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Tools and peripersonal space: an enactive account of bodily space

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Abstract

Peripersonal space (PPS) is frequently defined as a plastic, pragmatic and goal-directed multisensory buffer that connects the brain-body with its immediate environment. While such characterisations indicate that peripersonal spatiality is profoundly embodied and enactive, comparatively few attempts have aimed to systematically synthesise PPS literature with compatible phenomenological accounts of lived space provided by Heidegger and Merleau-Ponty. Moreover, in traditional cognitive neuroscience, neurophysiological activity is thought to map onto discrete 'cognitive correlates'. In contemporary 4E approaches to cognition, however, phenomenology-derived notions such as 'pre-reflective cognition' and 'motor-intentionality' frequently appear, yet their neural correlates may be comparatively difficult to pin down. Pre-reflectively, agents seemingly do not thematise spatial properties as operationalised in key experimental paradigms (e.g., spatial rotation tasks) but are instead inherently spatially embedded within the world. To refine this distinction, I survey how tools co-determine this distinctly spatial 'world-embeddedness' using a neurophenomenological methodology (Varela, *Journal of Consciousness Studies, 3*(4), 330–349, 1996). Specifically, I conduct two neurophenomenological analyses of tool-perception and tool-use, examining both how distance modulates affordance-perception and how tool-use remaps bodily space via the withdrawal of tools from intentional-objects into co-constituting motor-intentionality itself. I conclude by briefly distinguishing this interpretation of spatial cognition from cognitivist frameworks. Thereafter, I briefly highlight the temporal scaffolding underlying PPS while conceptually grounding my account within Embodied Simulation Theory (Gallese, *Reti, Saperi, Linguaggi*, (1), 31–46, 2018). What is at stake is thus both an explicitly embodied-enactive account of bodily space that is qualitative and situational instead of quantitative and positional, as well as a viable, interdisciplinary strategy for unifying pre-reflective cognition with neurophysiological data.

Keywords Neurophenomenology · Enactivism · Peripersonal space · Spatiality · Merleau-Ponty · Heidegger

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1 Introduction

Peripersonal space (PPS) is a term that emerged from cognitive neuroscience to designate the neural representation of the area of space surrounding the body.[1] PPS was first hypothesised by Rizzolatti et al. (1981), who proposed that this neural representation of near-space was inherently sensorimotor. Subsequently, peripersonal neurons (PPNs) were discovered in the macaque brain by Graziano et al. (1994), who observed the activation of tactile neurons when objects approached the body even if they did not actually make contact. PPNs are mostly found in brain area F4 and are multimodal and somatocentered (Fogassi et al., 1996). Currently, there is lively, ongoing debate as to the best definition of PPS (Bufacchi & Iannetti, 2018), but PPS can be broadly defined as the area of reachable space anchored to the body in which all physical interaction takes place, and which features significant variability in its shape and size, serving to connect the brain-body with its immediate environment or '*Umwelt*'.[2]

Here, in combination with experimental PPS literature from the past 25 years, I utilise phenomenological examinations of lived space provided by Heidegger (1927/2010) and Merleau-Ponty (1945/2012) to promote a "mutually illuminative relationship" (Varela, 1996), equipped to reveal the complex interrelation between affordances, tool-use and peripersonal space as jointly manifest in neural activity, behaviour and pre-reflective cognition. The resulting analysis should thereby clarify the 'pre-reflective cognitive correlate' and the 'motor-intentional profile' of PPS neural activity commensurate with delineated experimental tasks and activities. Finally, I briefly dissect the temporal undercurrents to embodied-enactive spatial cognition, arguing that a key difference between tool-perception and tool-transparency corresponds to a difference between potentiality and actuality respectively, linking this account with Embodied Simulation Theory (Gallese, 2016, 2018).

While the quantitatively measurable interval between agents and entities in space remains crucial for understanding PPS, depicting this relationship in solely metric terms does not exhaust the entirety of spatial cognition. Indeed, several diverse, even contradictory, factors reliably produce near-identical metric changes in PPS size, including joint action, tool-use (Iriki et al., 1996; Berti & Frassinetti, 2000; Canzoneri et al., 2013), fear (Taffou & Viaud-Delmon, 2014), confidence (Masson et al., 2021) and co-operation (Teneggi et al., 2013). Foregrounding these factors is important for theoretically contextualising experimental findings because what appears homogenous at the *quantitative* level (e.g., extension or retraction of PPS by 10 cm) may nevertheless conceal significant heterogeneity at the *qualitative* level. For instance, a PPS expansion engendered by fear is qualitatively distinct from, or even juxtaposed to, a comparable expansion engendered by confidence, and different still from co-operation.

[1] The term 'representation' is controversial in 4E cognitive science. Here, I take no explicit stance on the matter, but only employ it here when explicating the standard definition of PPS.

[2] See Ferroni and Gallese (2022) for a recent, cross-disciplinary overview of PPS as well as how it interfaces with other contemporary concepts of selfhood.

Such heterogeneity indicates that crucial dimensions of spatial cognition are intimately attuned to the *meaning* of the immediate environment, and that the brain-body possesses an inherently qualitative, as well as quantitative, relationship to its surrounding space. Accordingly, solely observing peripersonal space's metric alterations obscures the richness of how situated agents are spatially embedded in the world in a manner typically characterised as pre-reflective. Because living organisms do not experience their spatial surroundings abstractly as a continuous, geometric grid (whereby each metric area of space is interchangeable with another), the spatial dynamic, or 'multisensory interface' (Serino, 2019), uniting organism with *Umwelt* (via PPS) is constantly reshaped according to what its surroundings *mean* for its situated existence.[3]

This fact is clearly not lost on experimental PPS researchers. Bassolino et al. (2010, p.804) note: "an important property of PPS is the possibility of being modified as a function of experience", while Spaccasassi et al. (2021, p.2150) claim: "objects located inside PPS are represented in terms of potential actions… PPS is not solely a metrical representation of the space around us but includes a more complex (operational) representation". Ferri et al. (2015, p.469) contrast a 'metric' with a 'functional' understanding of PPS as follows:

> According to the metric hypothesis, all the objects located within a given physical distance (e.g., 50–60 cm) from the body will fall into the PPS. Conversely, if the functional understanding of the PPS holds, PPS boundaries will dynamically change according to contingent factors. Currently, there seems to be a consensus reached that supports the functional hypothesis.

Even as far back as 1997, Rizzolatti et al. (1997) compared PPS with Merleau-Ponty's spatial phenomenology. Moreover, Gallese (2018, p.33) frames motor spatiality in explicitly embodied-enactive terms that strongly evoke phenomenological descriptions of lived space when he argues that "the functionality of the motor system literally carves out a pragmatic Umwelt, dynamically surrounding our body" and that the inescapably sensorimotor dimension to spatial cognition means that "the visual world is always also the horizon of our potential pragmatic relation to it" (Gallese, 2016, p.300). Indeed, compare these assertions to Merleau-Ponty's phenomenological account of bodily space's sensorimotor dimension: "vision and movement… are not united "under the domination of an 'I think' but rather by orienting them toward the intersensory unity of a 'world'" [172/139].

These empirically-derived insights indicate need for a conceptual framework of peripersonal spatiality that gives requisite attention to its embodied and enactive dimensions. Following the phenomenological tradition, we might designate this phenomenon 'lived space', or, perhaps more narrowly: 'bodily space'. For present purposes, I use peripersonal space and bodily space interchangeably. Not only was the term 'bodily space' employed rather prophetically by Merleau-Ponty (1945/2012) but as Gallese and Sinigaglia (2011, p.132) stipulate "peri-personal space *is a* bodily

[3] See also Jackson (2014), who already made this connection explicit.

space characterized by an action-dependent dynamic plasticity" [emphasis added]. Indeed, 'bodily space' naturally extends the notion of a 'lived body' (*Leib*), which has arguably been a noteworthy success story of phenomenological and neuroscientific cross-fertilisation.

While, with respect to some prominent topics in 4E cognitive science, there have perhaps been comparatively few systematic syntheses of the PPS and phenomenological literatures, some scholars have offered fruitful interdisciplinary accounts of bodily space using both (e.g., Gallese & Sinigaglia, 2011; De Preester, 2012; Jackson, 2014). Here, I intend to emphasise and clarify different modes of tool-interaction in PPS, with special emphasis on how particular empirical findings complement an array of phenomenology-derived notions. Indeed, both phenomenology and cognitive neuroscience indicate that 'lived' bodily space, in contrast to the objective position occupied by the material body, actually extends beyond the epidermic layer and into a space of world-interaction (Jackson, 2014).

Like objective space, 'lived' or 'bodily' space is a relational phenomenon. Yet, unlike objective space, non-quantitative factors co-determine how organisms and entities interface with each other. Accordingly, an embodied-enactive account of PPS should emphasise spatial relationships in terms of what they *mean* for situated agents engaged in the world. In this paper, I narrow my focus down to two examples pertaining to the meanings of objects: (1) perception of tools; (2) use of tools. That is, I ask: primarily, what does an object *mean* when the brain-body perceives or wields it*?* Is the brain primarily interested in the object's height, width, or depth? Or should we emphasise, following the above quotations, object interaction in peripersonal space in 'operational, pragmatic and experiential' terms?

A central argument is that perceiving an object's use-value, which goes beyond the 'mere' visual perception of its Euclidian properties, profoundly modulates agent-object spatial relationships, supporting the 'functional' as opposed to 'metric' interpretation of PPS (Ferri et al., 2015). In fact, it is precisely 'use-value', a factor inherently affiliated with function, which marks out 'tools' as distinct from other objects, such as triangles, protons or clouds. If agent-object relationships are central to revealing how agents are pre-reflectively embedded in their environments via PPS, which terminological tool-kit is most suitable for articulating it? Phenomenological resources serve this need in two ways. Firstly, by disclosing first-person experience or the 'pre-reflective cognitive correlate' (PrCC) to neurophysiological data in a faithfully descriptive fashion with domain-appropriate terminology. Secondly, by clarifying the third-person 'motor-intentional profile' (MiP), which provides further clarity as to *which kind* of entity the brain-body is attuned to and *how* it is attuned to it.

Here, I survey two dimensions of tool-interaction that have received considerable experimental attention: tool-*perception* and tool-*use*.[4] First, I clarify how the brain-body perceives tools as 'ready-to-hand' in relation to affordances (Gibson, 1979).

[4] This should not imply that perception and action belong to wholly discrete realms, as it were. Indeed, as should become clear, perception and action are co-constitutive. I thank reviewer 2 for prompting me to clarify this issue.

Thereafter I highlight the role spatial distance plays in affordance-perception before examining tool-use, or what may be better termed tool-*transparency*. When agents wield particular objects ('tools' or '*pragmata*') in a goal-directed fashion, PPS is frequently observed to expand. I argue that this effect is important insofar as it showcases how material things transition from being intentional-*objects of* perception into directly *co-constituting* motor-intentionality itself. Finally, I examine some exceptions to this rule and offer theoretical contextualisation. Thus, the distinction between the enactive perception *of* objects and bodily interaction *with* objects is disentangled from a neurophenomenological perspective, highlighting the distinctive experiential and motor-intentional profiles underlying each act.

2 Tools as 'ready-to-hand'

One of Heidegger's most noted contributions to philosophy and beyond is his introduction of the term 'ready-to-hand' [*Zuhandenheit*]. Several overviews of this notion exist and, while a detailed analysis is far beyond this paper's scope, it is sufficient to emphasise that ready-to-hand denotes a modality which determines how entities are immediately presented to consciousness.[5] Specifically, within this modality, entities are not understood via their objective properties (e.g., atomic weight, material composition) but rather their pragmatic utility, itself understood in connection with tasks that the entity is suitable for. When found as ready-to-hand, a material object is a tool. A ready-to-hand hammer, to use Heidegger's famous example, is understood *in relation to* the local task of hammering and the wider context of building, carpentry or DIY. By contrast, 'present-to-hand' [*Vorhandenheit*] entities do not refer onto any further task, as we must strip them of their contextual relation to human activity ('worldliness') to successfully access their objective properties as accomplished in science or metaphysics.[6]

Let's apply this distinction to another everyday example. The water bottle next to me can be 'presented' as something materially composed of aluminium that (when empty) weighs 0.2 kg and is 30 centimetres in height. Alternatively, it may be 'ready' as a 'for-drinking' utensil, for the specific purpose of quenching my thirst when contextually appropriate (i.e., not when I'm swimming).[7] 'Ready-to-hand' objects are clearly analogous with, and inspired, the term 'affordance' introduced into the psychological literature by Gibson (1979). An affordance designates which task an object serves: e.g., pens *for-writing*, doors *for-opening*. It is thus the direct perception of this context-dependent use-value that renders a 'mere'

[5] Another terminological issue arises here, as Heidegger did not use 'consciousness' as did Husserl and Merleau-Ponty.

[6] During the review process, I encountered a book chapter by De Preester (2012) that cogently deals with ready-to-handness, peripersonal space, tool-use and embodiment from within a Heideggerian framework. For a comparable but alternative perspective on the themes covered in this article, as well as those of prosthetics and technics, I refer the reader to her work.

[7] Or, in rarer situations, I can use it to pour water and clean something or throw it as a weapon at some kind of offending stimulus.

three-dimensional object into a tool. Importantly, while ontologically dependent on a perceiving subject, affordances are scientifically measurable via neuroimaging (Grafton et al., 1996; Chao & Martin, 2000).

Almost as famous as Heidegger's notion of ready-to-hand is that he did not integrate it with any explicit account of human embodiment. According to Malpas (2000, p.221), Heidegger "seems effectively to consign the body to the realm of Cartesian spatiality", where, by contrast, "Dasein's locatedness must thus be a matter of its engagement in the world on the basis of a differentiated and extended body". Carman (1999) adds that Merleau-Ponty recognises the importance of worldhood as described by Heidegger, synthesising it with Husserl's writings on the lived body (*Leib*) to highlight the more concrete, 'ontic' instantiations of embodiment, providing rich descriptions of the spatial harmony between body and world. Put broadly, a tool's ready-to-handedness hinges on our bodily constraints and situated attunement to the environment. Heidegger and Merleau-Ponty can thus help us reveal embodied spatial cognition in its pre-reflective dimensions as has been achieved in other enactive accounts.[8]

As Dreyfus (1991) emphasises, unlike abstract entities, tools are experienced as available for use, not just as occurrent entities in geometric space. The brain-body engages tools as grounded within a spatiality of situation defined by embodied locatedness (Malpas, 2000), not as positional sites perceived by a disembodied *cogito*. In parallel to these phenomenological accounts of embodied tool-use, a rich experimental literature continues to investigate affordance-perception in relation to spatial proximity, to which phenomenology can plausibly contribute. Because phenomenological nearness is not interchangeable with metric distance, agent-object proximity must have an experiential imprint that escapes the language reserved for quantifiable relationships. While the quantitatively measurable interval between agents and tools indisputably influences neurophysiological responses to affordance-perception, I aim to show that this modulation does not *only* manifest as objective distance.

Borrowing Merleau-Ponty's terminology, I posit that agent-object proximity can be framed in terms of 'holds' comprised by 'intentional threads'. As we shall see, 'hold' denotes that, the closer objects are to the lived body, the more they are gifted with powers of influence over it. 'Intentional thread' designates the transient connection that arises between agent and object at the motor-intentional level that scaffolds situated motor-intentionality. We can then ask: if objects *qua* tools are ready-to-hand, *and* tools co-constitute the structure of bodily space, how then does distance modulate their 'readiness'? Moreover, how might an enactive spatiality of *situation* apply to experimental data where the *position* of objects (whereby 'metric distance' is operationalised) appears essential?

[8] The notion of 'ready-to-hand' has already been operationalised in at least one experimental paper on PPS and affordances (Costantini et al., 2011).

3 Neurophenomenology of tool-perception

As the PPS literature demonstrates, a tool's perceptible usefulness is not equally pressing irrespective to its location relative to the agent. A truly embodied-enactive account of spatial affordances should emphasise that useful objects of further or closer proximity to agents are registered in interactive, motoric terms. To this end, Cardellicchio et al. (2011) measured motor-evoked potentials (MEPs) in the hand muscles of participants who were presented with tools (e.g., mugs) both inside and outside of their PPS. They found that hand-muscle produced MEPs were higher in amplitude for the tools placed *inside* of participants' PPS. That is, the closer the tool to the agent's reach, the greater was the activation of interaction-relevant muscles. Crucially, this indicates that, even non-volitionally and below awareness, tool-relevant body parts are motorically prepared for interaction whenever such tools are realistically reachable. This 'interaction-preparation' effect substantially diminished when non-functional, non-tool-like objects (such as cubes) were presented.[9]

Reachable tools thus powerfully co-determine the quality of the agent's spatial embeddedness by automatically eliciting the body (lived *and* objective) into an interaction-ready state. Even when no action is executed, a perceived tool *simulates* its most likely usage throughout the brain-body. Accordingly, tools produce higher-amplitude MEPs because their perception pre-reflectively carves out a field of potential action that animates the body, co-determining the meaning of the agent's spatial situation. The lived hand as a 'power for action' (Merleau-Ponty, 1945/2012) is therefore automatically sculpted by the particular action-possibility that the tool affords.

Similarly, Wamain et al. (2016) used a virtual reality experiment to test neural responses to objects placed both inside and outside of PPS (as measured by EEG) during a reachability judgement task and an object identification task. They found that there was greater *Mu* rhythm desynchronsiation for the objects within PPS; i.e., those which were realistically graspable. This modulation was task-dependent, as when subjects were only asked to *identify* manipulable objects in PPS, the effect was diminished: "the greatest mu desynchronization was observed when participants judged the reachability of prototypical objects presented in peripersonal space. Such desynchronization reduced progressively when objects approached extrapersonal space" (p.26). As *Mu* desynchronisation has been correlated with the affordance-perception, these data further support the claim that agent-object proximity is neurologically mapped in interactive terms. Closer objects are not *just* processed metrically but present the situated brain-body with specific opportunities for contextual action, the strength of which are negatively correlated with distance.

What then if one's hands are immobilised? Iachini et al. (2014) introduced one condition involving tying the hands of participants behind their backs while objects were presented. The authors claimed that their results "confirmed that spatial

9 As Vittorio Gallese pointed out to me, a three-dimensional object *can* nevertheless function as a tool, such as a cube used as a paperweight. In such cases, three-dimensional objects are tools proper, as they acquire a relational structure with the purpose served.

localization of both manipulable and non-manipulable stimuli was facilitated by having free than blocked arms in peripersonal space".[10] Thus, the metric distance between participants and objects remained identical throughout, yet their perception of objects was modulated by their (in)capacity to grasp them. It follows that the interdependence between perception and action entails that blocking one's arms render objects more difficult to localise. Interestingly, when non-manipulable objects were presented in *extrapersonal* space for the blocked-arm group, localisation accuracy *increased*. The authors (p.79) suggested that reducing the subject's capacity for movement increases localisation accuracy suggesting "extrapersonal space could instead primarily rely on visuo-spatial ventral processes" in which the enactive component of perception is comparatively diminished, implying that motor resources are comparatively less important when objects are not realistically graspable.[11]

Closer tools are thus represented not only by a decrease in measurable distance but by an increase in their temporary 'occupation' of the situated sensorimotor system via simulated action-potentials. When the brain-body perceives a tool, its task-attunement (or 'the activation of motor programmes' in computational terms), signifies that the brain-body views the object as something '*for-handling'*. This phenomenological 'for' structure is either not present or significantly diminished, as the experimental evidence indicates, if we cannot *really* reach out and use the tool. Reachable objects thus confer a greater bodily and neural 'imprint' by presenting agents with more strongly suggestive action-possibilities.

To elucidate this phenomenon in greater detail at the experiential and motor-intentional levels, we may consult the phenomenological literature in greater depth. We saw that agent-object proximity – while not reducible to quantification – inevitably intersects with metric distance during affordance-perception. How then can we cash out proximity in qualitative terms? In his analysis of depth perception, Merleau-Ponty (1945/2012, pp.303/265–317/279) offered a prototypical phenomenology of affordance-perception modulated by distance, conceptualising agent-object proximity in terms of the 'hold' that the latter has over the former. As he aptly puts it: "The man at two hundred paces away is a less articulated figure, he offers my gaze fewer and less precise 'holds' [and] is less strictly geared into my exploratory power" (p.310/272). By clear implication, the closer man exerts an *increased* hold over my current spatial situation by pre-reflectively soliciting my embodied consciousness for an imminent interaction according to the contextual demands of our encounter. Qualitatively, he thus enjoys a greater presence in my spatial situation.

[10] It appears that here also non-tool objects produced the same effect as did tools. The authors conclude that motor resources only interfere with object localisation if the object is outside of reaching range.

[11] It is interesting to speculate how subjects may adapt after prolonged time periods. Merleau-Ponty writes on phantom limb phenomena and experiments involving immobilizing the legs of insects, that the "the tied limb is not replaced by the free one because the tied one continues to count in the animal's being and the impulse of activity that goes toward the world still passes through that limb" (107/80). However, such 'ecological' instances are outside of timespan typical of laboratory settings used in human subjects research. Nonetheless it is interesting to speculate whether the effect found would diminish on a larger timescale, as in the case of amputees. Thank you to reviewer 2 for drawing my attention to this point.

Switching from persons to tools, the potential interaction that is perceptually presented via the further tool has a diminished presence in my exploratory power. The 'content' of a situated agent's motor-intentionality is equivalent to whichever task that specific tool is useful for. As the tool's distance increases, its presence diminishes, and alternative action-possibilities come into focus; their 'holds' increase. But this does not imply a precise boundary. As Bufacchi and Iannetti (2018) have recently argued, proposing a strict, 'in-out' PPS dichotomy is inadequate, as PPS is better conceived as a gradient. Indeed, as Merleau-Ponty intuited, we can still 'hold' something located further away in EPS, albeit in a diminished way:

> we 'have' the object that is moving away, we do not cease 'to hold' it and to keep a hold on it… the increasing distance merely expresses that the thing begins to slip away from the hold of our gaze and that it joins with it less strictly (311/273).

Nonetheless, nearer objects are more 'geared into our exploratory power' by co-determining the overall meaning of our spatial situation more pronouncedly. Because the brain-body is spatially embedded in the world via PPS, when an object comes within reaching distance it solicits the body toward task-appropriate action without need of reflective cognition. Pre-empting Cardellicchio et al. (2011), Merleau-Ponty adds:

> No sooner have I formed the desire to take hold of an object than already, at a point in space that I was not thinking about, my hand as that power for grasping rises up toward the object (181/147).

In Cardellicchio et al. we saw that participant's hand muscles produced higher amplitude MEPs (i.e., were more prepared for action) when tools were presented *within* PPS. These higher-amplitude MEPs can be viewed as consequential to the occupation or 'hold' the nearby tool possesses over the situated sensorimotor system, whereby the body is pre-reflectively solicited towards physical engagement with the presented tool if it is within reach. The motor-intentional profile is that of an agent perceiving contextual action possibilities *in* the direct perception of a tool's use-value.

To reiterate, tools inside PPS occupy a greater 'hold' over the sensorimotor system as compared to those outside PPS. Should the computer mouse next to my right hand be moved further away at a distance of three metres, my phenomenological relationship to it changes insofar as it does not literally offer a *for-navigating* opportunity during that precise moment in the spatial situation, since I cannot actually wield it. As I walk away from the computer, typing-relevant body parts are less actuated by the possibility of typing and the availability of the tasks it presents to me are experienced as increasingly dimmer on the horizon of possibility (Gallese, 2016). Thus, a quantitative *increase* of distance has its experiential correlate in a qualitative *decrease* in hold. And a decrease in hold means that the object enjoys a diminished presence in the situation, and the agent is offered fewer or more coarse-grained interaction-potentials.

This analysis of tool-perception can be further explicated by reference to two more notions found throughout *PoP*: (1). Optimal grip; (2). Intentional threads.

Merleau-Ponty emphasises that our conjoined sensory, postural and motor capacities always tend towards the functional maximisation of our orientation to our environment. He labels this phenomenon: 'optimal grip'. In some sense, all perceptual experience attests to this pre-reflective tendency. If I intend to cross a busy road, my perceived spatial surroundings are innately structured to optimise this goal. Instead of receiving a mess of undifferentiated sensory stimuli, the combination of one's bodily abilities, immediate goal-directedness, and higher-order purpose(s) generates a cross-modal stabilisation of perceptual input on pragmatic grounds, globally directed towards successful engagement in the world. I see a gap in the cars in the road *as a* place to cross, subordinated to my local goal of crossing the road for the higher-order purpose of reaching the supermarket. Again, all of this pre-reflectively structures my sensorimotor opening to the spatial world rather than featuring as reflective content of my thought.

With regards (2), we saw that perceiving certain affordances brings task-relevant body parts into salience. This evokes Merleau-Ponty's key insight into the body schema: the body schema's schematic is conceptually impoverished if it only includes body parts themselves. For Merleau-Ponty, we develop our body schema through tools and tasks that certain body parts are appropriate for. The body *qua* motor-intentional entity is inconceivable if we exclude the *objects of* motor-intentionality from our account, which 'bring to life' the body parts used to engage them. Merleau-Ponty provides a rather topical example (for our purposes) of how bodily space is shaped by nearby tools:

> The subject placed *in front of* his scissors, his needle, and his familiar tasks has no need to look for his hands or fingers, for they are not objects to be found in objective space, but rather powers that are already mobilized by the perception [of them], they are the centre-point of intentional threads (p.136/108). [italics added].

'Intentional threads' thus complements the notion of 'hold' by emphasising the bidirectional link existent between agents and tools. This motor-intentional thread can be broken whenever tools drop out of salience or accessibility. Should I turn away from the keyboard, or should my arms by immobilised by (hopefully) an experimenter, the 'thread' linking me to the object becomes weakened or obliterated (Iachini et al., 2014). These '[motor-]intentional threads' link the situated agent to surrounding objects (and the tasks they present) at every moment, but we should note that one's motor-intentional directedness is rarely dispersed to all surrounding things equally; attention, valence, salience, proficiency etc., all co-determine which objects in our *Umwelt* are most prominent. Spatial distance is one such factor, determining the potency ('hold') of the intentional thread linking agent with object. Indeed, nearer objects produce more pronounced responses in experimental settings (e.g., quicker RTs, stronger MEPs) because we are phenomenologically more integrated with the intentional-object in question. As Heidegger writes in the section of *Being and Time* (1927/2010) devoted to space, Dasein cannot help but 'make room' for things that are near us or seize our attention (see De Preester, 2012). We are not necessarily always conscious of this nearness, nor need we thematise alignments between ourselves and objects in reflective cognition. Instead, nearness fundamentally co-constitutes how our surrounding space, and the entities within it, manifest.

To summarise, these cross-disciplinary insights support the fundamentally enactive notion that tool-perception is profoundly and pre-reflectively modulated by our capacity for embodied interaction. The aforementioned empirical studies demonstrate that nearby objects modulate perception and bodily posture, sculpting the body as to optimise a forthcoming interaction. Intentional access to tools via visual perception is co-constituted by bodily-motor capacities, even when agents are stationary. Furthermore, it appears that metric distance does not map isomorphically onto the cognitive correlate of spatial perception. That is, our brains do not *only* objectively perceive objects that are one, three or ten metres away *as such*. It is also the *tasks* they afford that are more present within our situation due to the tool's hold, as may be measured with localisation accuracy, *Mu* rhythm or hand-muscle produced MEPsAt the motor-intentional level, closer tools serve as more pronounced objects of motor-intentionality, strengthening the intentional threads between agents and tool(s). On the experiential side, objects appear *ready*-to-hand in the most literal sense upon entering reachability by pre-reflectively presenting agents with action-possibilities that animate the body itself, even eliciting muscle activity in task-relevant body parts.

The phenomenological notions of 'ready-to-hand', 'hold', 'optimal grip' and 'intentional thread' inform the empirical PPS and affordance literature by disclosing the PrCC and MiP in a manner complementary with the behavioural and neurophysiological findings. Thus, while the brain certainly perceives objective distance, and can make quantifiable estimates by thematically objectifying it, agent-object proximity also features a more immediate, *qualitative* profile. This profile highlights how, owing to the presence of potentially useable objects, the brain-body is pragmatically embedded in its surrounding space as a "horizon of action possibilities" (Gallese & Sinigaglia, 2011, p.130).

But what then if just *one* of these action-possibilities are chosen and acted upon? This distinction takes us from tool-*perception* onto tool-*use*.

4 Neurophenomenology of tool-transparency

After observing how the brain-body perceives certain objects *qua* tools offering specific interaction-possibilities, we can now focus on what happens when these affordances are 'realised' by acting upon them. While affordances appear to be modulated by the strength ('hold') of contextual action-potentials, we see a remarkably different experiential, neurological and motor-intentional profile emerge if one acts upon this potentiality to *actually* use the tool; in other words, the manifold of observed action-possibilities decreases to one concrete instance of tool-usage.

Following Heidegger, I claim that the way in which agents access tools via perception is notably distinct from how they access them via practical usage. Thus, a superficial glance at the seemingly simple transition from just looking at tools to wielding them conceals a richness at the neural, motor-intentional and pre-reflective levels. As we shall see, agents who purposefully wield tools differentially experience their spatial surroundings, with the tool acting as an irreducible element in the equation. While Heidegger had reason to sidestep the Brentanian-Husserlian language of intentionality in *Being and Time*, he astutely emphasised this difference in claiming that, in contrast to perceptual identification, the "handling, using, taking care" of things, all feature "their own kind of 'knowledge'" (67/67).

Once more, Merleau-Ponty (1945/2012) took up and reapplied this Heideggerian motif with enhanced focus on the phenomenon's 'ontic' and bodily instantiation. Using the classically academic example of a (typing) keyboard to cast light on the interplay between body, space and tool-use, Merleau-Ponty argues that: "The subject who learns to type literally incorporates the space of the keyboard into his bodily space" (180/146). That is, tool-use carries the tool *into* bodily space because the task-at-hand that it facilitates fundamentally remoulds the way in which the agent is spatially embedded in her environment. Consequently, whenever we 'understand' tools by correctly using them, our bodily space is altered in direct attunement with whichever activities that specific tool facilitates. This tool-enabled 'opening-up' of new spatial horizons is strongly reflected in Heidegger's (1927/2010) claims that using, not merely perceiving, tools represents a distinct way of knowing them because, during activity, tools must withdraw from being objects of explicit intentional focus while nonetheless determining the nature of the activity:

> What is peculiar to what is initially at hand is that it withdraws, so to speak, in its character of handiness in order to be really hand. *What everyday dealings are initially busy with is not the tools themselves, but the work* (69/69) [emphasis added].

During purposeful activity, agents *understand* tools in a manner distinct from viewing or objectifying them because something *other than* the tool itself is made immediately available; namely, "not the tool, but the work". Importantly, this intentional phenomenon has an observable neural correlate, as some of the most well-replicated empirical findings in PPS research have demonstrated that tool-use alters the shape and size of PPS. A foundational experiment to note is Iriki et al.'s (1996) investigation into the peripersonal spaces of Macaque monkeys, in which they investigated PPS size following a session of tool-use in service of motor tasks. Specifically, Iriki and his team trained several macaque monkeys to use a long, hooked stick to retrieve a foodstuff placed outside of their reachability while undergoing neuroimaging. As monkeys are not renowned for their self-constraint, on acquiring the skill they continuously reached for the previously out-of-reach food. This engendered a spatial relationship that synthesised body, tool, and food according to the enactive logic of the task-at-hand.

Let's consider the operative motor-intentional profile here. Beforehand, the out-of-reach foodstuff featured the affordance 'for-eating', though presumably with a degraded 'hold' since they fell outside PPS. Pre-training, the stick may to have been a mere perceptual object to the Macaque, devoid of use-value. Upon learning to use the stick, however, the macaque's motor-intentional relationship to it underwent a phenomenological transformation from 'object' into 'tool' as it became an integral component to the task-at-hand. The tool-stick and the goal thus acquired a relational structure, bound together within bodily space. Bodily space had extended outwards to incorporate the (withdrawn) tool, allowing the foodstuff to show up as *actually* reachable. Now, the desired object previously outside of PPS automatically shows up as obtainable, qualitatively altering the way in which the monkeys were spatially embedded within their environment. The tool thus enabled the Macaque to 'bring close' what was previously far-space.

But this change was not limited to experience alone. Indeed, it had a clear neurophysiological signature. After several minutes, intracranial neuroimaging showed that their visual receptive fields (vRFs) typically terminating at the hand had extended to the far edge of the stick. These bimodal neurons coding PPS now included the length of the stick into their 'representation'. The Macaques' situated motor-intentionality was no longer directed *at* the stick but rather *through it*, at the food; to be effective, the stick withdrew from intentional prominence, rendering the foodstuff the intentional-object. This phenomenon can be labelled 'tool-transparency' since, at both the neural and experiential levels, the tool retreats from being an *object of* motor-intentionality (affordance) to instead *co-determining* the agent's motor-intentional capacity to engage the task. In some sense, the brain ceased to sharply distinguish between the boundaries of the body and the tool, treating both as a unified entity to the extent that both were temporarily conjoined to facilitate the task-at-hand.

Iriki et al. introduced a 'passive holding' condition to see if PPS expands whenever Macaques held the stick. Importantly, the extension of VRFs to the end of the tool was not observed when the macaques simply gripped it. Accordingly, bodily space as a situated, goal-directed phenomenon cannot be the mere combination of the objective lengths of the arm and the tool. Rather, the global task-at-hand both triggers and determines bodily space's extended size and shape. Indeed, goal-directed action with the tool in-hand was an essential triggering condition for tool-transparency. Embodied interaction with tools, not passively holding them, triggers the tool-transparency effect because it is the task-at-hand that mandates the brain-body's spatial embeddedness in its *Umwelt*, absorbing each component into a single, unified Gestalt, co-ordinated in reference to the current goal. Thus, goal-directed, tool-enabled interaction with the environment initiates a global motor-intentional realignment that synthesises the lived body with the tool for the duration of the task.

On similar grounds, another foundational study by Berti and Frassinetti (2000) found that patient P.P, who suffered from hemispatial neglect localised to near-space, had their deficit's boundary temporarily extended outwards following a session of tool-use. The task involved the bisection of a line on a wall in far-space. Crucially, the session of tool-use automatically extended the patient's PPS boundary. Because patient P.P's spatial deficit was localised to near-space, P.P underwent the temporary 'tool-transparency' effect after using a stick to bisect a line on a wall in extrapersonal space. Subsequently, what was previously 'near-space' for P.P, anchored around the body's extremities, expanded outwards to the end of the stick in 'far-space'. As the authors claimed in the title: "near became far".

After undergoing the tool-transparency effect, the brain-body's immediate sense of bodily space no longer terminated near the body but rather at the end of the tool, which withdrew from being an intentional-object to facilitate the task-at-hand. The patient's dominant motor-intentional orientation was directed not at the stick but at the line on the wall. As withdrawn, the stick could certainly not disappear from the spatial situation, as it was an integral element to the task-at-hand. Rather, it was transparently integrated into P.P's bodily space, so that, for the brain-body in action, 'near-space' became what was near the *tool*, not near the objective body itself. What these studies suggest is that tools can be temporarily embodied insofar as the space lying at their outermost boundary temporarily becomes a constituent component of the task-engaged, spatially embedded lived body.[12] This unification between tool and body has wide-reaching implications; Canzoneri et al. (2013) found that the tool-use even alters one's body image.

Crucially, however, this effect largely only occurs during, and consequential to, goal-directed activity, whereby the task-at-hand *replaces* the tool as the principal reference point of motor-intentional attunement. Once more, the phenomenological canon pre-empted these experimental findings, as found in Heidegger's classic example of tool-use: a carpenter at work with his hammer. Heidegger wishes to emphasise that, while at work, the carpenter's tool is not experienced as a present-to-hand, three-dimensional entity comprised of wood and metal in particular formations. Rather, when engaging it via the skill of carpentry, the hammer and the carpenter no longer resemble a strictly-delineated subject/object distinction. In the modality termed ready-to-hand, the carpenter has no explicit intentional relationship *to* the hammer; the hammer has become part of the carpenter's motor-intentional attunement to something higher-order (the task-at-hand).

Of course, the characteristic flexibility of bodily space entails that his situated spatial embeddedness in the *Umwelt* might rapidly change. Maybe the hammer is discovered to be too light or too heavy and the motor-intentional circuit encircling the carpenter, the tool, the task and the space in which their interaction occurs breaks down. During cases where this flow is disrupted ('breakdown'), the carpenter might *look at* the hammer, establishing an intentional relationship to the tool via perception only. Or perhaps he smashes his thumb and his intentional relationship to the hammer is best represented by swear words in his mother tongue. Whatever the case, in breakdown, the wider relational structure to the task-at-hand dissolves. Accordingly, while the same hammer can be intended in a multitude of ways, it is typically only during engaged activity or 'absorbed coping' (Dreyfus, 1991) that it withdraws into the background, i.e., is rendered transparent.

Heidegger's emphasis on the importance of the absorption of tools during engaged activity cannot be psychologised away as a penchant for idyllic, homespun craft. Indeed, we now see a clear parallel to this phenomenological picture emerge in the neuroscientific literature. If we were to subject Heidegger's hypothetical carpenter to modern neuroimaging, we would likely observe that when he utilises the hammer in its optimal context towards its designated purpose of hammering nails, the carpenter's brain expands its peripersonal boundary

12 For an important overview of the ways in which tools *are* not embodied in a manner indistinguishable from the 'real' body (most notably the absence of pain) see de Vignemont (2018) and De Preester (2012).

to 'in-corporate' the hammer. Itself no longer an intentional-object, the hammer co-constitutes his capacity to complete the task-at-hand, triggering a global motor-intentional realignment. The motor-intentional profile of hammering a nail, scaffolded by the *body* + *hammer* + *task* spatial unity, thereby encloses each component within a single spatial event that only dissipates after the tool is put aside.

Recalling Merleau-Ponty's example of a keyboard, let's consider tool-transparency in light of the previous discussion of spatial affordances. If you walk through the aisles of a computer store, you may come very close to a keyboard. Perhaps, if you notice it, it will trigger the affordance of *for-writing*. Should you move away from it, its hold over your situated brain-body (your hands and fingers in particular) gradually weakens. However, an alternative agent-object spatial dynamic arises should you decide to *use* that keyboard. While using it to type, the keyboard becomes incorporated into bodily space so that your situated spatial embeddedness is co-determined by the task of typing. Your dominant motor-intentional reference point is redirected away from the tool itself and toward the task-at-hand that the tool permits. Accordingly, the keyboard withdraws into transparency when bodily space reconfigures itself to include it. Thus, for this facilitation to occur, the tool *must* withdraw so that the act of typing (not the keyboard) determines bodily space's immanent structure.

We can now summarise the difference between tool-perception and tool-use. When the brain-body perceives a tool, the content of its motor-intentionality is determined by that tool's use-value, oftentimes according to a gradation of intensity via the phenomenon of hold. A tool's affordance is accessed perceptually (as a *for-something*) but this perceived '*for*' aspect must necessarily recede whenever we *act* upon an affordance. Thereafter, using a tool in service of a goal triggers tool-transparency, causing bodily space to temporarily expand and include the tool, as bodily space's shape and size reflects the task it is currently engaged in. At this point, the task-at-hand, not the tool, becomes the primary reference point of motor-intentionality, itself co-constituted by the now-transparent tool.

Consequently, tool-using agents can be motor-intentionally oriented towards intentional-objects *other than* the tool used to perform the action. Only following tool-transparency, whereby the tool is functionally integrated into bodily space, can a specific task-dependent affordance show up, as novel, previously unavailable action-possibilities become accessible via the tool. Consider, for example, an area of floor when wielding a vacuum, the nail while wielding a hammer, the basketball hoop when wielding a basketball, etc. Thus, the open spatial dynamic of potentiality that characterises tool-*perception* (where one typically faces various action-possibilities) recedes during active tool-*use*, whereby the agent is fully absorbed in the performance of one *particular* action that dominates their spatial situation. Tool-transparency thus highlights the characteristic contextuality and flexibility of PPS, showcasing how bodily space automatically reconfigures itself according to worldly demands. It is in this sense that bodily space is inherently situated as an enactive interface with the *Umwelt*.

5 Embodied Simulation and Spatio-temporality

The prior analyses have distinguished between potential and actual tool-interaction, corresponding to tool-perception and tool-transparency respectively. Key to tool-transparency is that it is typically not observed in conditions where agents grip but do not practically utilise tools. Yet, the PPS response labelled tool-transparency can be observed in some unique cases of 'mere' tool-perception; namely, in cases of tactile perception of highly familiar objects. Among other tools, this effect has been found with canes employed by the blind (Serino et al., 2007) and the computer mouse (Bassolino et al., 2010). When habitual users touch these tools, experimenters observe a PPS expansion otherwise observed only during actual, concrete usage. Importantly, this is not the case for non-habitual users, even if they used the tool 24 h prior (Serino et al., 2007). Thus, tool-transparency effects can occasionally be observed even when tools are passively gripped but not functionally wielded, seemingly blurring the present distinction between tool-perception and tool-transparency.

However, this puzzling effect is explainable by recourse to a promising meta-theory that unifies phenomenological with cognitive neuroscientific resources known as Embodied Simulation Theory (EST). As Gallese and Sinigaglia (2011) note, EST applies to tool-interaction, since tool-perception (seeing an affordance) elicits the cortical motor system absent any 'real' motor output; the cortical motor system automatically simulates a tool's possible uses upon perceiving it by activating the same neural pathways. Because identical motor pathways are used in real interaction as in the simulated cases, "bodily space is basically and constitutively given to us as the horizon of our own action possibilities" (Gallese & Sinigaglia 2010, p.130). As discussed, action-possibilities are presented in a gradation of strength ('hold') when perceived visually. For very frequent tool-users, however, the simulation conferred by touch appears stronger than that of vision, simulating not just motor output but PPS expansion and tool-incorporation. With the tactile perception of highly familiar tools, the simulated action is sufficiently strong as to mimic the PPS profile of tool-transparency *sans* the enactment of any real task. Why? Because the habitual agent is so strongly attuned to imminent interaction, this phenomenological fact must be reflected in their bodily space.

Thus, when an agent tactilely perceives, say, a computer mouse (Bassolino et al., 2010), the cortical motor system stimulates the most appropriate possible use of it, thereby shifting the way the agent is spatially embedded and sculpting bodily space for a specific interaction. This strongly evokes the non-linear temporal scaffolding to lived space articulated by Heidegger (Malpas, 2000) and in Merleau-Ponty's notion of *praktognosia*, which combines corporal knowledge with potentiality (Gallese & Sinigaglia, 2011; Ferroni & Gallese, 2022). For presently situated agents, these future-oriented neural simulations depend on a past familiarity with the tool in question (Serino et al., 2007; Bassolino et al., 2010; Gallese, 2018) adds that simulated motor output contributes to the mapping of distal goals and to action anticipation. Both 'distal goals' and 'action anticipation' denote future states intended in the present. In both cases, a simulation of a real action (i.e., tool-use) that *could* be performed informs the agent's spatial present even if no action *is* performed, serving as a kind of temporal bridge between potential and actual tool-use. The way that habit sediments into one's permanent sense of spatial embeddedness and predisposes one to forthcoming action showcases why only tactile perception of highly familiar tools mirrors the tool-transparency effect: the conditions indicate that agents are powerfully attuned toward performing a particular, well-practiced action in that moment.

EST thus helps us understand that there is a temporal scaffolding to PPS and tool-interaction. Indeed, Heidegger likewise argued that "equipmental ordering derives from the directionality of temporality" (Malpas, 2000, p.211). In such cases, the brain-body pre-reflectively anticipates ('protends') the tool's withdrawal, allowing the task to already appear as the primary motor-intentional referent. This is how the brain-body 'knows' how to automatically simulate a highly familiar tool's possible usage upon gripping it, as the spatially embedded brain-body is pre-reflectively directed towards forthcoming interaction. Subsequently, if this simulated act turns into a concrete instance of real usage, the simulation ceases; the simulated possibility became a concrete actuality. Therefore, when possibility (tool-perception) becomes actuality (tool-transparency), the previous "manifold of action possibilities" shrinks to one 'action actuality', cancelling the other simulations. Accordingly, just as situated spatiality is not metric, situated spatiotemporality is not chronometric. EST thus provides a plausible theoretical framework for unifying body, space and time that explains why rare instances of tactile tool-perception resemble the profile of tool-transparency.

6 Conclusion: an enactive account of bodily space

We have observed several mutually illuminative convergence points between the phenomenological and neuroscientific literatures on tool-interaction and space, with an emphasis on how tools co-determine the way in which agents are spatially embedded in their environments. As numerous PPS researchers have noted, peripersonal spatiality is pragmatic, dynamic and goal-oriented, comparable to the phenomenological modality of 'ready-to-hand'. Unlike a positional, quantitative spatiality, a situational, qualitative spatiality is defined by an ever-shifting horizon of contextual interaction, both possible and actual. Divergently contingent upon perception or actual usage, I have aimed to show that useable equipment always contributes to the dominant meaning of the brain-body's surrounding space, either by presenting action-possibilities or by reconfiguring bodily space itself whenever those action-possibilities are taken up. Conceived thusly, lived space is far from a sequence of sites mappable onto a Cartesian grid. Instead, the brain-body's surrounding space is referentially structured so that it is tethered to its *Umwelt* via possibilities, tasks and goals and not only via geometric properties of width, height and depth. Detailing some of the specific ways in which this is the case has been the aim of this paper.

What then does all this imply for an enactive account of bodily space? In stark contrast to quantitative and/or physical models of space, which are devoid of both meaning and an embodied-located 'here', both space itself and the entities within it are meaningfully structured and anchored to the extended *Leib*. Moreover, drawing inspiration from Varela's (1996) interdisciplinary work, this examination has further sought to showcase two replicable strategies for rendering phenomenology and cognitive neuroscience mutually informative; specifically, in the articulation of the *pre-reflective cognitive correlate* and *the motor-intentional profile* in a manner cohesive with objective neuroscientific results. Indeed, I argue that phenomenology is uniquely well-positioned to interpret behavioural and neuroimaging studies in which subjects are not explicitly cognising objective properties (i.e., reflective cognition) but where delineated neural and cognitive-experiential signatures are nonetheless detectable.

Finally, PPS deficits have been implicated in several disorders (Noel et al., 2017; Di Cosmo et al., 2018; Ferroni et al., 2022; Ferroni & Gallese, 2022; Ferroni et al. 2020). The concepts developed here may have potential clinical applications, following a long tradition of phenomenological psychopathology. Merleau-Ponty (1945/2012), for instance, examines bodily space disruptions in brain lesions and schizophrenia in detail. More recently, Noel et al. (2017) suggest that ASD and schizophrenia occupy opposite ends of a PPS spectrum. While we lack sufficient room to tackle these topics in requisite detail, one avenue may be to view schizophrenia as characterised by excessively strong holds and a high sensitivity to tool-transparency. Indeed, classic symptoms such as 'thought insertion' 'telepathy' and 'disturbances of self-other boundary' indicate that the spatial boundaries between patients and other entities overlap excessively. At the opposite pole, considering the abnormally steep PPS boundaries in ASD may shed light on the way ASD populations find it difficult to resonate with others, find close personal contact uncomfortable, or are highly attracted by ('held') by physical objects. Since there is a mounting body of evidence implicating PPS in psychiatric conditions, employing the neurophenomenological concepts developed here may prove helpful in detailing the ways in which clinical populations are spatially mis-attuned to their surroundings.

In sum, peripersonal spatial experiences, like their neurophysiological counterpart, are dynamic, flexible and continually sculpted by experience. It is precisely these characteristics that render PPS highly fertile for a neurophenomenological interpretation. Motor-intentionality, affordances, tool-transparency, context-sensitivity and non-linear temporality all seem informative to the interpretation of certain instances of neuroscientific data. Such interdisciplinary applications may help explain, to reiterate prior examples, why nearer objects elicit stronger MEP responses or why active tool-use and passive tool-holding confer measurably different peripersonal responses. Moreover, aside from an explanatory role, phenomenology helps describe the first-person correlate to third-person brain activity in a language more suitable for the target domain of experience. The result is thus a strongly embodied-enactive account of bodily space that showcases the PPS network as inherently meaningful and situational. We may thus give the last word to Merleau-Ponty:

> Places in space are not defined as objective positions in relation to the objective position of our body, but rather they inscribe around us the variable reach of our intentions and gestures. [179/144]

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