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What is the body schema?

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C1.S1

1.1 An action-orientated representation

C1.P1 The body schema is commonly defined as the representation of a body for action (e.g., Paillard, 1999; Dijkerman & de Haan, 2001; de Vignemont, 2010; Schwoebel & Coslett, 2005).[1] But what do we mean exactly by that? Is it only that it contributes to the planning and the control of bodily movements? If that is the case, then there is actually nothing specific about this type of representation of the body. Many states indeed can play such a causal role, including some very high-level states. Imagine, for instance, that you want to cut a cake into six equal slices. To do so, you can exploit your mathematical knowledge that 360 degrees divided by 6 equals 60 degrees. This knowledge can guide your hand while splitting the cake. Your ability to do maths can thus play a role in guiding your action, but clearly, we want the body schema to be more intimately connected to action. The crucial question is what makes the body schema so special. One might believe that the theories of motor control should be able to shed light on its nature, but they generally stay remarkably silent about the body schema. Here we shall characterize in detail its relation to action by analysing the type of information that it represents, the way this information is represented, and the function of this representation.

C1.P2 Let us start with a first provisional definition of the body schema:

C1.P3 *The body schema represents bodily parameters that are useful for action planning and control.*

C1.P4 Clearly, intentional movement requires information about the properties of one's body—but which properties exactly? Since action occurs on a very brief timescale, one may believe that only short-term properties are of direct relevance for guiding action. For instance, one needs to know the precise posture of one's limbs. However, to move one's arm, one needs to know its position at time t but also its size, which usually has not changed for the last 10 years. For example, to switch on the light, you need to know your starting position, but also the length of your arm in order to plan how far you

[1] For a detailed discussion of the notion of body representation and its many controversies, see Alsmith (2019). In brief, we take representations to be content-bearing states of the central nervous system. We further assume that body representations play the role of models that represent in virtue of their resemblance to the structure of the body.

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should stretch it. Hence, one needs knowledge about long-term structural properties of the body, including bodily configuration, bodily size, flexibility of the joints, and muscle strength. It is thanks to the knowledge of these structural properties that one does not attempt to move in biologically impossible or painful ways. It is also thanks to that knowledge that one does not over- or under-reach when trying to get an object.

C1.P5 Now the problem with this definition is that one can be aware of these bodily properties independently of any intention to move. Imagine that you are lying in your bed half-asleep. You consciously experience your legs stretched on the cold sheet. Does this postural sensation involve the body schema or not? Put it another way, does the body schema play a role exclusively for action, or also for bodily awareness? If it has a dual function, then one might wonder for what reason we actually give more emphasis to its motor contribution than to its experiential contribution. Furthermore, we would not be able to understand the fact that postural sensations do not always consciously express the way we act. In one study, for instance, after the vibration of the tendon of the biceps, participants had the illusory experience that their arm was stretching, but when asked to point to the position of their hand, their motor response remained immune to the illusion and they pointed to the correct hand location, and not to the felt hand location (Kammers et al., 2006). What this study, among others, reveals is that there are several ways to represent bodily properties useful for action. It is thus insufficient to define the body schema only in these terms. More is needed. One suggestion is that the body schema encodes information about these properties in a specific *format*. The idea of a format or code of mental representation is familiar in cognitive science, although there is no consensus about what formats there are or how to individuate them. Some formats are modality-specific—a visual format, a tactile format, and so forth. Another type of format can be an amodal or purely conceptual. A further type of format, which is at the core of our interest here, is the sensorimotor one. In brief, a sensorimotor content is a content that can be directly exploited by the motor system. If we go back to our original example of the mathematical belief, the mathematical result needs to be translated into a different format for it to be usable to guide action. The transition to action is then indirect. By contrast, the motor intention to cut the cake represents the movements to perform in sensorimotor terms and can thus be of immediate use for the motor system. For the body schema to be in direct connection to action, it must thus be encoded in the same format as the motor intention. We can then suggest this new definition:

C1.P6 *The body schema represents in a sensorimotor format bodily parameters that are useful for action planning and control.*

C1.P7 Let us briefly elaborate on how the notion of format allows us to account for dissociations between bodily sensations and movements. The hypothesis is that there can be distinct representations about the same properties (such as posture), but encoded in different formats. One may, for instance, suggest that the body is encoded in three different codes: sensorimotor, visuo-spatial, and linguistic (Schwoebel & Coslett, 2005). The difference between the three formats can be well illustrated if we consider body metrics. Action requires fine-grained spatial content. It thus seems a plausible hypothesis that the sensorimotor content of the body schema is detailed and specific (the arm as being 70.5 cm long, for instance—though, obviously, in whatever unit that can be exploited by the motor system). By contrast, bodily experiences do not require such high resolution and the visuo-spatial content can be more approximate and sketchy (the arm as being between 69 and 71 cm long, for instance). Finally, the linguistic content could simply represent the fact that this is a relatively long arm.

C1.P8 One may wonder, however, if this new definition exhausts the specificities of the body schema. In particular, in this definition, the link to action still remains relatively remote insofar as the body schema remains causally inert. Its content seems to be purely descriptive—it simply gives information about the body, for instance where my limbs are located. Describing how the body is is not the same as *prescribing* how the body should be. To see the difference, compare the following two mental states. I have a visual experience of the blue sky. My visual content can be accurate or not, depending on whether it matches the actual colour of the sky. It is then said to have a 'mind-to-world direction of fit' (Anscombe, 1957)—the content of the representation must fit with the world to be true. Now I form the motor intention to grasp a bottle. My motor intention issues commands to the skeletal muscles. Its directive content cannot be true or false. Instead, it can be successful or not, depending on whether I actually grasp the bottle. It has a 'world-to-mind direction of fit'—the world must be made to match the content of the representation for it to be successful. For many, it is only when its content is directive that a representation qualifies as action-orientated because then only does it tell us what to do (Grush, 2004; Millikan, 1995; Clark, 1998; Mandik, 2005). Now the question is whether the content of the body schema is comparable to the visual content of the blue sky or to the motor content of the intention. If it were only descriptive, as our earlier definition seems to imply, then the body schema would *not* be action-orientated—a counterintuitive conclusion.

C1.P9 However, there may be a different interpretation of the body schema, according to which it has not only a descriptive content, but also a directive content. As summarized by Millikan (1995, p. 191):

C1.P10 The representation of a possibility for action is a directive representation. This is because it actually serves a proper function only if and when it is acted upon. There is no reason to represent what can be done unless this sometimes effects its being done.

C1.P11 More specifically, in the now classic control-theoretic approach to action, the motor system uses two types of internal models: the inverse model and the forward model (Wolpert et al., 2001). The inverse model has the role of computing the motor command needed to achieve the desired state, given the agent's bodily postures and capacities, as they are represented by the body schema. One may even say that the content of the body schema is coercive—it heavily constrains action planning, so that one normally cannot help but use it to guide one's bodily movements. In short, the body schema makes you act in a certain way. In parallel with the inverse model is run the forward model, which predicts what the action will be like, given the specific body that executes the motor command, and allows anticipatory control of movements. Here also, we argue, the body schema has a clear directive function. It represents the desired posture and location. For it to be satisfied, the body must meet this posture and this location. Hence, the direction of fit is world-to-mind—the body must match its representation, and if it does not match it, then the agent must update the motor command.

C1.P12 To conclude, the function of the body schema is dual—it is both to describe the body (at a level of spatial resolution and in a format appropriate for action) and to guide action. This dual function is fulfilled if it provides an accurate representation of the bodily parameters useful for action and if the motor system obeys it. The body schema corresponds to what Millikan (1995) calls a *pushmi-pullyu representation*. Pushmi-pullyu representations (hereafter PPRs) are governed by both truth and activity guidance. Like Dr Doolittle's mythical animal, PPRs face two directions—they have a mind-to-world and a world-to-mind direction of fit. The content of PPRs varies as a direct function of a certain variation in some aspect of the environment that it represents and directly guides behaviour directed toward this particular aspect of the environment. PPRs need no inferential structure for them to have a relation to action. There is no need to translate descriptive information into directive information. It is constitutive of the content, which builds the command for certain behaviour into the representations. As such, PPRs afford great economy in terms of response time and cognitive effort. We can now propose the following final definition for the body schema:

C1.P13 *The body schema represents in a sensorimotor format bodily parameters that are useful for action planning and control. Its function is both descriptive and coercive.*

C1.P14 Now that we have a better understanding of the role that the body schema plays for action, including the type of information that is represented, its format, and its function, it is important to acknowledge that there is not a unique representation that meets this description.

C1.S2 1.2 Species of body schema

C1.P15 There is a sense in which the term 'body schema' is ambiguous, in that it functions as a general term—a term for the *genus*, if you will—which groups together various body representations which count as *species* of the body schema in virtue of satisfying the criteria outlined earlier. We have already distinguished between the representation of short-term properties such as bodily posture and the representation of enduring properties such as body metrics. We have also discussed the roles of body schematic processes in inverse and forward model-based motor control. Those distinctions apply independently of the type of action that one performs. We now want to propose that there is a further major distinction, which is, this time, context-dependent—a distinction between two species: the working body schema for positive affordances, and the protective body schema for negative affordances (de Vignemont, 2018).

C1.P16 Most research in cognitive neuroscience has restricted their investigation of the body schema and, more generally, of action to bodily movements such as reaching, grasping, or pointing. These movements allow us to act on the world, to explore it, and to manipulate objects. From an evolutionary point of view, these are the movements with the ultimate function of mostly to find food and eat it. But there is another class of movements, possibly even more important, the function of which concerns a different dimension of survival, namely self-defence. These movements are sometimes summarized with the famous three Fs: freeze, fight, and flight (Hediger, 1950). One should not believe, however, that we engage in protective behaviour only when there are predators. At any moment, we avoid obstacles on our path, we retrieve our foot from the burning bathwater, and so forth. We can thus distinguish between these two fundamental functions, to exploit the world and to protect oneself from the world.[2] What we propose is that to these two functions correspond two species of body schema, which we call the working body schema and the protective body schema. Here are two important implications of this functional distinction. First, the working body schema is centred on the hands, whereas the protective body schema covers the whole body. Second, the working body schema is highly malleable and can easily incorporate tools, whereas the protective body schema is more stable, keeping track of the body to protect, which, from a biological standpoint, consists of the body that nature gave us.

C1.P17 Let us first consider the working body schema. Its function is to reliably covary with any bodily instrument that can act on the world and to guide these exploratory actions. As a consequence, it does not represent the whole acting body homogeneously. It is indeed with the hands that we mainly act on the world, whether it is to pick berries and bring them to our mouth, to plant seeds, or to open doors and turn on the light. We wash our hands more often than any other parts of our body, because they are the parts of our body that interact the most with the world. We already know that the hands are over-represented, compared to the rest of the body, in the famous homunculus in the primary somatosensory and motor cortex. Here, we suggest that the working body schema, which is implemented at a later cortical stage, also represents the hands in greater detail than other body parts because of their special significance for acting on the world. But we also explore the world with tools. Tools extend our space of actions, allowing us to act further away and more efficiently. They do so by extending the space of our body, and more specifically our working body schema. Evidence for such embodiment can be found in the following study (Cardinali et al., 2009). In this study, participants repeatedly used a long mechanical grabber. When subsequently retested while reaching to grasp with their hand alone, the kinematics of their movements was significantly modified, as if their arm were longer than before using the grabber.

[2] One might wonder whether there is not a risk of an infinite multiplications of motor functions, and thus of a corresponding body schema. Our level of analysis, however, is at a higher functional level, based on a fundamental distinction between negative and positive affordances.

Moreover, this effect of extension was generalized to other movements, such as pointing on top of objects, although they were never performed with the grabber. Interestingly, we constantly take, use, and drop tools of different sizes and shapes. This requires the working body schema to adjust each time, showing an important plasticity.

C1.P18 Consider now the protective body schema. Its function is to reliably covary with the body to protect and guide defensive actions. Although rarely mentioned in the literature on body representations, this notion of the body schema can be found in the literature on pain (Klein, 2015, p. 94):

> C1.P19 There's a body schema representation which is primarily concerned with protective action: that is, one which maps out parts of our bodies that we should pay special attention to, avoid using, keep from contacting things, and so on. Call this a defensive representation of the body: it shows which parts of the body are in need of which sorts of defence.

The relatively uncontroversial starting point is that survival involves preservation of one's body. This is why the brain evolved dedicated mechanisms specifically tuned to the body and its immediate surroundings, which is in direct relation with the motor system in order to protect the body. In particular, it has been found that the perceptual system encodes in a specific way a spatial margin of safety around the body, also known as the peripersonal space—predators cannot approach this specific zone without eliciting their prey-specific defensive responses (Graziano, 2018). Peripersonal space is anchored in various parts of one's body, not only the hands, but also the head, the torso, and the feet. If there is to be a key body part to protect, it is the head rather than the hands. But the whole surface of the body is important and no matter where it hurts, we are able to react in the appropriate way. What is important to realize, however, is that protective behaviours are not necessarily directed toward one's biological body; they are directed toward the body that one takes oneself to have, namely the body as it is represented in the protective body schema. If the protective body schema is impaired or manipulated, then one can fail to protect part of one's own body (Romano et al.,
C1.P20 2014) or start protecting a rubber hand (Ehrsson et al., 2007). Nonetheless, situations such as these are exceptional and most of the time the protective body schema fulfils its function and targets exclusively one's own biological body. In particular, it normally does not integrate the tools that we use in everyday life. We do not feel pain in the fork that just fell on the floor. If we protected tools as we protect our limbs, we would not be able to use them as extensively as we do and the range of our actions would be far more limited—we could no longer stoke the hot embers of a fire or stir a pot of boiling soup (Povinelli et al., 2010). This claim does not contradict the fact that we protect tools and react if they are under threat (Rossetti et al., 2015). We actually need to keep them in good shape in order to be able to use them. Nonetheless, their significance is not of the same kind as the evolutionary significance of our own body and it is likely that their protection is subserved by different mechanisms. The lack of tool embodiment at the level of the protective body schema is actually important because it prevents us from

losing track of our biological body—thanks to the unaltered protective body schema, we keep a default body representation that can be used to recalibrate the working body schema once we drop the tools.

C1.P21 One may reply that we can use tools such as knives to defend ourselves. This shows only that protective behaviours can recruit the working body schema, in addition to the protective body schema, but they play distinct roles, one to actively interfere with the threat and the other to fix what is to be protected. More generally, although it is nomologically possible for them to be dissociated, the two types of body schema generally work hand in hand. While reaching for the salt on the table, you also avoid bumping into the bottle of wine. While cutting a carrot, you also pay attention to not cutting your finger. And so forth.

C1.S3 1.3 Local and global body schemata

C1.P22 There may be another distinction to draw within the body schema, this time in terms of spatial scale. Jacques Paillard (1982) investigated the notion of body schema perhaps more than anybody else. Consider the following remark of his (p. 66, translation FV):

> C1.P23 It would thus seem that the 'body schema' could be fragmented into action subsystems corresponding to the motor instruments involved in the specification of the structure of the paths of considered visuomotor sub-spaces.

C1.P24 Paillard introduces the notion of a visuomotor sub-space ('*sous-espace*') as a means to characterize the content of representational processes underlying visuomotor adaptation effects across body parts. A natural corollary to Paillard's notion of a sub-space is that of a high-order representation (a '*super-espace*'; cf. Paillard, 1982, p. 67) which serves to coordinate its subordinate elements. This broadly reflects an intuitive explanandum phenomenon. Try, for instance, using a hand to touch your foot while using the other to touch your face. To perform this task, is it sufficient to have local body schemata that represent individual body parts, and if so, what is the best characterization of these local body schemata? Or do we also need a global body schema, the function of which would be to structure these local representations? In Paillard's terms, does action require a high-order representation (a '*super-espace*', cf. Paillard, 1982, p. 67) to coordinate its subordinate elements?

C1.P25 Typically, when an agent acts with its body, it cannot act with it as a mere collection of parts. Rather it must act with it as a structure, a structure of the kind that Casati and Varzi (1999) refer to as a mereotopological structure, a whole composed of interlocked parts, or what we will more simply refer to as an integrated whole. As an integrated whole, body parts are interlocked, bearing a mutually constraining connection to one another, constraining bodily movement due to the nature of their connection. We can bring the point out by considering how different our capacity for action would be if our bodies did not have this structure. We can try and imagine a creature, call her Scatty, whose parts comprise a disintegrated whole. Scatty's body parts do not form a whole in the same sense that we would say the front and back of a sphere form a whole (Madden, 2015), but rather in the sense that the top and bottom of a bikini are part of the same bikini. Imagine, for instance, that Scatty's body consists only of two detached hands capable of independent movement, like the character *Thing* from the *The Adamms Family*, but in duplicate. Scatty could do much that normally embodied subjects could not. She could rotate each of her parts 360° in a single plane in opposite directions, or simultaneously grab an elephant's trunk and tail. By contrast, in our case, bodily actions are spatiotemporally constrained by the body itself as an integrated whole—when we move a body part, it will take as long as it does and involve the physical displacements it does, because that part is a part of an integrated whole (Latash, 2008).

C1.P26 A difficult question is how the parts of this integrated whole are individuated. Under one description, the human body is a physical object. And just like any other such object, it can be divided in any of an infinite number of ways we can imagine. However, not just any manner of division will be appropriate in specifying potential objects of body schema. Our guiding principle is that the body must be divided into parts in a manner that retains a conceptual priority of the whole, such that representing said parts may yield coordinated bodily action. On this analysis, the whole corresponds to a causally interlocked structure in which physical forces are distributed in virtue of causal connections such as hinging, overlapping musculature, connective tissue, etc. Accordingly, the body is divided into parts, which correspond to the causally efficacious elements of a bodily movement. This meets our guiding principle insofar as this manner of division retains a conceptual priority of the whole. This can be seen by contrasting the parts with the notion of a component (Casati & Varzi, 1999, p. 32; see also Sanford, 1993, pp. 221–223). Components are distinguishable such that each can be discerned, independently of its combination with other parts. But parts of the body as a causal unity can only be discerned by their mutual causal relations to other parts and the body as a whole.

C1.P27 One worry here is that this type of causal analysis of the body does not yield clear enough part–whole distinctions, as such distinctions seem to be a matter of emphasis. An analysis might emphasize causal unity to such a degree that the only object it licenses is the single dynamic unity; or it might emphasize the plurality of causally efficacious elements to such a degree that it licenses every such element as an object of body schematic representation. Neither option seems appropriate. The issue here, however, is really one of scale. The two options described are just the two extremes of various scales at which the causal structure of the body might be analysed. The appropriate scale for our purpose is an intermediate scale—beneath the highest-level analysis at which there is no division at all, but above lower-level analyses concerning, for example, individual muscles and their connection across fascial planes and joints. At this intermediate scale, low-level elements are brought together as functional units. Functional units (or synergies) provide a way of drastically minimizing the body's multiple degrees of freedom (Latash, 2008; Turvey, 1990). These emerge in development as infants learn the intrinsic dynamics of their particular body (Thelen & Smith, 1994).

New functional units can emerge in adulthood when an individual learns to manipulate low-level elements in the service of learning a new skill, e.g., by moving through a stage at which joints are held rigid and then gradually unfrozen as they come to be coordinated as a single unit (Anderson & Sidaway, 1994; Southard & Higgens, 1987). These functional units may correspond to conventional body part names in English or other linguistic partonomies, but they need not do so.

C1.P28 This might, in turn, raise the worry that whatever is gained through a more general causal analysis comes at the cost of determining boundaries between parts. But this worry is misplaced. First, hinges are a crucial kind of causal connection and these may serve to specify boundaries between causally interacting parts as a feature of the causal analysis (Bermúdez, 1998). Second, it is worth noting that even though we may mark boundaries within the structure of the body, none of these are bona fide boundaries, i.e., closed continuous boundaries, such as might be provided by enveloping skin. Rather, these are what Smith and Varzi (2000) refer to as *fiat* boundaries. Fiat boundaries, and their corresponding objects, are of the mind's creation, reified in their psychological significance, and they may be shared between connected objects, making their demarcation semantically vague. Thus, although the analysis posits a distinction between functional units in causal interaction, for each functional unit posited, there may be a range of equally plausible candidates of very slightly differing spatial extent. Though only one of these is, in fact, that which plays the relevant causal role, the analysis per se does not distinguish it from other candidates. But this is just what we would expect on analysis of the body's division that prioritizes the whole. The analysis produces a structure composed of continuous, interlocked objects, rather than a structure composed of discontinuous, discrete objects.

C1.P29 On this analysis of body parts, and given their corresponding representations, one may wonder whether there is any need for positing a representation of the body as an integrated whole. This is an issue that has undergone very little explicit investigation, but a reasonable reflection on influential accounts in light of the remarks above suggests the following rationale (O'Shaughnessy, 1980; de Vignemont, 2018). Adequate representation of body parts for the control action requires local body schemata to be coordinated in a manner that is sensitive to each body part's interlocking within the whole. Integration of structural information about all parts of the body in a global body schema would achieve this—for it would serve as a constraint or regulatory principle, modifying the content of local body schemata in a manner that is sensitive to the interlocking between body parts. Thus, a set of local body schemata would be coordinated according to a specific set of relations in virtue of a global body schema.

C1.P30 However, it remains an open issue of whether an account of even this more refined explanandum actually requires positing a global body schema at all (Alsmith, 2019). For given the interlocked nature of the body itself and the representation of its parts, an explanation of the structure of bodily action arguably need not appeal to a global body schema. The purpose of such a representation, as suggested above, would be to encode structural information about the relations between parts of the body, which can then serve to constrain local body schemata. But it is not clear why this particular explanatory role could not be served by the body itself, consisting, as it does, of interlocked parts. That is, rather than being constrained by an overarching global body schema encoding relations between body parts, local body schemata might be constrained by the patterns of sensory feedback reflecting relations between body parts themselves.

C1.P31 Note, moreover, that there is no sensory signal dedicated to the body as an integrated whole. There is only sensory feedback concerning body parts. Yet it is clear that this feedback affects motor coordination. For instance, Shadmehr and Mussa-Ivaldi (1994) showed that motor adaptation—adaptation to changes in the dynamics involved in motor tasks—generalized across tasks which were structurally similar in terms of joint torques and trajectories. If local body schemata are themselves adaptive, it becomes redundant to appeal to a global body schema in an account of the particular way in which they are coordinated. The question of why a global body schema encodes one set of relations, rather than another, must be answered by recourse to the local body schema itself imparting the structure of the body as an integrated whole. It is not clear then why we should appeal to the former higher-order representation in the first place. Any structure in that representation that would enable its supposed coordinative function would be due to the structure transferred through representations it is supposed to coordinate.

C1.S4 1.4 Towards a Bayesian model of the body schema

C1.P32 The question now arises—how are all these representational processes constructed in the brain? The computational processing underlying the generation of a body schema is still poorly understood. Since it is still relatively controversial whether there are innate body representations, one can question when they start developing. Is it as early as *in utero*, during which spontaneous motor activity can lead to the differentiation of the body into parts at the cortical level, or later when more complex behaviours emerge (Bremner, 2017)? Here we shall not answer this question but rather highlight the challenges that any account of the generation of a body schema must meet and the constraints that it must respect. Appealing to the Bayesian model of brain functioning, we shall then sketch the first outlines of a computational model.

C1.P33 The main challenge is that a body schema is not an immutable form of representation, encoded once and for all. The construction of a body schema should not be conceived as set in stone. Rather it is continuously renewed in order to adapt to structural and contextual changes of the body. It should thus be seen as a dynamic process. Not only do short-term properties, such as bodily posture, keep changing, but enduring properties, such as joint flexibility, muscle strength, weight, and size, also vary across time. Clearly, our hands are not the same when we are 10, 20, or 80 years of age. This is particularly true in infancy, when the growth process engages profound structural bodily changes, but it is also true during pregnancy, for instance, or with the deterioration of the body in later life or ill-health. As noted earlier, this is also specifically true for the working body schema each time we use and then discard a tool. How is this ever-running process of adaptation and refinement of the body schema encoded? A model of the underpinnings of a body schema should describe not only how it is generated at the beginning, but also how this construction process can adapt in time.

C1.P34 One way to address this issue is to consider the sensory determinants of a body schema. Consider the act of peeling a fig. In addition to information about the location and the shape of the fruit, one needs information about: (i) the posture of the fingers of the hand holding it; (ii) the posture of the hand holding the knife; (iii) the relative location of the two hands; (iv) the size of the various segments of the upper limbs; and (v) the size of the knife. To this aim, several sensory inputs can be involved. It is optimal to combine visual information with proprioceptive and tactile information in order to achieve the most reliable estimates of the bodily parameters (van Beers et al., 1999). Here it is important to understand that the sensorimotor format, which is classically opposed to the visuo-spatial format, does not prevent vision from playing an essential role for the body schema. We act on the world that we primarily see and the dorsal pathway of visual processing directly feeds the motor system (Milner & Goodale, 1995). Vision is important for the information that it delivers not only on the world on which we act, but also on the body that acts on it. Indeed, it offers more reliable information about spatial properties than touch and proprioception, and it often dominates over them when in conflict (Welch & Warren, 1980). The interaction between the senses thus improves the likelihood of detecting, localizing, and identifying bodily events and properties, and any viable body schema must emerge from such a process of multisensory integration.

C1.P35 The multisensory nature of the body schema has been already emphasized by several authors (de Vignemont, 2018; Wong, 2014). However, the computations underlying how the body schema is built up out of several distinct sensory signals remain unclear. At least two sets of important issues arise. The first problem is known in the binding literature as the parsing problem—how to identify and select only the relevant sensory signals to bind together. Typically, one should not integrate proprioceptive information about one's hand with visual information about someone else's hand. Spatiotemporal congruency is part of the answer, but it cannot suffice. Let us imagine that the patient feels her phantom hand to be at a location where there is a book. Nonetheless, seeing the book does not cancel the experience of the phantom hand. One explanation why vision does not erase the phantom hand is that the perceptual system does not combine the visual information about the book with the proprioceptive information about the hand, despite the fact that they are experienced at the same location. Tsakiris (2010) thus suggests the existence of a body template or model, which guarantees that the information bound together is about the body. The difficulty with this reply is that multisensory integration also occurs for tools that have been incorporated into a body schema and tools hardly meet the constraints of a body template. Furthermore, a common location does not seem to be a necessary condition. Let us consider this time prism adaptation. When wearing prisms, visual information about the location of one's hand is in conflict with proprioceptive information. Yet, they are integrated together despite the spatial discrepancy.

C1.P36 The second set of issues arises once the relevant information is selected. How are the relevant sensory signals integrated together to form a coherent body schema? For one thing, the temporal encoding of sensory information changes across different sensory modalities. Furthermore, each sensory modality is encoded in its own format and, in particular, in its own spatial frame (e.g., eye-centred vision, head-centred audition, skin-centred touch). Consequently, the brain cannot just combine the converging sensory inputs. Rather, the perceptual system needs to go beyond the differences between sensory formats and spatial frames of reference. Finally, sensory cues are not given the same weight in the integration process. Consider again the example of the fig peeler. When in the dark, visual information is downgraded while somatosensory information is upgraded. Put the light on and the grading of sensory cues changes. The question is: how is this order of priority settled and how is it adapted to ongoing circumstances?

C1.P37 The Bayesian model has been gaining success to account for a wide range of cognitive processes. In brief, it postulates that the process underlying the construction of mental representations stems from the ability of the brain to compute probabilistic statistics. At the core of the model lies the idea that the brain computes the most probable output, given all available cues. Each time a representation is constructed, the brain settles one set of rules integrating all relevant cues. Regarding body representations, two kinds of information are available. On the one hand, sensory signals from distinct modalities are integrated. On the other, previous attempts at building body representations serve as priors for future ones, i.e., ongoing body representations are constructed in light of past body representations. The weight of those 'priors' is adjusted, depending on the correspondence between present and past circumstances. If the present bodily situation is new, sensory cues will be favoured since past experiences cannot reliably inform about the current situation, and vice versa. In addition to past experiences, priors also include other types of mental representations. For example, species of body schema can serve as priors for each other's construct—even if, with distinct functions, the working and the protective body schema refer to the same body. One can therefore postulate that they are not constructed separately, but that one can inform about how the other is built up. Along the same lines, we recently proposed that the body schema can work as a prior for the construction of the body image (Pitron & de Vignemont, 2017; Pitron et al., 2018). Arguably, sensory processing evolved, in the first place, not to provide conscious perceptual experiences, but to provide sensory control of movements. It was only later in evolution with the emergence of more and more complex behaviours that sensory processing evolved to provide internal models of the world, stored in memory and accessible to other cognitive systems. If something like this story is true, then the body schema is evolutionarily prior to the body image. From a developmental perspective too, it is classically assumed that the body schema has a greater influence on the body image than the other way around. It thus seems to indicate a predominance of the body schema over the body image. However, the body schema is only one prior, among others, on which the body image is built, which also takes into account social priors, affective priors, and so forth. The body image is thus not a mere copy of the sensorimotor representation. In the process of its construction, it gains in complexity (by taking into account new inputs on top of the information that fuels the body schema) but loses in detail and accuracy. The two types of body representations are thus functionally distinct, but their construction is partly based on their interactions, which allow them to minimize discrepancies between them as much as possible.

C1.P38 We shall not enter into further details about computational mechanisms of the Bayesian model here. However, we wish to emphasize one important feature about it—not only does the Bayesian model define a set of rules underlying how mental representations are constructed, but it also accounts for how those rules are adjusted in time. Once the set of rules is defined and a body schema is built up, the brain has post hoc feedback informing whether the selected set of rules is the right one or not. Feedback springs from the very nature of the body schema being constructed for action. As previously outlined, the body schema not only represents the acting body, but it also mediates how the action is performed. Subsequently, the body schema can be considered well constructed when the action is well achieved. In turn, success or failure of action thereby indicates whether the construction of the body schema was correctly computed. When the action fails, that means that the process underlying the construct of the body schema was inadequate and it has to be updated for future actions. On the other hand, when the action succeeds, the process constructing the body schema is confirmed.

C1.P39 Having emphasized how the Bayesian model can adjust its own computational rules, we can now sketch the outlines of a computational model of the body schema. On the Bayesian view, the body schema is dynamically constructed through a trial and error process. On a first attempt, available cues are integrated with one particular set of rules, with some of them being upgraded and some not. In this first try, all possible priors and sensory cues can be taken into account, irrespective of the sensory modality or the timescale. The set of rules can be settled by chance if no previous experiences are stored. The system can then determine whether this attempt was successful, thanks to feedback from action. Through multiple trials, pertinent cues can be identified, both contextual (priors) and sensory. The set of computational rules can then be refined in order to reach the best bet about how the body schema shall be constructed. According to this view, the refinement of a body schema is thus conceived as an ongoing process. From birth on, the brain aims to identify reliable sets of rules for the construction of a body schema and, through multiple trials, adapt them to present body constraints.

C1.S5 1.5 Conclusion

C1.P40 What is the body schema? To say that it plays a role for action is to say very little. Here we tried to understand what role precisely it plays and how it achieves it. More precisely, we characterized the body schema by its sensorimotor format and by its dual function, both descriptive and directive. However, we also highlighted the variety of representations of the body that match these basic criteria. In particular, they can vary along the following dimensions:

- C1.P41 their temporal scale (short-term versus long-term)
- C1.P42 their spatial scale (local versus global)
- C1.P43 their evolutionary role (for exploratory versus defensive actions)
- C1.P44 their motor contribution (for planning versus control)
- C1.P45 the weight given to their sensory inputs (vision versus somatosensation)
- C1.P46 their malleability (relatively rigid versus highly plastic).

C1.P47 Many have looked for dissociations between the body schema and the body image, but it may be time to look for dissociations within the body schema. Then only shall we be able to determine whether these distinctions are merely conceptual or whether they also have an empirical reality.

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