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ORIGINAL RESEARCH

Bodily sense and structural content

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Abstract
Bodily awareness seems to present the body as a topologically connected whole, composed of many parts. In consequence, the source of topological and mereological content of bodily awareness comes into question. In particular, it may be asked whether (a) such content is provided by the bodily sense, i.e., sensory mechanisms which, like proprioception, presents the body "from the inside," or (b) it is a product of "exteroceptive" elements of bodily awareness, which represents the body "from the outside" in a similar way to that of other physical objects. This paper argues that while passive touch and proprioception are unlikely to present the body as a topological and a mereological whole, such content is likely to be provided by kinesthesis. In consequence, it is plausible that holistic topological and mereological bodily content is present in virtue of certain mechanisms of bodily sense.

Keywords Bodily awareness · Bodily sense · Bodily perception · Spatial content · Proprioception · Touch · Kinesthesis

One of the main intuitions regarding our bodies is that a body is a whole that is composed of many parts. This conviction has a 'topological' aspect; bodily fragments seem to be connected to each other to form a connected whole. For instance, the arm is attached to the torso, which is connected to the other arm, legs, and head. It also has a 'mereological' aspect; the body is believed to have a hierarchical structure, such that it is a whole composed of smaller parts. For example, the foot is a part of the leg, and both these fragments are parts of the whole body.

Such topological and mereological intuitions are also often included in scientific and philosophical theories of bodily awareness. For instance, it is proposed that bodily awareness presents the body as a structure made of connected parts (e.g., Alsmith,

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2019; O'Shaughnessy, 1989; Schwenkler, 2011; de Vignemont et al., 2006), and in experiments such as the rubber hand illusion, there is consideration as to whether a fake hand is represented as a part of the body (Longo et al., 2008). Nevertheless, it is also well-recognized that bodily awareness is multimodal because its content is shaped by, *inter alia*, touch, proprioception, interoception, vision, and body-related beliefs (Vignemont, 2014). In consequence, the source of topological and mereological content of bodily awareness comes into question[1]. In particular, I am interested in considering whether (a) such content is provided by sensory mechanisms which, like proprioception or passive touch, presents the body 'from the inside,' or (b) it is a product of 'exteroceptive' elements of bodily awareness, such as vision or propositional knowledge, which represent the body 'from the outside' in a similar way to that of other physical objects. Later, I use the term 'bodily sense' to name the sum of all sensory systems presenting the body 'from the inside.' The content provided by bodily sense is a component of the content of bodily awareness, which is shaped both by the bodily sense and the functioning of exteroceptive systems. In particular, I focus on the contribution of passive touch, proprioception, and kinesthesis due to the fact that these systems may plausibly be important sources of topological and mereological bodily content as they seem to possess significant abilities to represent spatial properties (in opposition, for instance, to pain perception, see Cheng, 2020; Mancini et al., 2015; Skrzypulec, 2021)[2].

More specifically, my method consists of investigating the relevant sensory systems one by one, and asking whether the information processed by a given system, even without help from other systems, will allow the topological or mereological features of the body to be represented. If the answer is positive, then it is likely that the given system contributes to the topological or mereological content of bodily awareness. Relying on such investigations, I argue that while content provided by passive touch and proprioception does not allow the body to be represented as a topological and mereological whole, such representations can happen due to kinesthesis. In consequence, it is likely that holistic topological and mereological content is provided by certain mechanisms of bodily sense. Simultaneously, I observe that the mereological content provided by kinesthesis concerns various bodily parts that are not particularly salient in our everyday bodily awareness. This raises the question of why certain bodily parts are more salient than others. I propose that in addition to factors such as visual perception and culturally mediated propositional knowledge, a significant role can be attributed to self-touch.

It should be noted that I do not intend to show that kinesthesis and other components of the bodily sense are the only sources of topological and mereological content. Indeed, it is likely that such content is also provided by vision (see de Vignemont, 2014) and by some innate spatial representations (see Matthen, 2014 for a contempo-

[1] Of course, I do not want to claim that topological and mereological content is the only content of bodily awareness. In particular, I do not investigate content which allows for self-reference (see Bermúdez, 2023).

[2] While there is no sharp border between proprioception and kinesthesis, by proprioception I mean the passive aspects of bodily sense connected to the perception of bodily posture, and by kinesthesis I mean the dynamic aspects related to the perception of bodily motion.

rary account of pre-perceptual spatial representations)[3]. My goal is merely to show what topological and mereological content is plausibly provided by the considered components of the bodily sense and not that there are no other ways to obtain such content. Furthermore, I do not claim that the contribution of the bodily sense concerns only online representations based on current sensory input. It is possible, for example, that information provided by kinesthesis leads to the creation of an offline topological and mereological bodily representation that can then represent the body even in the absence of kinesthetic input.

The conducted investigations are philosophically important for two major reasons. First, an important topic in the contemporary philosophy of perception is the multimodal character of perceptual experiences. In this context, the following questions arise: what is the content of multimodal experiences, how is this content structured, and how do interactions between sensory modalities determine the content and phenomenal character of multimodal experiences (e.g., Briscoe, 2016; Macpherson, 2011; O'Callaghan, 2012)? However, despite a recognition that bodily awareness is multimodal (de Vignemont, 2014), such investigations usually concern the exteroceptive experiences presenting external objects, and not one's body presented 'from the inside' by bodily sense. My considerations constitute a step in understanding the multimodal character of bodily awareness, as I analyze certain mechanisms involved in the bodily sense to assess how they contribute to the topological and mereological content of our bodily perception.

Second, a major discussion regarding bodily perception concerns the characteristics of bodily representation; for instance, bodily representations that exist, their content, the way they are created, and whether—and in what respects—the body is represented as a whole (see Carruthers, 2008; Hochstetter, 2016; Longo, 2016; O'Shaughnessy, 1989; de Vignemont, 2010 for alternative approaches to these issues). My investigations are relevant for these discussions because they show how various elements of bodily sense may contribute to the topological and mereological content of bodily representations. In particular, I propose that kinesthesis can provide a holistic topological and mereological content.

The paper starts (Sect. 1), by explicating the possible weaker and stronger relations between bodily sense and the mereotopological content of bodily awareness. Further, in Sects. 2, 3, and 4, I consider (a) passive touch as a potential source of mereotopological content, (b) proprioception and kinesthesis as sources of topological content, and (c) proprioception and kinesthesis as sources of mereological content. Finally, in Sect. 5, I suggest that self-touch may be an important factor shaping the mereological content of bodily awareness in addition to kinesthesis, vision, and propositional knowledge.

[3] However, it should be noted that it is empirically difficult to distinguish between innate bodily representations and representations created due to proprioceptive and kinesthetic information obtained before birth (see Bremner, 2017).

1 Topological and mereological content

Topological content concerns the organization of bodily fragments by relations of connectedness; for instance, it may specify that the left arm is connected to the torso and the torso is connected to the legs. Mereological content characterizes bodily parts as organized by parthood relations; for example, that a finger is a part of a hand. A widespread practice in works concerning bodily awareness is to describe the content of bodily representations in terms of 'bodily parts' without explicitly arguing that the postulated content contains relations of parthood (e.g., Alsmith, 2019; Bermudez, 2019; Martin, 1998; Schwoebel & Coslett, 2005). To avoid possible terminological confusion, I use the term 'bodily fragment' to refer to an object represented by bodily sense, without presupposing that it is represented as standing in connectedness or mereological relations to other objects represented by bodily sense. In normal situations, these objects correspond to the physical fragments of our body. However, there may be cases in which a bodily fragment is represented that does not correspond to an actual fragment of the body. Note that not all physical fragments of the body need to be represented by a particular sensory system that constitutes bodily sense, and different sensory systems that constitute bodily sense can represent different bodily fragments. The mere fact that a sensory system represents that there is a bodily fragment A, and a distinct bodily fragment B does not mean that A and B are represented as standing (or not standing) in a topological or mereological relationship.

My goal is to investigate whether different systems that make up the bodily sense normally represent bodily fragments as standing in topological or mereological relations. By 'normally,' I mean cases in which there are no serious perturbations to the functioning of the bodily sense, and the systems under consideration have access to relevant information. I do not claim that the functioning of such systems is necessary to provide topological and mereological content. For example, it may be the case that even if proprioceptive mechanisms are unable to provide mereotopological content, an exteroceptive system such as vision can supplement this content.

The topological connectedness relation is a symmetric and intransitive relation; for example, by symmetry, if the arm connects to the torso then the torso also connects to the arm. Similarly, due to intransitivity, if the left arm connects to the torso and the torso connects to the right arm, it does not follow that the left arm connects to the right arm. Note that in a loose sense, one can say that the left arm can connect to the right arm through the torso. However, in the technical sense used in topological theories, the connectedness relation is a relation of 'direct connection' without intermediate elements.

By referring to the connectedness relation, we can define both a weaker and a stronger thesis regarding the association between the bodily sense and the topological content. According to the weaker thesis, a sensory system constituting bodily sense represents that there are bodily fragments standing in the connectedness relation:

(Weak Topology) *There is a sensory system* S *constituting bodily sense which represents that there are bodily fragments* A *and* B *such that* A *is connected to* B.

The Weak Topology characterizes the minimal topological content that bodily sense can provide. If the Weak Topology is not satisfied, then all topological content must be provided by some other sources than bodily sense. However, one may propose a stronger thesis that not only states that bodily sense represents some bodily fragments as connected, but that it actually represents the body as a topologically connected whole composed of bodily fragments:

(Strong Topology) *There is a sensory system* S *constituting bodily sense such that for any bodily fragments* A *and* B *represented by* S, *this system represents a chain of bodily fragments* [A, F1,…,Fn, B] *such that each element of the chain stands in the connectedness relation to the subsequent element.*

If the Strong Topology thesis is true, then in virtue of bodily sense, the body is represented as a connected entity where from each bodily fragment there is a path going through the body to any other bodily fragment. Due to the fact that connectedness in topological theories concerns ‘direct connection,’ the Strong Topology is coherent with the intransitivity of connectedness. If the Strong Topology is true, then there is a chain of bodily fragments between each two bodily fragments; but it is not the case that if a bodily fragment A is directly connected to a bodily fragment B, and B is directly connected to a bodily fragment *C*, then *A* is directly connected to *C*.

When I speak of parthood relations between bodily fragments, I have in mind the mereological relation of ‘proper parthood’: a proper part of A is a part that is not identical with A itself (later, for brevity, I will use the terms ‘part’ and ‘parthood’ rather than ‘proper part’ and ‘proper parthood’). This relation has different properties than the topological relation of connectedness: it is asymmetric and transitive. For example, by asymmetry, the toe is a part of the foot, but the foot is not a part of the toe. Similarly, by transitivity, if the toe is a part of the foot, and the foot is a part of the leg, then the toe is also a part of the leg. While the topological content characterizes the ‘horizontal’ structure of the body by determining which fragments connect, the mereological content characterizes the ‘vertical,’ hierarchical structure of the body by determining how some bodily fragments compose other fragments.

Analogously, as in the case of topological content, in the case of the mereological content one may propose both a weaker and a stronger thesis regarding the relation between bodily sense and parthood relations. According to the weaker thesis, a sensory system constituting the bodily sense represents that there are parthood relations between bodily fragments:

(Weak Mereology) *There is a sensory system* S *constituting bodily sense which represents that there is a bodily fragment* A *and a bodily fragment* B *such that* A *is a part of* B.

Analogous to Weak Topology, Weak Mereology specifies the most rudimentary mereological content that can be provided by bodily sense. If Weak Mereology is not true, then there is no mereological content provided by bodily sense.

The stronger thesis not only states that there are parthood relations within the bodily structure, but also that the body is a mereological whole, i.e., there is a maximal bodily fragment—the whole body—that has all other bodily fragments as its parts:

(Strong Mereology) *There is a sensory system* S *constituting the bodily sense which represents that there is a bodily fragment* A, *the whole body, such that any other bodily fragment represented by* S *is a part of* A.

The above four theses constitute a conceptual framework that allows the expression of various positions regarding the significance of bodily sense for topological and mereological bodily content. For instance, one may postulate that both the Strong Topology and the Strong Mereology theses are true, so bodily sense is sufficient to represent the body as a mereotopological whole. On the other hand, one could oppose such a claim by arguing, for example, that while the Strong Topology is true, only the Weak Mereology is satisfied, and in consequence the bodily awareness of the body as a mereological whole comes from a source other than bodily sense. Furthermore, variants of the considered theses could specify which bodily fragments are represented by different sensory systems that make up bodily sense. For example, a sensory system may represent topological and mereological relations between skin fragments, but not between fragments such as forearm or palm, distinguished by the presence of joints (later I argue that this is likely to be true for passive touch). This leaves room for the possibility that there is more than one holistic representation of the body. For example, it is possible that one system represents the body as a topological whole composed of skin fragments, and a second system represents the body as a topological whole composed of fragments distinguished by joints. Similarly, my approach allows characterizing a situation where there is a holistic representation of the body as composed of bodily fragments distinguished by joints, obtained by one sensory system, and a second non-holistic representation of the body as composed of different bodily fragments, obtained by another sensory system.

2 Passive touch

An important aspect of bodily sense is the passive touch constituted by mechanisms processing information gathered by cutaneous receptors covering the body surface. The receptive fields of such receptors constitute a two-dimensional layout. According to some authors (see Cheng & Haggard, 2018; Haggard et al., 2017), due to the presence of such a layout, a low-level bodily representation named 'skin space' can be created that allows various spatial and temporal relations between tactile sensations to be recognized (see also Longo, 2010 for a contemporary discussion on the similar concept of 'superficial schema'). In fact, there is a significant body of results showing that passive touch allows for the experience of various relational arrangements of cutaneous sensations.

First, people are able to recognize the application of tactile stimulation to disjointed skin fragments. This is demonstrated by studies utilizing the two-point distance paradigm, in which the minimal spatial distance between simultaneously applied tactile stimuli is measured—allowing the recognition that, rather than only one stimulus, two stimuli have been used (e.g., Haggard & Giovagnoli, 2011; Mancini et al., 2014). Second, people are not only able to recognize whether one or two stimuli have been applied, but can also discriminate between shorter and longer distances between locations of tactile stimulation (e.g., Longo & Golubova, 2017; Mancini et al., 2015; de Vignemont et al., 2009). Further evidence for the spatial capabilities of passive touch comes from path integration studies (Fardo et al., 2018; Haggard et al., 2017). In such studies, a tactile stimulus moves continuously across a patch of skin. At the end of the stimulation, a participant is asked to point to the midpoint between the stimulus start and end points. Because the stimulus moves along a curved, S-shaped path, the midpoint along the shortest path between the start and end positions may be a point that has not received tactile stimulation. The observed success in path integration tasks suggests that participants can track a stimulus moving continuously through a skin fragment. Of course, in such behavioral studies, it is not possible to completely separate the influence of the passive touch from the influence of other systems, like proprioception. However, in the above studies, the proprioceptive component is quite limited as these studies do not involve conducting actions by participants, and do not require referring to proprioceptive information about bodily position, or to propositional knowledge about the organization of the body. In consequence, it is likely that they can tell us something important regarding the specific contribution of passive touch.

While the ability to recognize relations between cutaneous sensations is imperfect—all the above experiments reveal the presence of biases—the available data strongly suggests that in virtue of passive touch, some topological relations between bodily fragments can be represented. First, people are able to recognize the application of cutaneous stimuli to bodily fragments, which do not stand in the connectedness relation as another fragment of the skin separates them. Second, as revealed by path integration studies, people have the ability to determine that subsequent stimulation is present in a skin fragment that connects to the previously stimulated skin fragment such that there is a perceived continuous movement of a tactile stimulus. This shows that the way in which passive touch functions, justifies the Weak Topology thesis: Passive touch represents that bodily fragments, i.e., skin fragments, stand in relations of connectedness.

On the other hand, there is no equally compelling evidence that passive touch functions in a way that supports the Strong Topology thesis, i.e., that passive touch allows us to experience the body as a topologically connected whole. First, the studies on the ability to perceive spatiotemporal relationships between cutaneous sensations concern those sensations evoked within limited regions of the body. For example, participants were asked to report relations between sensations occurring in one hand (Haggard & Giovagnoli, 2011) or on opposite sides of the wrist (de Vignemont et al., 2009). It has not been evaluated whether the ability to detect spatiotemporal relationships within the skin space is preserved; for example, when one sensation is evoked on the hand and another on the leg. Second, there is a theoretical reason why such data supporting the existence of connectedness relations between the fragments of skin space are less likely to be obtained with respect to distant bodily fragments: while the receptive fields of cutaneous receptors form a continuous layout, the sizes of the receptive fields on different fragments of the body are different. Thus, it may be difficult for passive touch mechanisms to compute spatial relations regarding sensations occurring on distant skin fragments, since the same number of stimulated receptive fields may correspond to different physical distances (Matthen, 2021). Finally, studies on passive touch show that biases in the evaluation of spatial relations are not the same for all skin fragments, but actually differ even for proximal fragments such as the different skin surfaces of a single hand (Longo & Haggard, 2012). For example, the lengths of finger surfaces are underestimated on the dorsal surface of the hand, but there was no such observable effect on the palmar surface. While it is possible for different parts of the same spatial representation to have different biases, such results make it more likely that different skin fragments have different representations. For example, if there is a mechanism that produces a single representation of both the dorsal and palmar surfaces of the skin, then it is not obvious why such a mechanism would underestimate some distances but not others. One cannot explain these differences by postulating that information from the dorsal side is less accurate, because on the dorsal side, lengths are not simply less accurately represented but are consistently underestimated. Furthermore, such a mechanism that produces a single dorsal and palmar skin representation would represent the dorsal and palmar surfaces of a finger as connected and forming a curved, tube-like surface, while somehow simultaneously representing the opposite sides of this surface as having different lengths. On the other hand, an easy explanation of the observed differences is the presence of distinct representations of both surfaces.

The above observations do not imply that passive touch does not represent the body as a topological whole. It is possible that such a single representation exists, but has parts with distinct spatial biases, and due to differences in the size of receptive fields, inaccurately represents spatial relations over larger distances. However, while it is plausible, according to the available evidence, that passive touch can represent connectedness relations between bodily fragments, the above considerations show that it is far less clear that passive touch can represent a chain of connected bodily fragments between any skin fragments[4].

Moreover, even if passive touch justifies the Weak Topology thesis, the topological content provided by passive touch differs in an important respect from the topological content of bodily awareness. This is not only due to the fact that passive touch may not represent the body as a topological whole, but also because passive touch is unable to represent connectedness relations between various important bodily fragments that bodily awareness represents. For instance, passive touch does not represent that an arm connects to the torso or that a finger connects to the palm, since by relying merely on the layout of cutaneous receptors it does not have the means to distinguish bodily fragments such as hands or legs (see de Vignemont, 2014). The presence of joints designates such bodily fragments, but the layout of cutaneous receptors does not indicate where a joint is present. In consequence, the topological content provided by passive touch does not concern such bodily fragments; rather, it characterizes relations between various skin fragments.

This is not to argue that due to this reason the topological content provided in virtue of passive touch is absent from bodily awareness. For instance, it may be the case that in virtue of mechanisms of passive touch, the experience of the back of the hand is of a topologically connected surface. Nevertheless, there is a significant amount of topological content which is present in bodily awareness, but it is unlikely that passive touch will provide it.

Note that the above points concern the represented bodily fragments and the represented relations between them, and not the relations between physical fragments of the body. For example, one might propose that because fragments of the body such as

[4] Of course, this is not to deny that such a holistic topological representation may be provided by some other systems. However, if such system does not belong to the bodily sense, then it does not support the Strong Topology.

forearm or palm are composed of tissue fragments, if these tissue fragments connect appropriately, the forearm and palm also connect. However, it is still possible for a sensory system to represent connections between tissue fragments without representing the forearm, the palm, and the relations between them. This point shows that different sensory systems constituting bodily sense can justify Weak or Strong versions of the Topology or Mereology theses in diverse ways, depending on the differences in the bodily fragments represented. In the following sections, I consider proprioception and kinesthesis, which unlike passive touch, represent bodily fragments characterized by the presence of joints.

The situation is similar if we consider the contribution of passive touch to the mereological content of bodily awareness. It is plausible that in virtue of passive touch, parthood relations between skin fragments can be represented. For instance, in path integration studies, participants are aware that there is a tactile stimulation having a form of a continuous line drawn on the skin (Fardo et al., 2018). It seems that in order to recognize the presence of such a pattern, one has to be aware that there are smaller fragments of the skin, stimulated in succession, which constitute a larger fragment through which the stimulus was travelling when evoking a line-like sensation. Similarly, there are studies showing that when a letter-shaped stimulus is pressed to the skin, a person is able to recognize the letter (see Job et al., 2021). Again, it seems that in order to recognize the presence of a letter on a skin fragment, one has to represent that there are parts of this fragment on which appropriate edges, constituting a particular letter, are positioned.

While such results make it plausible that in virtue of passive touch, the Weak Mereology thesis is true, there are no data to justify that the way in which passive touch works also supports the Strong Mereology thesis, which would be the case if passive touch allowed the experience of every skin fragment being part of the maximal skin fragment (i.e., the whole skin covering the body). Furthermore, in a similar way to topological content, passive touch does not represent the parthood relations between many important bodily fragments which we distinguish in bodily awareness—for instance, that a finger is a part of a hand—but merely between some skin fragments.

Overall, passive touch represents both connectedness and parthood. However, it is less likely that passive touch allows for the experience of the body as a topological or a mereological whole. Furthermore, passive touch represents relations solely between skin fragments, and not fragments such as legs or hands. Consequently, if bodily sense supplemented the topological and mereological content of bodily awareness only by means of passive touch, some exteroceptive or non-perceptual sources would have to provide a major part of such content.

3 Topology, proprioception, and kinesthetics

Of course, passive touch is not the only aspect of bodily sense that can contribute to the topological and mereological content of bodily awareness. In particular, topological and mereological content may be introduced by proprioception —i.e., in virtue of mechanisms providing information about the position of our body—and kinesthesis, i.e., due to mechanisms allowing perception of our own bodily motion.

The mechanoreceptors located in joints, tendons, and muscles provide information about places in the body where a discontinuity between two rigid fragments occurs (see Longo, 2010; Schwoebel & Coslett, 2005; de Vignemont, 2014). This sensory information is integrated with that provided by passive touch and is an important element of our bodily sense. For instance, the experience of the distance between two tactile stimuli seems to increase if each stimulus is applied to the opposite side of a joint (see de Vignemont et al., 2009). The mechanisms of passive touch are unlikely to be responsible for this result as the layout of cutaneous receptors does not identify the locations of the joints. Rather, it is the case that passive touch and proprioception jointly constitute bodily sense and determine the way we experience the structure of our body.

The presence of proprioceptive information that allows the division of the body into fragments by relying on the presence of joints, already suggests that in virtue of proprioception, topological relations can be represented. For instance, information used to divide the body by joints allows a connection between body parts A and B to be represented because there is a joint between them, while there is no such connection between A and C. Furthermore, the division by joints provided by the proprioceptive mechanisms quite closely corresponds to the way in which we intuitively divide our bodies in bodily awareness, since we treat fragments connected by joints (like arm and forearm) as separate bodily fragments. In consequence, it seems plausible that the functioning of proprioception at least justifies the Weak Topology thesis.

Is it also the case that the functioning of proprioception justifies the Strong Topology thesis, i.e., that in virtue of proprioception, we experience our bodies as topological wholes? If the Strong Topology thesis is true in virtue of proprioception, then proprioception represents not only that some bodily fragments are connected, but also that between each two bodily fragments there is a chain of bodily fragments connecting them. In the philosophical literature, one can find approaches to bodily representations that suggest that in virtue of proprioception, the body's representation is in accordance with the Strong Topology thesis, as well as approaches that deny this proposal.

For instance, Bermúdez (1998, pp. 154–161, 2017, 2019) analyzes body structure in terms of bodily fragments connected by 'hinges,' which usually correspond to joints. According to this approach, we localize bodily sensations in relation to hinges. For example, the localization of a sensation on a hand occurs because it is in a certain relation to a wrist (this is the so-called A-location, which is independent of a particular position of bodily fragments at a given time). Furthermore, the localization of a sensation is presented not only as being on a hand, but also as being in a spatial location that is determined by, among other things, the arrangement of the hand, forearm, and arm at a given moment. This is a B-location designated by a current pattern of relations between bodily fragments. It seems that localizing bodily sensations in this way requires the presence of a comprehensive structural representation of the body as a whole, made up of fragments that are connected by hinges. In particular, Bermúdez (2017, 2019) proposes that the ability to A- and B-localize bodily sensations underlines two important features of bodily awareness: (a) 'boundedness': sensations are experienced as being within the body, and (b) ‘connectedness’: sensations are experienced relative to the background of the whole body and bodily dispositions. For example, a sensation in a hand and a sensation in an arm can be represented as being located within a topologically connected body because between the hand and the arm there is a chain of connected fragments consisting of the hand (designated by the wrist), the forearm (designated as being between the wrist and the elbow), and the arm (designated as being between the elbow and the shoulder).

On the other hand, there are positions (in particular, see Alsmith, 2009, 2019) according to which there is no topological representation of the holistic bodily structure. It is rather the case that there are only separate representations of various bodily fragments, and the fact that they operate as a coherent whole does not rely on possessing complex topological content but is guaranteed by the actual physical structure of the body. A radical interpretation of Alsmith’s proposal would lead to a theory, according to which, there are representations of bodily fragments A, B, and C, but no connectedness relations are represented between them. It would mean that both the Strong and the Weak Topology theses are false as there is no representation of connectedness relations between bodily fragments provided by bodily sense. However, given the way in which proprioception functions, such a position is likely to be false. Bodily fragments are proprioceptively distinguished by relying on identifying joints that mark places where one fragment ends and another starts. Hence, the identification of bodily fragments already relies on the identification of connectedness relations.

Nevertheless, there is a question whether dividing the body into connected fragments by relying on joints is actually sufficient to represent the chains of fragments required by Strong Topology. To investigate this question, let us consider a simple body composed of three fragments. The first fragment is connected to the second by the joint J1, and the second fragment is connected to the third by a different joint, J2. A proprioceptive mechanism relying on information from joints may represent that there are two fragments—let us name them A and B—connected by the joint J1, and that there are two fragments—let us name them C and D—connected by the joint J2. However, in order to represent that fragment A is connected by a chain of fragments to fragment D, additional information is required; namely, that fragment B is the same as fragment C. Nevertheless, it is not obvious that proprioceptive mechanisms can access such information, since it is not simply provided by input about the presence and position of joints. Consequently, I believe that the functioning of proprioception does not provide sufficiently strong evidence for the truth of the Strong Topology thesis. However, below I argue that the above gap can be filled by incorporating the role of kinesthesis (see also Bermúdez, 2017 for the idea that information about bodily dispositions for movement is used to represent the body as a connected whole).

The mainstream representational view of voluntary bodily movements is that to perform such movements—for instance, aimed at grasping an object—the cognitive system creates two models: a forward model and an inverse model (see Kawato, 1999; Wolpert & Ghahramani, 2000). The forward model specifies the execution of specific motor commands in order to achieve the desired result of a movement. The inverse model characterizes the expected result of realizing the forward model; for example, the input from the proprioceptive receptors after making a movement. The interactions between forward and inverse models allows an assessment of the success of an action, and modifications to the way that actions are conducted.

In order to successfully conduct an action by relying on the forward and inverse models, the mechanisms of kinesthesis must track changes to the input from proprioceptive receptors; for instance, whether the input from bodily fragment B changes as planned in the forward model and whether this leads to inputs from fragment A being as predicted by the inverse model. In our earlier example, proprioception alone, by relying on the presence of joints, can distinguish that part A connects to B, and that part C connects to D, but it does not have access to the information that B is identical to C. However, by tracking motor input, kinesthetic mechanisms have access to data showing that inputs from fragments B and C are always the same. For instance, when B obeys motor commands, they are also obeyed by C, and if input from C shows that it has moved, the same input comes from B. This plausibly may lead to representing that B and C are in fact the same fragment, and in consequence, allows the representation that there is a chain of connected bodily fragments such that A connects to B = C, and B = C connects to D.

The above considerations suggest that combining proprioception with kinesthesis not only allows the representation of connectedness relations between bodily fragments (as required by Weak Topology), but also represents that bodily fragments are linked by chains of other bodily fragments (as required by Strong Topology). However, one may still oppose the notion that the functioning of kinesthesis justifies Strong Topology by proposing that a chain of connected bodily fragments is only represented between fragments engaged in common actions and not between any bodily fragments. For instance, a chain of connected fragments is represented between the finger and the shoulder because these fragments are often engaged together in actions such as grasping an object, but there is no represented chain between the hands and the feet. Nevertheless, in practice, the majority of bodily actions require information about the position of the whole body. For instance, when grasping an object, it is not only important to achieve a specific arrangement of bodily parts from hand to shoulder, but also to ensure that legs and feet are in such a position that the posture will be stable. Furthermore, there are some specific actions that in a more active way engage nearly all bodily fragments distinguished by joints. An illustrative example of such action comes from studies on body representations in which people are asked whether they are able to go through an aperture (Guardia et al., 2010). Conducting such an action requires a proper arrangement of legs and hands, rotating hips and torso, and also some head movements.

Another doubt may be that motor inputs processed by kinesthesis are relevant for fine-grained action guiding and do not contribute to the content of bodily awareness. In particular, kinesthetic content may constitute the 'body schema,' a representation which, in opposition to 'body image,' is often considered to be connected with conducting actions, and not the conscious perception of bodily features (see de Vignemont, 2010, 2014; Gadsby & Williams, 2018; Longo, 2016; Schwoebel & Coslett, 2005). In fact, when conducting actions, we are not aware of details concerning the changing relations between various bodily fragments but only of a general pattern of bodily movement (Wolpert & Ghahramani, 2000; Wong, 2015). Furthermore, we do not seem to vividly experience the whole topological structure of our body.

Rather, it serves a background which allows us to focus attention on some bodily fragments, which then receive a more detailed conscious representation (Hochstetter, 2016; Kinsbourne, 1998; Lara, 2018).

There are two reasons to refute this doubt. First, there are phenomena that suggest that the information provided by kinesthesis does indeed contribute to the conscious content of bodily awareness. Second, there are theoretical reasons for refuting a strict division between the conscious content of bodily awareness and the unconscious, action-related content. Regarding the first point, phenomena, such as vibration-induced motion illusions, show that kinesthetic information influences conscious bodily perception (e.g., Taylor et al., 2017). In such illusions, vibrations applied to the muscles and tendons of an immobilized limb lead to a bodily perception of limb movement. Such phenomena demonstrate that kinesthetic information about changes in muscles and tendons can lead to a conscious experience of the movement of connected bodily fragments. Furthermore, while many argue that fine-grained action guidance relies on unconscious content associated with dorsal stream processing, it is also generally accepted that action selection, perception of success or failure, and correction of failed actions often rely, in part, on conscious representations (e.g., Briscoe & Schwenkler, 2011; Kozuch, 2015). In this context, we can imagine a situation in which a person attempts to put a hand into a narrow hole without the aid of vision. The person realizes that the action is not successful when positioning the hand vertically and changes the orientation of the hand to horizontal. It seems that in such a situation, kinesthesis partly provides one's awareness of the body because kinesthesis informs one as to which movement has failed and helps to recognize that the subsequent movement has changed the hand's position from vertical to horizontal.

From a theoretical perspective, there are proposals that a strict separation between conscious, perceptual representations such as 'body image,' and unconscious, action-related representations such as 'body schema,' is unlikely (Pitron & de Vignmeont, 2017; Pitron et al., 2018). It has been observed that contents associated with body image and body schema are closely correlated, both in normal situations and in the case of disorders. For example, individuals with anorexia nervosa tend to both perceive their bodies as larger and perform physical actions, such as walking through an aperture, as if their bodies were larger (e.g., Gadsby, 2017). In addition, factors such as tool-use change both the performance of actions and the perception of the body. For example, after adapting to the use of a long grasping tool, people both act as if they have extended reach, and make errors in perceiving the center of their arm as if it were longer (Sposito et al., 2012).

Such findings suggest that the contents of body image and body schema are largely shaped by the same type of information. As shown in the example of the influence of tool-use, kinesthesis partly provides this common information, which is likely to involve information about the connections between bodily fragments that allow the determination of appropriate actions. Consequently, it is likely that kinesthetic information does not merely shape the unconscious content of the body schema with no influence on how the body is consciously perceived. Rather, it is the case that some topological content available through kinesthesis is also available to bodily awareness. Indeed, it is not arbitrary that proprioceptive and kinesthetic content related to body topology is present in bodily awareness, as such content is useful for conscious action planning without the use of vision (cf. Baud-Bovy & Viviani, 1998; Darling & Miller, 1993) and may allow the body to be experienced not simply as an object with certain spatial properties, but as having structural affordances, i.e., properties that characterize the ways in which the body can be moved to achieve certain goals (de Vignemont, 2016).

Furthermore, it should be noted that the strong topology thesis does not require the entire topological structure of the body to occupy a central place in one's bodily awareness. It merely means that we are aware that all bodily fragments are somehow connected; it does not imply that we have to saliently experience all changes in spatial relations during body movements.

4 Mereology and kinesthetics

In virtue of proprioceptive mechanisms, a representation of the body can be composed of fragments standing in some relations of connectedness. This provides justification for the Weak Topology thesis. Nevertheless, such a way of representing the body does not introduce any mereological content, as it characterizes the bodily structure merely in terms of symmetric relations and not asymmetric parthood relations. In other words, in virtue of proprioceptive mechanisms, there may be a representation that a hand is attached to a forearm but not that both the hand and the forearm are parts of a larger bodily part. However, in the context of topological content, I have argued that while the functioning of proprioception justifies only the Weak Topological thesis, the dynamic aspects introduced by kinesthesis provide reasons to accept the Strong Topology thesis. Below, I claim that dynamic aspects of bodily sense can also be used to justify the Strong Mereology thesis.

In fact, there are results from studies of the rubber hand illusion that suggest the relevance of bodily actions for the awareness of bodily mereology. In particular, important results has been obtained by Tsaskiris, Prabhu, and Haggard (Tsakiris et al., 2006). In their study, they compared the usual 'passive' experimental setup with an 'active' one. In the usual passive setup, a participant sees a rubber hand receiving tactile stimulation while there is an application of an analogous stimulation to the real hand, which is out of sight. In the active setup, however, the stimulus is a self-generated movement of a finger of the invisible real hand, accompanied by the projected image of the moving finger. One of the effects observed in such studies is 'proprioceptive drift': when asked to report the position of their hand, participants are biased toward the rubber hand (e.g., Tsaskiris and Haggard, 2005). Tsaskiris and colleagues observed that in the case of passive stimulation, when a tactile stimulus is applied to a finger (or the finger is moved by an external force), proprioceptive drift only affects the stimulated fragment, a single finger, but not the rest of the hand. However, the situation is different in the active setup. In this case, even if only a single finger is moving, proprioceptive drift occurs with respect to the whole hand. Such results suggest that due to the perception of a self-generated movement, a bodily fragment, such as a finger, is not only experienced as an element of the bodily topological structure, but also as part of a larger mereological entity, such as a hand.

Furthermore, as already suggested in the previous section, kinesthetic perception may, by informing about relations between motor inputs coming from distinct bodily fragments, allow a representation that there are certain dependencies between fragments of the body. Such dependencies are often asymmetric; for instance, the modification of the position of an arm modifies the spatial position of fingers, but fingers may change their position without causing any difference in the spatial location of the arm. One may suppose that such asymmetric dependencies can serve as the basis for representing bodily fragments as organized, not only by symmetric connectedness relations, but also by mereological relations. In fact, observations confirm that prostheses integrate more easily with the body if they are designed so that the closest intact joint receives realistic sensory feedback during movement (see Bermúdez, 2017).

The development of this idea may happen in two directions. First, if there is an identification of an asymmetric dependency between bodily fragments, then it may be represented that the dependent bodily fragment is a part of the dominant fragment. In other words, dependency between fragments leads to the representation of a parthood relation between these fragments. Alternatively, there may be a proposal that if a dependency between bodily fragments is identified, then it also represents that those fragments are parts of a larger fragment composed of them. In this case, the dependency does not lead to a representation of parthood between fragments standing in a dependency relation, but between each fragment and a larger one. Below, I consider both these options and argue that the second of them provides mereological content that justifies the Strong Mereology.

More specifically, the first option proposes that if spatial properties of a bodily fragment A causally depend on spatial properties of a bodily fragment B, but spatial properties of B do not causally depend on spatial properties of A, then A is a part of B. Nevertheless, such an approach immediately leads to various unintuitive results. For instance, according to the above idea, the hand is a part of the forearm since movements of the forearm modify the spatial position of the hand, but there are various movements of the hand that do not modify the location of the forearm. However, it does not seem that we experience our body in such a way that we treat a hand as a part of the forearm. Similarly, the considered approach would introduce various other implausible parthood relations; for instance, that the arm is a part of the torso or that the foot is a part of the ankle. Furthermore, attempting to justify the Strong Mereological thesis by using the above approach would lead to a conclusion that the maximal mereological element—if there is any—is not the whole body, but rather one particular bodily fragment whose movements asymmetrically influence the position of all other fragments.

Nevertheless, the second approach is more promising. It consists in proposing that if spatial properties of a bodily fragment A causally depend on spatial properties of a fragment B or spatial properties of B causally depend on spatial properties of A, then there is a bodily fragment C such that both A and B are its parts. This approach allows a justification that the whole body is the maximal mereological element to which all other bodily fragments belong. For instance, because the position of the hand depends on the position of the forearm, there is a bodily fragment <*hand, forearm*> which contains both the hand and the forearm as its parts. Similarly, because the arm determines positions of both the forearm and the hand, there would be a fragment<*hand, forearm, arm*>. Further, by noticing the role of the torso, we will obtain a fragment<*hand, forearm, arm, torso*>. Extending this method further will result in a fragment encompassing the whole upper part of the body (above the hips) and a fragment encompassing the lower part of the body. Finally, due to the fact that the position of the lower bodily fragment influences the position of the upper bodily fragment—in particular by walking—there would be a fragment encompassing both upper and lower fragments, and subsequently, all of their parts.

Nevertheless, while this approach allows a justification that the whole body is the maximal mereological element, it introduces a mereological structure that involves various bodily parts, which intuitively does not seem to be a particularly salient in our usual bodily awareness. For instance, mereological content provided by kinesthesis distinguishes a bodily fragment composed specifically of the hand and the forearm, and a fragment composed of the torso and the arm. Furthermore, because movements of the torso determine positions of both the left and right hands, there would be bodily fragments<*torso, left arm*>, <*torso, right arm*>, and <*torso, left arm, right arm*>. There are many other similar cases of mereological relations introduced by the considered approach. For instance, if there is a bodily fragment<*hand, forearm*>and the movement of the arm changes both the position of the hand and the forearm, then there would be bodily fragments<*hand, forearm, arm*>as well as <<*hand, forearm*>, *arm*>, or even <*hand, forearm,* <*hand, forearm*>, *arm*>.

These observations do not mean that kinesthesis is unable to provide the mereological content satisfying Strong Topology. In fact, in virtue of kinesthesis, the most salient bodily parts, like arms, legs, and the head, all figure in the mereological content of bodily awareness. However, the number of bodily parts introduced by kinesthesis provokes a question of why certain bodily parts seem a far more salient than others. In the next section, I propose that in this respect, self-touch can have a certain role.

5 Self-touch and the mereological content

One obvious explanation as to why some bodily parts are more salient than others is that it happens in virtue of vision. This modality has a significant ability to represent the spatial structure of objects and may promote certain mereological divisions of the body. In particular, vision divides objects into parts relying on the presence of qualitative discontinuities and points of concavity created by the arrangement of edges (see Palmer & Rock, 1994; Xu & Singh, 2002). Hence, a bodily part composed of an arm and a torso may be less salient than torso and arm treated separately, as there is a visually apparent qualitative change at the point where the arm ends and the torso starts.

However, it is unlikely that vision is the only such factor, because while congenitally blind people differ from sighted people in perceiving certain metric properties of their bodies (see de Vignemont, 2014), it is not true that they do not experience certain bodily parts as more salient than others. A second obvious factor is language-mediated propositional knowledge: through life we learn names for certain bodily parts, which become more salient in bodily awareness than those which do not have common names.

I do not aim to establish the details regarding the influence of various factors in the way in which the mereological content of bodily awareness is generated. In these final paragraphs, I merely want to propose an additional sensory mechanism that may influence mereological content by modulating the saliency of bodily parts in addition to vision and propositional knowledge: the self-touch. It is often postulated that touch has two aspects (e.g., Fulkerson, 2011; Mattens, 2016; Richardson, 2011, see Katz, 1989 for a classic source): an 'exteroceptive' aspect, which informs about the properties of touched objects, and an 'interoceptive' aspect, which presents the state of the body. In the case of self-touch, these two aspects combine in a distinct way. Just as in touching any other object, the active, touching bodily fragment presents features of the touched object and also provides interoceptive information regarding its own state (e.g., that the fingers of the touching hand are in a particular position). However, the touched bodily fragment also provides interoceptive information about the received tactile stimulation and informs about properties of the object that touches it. Of course, in the case of usual self-touch, these aspects are correlated. In particular, the exteroceptive information from the touching fragment matches the interoceptive information provided by the touched fragment. Hence, self-touch, in contrast to passive touch, does not merely present the body 'from the inside,' but also presents the body as an external, touched object.

In fact, there are works which suggest that self-touch can influence the perception of bodily structure. Schütz-Bosbach, Musil, and Haggard conducted a particularly interesting study (Schütz-Bosbach et al., 2009). The task of participants was to use fingers of one hand to touch fingers of the second hand. However, by interleaving the participants' fingers of the passive hand with the experimenter's fingers, the researchers created a situation in which the number of objects touched by the active hand is higher than the number of stimulated fingers of the passive hand. To investigate how to resolve the discrepancy, they applied the 'in-between task': the participants had to judge the number of fingers between those fingers on the passive hand that were touched by the active hand. The participants tended to underestimate this number. Such a result does not explicitly concern the mereological relations, but it suggests that self-touch may influence the perception of the arrangement of bodily fragments.

Unfortunately, because self-touch has not been explicitly studied as a factor influencing bodily mereology, my suggestion that self-touch may contribute to the perception of the body as organized according to parthood relations is tentative and speculative. Nevertheless, there are theoretical reasons why this proposal is plausible. Active, haptic touch uses specific sequences of movements, known as 'exploratory procedures' (see Klatzky & Lederman, 2004). These provide access to various types of features possessed by touched objects. While, in contrast to vision, haptic touch has limited ability to represent the detailed arrangement of an object's edges, there are specific exploratory procedures, such as enclosing an object, making lateral movements, or applying pressure, that provide access to spatial changes in global shape, texture, and hardness (Lederman & Klatzky, 2009).

When applied to bodily structure, such exploratory procedures can lead to a perception of the body that promotes the saliency of certain bodily parts. For example, there are relatively small, tactile discontinuities between the hand, forearm, and arm, indicating the points at which the characteristics of a bodily fragment change, but there is a significant discontinuity between the arm and the torso. Consequently, a hierarchical structure of the body can be established on the basis of haptics, by representing that hand, forearm, and arm together form a larger part that ends at the point of a significant discontinuity between the arm and the torso. At the same time, a part consisting solely of the hand and forearm does not receive a similar salience by virtue of self-touch, since the discontinuity between these fragments is not significantly larger than a discontinuity between the forearm and the arm. Moreover, in the case of self-touch, the mereological information obtained through haptic exploration does not only refer to an external object but could refer to one's own body due to the presence of correlated tactile sensations on the touched fragments of the body. Consequently, through the correlation between active and passive aspects of self-touch, there can be a recognition that the mereological properties discovered are properties characterizing the bodily structure.

As stated above, these considerations are preliminary and require further verification by empirical investigation. I believe there are two lines of such investigations that might be particularly fruitful in exploring the influence of self-touch on bodily mereology. First, one may investigate whether tactile discontinuities similar to those that occur between salient bodily parts are such that haptic perception treats their presence as the end of one object and the beginning of another. For example, participants can haptically manipulate artificial objects composed of fragments separated by such discontinuities and determine the mereological structure of these objects. Second, one may investigate whether innate or early deficits in the ability for self touch, for example due to paralysis or missing limbs, influence the way people perceive their bodies as composed of parts. This may reveal whether the saliency of bodily parts divided by significant tactile discontinuities is lower when self-touch is not available.

6 Conclusions

There is strong intuition that bodily awareness presents the body as a topological and a mereological whole. However, bodily awareness is composed of various elements: Only some are sensory, and only some sensory elements present the body 'from the inside,' i.e., they constitute the bodily sense. I have argued that we have good reasons to accept that bodily awareness presents the body as a topological and a mereological whole in virtue of bodily sense, particularly in virtue of kinesthesis. However, the mereological content provided by kinesthesis concerns various bodily parts that are not particularly salient in our everyday bodily awareness. This provokes a question why certain bodily parts are more salient than others. I have proposed that in addition to factors such as visual perception and language-mediated propositional knowledge, an important role can be attributed to self-touch.

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Declarations

Compliance with ethical standards I comply with the Ethical Standards of Synthese. Informed consent and animal welfare: The research did not involve human participants or animals.

Conflict of Interest The author declares that he has no conflict of interest.

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