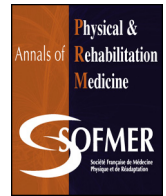




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Review

The bodily self: Insights from clinical and experimental research

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ABSTRACT

This review article summarizes neuropsychological descriptions of abnormal body representations in brain-damaged patients and recent neuroscientific investigations of their sensorimotor underpinnings in healthy participants. The first part of the article describes unilateral disorders of the bodily self, such as asomatognosia, feelings of amputation, supernumerary phantom limbs and somatoparaphrenia, as well as descriptions of non-lateralized disorders of the bodily self, including Alice in Wonderland syndrome and autoscopic hallucinations. Because the sensorimotor mechanisms of these disorders are unclear, we focus on clinical descriptions and insist on the importance of reporting clinical cases to better understand the full range of bodily disorders encountered in neurological diseases. The second part of the article presents the advantages of merging neuroscientific approaches of the bodily self with immersive virtual reality, robotics and neuroprosthetics to foster the understanding of the multisensory, motor and neural mechanisms of bodily representations.

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1. Introduction

In this review article, we present an overview of clinical and experimental approaches to the study of body representations (also called body schema, corporeal awareness or bodily self), providing insight into their neural and cognitive bases.

The first section provides an overview of unilateral and non-lateralized neurological disorders of the bodily self, often following damage to the right cerebral hemisphere. Here, we address hemiasomatognosia, feelings of disappearance and transformation of body parts, supernumerary phantom limbs, somatoparaphrenia and autoscopic phenomena involving the entire body. Disorders of the bodily self have been difficult to classify systematically, as noted historically by pioneering researchers [1–5] and in more recent works [6–8]. Indeed, the bodily self is in itself a conceptually complex topic, because its experience is inherently multimodal, subjective, and global. The bodily self arises from the dynamic integration of bodily and environmental visual, tactile, proprioceptive, vestibular, auditory, olfactory, visceral and motor information [9]. Unlike other worldly objects, the body is the source of its own perception, a subject and an object at the same time. The

human brain computes bodily information via different maps and networks, notably areas of tactile, proprioceptive, vestibular and interoceptive projection in the primary somatosensory, as well as unimodal and heteromodal cortices, providing an unified and global representation of the lived body, which allows for experiencing it as a unique self and agent. To these sensory components, recent research has added spatial and social factors involved in self-other bodily interactions, and ego- and altercentric perspectives on bodily and action perceptions [10,11].

Verbal and higher-level cognitive aspects of bodily knowledge are sometimes subsumed under the concept of “body image,” said to be a conscious and abstract representation of the body, involving for instance the naming of body parts and general knowledge about human bodies. This classical distinction with “body schema,” which involves situated, directly experienced, unconscious, and non-verbal aspects of the bodily self has been widely discussed elsewhere (e.g., [12,13]), and we adopt the view here that asomatognosia per se pertains to the body schema domain [14,15]. As such, we think that disorders such as autotopoagnosia (impaired naming and pointing of body parts on demand [16,17]), Gerstmann’s syndrome (among other symptoms, impaired naming and pointing of fingers on demand [18,19]), or ideomotor apraxia (impaired production of goal-directed gestures on demand [20]) – all involving damage to the left parietal lobe – are clinically, phenomenologically and conceptually different from disorders of

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the body schema and will not be addressed here. Thus, this review focuses on disorders of the body schema, which are predominant after right brain damage [21].

In the second section, we summarize current experimental investigations in healthy subjects regarding the bodily self. We focus on experimental paradigms that have created multisensory conflicts (often involving visual and tactile signals) to modulate the body schema (e.g., evoking a virtual Alice in Wonderland syndrome [22] or the sense of having a child body [23]), the sense of owning the body (e.g., evoking the rubber hand illusion [24]), and the sense of embodied self-location (e.g., evoking an out-of-body-like illusion [25]). These approaches have been found promising to better understand the sensorimotor mechanisms that underlie a large range of bodily disorders observed following brain damage or during epileptic seizures or migraine episodes (Table 1).

Finally, we offer some concluding remarks highlighting the importance of merging approaches from neuropsychology with modern neuroimaging techniques and protocols from cognitive neuroscience, immersive virtual reality, robotics and neuroprosthetics for establishing a more comprehensive model of the human bodily self and its disorders.

2. Disorders of the bodily self

2.1. Unilateral disorders of the bodily self

2.1.1. Hemiasomatognosia

The term “hemiasomatognosia” was coined by French neurologist Jean Lhermitte [3] to refer to a neglect, lack of interest, or unawareness of one part or entire half of one’s body. Such patients generally ignore their left arm and/or leg; they behave and speak as if these did not exist. One of Zingerle’s [26] patients, with left hemiplegia, did not pay the slightest attention to his left side, never looked at it, never spoke about it. All orders to move were executed on the right side, and, when confronted directly, the patient did not see any absurdity in having only one body side. Zingerle and Lhermitte saw in this profound unawareness for one body side the source of other clinical phenomena such as anosognosia and unilateral neglect. In the French clinical literature, notions such as unawareness (*méconnaissance*) and lack of ownership (*désappartenance*) were later often used to describe hemiasomatognosia’s diverse manifestations. Frederiks [27] attempted to clarify the issue by proposing a distinction between “conscious” and “non-conscious” hemiasomatognosia. The former referred to patients who perceived their body as incomplete or amputated, yet fully realized the illusory nature of these feelings. The latter referred to the subjective “disappearance” of one half of the body (most often the left one), without the patient being able to notice this very disappearance. Today, “non-conscious hemiasomatognosia” is conceived of as personal neglect, motor neglect, or anosognosia for hemiplegia. In each of these cases, there is some kind of

indifference for a body part. Personal neglect refers to the classical picture of a patient who “forgets” to comb, shave or make up the left side because of an attentional, perceptive or representational disorder. Motor neglect refers to patients without objective motor disorders who underutilize their left members [1,28]. These patients behave as if they were hemiplegic although they are not. Conversely, patients with anosognosia for hemiplegia behave as if they are not paralysed: importantly, they not only deny that they are paralysed, they also tend to ignore their left side in general. Frederiks [27] summarized these symptoms as “attentional disorders for the hemibody”. Garçin et al. [29] wrote of a particularly striking case: “The observer gets the feeling that the subject behaves as if he underwent an amputation of the left side of the body”. The loss of lateralized body part representations can occur at different levels of multisensory, sensorimotor or cognitive integration. For instance, patients may recognize their own body parts when presented visually but completely forget about them when they are out of sight.

2.1.2. Feelings of amputation, hemi-depersonalization

Here we address disorders labelled “conscious hemiasomatognosia” by Frederiks [27]. Such patients have vivid feelings that a part of their body has disappeared or feel it strongly diminished or blurred. Conceptually, these disorders seem to be the reverse of phantom limbs after amputation (most amputees retain a sensation of completeness despite having physically lost a body part). In both cases, patients fully appreciate the illusory nature of their sensations.

A related disorder is the feeling that a body part is no longer attached to the rest of the body, as if it were “floating” at some distance (sensation of disconnection or splitting). Symptoms of absence or separation of body parts are usually of short duration and appear mostly as part of seizures or migraine episodes [2,4,27,30]. Other cases occur due to cortical or subcortical strokes [31]. Direct electrical stimulation at the right temporo-parietal junction can also induce this type of illusion in the visual modality [32]. These symptoms are not necessarily accompanied by hemiplegia, unilateral neglect or anosognosia. Sometimes, a sensation of strangeness for an “absent” or “disconnected” body part, then felt as “alien”, “numb” or “empty”, is reported: the term hemi-depersonalization, or depersonalization for a body part, has been suggested [1,3]. Patients with such symptoms often feel the need to control these body parts by sight or touch, without such strategies being always able to restore normal bodily feelings [1].

Other symptoms can involve distortions in the perceived size of selected body parts or half of the body. These subjective alterations of bodily size are vividly experienced but are usually recognized as illusory. To refer to these symptoms, Frederiks [33] used the terms microsomatognosia and macrosomatognosia. Both terms are reminiscent of the concepts of *hyposchématie* (i.e., a shrinking of the body representation) and *hyperschématie* (i.e., an enlargement

Table 1
Main models for neuropsychological, neuroscientific and neuroimaging investigations of the body schema/image and the sense of body ownership and self-location/embodiment.

| Bodily experience | Clinical (neuropsychological) model | Experimental (neuroscientific) model | Functional neuroimaging model |
|--------------------------|--|--|--|
| Body schema/body image | Macro/microsomatognosia [33] Supernumerary phantoms [44] Anorexia, bulimia nervosa Body identity integrity disorder [108] | Rubber hand illusion [24] Immersive virtual reality [22,23,104] | Shrinking illusion [109] |
| Body ownership | Somatoparaphrenia [50] Body identity integrity disorder [108] | Rubber hand illusion [24] Virtual arm illusion [81] Numbness illusion [84] | Rubber hand illusion [85,87] Virtual arm illusion [110] |
| Self-location/embodiment | Autoscopic hallucinations: out-of-body experience [67] Heautoscopy [74] | Full-body illusion [92] Out-of-body illusion [25] Body swap illusion [98] Immersive virtual reality [103] | Full-body illusion [76] Body swap illusion [86] |

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