced choice” one, with the “mixed choice” always laying in an intermediate position.

5. MATERIALS AND METHODS

5.1 PARTICIPANTS

We recruited a total of 27 healthy volunteers, 8 males and 19 females [age range: 20-31 years old (M = 23.6 y, SD = 3.02); education level range: 13 – 18 years (M = 14.82, SD = 1.73)]. Twenty-two participants were native Italian speakers, all subjects were dexterous, except one ambidextrous, as determined via the Edinburgh Handedness Inventory (*EHI*, Oldfield, 1971), with no psychiatric or neurologic self-reported pathology nor self-declared assumption of psychotropic drugs concomitant to the experimental session. All subjects had intact global cognitive functioning, as assessed via the administration of the Montreal Cognitive Assessment (*MoCA,* Santangelo et al., 2015) (mean score = 28.115 ± 1.728). All of them were students of Psychology courses in the University of Pavia, except one who was recruited independently from the University, enrolled through the Psychology department newsletter, who received University credits for participation. Before starting the experiment, all participants read and signed the informed consent.

The Ethical Committee of Psychology of the Department of Brain and Behavioral Sciences of the University of Pavia approved the experimental procedures, which are in accordance with the Declaration of Helsinki.

5.2 TASKS

5.2.1 DELAY DISCOUNTING TASK

The Delay Discounting Task is a very versatile tool, widely used in research in the decision-making field as it asks participants to express their preferences and make decisions about different types of rewards.

We used the software E-Prime 3.0 (PST) to create and administer subjects an experimental paradigm in which we offered, trial-by-trial, two different hypothetical monetary rewards delivered at variable time lengths: the smaller option was offered immediately (“today”) (henceforth, smaller-immediate option), while the larger option was available after a specific amount of time (henceforth, larger-later option). In particular, following procedures in Sellitto and colleagues (2010), we used six different temporal delays of availability for the larger-later option, i.e. 2 days, 2 weeks, 1 month, 3 months, 6 months, and 1 year. Importantly, while the larger-later option was fixed at 40 euros, the amount of money of the smaller-immediate option was variable. Participants made five different choices at each of the six delays of availability of the larger-later option, for a total of 30 choices, with the delays being administered in blocks in a counterbalanced way within and across participants.

During the first trial of each of the six blocks, the starting immediate reward in the first trial was always 20 euros, which was subsequently changed in the next trials based on the previous choice of the participant. This was obtained by implementing a staircase procedure on the basis of a previously defined algorithm (Sellitto et al., 2010): in brief, if the subject chose the immediate reward over the delayed one, the next immediate reward offered was increased, otherwise it was decreased. This procedure was applied to all the five choices of the selected delay, and with the beginning of each new block it was repeated from the start. Since the immediate reward that was calculated was totally dependent on the participant's choices, it can be seen as the best guess of the *subjective value* attributed to the delayed reward; thus, we were able to measure the hypothetical immediate reward that could have been presented on a potential sixth trial, considering it as the estimate of the subjective value of the of the larger-later option at that specific delay, also called *indifference point*. Indifference points (one per each delay block) was used to calculate the *discount parameter k* to estimate the subjects' level of discounting or, said otherwise, of impulsivity (Sellitto et al., 2010; Ciaramelli et al., 2019). We modelled the indifference points via a hyperbolic function $[SV = 1/(1+kD)]$, where SV is the subjective value (i.e. the indifference point) and D is the delay – expressed in days – of each delay block, in order to determine, for every single subject, the *k* constant that could best describe their choices: the higher the *k* value, the steeper the hyperbolic discount function, the more participants are willing to choose small, immediate rewards over larger, future ones.

We created three different conditions of the Delay Discounting Task, namely the "free choice" condition, the "forced choice" condition, and the "mixed choice" condition.

In the "free choice" condition, we administered the task as it was just described, allowing participants to freely decide for each of the 30 trials their preferred option. A red dot appeared on the screen as a fixation point at the beginning of the task, followed by the concomitant presentation of the two hypothetical options (duration: 1 sec). Subjects were instructed to pay attention to the two rewards and, after the red dot had become yellow, they had a time constraint of 10 seconds to make their decision. We instructed them to press one between two specific keys on the keyboard and, once they made the choice, the non-chosen option disappeared and they could see appearing on the screen a yellow triangle indicating their selected option, as a feedback. An example of this first condition is shown in Figure 7.

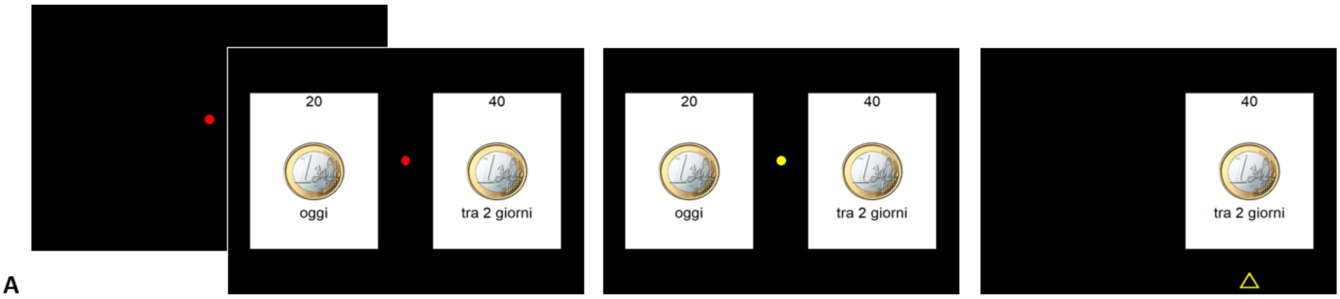

Figure 7: Example of a "free choice" trial

In the “forced choice” condition, subjects were instructed to always choose the option indicated by the computer, evidenced by the appearance of a yellow frame around the pre-determined reward, concomitantly to the appearance of the two rewards and the fixation point turning red-to-yellow. Also in this case, the participants had to press the key assigned either to the left or the right option. To determine the amounts of the immediate options at each trial, by not taking into account participants’ errors in options selection, we implemented the hyperbolic function by using an average discount rate *k* (value = 0.026) determined by the literature (e.g., Sellitto et al., 2010; Sellitto & di Pellegrino, 2016). Importantly, the forced choices were equally distributed between smaller-immediate options and larger-later options. Figure 8 shows an example of trial in this condition.

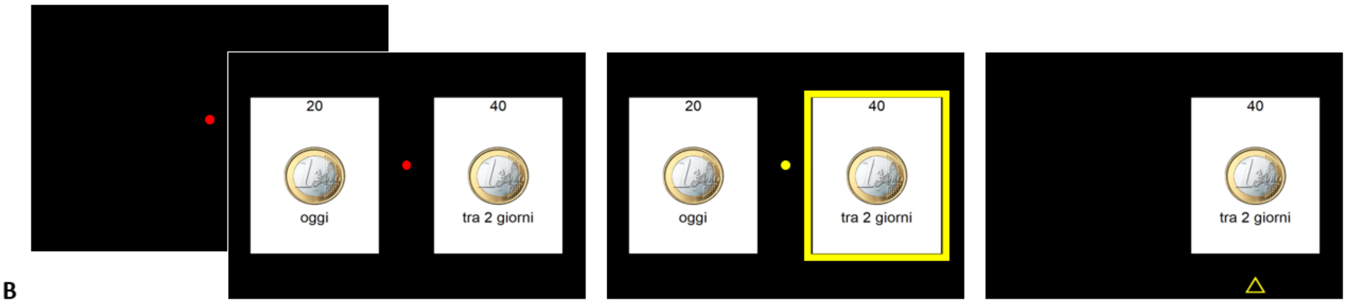

Figure 8: Example of a "forced choice" trial

The last condition, the “mixed choice” one, had half of the trials in which participants were free to choose their preferred option, whereas in the other half they had to select the designated option. The delay blocks were randomly presented to the subjects in this case too, and they could not know in advance whether the successive trial would have been a free-choice or a forced-choice one. We made it possible for the algorithm to consider the choices of the participant in the “free choice” trials, and the computer choices in the other case. Figure 9 shows an example of this condition.

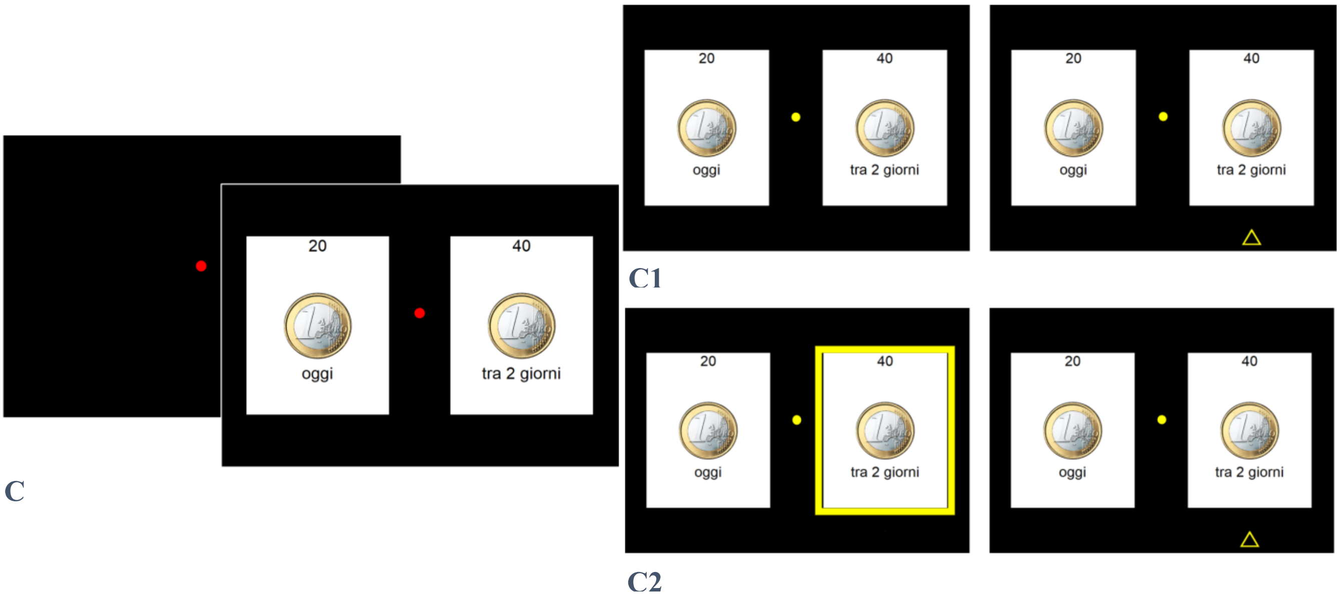

Figure 9: Example of a "mixed choice" trial

As this is the first study of this kind, we decided to administer the three conditions always in the same order (i.e. "free-choice" as the first one, "forced-choice" as the second one, and finally the "mixed choice" one), to not influence the true discount rate of the participants, which was later used as covariate in the analyses, where relevant, to correct for participants' level of impulsivity.

5.2.2 HANDS TEMPERATURE ASSESSMENT

Temperature was measured through a FLIR ONE PRO thermal camera and a tablet (e.g., Crivelli et al., 2023), both placed on a tripod in order to keep their position still throughout the experimental session. Before the beginning of the experiment, the room temperature was measured and kept at a constant temperature (i.e. 26°C) through a conditioner.

Before and after the delay discounting task, and for each condition, we took three consecutive thermal images of both hands. Specifically, we had these images taken at the beginning of each condition ("pre" images) and at the end of each delay block ("post" images), for a total of 21 acquisitions (3 pre and 18 post) for each of the three conditions. Between one block and another, subjects took small pauses in order to control that possible hands movements could influence their temperature. For each image, then, we extracted hands temperature from *Regions Of Interest (ROIs)* based on the pattern of 7 key points adopted by Crivelli and colleagues (2023), following the scheme in figure 10, trying to avoid knuckles. The final measure for each limb was obtained by calculating the mean value of the three consecutive measures for each ROI, and then the mean of each ROI for each hand. We had in this way a final mean value for each hand, for each condition, both for pre- and post-task. We were interested in calculating the delta (Δ), which we obtained by subtracting the mean before the condition ("pre") from the total mean of the means of the 6 blocks in that condition ("post"), so that we obtained positive values in cases of increase in temperature, and negative for decreases in temperature.

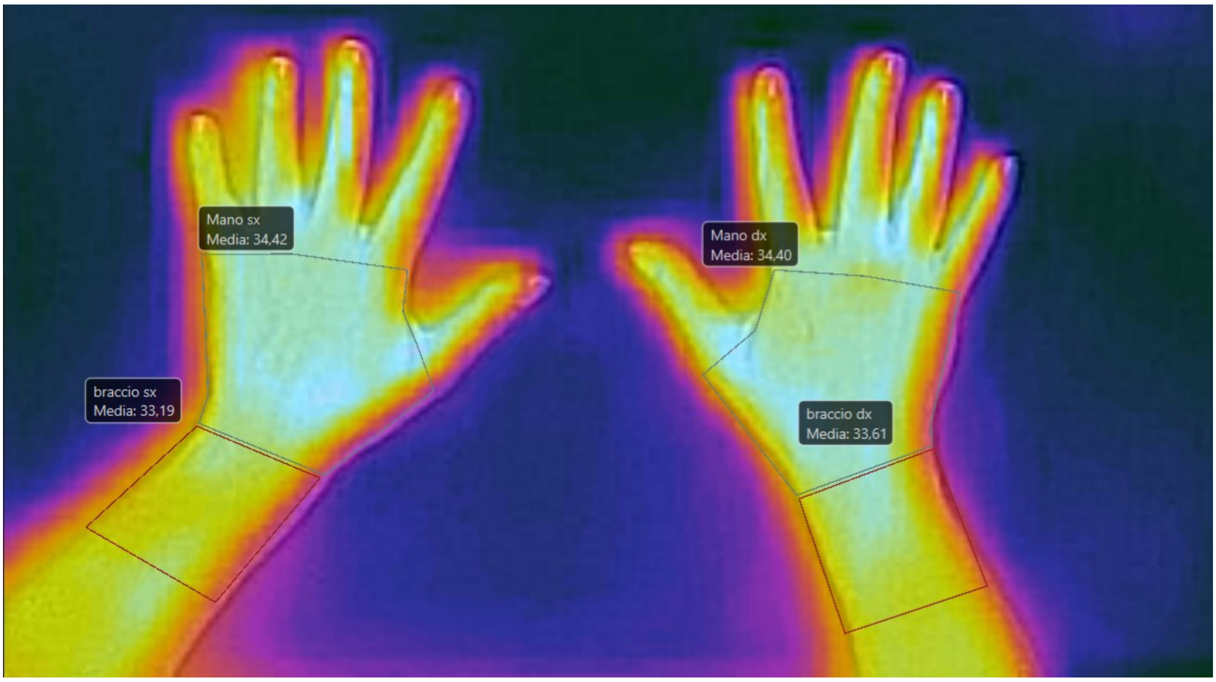

Figure 10: Example of ROIs used to extract temperature data

6.2.3 QUESTIONNAIRES FOR SoO AND SoA

As an explicit measure for Sense of Ownership and Sense of Agency, we built some questions based on two questionnaires already validated in literature (Zhang & Hommel, 2015; Roth & Latoschik, 2020; Najafabadi et al., 2023), which we administered to participants at the end of each condition, for a total of three times throughout the experimental session. Subjects had to indicate their degree of accordance with each of the 22 sentences (some of which were reverse items) through a horizontal VAS scale of 10 cm, with the two extremes being "totally disagree" and "totally agree" (see Appendix 1 for more details about the questionnaire).

For SoO, we presented 6 items (e.g., "I felt like the left hand with which I was making decisions was mine"; "I felt like my right hand no longer belonged to me, as if it was only the computer that decided"); 11 questions were dedicated to the investigation of SoA (e.g., "It felt like I was the one deciding the movements of my right hand to choose the rewards indicated on the right"; "It felt that the computer was controlling my decisions"). We then added one more question on the pleasantness of the task ("I enjoyed making decisions") and, finally, we had additional four items for the body scheme, two of them about the weight of the hands and two of them about their size.

Each item could have a possible range of rating values from 0 to 10, and we computed the mean value for SoO, SoA, weight, and size (for all of them both for each hand separately and for the two hands together), and for pleasantness.

5.2.3 OTHER TASKS AND QUESTIONNAIRES

We administered participants other questionnaires during the experimental session.

- ***Heartbeat counting task (HCT)***. We used a measure of interoception that could be considered during the analyses of temperature (Crivelli et al., 2023). Participants were asked to silently count their perceived heartbeat during 6 different time intervals (from 25 to 50 seconds in steps of 5, pseudo-randomly administered so that participants couldn't guess what the next interval would be). Each block started with an acoustic signal and ended with the same sound produced by the computer (via the open-source software *OpenSesame 3.3.7*). At the end of each block, participants were asked to say the number of heartbeats they counted and to rate the confidence they had in their answer, on a scale from 0 to 10. In the meantime, we measured the real heartbeat through a pulse oximeter (Shyonda) placed on the index finger of the left hand. The subject's accuracy was measured by comparing, for each time interval, the number of heartbeats perceived by the participant with the number of the actual heartbeats, then computing the mean value of the six intervals through a validated formula (Schandry, 1981; Vig et al., 2021).
- ***Barratt Impulsiveness Scale (BIS-11).*** A questionnaire on the level of impulsivity (Fossati et al., 2001) was also administered to the participants to be used as a side measure of the Delay Discounting Task (section 5.2.1). The BIS-11 is composed of 30 self-report items divided into three categories, *attentional impulsivity*, *motor impulsivity,* and *impulsive non-planning*. For each item, subjects had to express their level of agreement on a Likert scale of 4 points, from "never/rarely" to "almost always/always". Subjects who scored higher in this task are considered more impulsive than those who scored lower.
- ***Behavioral Activation Scale (BAS)***. This scale (from Carver & White, 1994) is composed of 13 items on a Likert scale from 1 ("Totally disagree") to 4 ("Totally agree")

and it is used to measure the motivational systems underlying behavior. Three subscales can be identified: *BAS drive, BAS fun seeking, BAS reward responsiveness*.

- ***State-Trait Anxiety Inventory X (STAI-X).*** This questionnaire (Spielberg, 1983) was helpful in this study in giving a measure of the influence that anxiety traits could have had on decision making and on skin temperature. It's composed of 40 self-report questions to be answered on a Likert scale from 1 to 4, divided into two subgroups: *state anxiety,* or anxiety about an event (STAI-XS), and *trait anxiety,* meaning a general level of anxiety as a dispositional characteristic (STAI-XT).
- ***Toronto Alexithymia Scale (TAS-20).*** Since in the context of delay discounting and skin temperature it is important to have a measure of the ability to elaborate the emotional-visceral content of stimuli (Scarpazza et al., 2017), we administered the TAS-20 (Taylor et al., 2003), which is composed of 20 items divided into three different factorial scales: *DIF (Difficulty Identify Feelings), DDF (Difficulty Describing Feelings)* and *EOT (Externally-Oriented Thinking)*. Subjects had to indicate their level of agreement with each item on a scale from 1 ("Totally disagree") to 5 ("Totally agree").

5.3 EXPERIMENTAL PROCEDURE

Participants were first asked to read the consent form and the privacy modules, and to sign them. Afterwards, we asked them some demographic information (e.g., age, education level). General information about the entire session were given to the subjects, which were followed by the administration of the EHI. Then, instructions to the first condition of the Delay Discounting Task were provided, while measuring the room temperature after having regulated it. After the first condition, and after having taken the pictures of the hands as specified in section 5.2.2, the subjects were administered the SoO and SoA questionnaire, then following the same procedure for the second and the third conditions. Subsequently, all the other tests were administered, in a random and counterbalanced order across participants.

5.4 ANALYSIS OF DATA

We planned to analyze the three main measures for SoA and SoO, i.e. hands' temperature (implicit measure) and SoO and SoA questionnaires (explicit measures). In particular, we planned a series of repeated measure analyses of variance (ANOVAs), with the dependent variables being, in turn, each of the three main measures, with the Condition of the Delay Discounting Task (three levels, "free choice", "forced choice", "mixed choice") as a within-subject factor.

Moreover, since there could be an effect of the level of “impulsivity”, or impatience, of the subjects on the experimental manipulation in the Delay Discounting Task (e.g., Peters & Büchel, 2010), we repeated the previous analysis by including as a covariate in the analyses on temperature the hyperbolic discount rate parameter *k* derived from the “free choice” condition of the Delay Discounting Task (Sellitto et al., 2010; Sellitto & di Pellegrino, 2016).

Additionally, we repeated the above analyses by including as covariates also participants’ scores at the questionnaires (all except from EHI and MoCA). All data will be analyzed by using the software JASP 0.18.

6. RESULTS

6.1 DESCRIPTIVE STATISTICS

As for the questionnaires administered at the end of the experimental session (i.e. BAS, BIS-11, STAIX, TAS-20, and MoCA), no significant outliers were found. Descriptive statistics are displayed in Table 1.

Descriptive Statistics

	BAS tot	BIS_TOT	STAIX1	STAIX2	TAS_TOT
Valid	27	27	27	27	27
Missing	0	0	0	0	0
Mean	35.704	61.185	35.222	44.407	43.074
Std. Deviation	6.933	11.184	9.649	10.013	9.821
Minimum	16.000	43.000	23.000	26.000	29.000
Maximum	48.000	87.000	62.000	68.000	62.000

Table 1: Descriptive statistics of BAS, BIS, STAIX, and TAS-20

6.2 EXPLICIT MEASURES FOR SoO and SoA: Ratings

As for the explicit measures for SoO and SoA, we performed a series of repeated measures analyses of variance (ANOVAs), with the three conditions of the Delay Discounting Task (“free-choice”, “forced-choice”, “mixed-choice”) being the within-subject factor.

6.2.1 SENSE OF OWNERSHIP

For the dependent variable SoO, the repeated measures ANOVA yielded a significant effect of Condition ($F_{(2,52)} = 6.64$, $p = .006$, $\eta^2_p = 0.18$) on the scoring of participants. Bonferroni-corrected post-hoc comparisons showed significantly higher values of SoO in the free compared to the forced condition (mean difference = 0.96, p = .013, Cohen’s d = .50) and in the free compared to the mixed condition (mean difference = 0.76, p = .030, Cohen’s d = .40), whereas no significant difference was observed for the forced condition compared to the mixed one. This means that, in general, subjects reported significantly higher rates of ownership in the free vs. forced condition and in the free vs. mixed condition. Despite nonsignificant effect for the last comparison, the mean difference (value = -0.193) suggests a trend of slightly increased SoO ratings for the mixed condition compared to the forced one. Figure 11 shows the mean rating of participants in the three conditions.

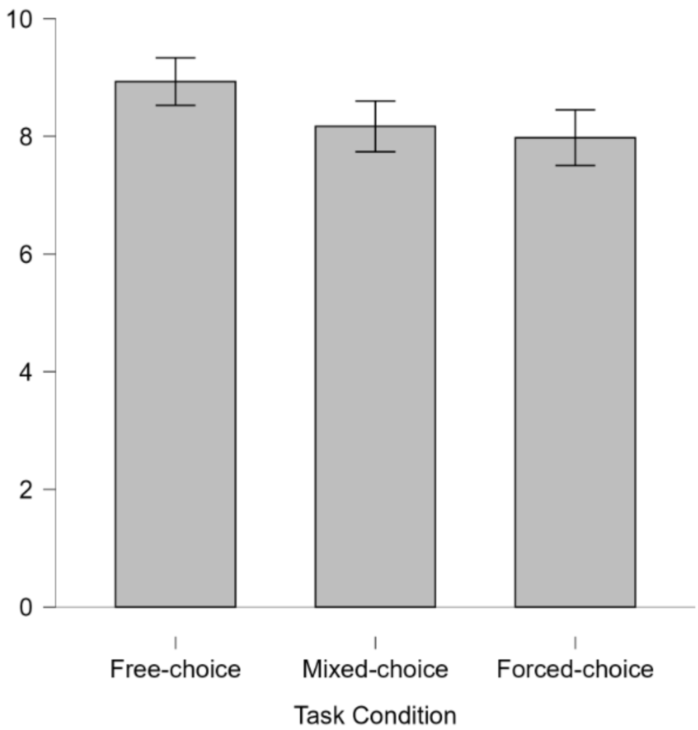

Figure 11: Bar plot of the mean scores of participants' SoO in the three conditions. On the Y axis the possible ratings for SoO, from 0 to 10. Error bars represent the standard errors of the means.

6.2.2 SENSE OF AGENCY

A repeated measures ANOVA on SoA also showed a significant effect of Condition ($F_{(2,52)}$ = 25.68, p < .001, η^2_p = 0.50), with Bonferroni-corrected post-hoc comparisons showing significant differences between all three pairs. In particular, participants showed significantly higher values in the free condition compared to the forced one (mean difference = 1.88, p < .001, Cohen's d = 1.03), in the free compared to the mixed one (mean difference = 0.73, p = .013, Cohen's d = .40), and also in the forced compared to the mixed condition (mean difference = -1.15, p < .001, Cohen's d = -.63). Thus, participants reported higher reported levels of agency in the free-choice condition vs the forced-choice one, with the mixed-choice laying in between the two. Figure 12 shows the bar plot of the mean rating of participants in the three conditions.

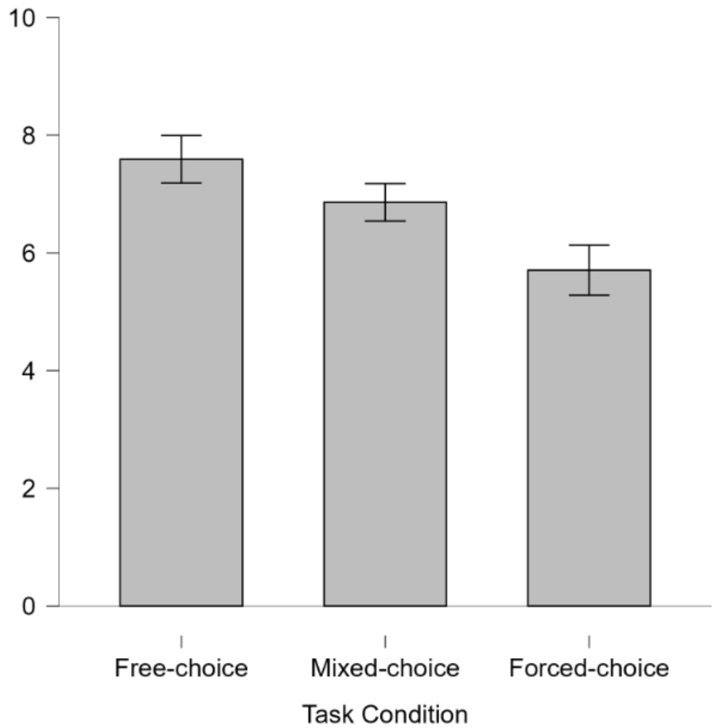

Figure 12: Bar plot of the mean scores of participants' SoA in the three conditions. On the Y axis the possible ratings for SoA, from 0 to 10. Error bars represent the standard errors of the means.

6.2.3 PLEASANTNESS

For the one item we included to investigate pleasantness, participants significantly differed in their ratings across the conditions: we found an effect of Condition even in this case ($F_{(2,52)} = 16.67$, $p < .001$, $\eta^2_p = 0.39$). Corrected post-hoc tests showed significant differences for all three comparisons: free-choice vs forced-choice (mean difference = 2.86, $p < .001$, Cohen's d = 1.27), free-choice vs mixed-choice (mean difference = 1.03, $p = .012$, Cohen's d = .46), and forced-choice vs mixed-choice (mean difference = -1.82, $p = .004$, Cohen's d = -.81), with the same trend of the previous results.

6.2.4 WEIGHT AND SIZE

No significant effect of Condition on the reported weight nor dimension of the hands was found (all ps > .303).

6.3 IMPLICIT MEASURES FOR SoO AND SoA: HAND TEMPERATURE

In this case, to better explore our data, we decided to perform two repeated measures ANOVAs, one considering the right and left hands separately, and the other one involving both together (mean value of the right and left hand).

The first repeated measures ANOVA on hands' temperature had, though, as within-subject factors both the Condition of the Delay Discounting Task (three levels: "free-choice", "forced-choice", "mixed-choice") and the hand involved ("Hand", two levels: "right", "left"). No significant main effect of Condition nor Hand was found (all ps > .173), as well as no significant interaction between the two (p = .325).

The second repeated measures ANOVA, this time with only Condition being the within-subjects factor, considering both the hands together, showed again no significant difference between the three different conditions in hands' temperature (p = .361).

We also visually inspected the data and noticed a trend of general decrease of the difference (Δ) in temperature across the three conditions, with Δ of "free-choice" being higher than the one in the "forced-choice", being in turn higher than the one in the "mixed-choice" condition (see figure 13).

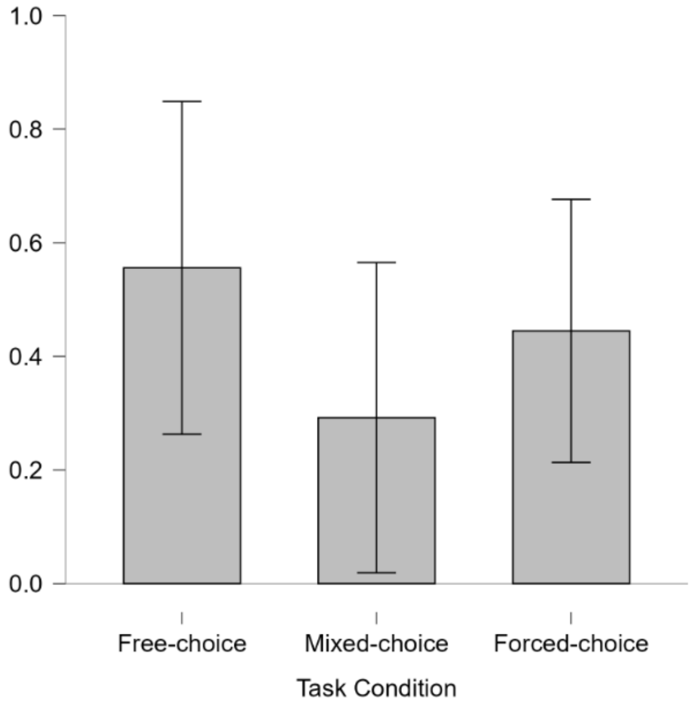

Figure 13: Bar plot of the difference (Δ) between the pre and post trials. Bars represent the mean temperature value, with the standard deviation of the means being represented by the error bars.

We also tested whether there could have been an effect of the variation of the temperature of the room on hand temperature. Again, we performed the main repeated measures ANOVA, with the Condition of the task being the within-subjects factor, by adding as a covariate the variation (Δ) in the room temperature, but no significant results were found either ($p = .491$).

6.4 EXPLORATORY ANALYSES

As this is a preliminary study of this kind, we performed some exploratory analyses to delve deeper into our trend of results.

6.4.1 EXPLICIT SOO AND SOA AND IMPULSIVITY

We performed a correlation analysis between all the five main measures from the SoO and SoA questionnaires with the logarithm of the hyperbolic discount rate parameter *k*. Only ratings of pleasantness in the "forced-choice" condition significantly correlated with the discount rate parameter k ($r = .41$, $p = .032$) (figure 14 shows the scatter plot of this correlation), whereas for all the other variables no significant results were found (all ps > .079).

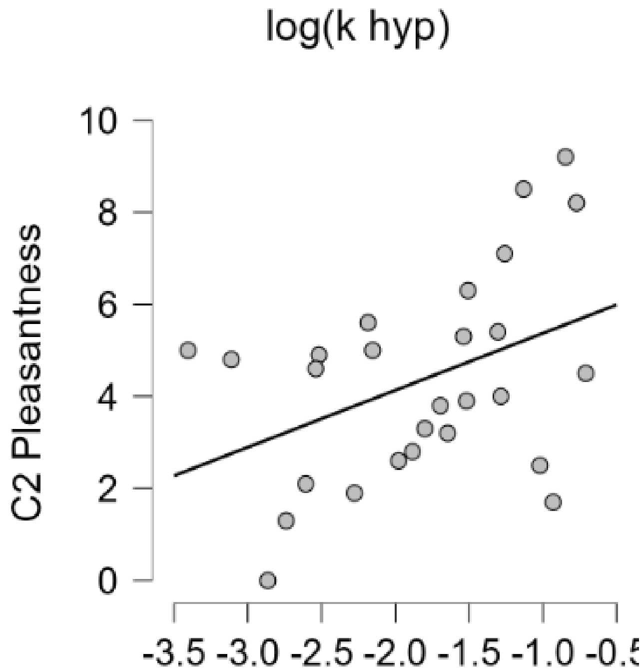

Figure 14: Scatter plots of the correlation between the scoring for the "pleasantness" dimension in the "Forced-choice" condition ("C2") and the logarithmic value of the discount rate parameter k (r = .41, p = .032).

6.4.2 HAND TEMPERATURE AND IMPULSIVITY

We also repeated the main ANOVA for temperature by including participants' discount rate (the logarithmic transformation of the *k* constant) from the free choice condition as a covariate, but results did not change (all ps > .461). Table 2 reports the main results.

Within Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Condizione	0.736	2	0.368	0.786	0.461
Condizione * log(k hyp)	0.284	2	0.142	0.304	0.739
Residuals	23.413	50	0.468		

Note. Type III Sum of Squares

Table 2: Repeated measures ANOVA with log(k hyp) as a covariate

6.4.3 IMPULSIVITY, INTEROCEPTION, AND OTHER PERSONALITY TRAITS

We explored possible (separate) correlations between the scores at the questionnaires (BIS, BAS, STAIX1, STAIX2, TAS-20, and HCT accuracy) and the logarithm value of the hyperbolic discount parameter *k,* but no significant result was shown (all ps > .329).

6.4.4. HAND TEMPERATURE, INTEROCEPTION, AND OTHER PERSONALITY TRAITS

To assess whether there could have been an effect of the ability of participants to perceive their interoceptive signals (i.e. performance at the Heartbeat Counting Task) on differences in temperature across the three conditions, we also performed another repeated measures ANOVA with HCT accuracy being the covariate. Even in this case, though, we had no significant differences between the groups (all ps > .718).

All other test scorings (i.e. BAS, BIS, STAIX, TAS-20), considered as covariates in the main repeated measures ANOVA, did not significantly influence our variable of interest (all ps > .383).

7. DISCUSSION

In the present study, we wanted to characterize the relationship between SoO and SoA from the neuroscientific point of view. In particular, we assessed whether alterations in SoA, obtained via the administration of a Delay Discounting Task in three different conditions (i.e. "free-choice", "forced-choice", "mixed-choice"), could induce changes in SoO of participants, reflected implicitly in a variation of the temperature of the effectors with which they made the decision (i.e. the hands). Based on the recent literature findings on the relationship between SoO and skin temperature (e.g., Moseley et al., 2008, Crivelli et al., 2020, Crivelli et al., 2023), we hypothesized that the condition in which the participant wasn't allowed to freely choose the preferred option (i.e. "forced-choice") would have caused as a consequence a significant decrease in subjects' SoO, and thus in their hands' temperature, compared to the "free-choice" condition. Furthermore, since in the "mixed choice" condition we had subjects to alternatively freely choose or follow the instructions of the computer, we expected that condition to lay in the middle between the two extremes.

While we confirmed our hypotheses at the explicit level (i.e. participants' explicit ratings), the results did not confirm our hypothesis at the implicit level. We had no significant differences in hands' temperature between the "free-choice" and the "forced-choice" condition, nor between the "free-choice" and the "mixed-choice" nor between the "forced-choice" and the "mixed-choice" ones.

7.1 EXPLICIT SoO AND SoA

As for the explicit measures for SoO and SoA, obtained via the administration of an ad-hoc questionnaire, we did obtain some significant results in the expected direction. Participants reported to experience higher levels of both SoO and SoA in the "free-choice" condition compared to the "forced-choice" one and in the "free-choice" compared to the "mixed-choice". For SoA, then, they also indicated higher ratings in the "mixed-choice" condition compared to the "forced-choice" one. This implies that they experienced the highest levels of SoO and of SoA in the condition in which they were always free to choose their preferred option (i.e. "free-choice") compared to the one in which they had to always follow the instructions of the computer (i.e. "forced-choice"); as expected, the ratings in the "mixed-choice" condition were placed in an intermediate position between the other two.

By definition, SoA is considered as the sense of perceiving oneself as the initiator or the source of the action and the responsible for the consequences of those actions (e.g., Gallagher, 2000a, b; Tsakiris et al., 2006). Our results are in line with this definition: subjects reported significantly higher levels of SoA in the condition in which they were allowed to exert their will to make the decision, as compared with the condition in which they could not choose freely.

In the same vain, SoO is defined as the feeling of belonging of the body, thoughts, and feelings (Frith, 1992; Gallagher, 2000; Tsakiris et al., 2007), with the natural consequence being that, in cases in which subjects are free to make their own decisions, they also experience a stronger SoO compared to conditions in which they are asked to follow instructions and decisions of others. Indeed, in our study participants reported higher levels of SoO in the "free-choice" compared to the "forced-choice" condition, with the "mixed-choice" one laying in between the two.

Moreover, and as expected, having the feeling of controlling and being agents of one's own decisions, then, has also an impact on the enjoyment of an experience: participants reported significantly higher scores of "pleasantness" in the "free-choice" condition with respect to the other two.

Interestingly, what we found in the correlation analysis was that the ratings for pleasantness of the experience in the "forced-choice" condition significantly correlated with the level of impulsivity as determined by the "free-choice" condition of the Delay Discounting Task. In the "forced-choice" condition, we implemented an average discount rate determined by the literature (e.g., Sellitto et al., 2010; Sellitto & di Pellegrino, 2016), with a k value equal to 0.026. We found that the more subjects were impulsive (i.e. the higher their k value), the more they enjoyed this task. Thus, participants who had a true discount parameter k (determined in the "free-choice" condition) very far from the one we set in this condition, i.e. people who would have chosen very differently with respect to what they were forced to choose, could also be the ones who enjoyed the most the experience, compared to those whose true k value was very similar to the average discount rate[39]. Indeed, the most impulsive participants are the ones who expressed higher ratings of pleasantness in the condition where they were forced to select the option they would be not likely to choose.

[39] Being our participants only 27, we would need a larger sample to draw more confident explanations. This one presented is only one of the possible speculations that could be given to explain this result.

7.2 IMPLICIT SoO and SoA: HANDS TEMPERATURE

As already mentioned in the previous chapters, SoO arises from the integration of different types of information, namely the exteroceptive, proprioceptive, and interoceptive ones (e.g., Tsakiris, 2010; Blanke, 2012; Critchley & Harrison, 2013; Park & Blanke, 2019; Salvato et al., 2020), with temperature playing a putative fundamental role (e.g., Crivelli et al., 2020). A large corpus of research started to demonstrate that disruption of temperature regulation could be linked to disruption of body ownership, and vice versa (e.g., Moseley et al., 2008), thus shedding light on new possible mechanisms underlying pathologies characterized by body ownership disturbances.

For instance, Crivelli and colleagues (2020) used the Mirror Box Illusion (*MBI*) paradigm to investigate this relationship, with the aim of altering subjects' SoO while tapping, synchronously or asynchronously, their left and right fingers against two mirrors and looking at their right hand, with the left hidden from sight, and then measuring the skin temperature of both hands. In line with results of previous studies (e.g., Kammers et al., 2011, Medina et al., 2015, Salvato et al., 2018), they obtained a bilateral cooling of the hands after the synchronous compared to the asynchronous condition. We thus expected our study to lie within this framework.

The results of our study, though, were not in line with this hypothesis. At the implicit level (i.e. measuring hands' temperature), participants didn't show a significant difference in their skin temperature across the three decision-making conditions. Based on previous studies showing a differentiation in the laterality of the effect (e.g., Crivelli et al., 2023), we also tested whether there could have been diverse effects of our manipulation based on the laterality (i.e. left and right hand), but even in this case we did not obtain significant results.

We managed to analyze whether variations in the temperature of the room could have significantly affected our data, thus impacting on subjects' hands temperature, but again no differences were found.

Already other studies did not report significant result as ours, as already mentioned in the previous chapters (see section 3.2.3). For instance, Rohde and colleagues (2013) tried to replicate Moseley and colleagues' (2008) results by implementing the RHI paradigm in three different experimental setups. In the first two experiments[40], they used two robot arms to stroke

[40] In the first procedure, the stimulation lasted only 200 seconds, compared to the second one in which the total stroking lasted for 7 minutes.

both the participant's and the rubber hands, and in both cases the authors only observed differences in explicit measures of SoO (i.e. vividness and proprioceptive drift), but no significant effects on the implicit measure, i.e. hands temperature (assessed via a two-way repeated measures ANOVA), nor between conditions or across time. In the third attempt, they tried to implement a more similar paradigm to the one used by Moseley and colleagues (2008), by manually stimulating both participants' and rubber hands. Here, again, they consistently found significant differences in vividness of the illusion between the experimental and the control conditions. Moreover, they performed a two-way repeated measures ANOVA on temperature measurement, by considering as factors the type of condition (synchronous or asynchronous stroking) and the involved hand (whether it was stimulated or not), and they did obtain, this time, some significant results: in particular, they showed a relative cooling of the stimulated hand, which was independent of the condition. What they hypothesized after these results was that the cooling effect could require a specific experimental procedure in order to be elicited, thus being not strictly "psychologically induced" by the subjectively experienced illusion. According to the authors, some possible explanations for this lack of effect in the first two experimental setups could be due to numerous factors, among which: a) social context: since social and empathic factors have been proven to be involved in the illusion (e.g., Asai et al., 2011), the presence of a real person in the third experiment could have had an impact on the effect; b) force of the brushes, which can differ between an automated setup with robotic arms and manual stroking; c) different lighting conditions in the setups; d) irregularities of the touch exerted by the experimenter in the manual stroking condition; e) unconscious biases in the amount or manner of stroking could have impacted in the manual stroking condition; f) different arousal of the participants in the different conditions.

Another research by de Haan and colleagues (2017) analyzed five RHI experiments in which they investigated skin temperature changes in relation to the illusion, converging to the same lack of consistent results towards a reliable cooling of the hands directly related to the RHI, and the same previously found dissociation between explicit and implicit measures for the induction of the illusion and the alteration of SoO.

Thus, our results are in line with other studies that showed difficulties in replicating the relationship between alterations in SoO and temperature changes related to it (e.g., Paton et al., 2012; Rohde et al., 2013; David et al., 2014; de Haan et al., 2017). As outlined in Rohde and colleagues' study (2013), there could be other external factors driving the link between subjectively felt ownership and temperature changes. Even though we didn't implement a RHI paradigm in our study, the same reasoning could be applied to our results. Moreover, since this is the first study of this kind, in which we attempted at manipulating SoA, and thus SoO, with a decision-making task, further research is needed to better disentangle the relationship between these variables, especially between decision-making tasks and bodily self-awareness.

Most importantly, what we observed was that the hands' temperature of subjects increased throughout the experimental session, independently of condition. In particular, we noticed a trend of decreased difference (Δ) in temperature across the three conditions, with Δ "free-choice" being the highest, and Δ "mixed-choice" being the lowest. This means that participants underwent a general increase in their hands' temperature during the experiment, but this is totally independent of the condition of the task they were doing. This general increase of the skin temperature could simply be due to their permanence in the room, to the heating of the environment and of the subjects themselves. In addition to that, it is plausible that the difficulty in validating our hypothesis could be caused by the order of administration of the conditions of the Delay Discounting Task: by necessity (i.e. in order to not influence the true discount rate of the participants), we decided to always make subjects perform the "free-choice" condition first, then the "forced-choice" one, and lastly the "mixed-choice" one. This, in turn, could have had a significant impact on the lack of the expected differences in temperature across the three conditions, since, as already mentioned, the contemporary and inevitable general heating of the environment and of the participants due to their permanence in the room. Future research in this field could manage to manipulate the order of administration of the different tasks in order to see whether significant effects on hands' temperature could be observed, implementing a different methodology to control for the true discount rate of subjects.

These same methodological factors just outlined could also be responsible for the lack of effect of subjects' impulsivity (measured through the delay discount rate) on their hands' temperature across the different conditions.

7.3 LIMITATIONS OF THE STUDY AND FUTURE PERSPECTIVES

Being, as already noticed, the first study implementing a Delay Discounting Task to manipulate SoA of participants, some limitations of our research and suggestions for future studies can be outlined, mainly related to the methodological factors related to our experimental paradigm.

First, a larger sample size could significantly improve our results, since we were able to recruit 27 participants only. A power analysis suggests a number of subjects equal to 66 to reach an effect size f equal to 0.20.

Some methodological aspects, then, can be outlined to be improved in further studies: since we noticed some variability in the room temperature, a more controlled environment would be necessary in order to control as much as possible for these alterations. More attention could then be paid to the exact position of participants' hands during the measurement of their temperature via the thermal camera: in our experimental design, subjects were relatively free to move their hands and to place them still when taking the pictures. Moreover, despite trying to minimize as much as possible their movements throughout the experimental session, some kind of shift in their position was necessary in order for us to take the pictures, which in turn could have impacted on the temperature of the effectors of the actions.

Another important consideration lies in the general increase of hands' temperature observed throughout the experimental session, which was totally independent on the condition of the Delay Discounting Task. As already outlined above, we deliberately decided to administer the three different conditions in the same order for all the participants – that is, first the condition in which they were free to choose, then the one in which they had to follow the computer's instructions, and lastly the one in which they alternatively had to select the option following their will or the computer – to not influence the true discount rate of the participants. Future studies could try to manipulate the order of administration of these conditions, counterbalancing it across the participants, to see whether it could have an effect on the main variables of interest.

A future study could offer new glimpses on the analysis of the relationship between SoO and SoA from a novel and unusual point of view. Further research could be of promising importance to better understand how to significantly alter SoO and SoA of participants by leveraging on our ability to exert our will to make decisions.

8. CONCLUSIONS

The present work focused on the relationship between the two main components of the so-called bodily self-awareness, namely *Sense of Ownership* (SoO) and *Sense of Agency* (SoA), both at an explicit and at an implicit level. Their link has been long studied, with a number of experiments proving their profound interconnection and bidirectional interaction, but the present was the first study that tried to analyze them via another core aspect of our cognitive activity, namely the decision-making process. More in detail, we decided to alter subjects' SoA by manipulating the possibility of exerting their will in some intertemporal choice tasks, in which smaller-sooner and larger-later hypothetical monetary options were offered. We then aimed at observing any possible consequent alterations in SoO and in physiological parameters related to it, namely the skin temperature.

We first created three different Delay Discounting Task conditions: the first one ("free-choice"), in which participants could freely choose one between two alternatives offered to them, the second one ("forced-choice") in which they were instructed to follow the choices determined by the computer, and the third one ("mixed-choice") in which they were half of the time allowed to express their preference and half of the time they were instructed to follow the choices determined by the computer. For each of these three conditions, we took two types of measures for SoO and SoA: an explicit one, via the administration of an ad-hoc questionnaire in which participants were asked to answer 22 questions about their experience during the task; and an implicit one, with the measurement of the temperature of their hands, considered as the effectors of their decisions, at specific times during the experimental session. We measured the hands temperature via an infrared camera.

In line with research in the field, we hypothesized, (i) at the explicit level, that subjects would report significantly less SoO and SoA in the condition in which they were instructed to follow what the computer told them to, compared to the one in which they could exert their will; (ii) at the implicit level, because of the alterations of SoO caused by manipulations of SoA, we expected skin temperature of participants to undergo changes following the same trend of the explicit parameters: we hypothesized a significantly decreased hands temperature in the condition in which they were forced to follow the instructions of the computer compared to the one in which they could freely choose the option they preferred.

Our results were in line with our hypothesis for the explicit measures of SoO and SoA; however, our results could not support our prediction of a relationship between alterations in SoO and changes in skin temperature.

While our study lays within the prominent line of research supporting, at the explicit level, the direct link between SoO and SoA, the two main components of bodily self-awareness, we could not demonstrate their indirect link via the hypothesized thermoregulatory changes in the body. In the literature, this debate is still open, whereby several studies show a significant decrease in skin temperature as a consequence of reduced SoO, especially in pathological conditions involving alterations of self-awareness as well as following the implementation of illusory paradigms such as the RHI. Other studies, though, had and still have difficulties in obtaining significant results when dealing with the thermoregulatory responses of the body following changes in the ownership perceived towards it. Our results at the implicit level seem to support the lack of the hypothetical relationship, but some limitations highlighted here could help understanding the next steps to take to level up our experimental settings and to sharpen research in this complex field. Most importantly, more attention could be paid to the experimental setting, with the main focus on temperature measurement: being changes in the order of hundredths of a degree, the smallest inaccuracies can have a significant impact on the results obtained.

One fundamental point to highlight is that our experiment demonstrated, at the explicit level, the validity of our insight about the possibility of manipulating SoO and SoA by operating at the decision-making level of action. Since feeling agents not only of one’s own actions, but also of one’s own decisions, is one of the main components of SoA, further research could leverage on this alternative and innovative way of manipulating our decision processes to explore, from a novel point of view, its relationship with SoA, SoO, and bodily self-awareness in general. Again, more clear-cut paradigms could be implemented to deepen the analysis of the most implicit aspects of this complex relationship, pointing to a more comprehensive and detailed understanding of how our body and our cognition are profoundly intertwined.

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APPENDIX

APPENDIX 1: SoO AND SoA QUESTIONNAIRE

Here the Italian version of the SoO and SoA questionnaire. An English version was also created to allow participation for non-Italian subjects.

1. Mi è sembrato come se la mano sinistra con cui prendevo le decisioni fosse la mia.
2. Mi è sembrato come se la mano destra con cui prendevo le decisioni fosse la mia.
3. Mi è sembrato come se la mano sinistra con cui prendevo le decisioni fosse di qualcun altro.
4. Mi è sembrato come se la mano destra con cui prendevo le decisioni fosse di qualcun altro.
5. Mi è sembrato come se la mia mano sinistra non mi appartenesse più, come se fosse solo il computer a decidere.
6. Mi è sembrato come se la mia mano destra non mi appartenesse più, come se fosse solo il computer a decidere.
7. Mi sembrava che le ricompense ottenute fossero decise dai movimenti della mia mano sinistra.
8. Mi sembrava che le ricompense ottenute fossero decise dai movimenti della mia mano destra.
9. Mi è piaciuto prendere le decisioni.
10. Mi è sembrato come se io fossi in controllo dei movimenti della mia mano sinistra per prendere le decisioni.
11. Mi è sembrato come se io fossi in controllo dei movimenti della mia mano destra per prendere le decisioni.
12. Mi è sembrato come se fossi io a decidere i movimenti della mia mano sinistra per scegliere le ricompense indicate a sinistra.
13. Mi è sembrato come se fossi io a decidere i movimenti della mia mano destra per scegliere le ricompense indicate a destra.

14. Le ricompense ottenute erano in sincrono con i miei stessi movimenti della mia mano sinistra.
15. Le ricompense ottenute erano in sincrono con i miei stessi movimenti della mia mano destra.
16. Mi è sembrato come se il computer stesse controllando le mie decisioni.
17. Mi è sembrato come se il computer stesse controllando i movimenti della mia mano sinistra.
18. Mi è sembrato come se il computer stesse controllando i movimenti della mia mano destra.
19. Mi è sembrato come se il peso della mia mano sinistra fosse cambiato.
20. Mi è sembrato come se il peso della mia mano destra fosse cambiato.
21. Mi è sembrato che la dimensione della mia mano sinistra fosse cambiata.
22. Mi è sembrato che la dimensione della mia mano destra fosse cambiata.