Artículo de revisión

Dolor crónico y modificaciones de la conciencia corporal
Chronic pain and disturbances in body awareness

Camila Valenzuela Moguillansky [1, 2*]

1 Laboratoire de Psychologie de la Perception CNRS UMR 8158, Université Paris Descartes. Paris, Francia.
2 Centre de Recherche en Épistémologie Appliquée CNRS UMR 7656, École Polytechnique. Paris, Francia.

Resumen

Este artículo aborda la relación entre el dolor crónico y la conciencia corporal. El dolor crónico se refiere a un conjunto de patologías que se caracterizan por la presencia constante de dolor, cuya intensidad y duración no pueden ser explicadas en términos de lesiones del sistema nervioso periférico. La falta de explicación en términos de daño periférico ha llevado a los investigadores a suponer que el sistema nervioso central desempeña un papel crucial en estos síndromes. En particular, se ha propuesto que la cronicidad del dolor causada posiblemente por una perturbación de los mecanismos involucrados en lo que podría llamarse la conciencia corporal "exteroceptiva". En la primera parte de este artículo presento estudios que muestran una relación bidireccional entre el dolor crónico y la conciencia corporal exteroceptiva, así como la hipótesis que el este dolor resulta de la perturbación de los mecanismos subyacentes a este tipo de conciencia corporal. A continuación, presento algunos problemas que esta hipótesis no logra explicar, y considero la relación entre el dolor crónico y el sistema nervioso autónomo. Por último, considero esta última relación a la luz de la noción de conciencia corporal "interoceptiva", y sugiero que la comprensión de los mecanismos que relacionan los aspectos exteroceptivos e interoceptivos de la conciencia corporal, podrían contribuir a la comprensión de la naturaleza y el desarrollo de dolor crónico.

Palabras clave: dolor crónico, conciencia corporal, esquema corporal, sentido de pertenencia del cuerpo, interocepción

Abstract

This review article addresses the relationship between chronic pain and body awareness. Chronic pain refers to an ensemble of pain conditions whose common characteristic is the fact that peripheral lesions cannot explain the duration and intensity of the pain. The lack of explanation in terms of peripheral damage has led researchers to assume that the central nervous system plays a crucial role in these conditions. In particular, one suggestion about how such central factors might operate is by influencing patients' body awareness. In the first part of this article I present evidence showing a bidirectional relationship between chronic pain and what might be called 'exteroceptive' body awareness, as well as the related hypothesis that pain results from a disruption in the mechanisms underlying exteroceptive body awareness. Next, I discuss some issues that this hypothesis fails to explain, and I consider the relationship between chronic pain and the autonomic nervous system. Finally, I relate this latter relationship to the notion of 'interoceptive' body awareness, and explore the idea that understanding the mechanisms that relate exteroceptive and interoceptive aspects of body awareness might shed light on the nature and development of chronic pain.

Keywords: chronic pain, body awareness, body schema, sense of body-ownership, interoception

[*] Correspondencia: camilavalenzuelamogui@gmail.com. Laboratoire de Psychologie de la Perception, Université Paris Descartes, 45 rue des Saints Pères, 75270, Paris cedex 06. Teléfono: +33 (0) 6 46 49 49 35

"(...) the stronger the sensations of pain are, the more you have the sensation of having a thick, heavy body (...) it's like being pregnant, I don't know if you've ever been pregnant? You're fat, a little bit handicapped because you make clumsy movements, constrained movements and it's kind of the same when you have a painful body, you have the impression of being voluminous, having a sort of amplitude in your gestures and your movements (...) For example, when I'm in my bed and I'm in pain, I turn around to try and find a different position, but I have the impression that I'm a barrel, it's crazily hard to lean over, in comparison to how I was before it still really frustrates me (...)"[1]. Extract of an interview of a patient with fibromyalgia

Introduction

Most of the time, the fact that we inhabit our body and that we experience life through it remains unnoticed: we wake up, stand up, walk, we manipulate objects, we go up and down stairs, we meet other people and interact with them, etc. All of these very simple activities involve different types of implicit and explicit body awareness that allow us to move skilfully through space and interact with other people, organisms and objects. But in certain situations, when the coordination between the different processes involved in maintaining a smooth relationship between our body, our movements and the space around us breaks down, suddenly the fact that we *are* a body becomes very evident to us. The experience of pain is one of those situations. Pain is always felt in our body, revealing its presence and limits.

In this article I will address the relationship between body awareness and chronic pain. Chronic pain refers to an ensemble of pain conditions, such as complex regional pain syndrome (CRPS), phantom limb pain, chronic back pain, and fibromyalgia, which have in common the fact that peripheral lesions cannot explain the duration and intensity of the pain. In these conditions pain does not represent a symptom of a disease but instead becomes the disease itself.

The lack of explanation in terms of peripheral damage has led researchers to attribute a central role to the central nervous system in the chronicity of pain. In particular, it has been suggested that one way in which such central factors might operate might be by determining different forms of body awareness.

In the first part of this article I will present the evidence of a bidirectional relationship between chronic pain and what might be called 'exteroceptive' body awareness. Then, I will present the hypothesis that pain results from a disruption of the mechanisms underlying exteroceptive body awareness. Next, I will discuss some issues that this hypothesis seemingly fails to explain, and I will consider the relationship between chronic pain and the autonomic nervous system. Finally I will relate this latter relationship to Craig's (2002; 2003) notion of interoceptive body awareness, and I will explore the idea that

an understanding of the mechanisms that relate exteroceptive and interoceptive aspects of body awareness might shed light on the development of chronic pain.

Before beginning it would be useful to be clear about the notions of body awareness that we will be using. After an overview of these concepts, I will briefly present the chronic pain conditions to which I will be referring in this article.

Terminology regarding body awareness.

The two terms most frequently used to discuss body awareness are "body schema" and "body image". The body schema and the body image are conceptual constructs that have been defined differently depending on which field of study (or researcher) is looking at them. In the context of pain research, the body schema has been defined as "a real time-time dynamic representation of one's own body in space, which is derived from sensory input and is integrated with motor systems in the control of action" (Moseley, 2004). The body image has been defined as a conscious representation of the body, thought to be maintained by ongoing tactile, proprioceptive, and visual input, which can be modulated by memory, belief, and psychosocial factors (Lotze and Moseley, 2007). The critical difference between these two aspects of body awareness appears to be the implicit character of the body schema and the explicit and interpretative character of the body image. However, the studies that I will present in this review rarely control for the implicit or explicit character of body representations.

Another concept that will appear in this review is the "sense of body ownership". The sense of body ownership refers to the sense that it is *my* body that is undergoing a certain experience (Gallagher, 2000). This concept is part of a neurocognitive model of "minimal" self-awareness: the awareness of oneself as an immediate subject of experience, without interpretative attitudes or intentional consciousness.

The last two concepts regarding body awareness that we shall be referring in this review are those of "interoception" and "exteroception". Interoception is defined as the sense of the internal state of the body, linked to homeostatic regulation and emotions, which results from the sensorimotor integration of internal stimuli and motor activity that is under autonomous control (Craig, 2002; 2003). Exteroception refers to the awareness of the body that emerges from sensorimotor integration of mechanoreceptive and proprioceptive inputs with motor activity that is under voluntary control (Craig, 2002; 2003; 2011).

In this review, I will refer to the whole range of these aspects under the global term of body awareness, employing the specific terms when they are relevant.

Pain syndromes referred to in this review[2]

Phantom limb pain is a neuropathic pain syndrome that follows limb amputation or partial or complete deafferentation (Flor, Nikolajsen & Jensen, 2006). Pain in the phantom limb is experienced by 50-80% of amputees regardless of the amputation procedure (Flor et al., 2006; Nikolajsen, Ilkjaer, Christensen, Kroner & Jensen, 1998). This pain has been described as burn-

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[1] Translated from French by Paul Reeve.

[2] Note that the diagnostic criteria for several of these chronic pain conditions are controversial topics; see Wolfe and Hauser (2011) and Harden et al. (2007) for comprehensive discussions on the definitions and categorization of fibromyalgia and CRPS respectively.

ing, cramping, crushing or lancinating, and it can last for years (Ramachandran and Hirstein, 1998).

Complex regional pain syndrome (CRPS) describes an array of painful conditions that are characterized by a continuing (spontaneous and/or evoked) regional pain that is seemingly disproportionate in time or degree to the usual course of any known trauma or other lesion. The initiating noxious event may include the absence (CRPS-I, formerly reflex sympathetic dystrophy) or presence (CRPS-II, formerly causalgia) of a peripheral nerve lesion. The pain is regional and usually involves a distal predominance of abnormal sensory, motor, sudomotor, vasomotor, and/or trophic functions linked to disruption in the sympathetic nervous system (Harden, Bruehl & Stanton-Hicks, 2007).

Chronic lower back pain has been defined as pain situated in the lower back that lasts for more than three months. Lower back pain can have a mechanical, non-mechanical (other diseases) or neuropathic origin. However, in many cases no clear abnormality is cannot be detected (Apkarian, Baliki & Geha, 2009; Andersson, 1999).

Fibromyalgia is defined by the presence of long-lasting widespread muscular pain, and the finding of at least 11 of 18 tender point sites on digital palpation. Other associated symptoms are fatigue and sleep disturbances (Wolfe, Clauw, Fitzcharles, Goldenberg, Katz, Mease, Russel, Winfield & Yunus, 2010; see Wolfe and Hauser, 2011 for an up to-date discussion).

1. The impact of pain on body awareness

In this section I will look at studies showing the different ways in which pain may modify body awareness. We will see that these modifications involve different aspects of body awareness such as motor control, body perception and cortical organization.

1.1. Motor dysfunction

We begin with motor dysfunction since motor systems and sensorimotor integration are at the basis of the different forms of body awareness. In addition, as we shall see, the studies that launched research on pain-related disruptions of body awareness were motivated by observations and hypotheses regarding motor dysfunction.

The objective of this section is not to present a full review of the literature on pain-related motor dysfunction, but rather to mention its relevance as one of the symptoms of pain conditions that might contribute to the development of chronicity and other symptoms related to body awareness.

A number of studies have shown that chronic pain conditions are associated with poor motor function. For instance, CRPS patients often present difficulties in motor performance expressed through reduced range of motion, weakness, tremor and dystonia (*e.g.*, Schwartzman and Kerrigan, 1990; Harden et al., 2007 Galer, Butler, Jensen, 1995; Maihöfner, Baron, DeCol, Binder, Birklein, Deuschl, Handwerker and Schattschneider, 2007). Reduced range of motion, strength and endurance has also been observed in other chronic pain conditions such as lower back pain (for a review see Hodges and Moseley, 2003) and fibromyalgia (*e.g.,*Yunus and Aldag, 1996).

Pain and problems with motor function can in turn lead to avoidance of physical activity affecting cardiovascular and musculoskeletal systems. This physical avoidance behaviour might lead to what has been called "disuse syndrome". Disuse syndrome has been associated, in addition to the cardiovascular and musculoskeletal symptoms, to mood disturbances such as irritability, frustration and depression; disturbances that in turn decrease pain tolerance, aggravating the patients' condition (Vlaeyen and Linton, 2000).

Thus far, various models have been proposed to explain pain and motor dysfunction but the underlying mechanisms remain unclear. One of the issues under discussion is whether a disruption in motor control is responsible for pain, or whether motor dysfunction is a result of pain experience. While some researchers defend the former possibility (Maihöfner et al., 2007; Panjabi, 1992), recent evidence also supports the latter. For instance, Hodges and Moseley (2003) show numerous findings from both experimental and pathological studies on back pain that suggest that motor dysfunction is a result of recurrent pain.

In a recent review article, Hodges (2011) presents another issue that remains under discussion regarding the relations between pain and motor control, which is whether pain increases muscle activity or inhibits it. The former possibility is favoured by the "vicious cycle" model, which proposes that pain increases the activity of muscles that are painful or that move the painful area. This increase on muscular activity is then though to produce ischemia, which in turn results in the accumulation of metabolites and became a source of further pain. On the other hand, the "pain adaptation" theory holds that pain inhibits muscle activity. This theory suggests that pain reduces voluntary movements, decreasing the activity of muscles in the painful area or that are involved in painful movement and increasing the activity of the antagonist muscles.

In his review article, Hodges (2011) presents evidence that runs in favour of and against both models. The author then develops a "new theory of adaptation to pain" that aims to deal with both of the issues raised above, namely the question of whether pain a) is a cause or a consequence of motor dysfunction and b) increases or decreases muscular activity. In his theory, Hodges suggests that it is pain that induces change in muscle activity in order to protect the tissues from further injury or pain. He argues that this change does not follow a stereotyped mode of inhibition or excitation; rather, muscle activity is redistributed between and within muscles differently according to persons and tasks. These changes, he suggests, are achieved through changes at different levels of the motor system, ranging from modulation of excitability at the spinal level to specific cortical effects related to the planning of motor action.

In conclusion, regardless of the mechanisms that relate pain and motor dysfunction, what is important to note is that pain, in most cases, is accompanied by a disruption of motor function, which can lead to increased pain and disuse, in turn contributing to the establishment of pain chronicity and other symptoms that we review below.

1.2. Body perception

In this section we will review evidence showing chronic pain-related disruptions in various aspects of body awareness, including a) the feeling of body ownership, b) the ability to

mentally rotate the painful body part, c) spatial reference frames and d) body-size perception.

1.2.1. Feeling of foreignness about the painful body part

Galer et al., (1995) reported that some patients who were suffering from CRPS-I declared that they felt that their limb was "disconnected from their consciousness". Based on a clinical study on 11 CRPS I patients, the authors hypothesized that these patients' motor impairment was due to neurological neglect-like behavior rather than to a conscious attitude aimed at protecting their painful limb. In 1999 Galer and Jensen conducted a study to test this hypothesis. They measured the frequency of neglect symptoms among 242 CRPS-I patients using a questionnaire. The questionnaire was designed to assess two types of neglect behaviour: those involving a feeling of "foreignness" regarding the affected limb, which they called "cognitive neglect" and those involving the need to focus mental and visual attention in order to voluntarily move the limb, which they called "motor neglect" (Galer and Jensen, 1999). The results demonstrated that 84% CRPS-I patients affirmed that they experienced at least one of the neglect types, and that 47% reported both "cognitive" and "motor" neglect symptoms. The authors concluded that CRPS-I is not only a pain and autonomic nervous system dysfunction, but might also involve a neglect-type disorder wherein motor and attention dysfunction are also critical. In order to further investigate the neglect-type symptoms of CRPS patients, Förderreuther, Sailer & Straube (2004) performed a study in which, besides a routine neurological examination, the authors performed special tests to assess hemispatial neglect, sensory extinction to simultaneous stimulation, and the ability to identify their own fingers. The results showed that, a) out of a population of 105 CRPS-I and 9 CRPS-II patients, 54.4% reported a feeling of "foreignness" or "strangeness" towards the affected hand, b) there was no difference between CRPS patients and healthy controls in the hemispatial neglect test, c) no patient presented sensory extinction and d) 48% of the patients presented greater difficulties in identifying the fingers on the affected hand compared to the unaffected hand while only 6.5% of the patients presented the opposite pattern. Based on these results, the authors question the pertinence of the use of the term "neglect" to denote the observed disruption in body perception, suggesting that mechanisms other than those underlying neglect might be at the basis of the feeling of foreignness. The authors discuss the possibility that this feeling of foreignness may be related to a disruption of the mechanisms underlying the body schema.

In the same line, Lewis, Kersten, McCabe, McPherson & Blake (2007) performed a qualitative study in order to explore the nature of pain-related neglect-type symptoms. The authors gathered descriptions of CRPS-I patients' body perceptions and pain experiences through semi-structured interviews. They found that participants revealed peculiar perceptions about their body such as hostile feelings, a feeling that their painful limb is foreign, a disparity between what patients felt and the appearance of the painful body part, distorted sense of size and shape, and difficulty determining the position of the affected limb. The authors also concluded that the type of body perception disruption found in CRPS-I does not correspond to neglect and, like Förderreuther and co-workers, they rejected the possibility of referring to these symptoms as 'neglect-like'

symptoms. They hypothesised that modifications in the body schema through a remapping of the central nervous system play a crucial role in CRPS pain.

This type of observation is not limited to CRPS: the feeling that a painful body part is foreign has also been reported in patients suffering from lower back pain (*e.g.,* Wand, Parkitny, O'Connell, Luomajoki, McAuley, Thacker and Moseley, 2009)

In summary, a significant proportion of chronic pain patients undergo the paradoxical experience of feeling that painful parts of their body do not belong to them. Galer and collaborators interpreted this feeling of foreignness as a neglect-type condition. Further evidence indicates that the neurological neglect syndrome might not be the best approximation to this disruption in body ownership, since chronic pain patients do not meet several of the clinical criteria for neglect. The feeling that the painful body part is "foreign" seems to be related to a disruption of patients' body schema, possibly due to remapping in cortical structures.

1.2.2. Disruptions in the ability to imagine movements of the affected body part

The feeling of foreignness toward the painful body part is often accompanied by an inability to imagine the affected body part and mentally move it.

Schwoebel, Friedman, Duda & Coslett (2001) used the hand laterality task[3] in order to assess CRPS patients' ability to mentally rotate the painful body part. The patients[4] were asked to indicate the laterality of images of hands in different orientations. The results indicated that patients had longer response times (RTs) when indicating the laterality of the images that corresponded to their painful hand than to their healthy hand. The authors interpreted this result as suggesting a disruption of the body schema in CRPS patients. In a second study, Schwoebel, Coslett, Bradt, Friedman & Dileo (2002) performed a similar experimental procedure, adding a period of music therapy that had an analgesic effect. RTs for the judgment laterality task and pain were measured before and after the period of music therapy. The results showed that pain and RTs decreased after the music therapy period, suggesting that pain intensity affects the degree of body schema disruption. Based on these two studies the authors concluded that pain alters the body schema through a moment-to-moment incorporation of sensory (nociceptive) changes. Moseley (2004) questioned Schwoebel et al.'s interpretation that pain intensity is the basis of delayed response times, suggesting that different mechanisms could explain increased response times. Moseley proposed two alternative mechanisms: the first was that a neglect-like effect, resulting from chronic disuse might explain the disrupted body

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[3] In the hand laterality task the subject has to determine whether the hand image that she sees, usually presented in different degrees of rotation, corresponds to her right or left hand. In order to answer this question, it is thought that the subject has to imagine her own hand in such a position and to do so, she has to imagine the movement of her hand from its current position to the target position. This experimental paradigm is based on Parsons' finding that the temporal and kinematic properties of imagined movements are similar to those of real actions, meaning that the time it takes to mentally move a given body part is proportional to the time it actually takes to move that part of the body. His findings also suggested that the spatial origin from which someone begins to imagine the movement of their body corresponds to their current position, suggesting that the body representation is continually updated rather than a fixed canonical representation (Parsons 1987, 1994).
[4] The study does not specify whether patients suffered from CRPS type I or II.

schema, and the second was that disruption of motor processes induced in an attempt to guard the painful hand might be behind the delay in hand recognition. The author tested the following two hypotheses on CRPS-I patients: a) if chronic disuse is responsible for the delay in hand recognition, then RTs should be proportional to the duration of the CRPS symptoms and b) if a guarding response contributes to the delay in hand recognition, then RTs should be proportional to the pain that would be evoked by performing the mental movement. The results showed that the duration of the symptoms was correlated to RTs—suggesting the involvement of long-term changes associated to chronic pain and disuse—and that RTs were not correlated to the intensity of the pain contradicting the hypothesis of Schwoebel et al. (2002). In addition, the results showed that RTs were correlated to the pain that would be evoked by executing the movement rather than to the awkwardness of the movement, suggesting that a "guarding-type" mechanism affecting motor processes at the level of the planning of the movements could also be in place. A second study done by Moseley Sim, Henry & Souvlis (2005) corroborated both of these possibilities. The authors performed a study with a similar task in two groups: CRPS-I patients and healthy participants with experimentally induced pain. The results confirmed a delay in recognition of the painful hand for the CRPS-I group, but no change in response time was found for the experimentally induced acute pain group, suggesting that the alteration in the body schema involve long term changes probably in cortical structures.

Similar results have been obtained from lower back pain patients. Bray and Moseley (2010) found that patients with bilateral back pain made more mistakes on a left/right trunk rotation task than patients with unilateral back pain, who in turn made more mistakes on that task than healthy subjects.

In summary, the evidence presented above suggests that pain disrupts the ability to mentally rotate the painful body part, an ability that is thought to be sustained by a functioning body schema. This disruption seems to be modulated by the duration of the pain condition rather than by the intensity of the pain, which suggests that long-term changes in cortical structures may be involved. In addition, difficulty in mentally rotating the painful body part seems to be related to the pain that CRPS sufferers believe the movement would produce rather than to the difficulty of the movement itself, suggesting that movement planning might be disrupted by an attempt to "guard" the affected body part.

1.2.3. Disruption in spatial reference frame and body localization

Another type of indicator of pain-related disturbances of body awareness concerns the distortion of spatial reference frame and body localization.

Sumitani, Shibata, Iwakura, Matsuda, Sakaue, Inoue, Mashimo, & Miyauchi (2007b) assessed spatial perception of CRPS-I patients using subjective body midline judgements.

Subjective body midline was determined by asking patients to direct a dot that appeared in a screen in front of them to a position that crossed their body midline using verbal commands. The authors found that midline judgements were shifted towards the affected side of the body. In addition, therapeutic nerve blockage caused a transient deviation of mid-

line judgements towards the unaffected side of the body. According to the authors, this result suggests that pathological pain might provide "exaggerated" information from the affected side of the body, resulting in a multisensory imbalance between the two sides of the body that shifts patients' egocentric reference frame. As the egocentric reference frame is crucial for the performance of spatially oriented action, the authors suggest that distortion of the egocentric reference frame in CRPS-I might provoke a vicious cycle between sensorimotor incongruence and pain.

In a recent study, Lewis, Kersten, McPherson, Tylor, Harris, McCabe & Blake (2010) assessed limb position in type I and II CRPS's patients. The authors asked a group of CRPS patients and a group of healthy participants to position one arm at a time in a series of horizontal positions corresponding to the hours of a clock. The results showed that CRPS patients were significantly less accurate in matching the position of their arms with the targets than the control group. Interestingly, within the CRPS group, there was no significant difference in limb position accuracy between the affected and the non-affected arms. The authors propose that central mechanisms play a key role, suggesting that a disruption in the body schema of the affected limb, impairing the ability to accurately position the limb, might be involved in disrupted limb localization.

In summary, these two studies show that CRPS pain has an impact on body localization. Importantly, Sumitani et al. showed that CRPS patients' egocentric reference frame is shifted toward their painful side. This shift might explain the results of Lewis et al. (2010), particularly the fact that CRPS patients position both affected and unaffected limbs less accurately than healthy controls, since a shift in the egocentric reference frame would globally affect the ability to localize one's own body in space.

1.2.4. Disruption in body-size perception

Finally, evidence shows that chronic pain also affects the perceived size of the painful body part.

Moseley (2005) tested the possibility that CRPS-I patients might experience a disruption in body perception such as that found in regional anesthesia, wherein the anesthetized body part is reported to feel larger than it really is. The author asked patients to estimate the size of affected hand using different-sized pictures: the results showed that patients estimate that the painful hand is larger than it really is. The author suggested that a mechanism involving changes in the primary somatosensory cortex similar to those found in regional anesthesia might underlie these findings.

The fact that CRPS patients' overestimate the size of the affected limb has been further confirmed by McCabe, Shenker, Lewis, & Blake (2005b), Lewis et al. (2007) and Peltz, Seifert, Lanz, Müller & Maihöfner (2011). Peltz et al. (2011) expanded this result assessing neglect-type symptoms and tactile acuity. Tactile acuity refers to the ability to discriminate between two tactile stimuli that are presented close to one another and is measured by the two-points discrimination threshold, which is the minimum distance between two adjacent tactile stimuli required for an individual to distinguish them as distinct. Neglect-type symptoms were assessed using the Galer and Jensen questionnaire. The results showed that overestimation of the size of affected limb was correlated to disease

duration, neglect scores (perceived foreignness) and differences in tactile acuity. In contrast, no correlation was found with pain ratings. The authors suggest that the ability to identify the size of one's own hand is related to the ability to mentally rotate it, and propose that similar mechanisms might be involved in their results and those on imagining the rotation of body parts described above in section 1.2.2. The authors suggest that these findings are related to a disruption of the body schema mediated by cortical shrinkage of the hand representation, emphasizing the role of the central nervous system.

In summary, we have seen that pain seems to alter the perception of the size of the painful body part. This distortion appears to be related to the duration of the disease as well as to the feeling that the affected body part is "foreign" and disturbances in tactile acuity. Like the other disturbances of body awareness reviewed above, distortions in size perception have been related to dysfunction in the body schema.

The various studies considered in this section present evidence that chronic pain has an impact on different aspects of body awareness, including a perturbed feeling of body ownership, difficulty in mentally rotating the painful body part, a disrupted egocentric spatial reference frame and body localization, and distortions of body-size perception. The relationships between these symptoms and the underlying mechanisms are not clear, although most of the investigators interpret these results in terms of a disruption of the body schema. But what does a "disruption of the body schema" mean? Recall the definition of the body schema. The body schema is first of all a conceptual construct that, in the context of pain research, refers to a real time-time dynamic representation of one's own body in space derived from sensory input and is integrated with motor systems for the control of action. The meaning of the word "representation" is not entirely clear either. However, what investigators seem to point to when referring to a "disruption of the body schema" is a change in the body's cortical representation: in other words, the cortical activity of certain brain areas, mainly the primary somatosensory (S1) and motor cortices (M1), which is correlated to the stimulation of a given body part. In the case of S1, neural activity of a specific area correlates with stimulation of a specific body surface and in the case of M1 it correlates with the movement of a given group of muscles. These brain areas follow the topography of the body, which is why they are often called as the "brain's body maps". In fact, as we will see in the next section, many studies show a pain-related reorganization of these brain body maps.

1.3. Cortical reorganization as a mechanism for the impact of pain on body awareness

Reorganization of the primary somatosensory cortex following amputation has been described in primates and humans (Ramachandran, 1993). Interestingly, Flor, Elbert, Knecht, Wienbruch, Pantev, Birbaumers, Larbig and Taub (1995) reported that changes in the primary somatosensory cortex of phantom limb patients were strongly correlated to the amount of phantom limb pain but not to non-painful phantom phenomena. The authors suggested that phantom limb pain might be a result of plastic changes in the primary somatosensory cortex. Later, Flor, Braun, Elbert, & Birnaumer (1997) used magnetic source imaging to test the hypothesis that chronic pain might result in extensive proprioceptive discharges and ultimately to

cortical reorganization. The results showed a) enhanced cortical reactivity in states of chronic pain, b) a correlation between the duration of the chronic pain state and increased cortical response and c) that the cortical representation of the back in the chronic pain sufferers had undergone a shift in the medial direction. Source localisation on the brain activity suggested that early activity originates in the expansion of the back representation in the primary somatosensory cortex into the neighbouring area.

Sörös et al. (2001) tested whether acute pain in itself was sufficient to produce cortical reorganization, or whether the pain had to be chronic. To do so, the authors recorded somatosensory magnetic potentials evoked by the tactile stimulation of the fingers of the left hand as well as the left lower lip of six healthy subjects. The recordings were performed before the induction of acute pain by intradermal injections of capsaicin in the middle of the left tenar and repeated five minutes after. Thresholds for light touch and pain in the left hand fingers and in the tenar were measured with von Frey filaments in order to measure any capsaicin-induced changes in the sensitivity of C-fibers. Thresholds were measured before the first and after the second recording of somatosensory evoked potentials. Interestingly, the results showed that nociceptive input caused a spatial shift of the hand representation in primary somatosensory cortex after only five minutes. Thresholds for light touch and pain did not change after the capsaicin injections in the sites of tactile stimulation (left hand fingers and lip) suggesting that capsaicin induced no peripheral sensitization or blockage of C-fibers. The authors suggested that changes in the cortical representation of the hand were due to the direct activation of C-fibers, rather than peripheral sensitization, and that the rapid changes in the organization of cortical activity were due to the unmasking of latent afferent inputs by intracortical inhibition.

Later, Maihöfner Handwerker, Neundörfer & Birklein (2003) tested cortical reorganization in CRPS-I. Using magnetoencephalography (MEG), they investigated whether potential changes in the organization of primary somatosensory cortex in CRPS-I relate to sensory, motor, or autonomic symptoms. Sensory symptoms were assessed by the McGill questionnaire, by a numeric rating scale on which patients evaluated their pain at the time of the MEG recordings, and by pinprick hyperalgesia using von Frey filaments. Motor dysfunction was assessed by measuring the range of motion at the level of the fingers and the wrist and by a questionnaire that measured the extent of disability in daily activities. Autonomic complaints were assessed by measuring the presence of a) significant skin temperature differences, b) changes in skin color, c) presence of sweating abnormalities, d) presence of distal edema and e) trophic changes in skin, nail or hair. Shifts in the cortical representation of patients' hands was assessed by recording somatosensory evoked magnetic fields following the tactile stimulation of patients' fingers. The results showed a shift of the cortical representation of the hand toward the cortical representation of the lip on the affected side and also a significant shrinkage of the cortical representation of the affected hand. The cortical reorganization correlated with the amount of CRPS-I pain and the extent of mechanical hyperalgesia but not to motor or autonomic dysfunction. The authors suggested that persistent chronic pain might induce central nociceptive sensitization by gating sensory discharge to spinal, subcortical and cortical relays. They proposed that, since me-

chanical hyperalgesia is considered to be a hallmark of central nociceptive sensitization, the correlation found between cortical reorganization and mechanical hyperalgesia suggests that there is an important connection between central nociceptive sensitization and cortical reorganization. As the results showed no correlation between cortical reorganization and motor dysfunction, they ruled out an influence of misuse of the limb or motor disability on the reorganization of somatosensory cortex.

Recent studies have also found reorganization of the motor cortex (M1) in chronic pain conditions. For instance, Krause, Förderreuther & Straube (2006) assessed the motor cortical representations of patients suffering from upper-limb CRPS-I using transcranial magnetic stimulation. The results showed that the cortical representation of the affected hand was significantly smaller than the unaffected hand. Tsao, Galea & Hodges (2008) showed that the motor cortical representation of contraction of the transversus abdominis muscle was shifted and enlarged in patients with recurrent lower back pain. Tsao and collaborators suggested that one way to explain the discrepancy between their results and those of Krause et al. would be to suppose that different types of pain pathologies result in the motor cortex being reorganized in different ways. According to the authors, CRPS-I involves immobilization: they related the decrease of hand representation found by Krause et al. to disuse rather than pain and injury.

The evidence reviewed in this section confirms the presence of cortical reorganization in pain syndromes, showing a change in the brain's body maps. These findings are consistent with the view that pain-related disturbances in body awareness result from changes in cortical organization. However, the relationship between pain, motor dysfunction, disturbances in body perception, and cortical changes is not yet well understood. The question of whether pain is at the basis of motor dysfunction, body perception disturbances and cortical changes, whether cortical changes are instead at the basis of pain, motor dysfunction and body perception disturbances, or if it is even possible to establish a causal relation at all, remains open. So far we have reviewed evidence showing the impact of pain on body awareness; in the next section we shall see that modifications in body awareness can also have an impact on pain.

2. The impact of body awareness on pain

In this section we will review examples of research showing that the modification of body awareness through different devices can modulate pain.

2.1. The sensorimotor incongruence hypothesis

Ramachandran, V.S., Ramachandran, R. & Cobb (1995) introduced the "mirror-box", a very ingenious arrangement that contributed to a rethink of the unsolved problem of phantom limb pain and, along with it, also other kinds of chronic pain syndromes. Ramachandran and colleagues placed a vertical sagittal mirror on a table in front of upper limb amputees suffering from phantom limb pain. The mirror was placed in such a way that patients could see the reflection of their remaining arm superimposed on the felt location of the phantom arm. Patients were asked to do mirror-symmetrical movements with 'both' arms while looking at the mirror. Patients received the visual feedback that their phantom arm was following their in-

tention to move. Later, Ramachandran, V.S. & Ramachandran, R. (1996) used this arrangement to study the effect of the mirror-box in ten phantom limb patients. The authors found that four out of ten patients were able to use this device to unclench a painfully clenched phantom hand and relieve their pain. The authors proposed that phantom limb pain results from the disruption of the normal interaction between motor intention and proprioceptive input. Based on this idea, Harris (1999) put forward the hypothesis that pain is a result of distorted cortical representation due to discordance between motor intention, proprioception and vision. Harris compared pain to the sensation of nausea caused by conflict between visual and vestibular input. This hypothesis was well received and tested by several groups.

For instance, McCabe, Haigh, Ring, Halligan, Wall & Blake (2003) tested this hypothesis using the mirror-box on CRPS-I patients. Patients were classified according to disease duration: early disease (less or equal to eight weeks), intermediate duration (between five months and one year) and long-standing disease (equal to or more than two years). The experimental protocol had three phases: a control phase using no device (control phase 1), a control phase using a non-reflective surface (control phase 2) and the mirror phase. In the second control phase and mirror phase, participants were asked to perform synchronized movements with the affected and unaffected limb while looking at the non-reflective surface (control phase 2) or the reflective surface (mirror phase). Participants were asked to evaluate their pain on a visual analogue scale after each phase. The results showed that congruent visual feedback from moving the unaffected limb significantly reduced the perception of pain in early CRPS-I. In the group of patients that had been experiencing the disease for an intermediate duration congruent visual feedback did not reduce pain, but reduced stiffness. The long-standing disease group showed no effect of visual feedback. The authors suggest that these results support the hypothesis that incongruence between sensory feedback and motor intention, resulting from changes in the central nervous system, generate a feedback-dependent state that produces pathological pain.

To further explore the possibility that sensorimotor mismatch causes pain, McCabe, Haigh, Ring, Halligan & Blake (2005a) used a bilateral coordination task of the upper and lower limbs to create sensorimotor incongruence in healthy subjects. Participants performed synchronous and asynchronous movements with their arms or legs while looking at the mirror or a non-reflecting surface. Participants' experiences were collected and analyzed using a qualitative methodology. The results showed that 66% of the participants reported at least one "anomalous" symptom. Anomalous symptoms included discomfort, mild pain, impression of temperature change, impression of weight change, the impression of the loss of a limb, and impression of having a third limb. The authors concluded that this evidence supports the hypothesis that sensorimotor conflict can induce pain. McCabe and collaborators further developed this idea and suggested that mismatch between motor output and sensory input triggers a warning mechanism within the predictive system for motor control, generating sensory disturbances and pain (McCabe et al., 2005a). They further suggested that the innate susceptibility of some individuals to sensorimotor incongruence explains why only some participants experienced sensory disturbances, and

said that this could be the basis of pain with no organic cause, as in fibromyalgia. In order to explore this possibility, McCabe, Cohen & Blake (2007) used a similar protocol to test whether sensory-motor mismatch increased existing symptoms in fibromyalgia. The authors hypothesized that if the fibromyalgia symptoms were a result of sensory-motor mismatch, then exacerbation of this mismatch would increase baseline symptoms. The same methodology as in McCabe et al. (2005a) was used to compare the results with those of healthy participants. Fibromyalgia patients were asked to describe their sensations after performing a series of standardized synchronous and asynchronous movements with their arms or legs while looking at the mirror or a non-reflecting surface. The results showed that fibromyalgia patients reported the same type of symptoms as in the previous study with healthy participants. Only two new sensations were present in the group of fibromyalgia patients: the perception of swelling of the limb and tiredness. Recall that in the previous results, healthy participants reported increased symptoms in the mirror condition with maximum symptoms in the mirror-asynchronous condition. Fibromyalgia patients presented increased baseline symptoms and higher frequency of reported symptoms than healthy participants, but this was true for all conditions: while looking at the mirror and the non-reflecting surface and while performing synchronous or asynchronous movements. Surprisingly, even though no additional exacerbation of symptoms was seen during incongruent mirror visual feedback, the authors interpret these results as confirming their hypothesis that pre-existing sensory-motor mismatch is present in fibromyalgia patients and the exacerbation of this mismatch increased the symptoms. Based on their idea, developed in McCabe et al. (2005a), that mismatch between motor output and sensory input triggers a warning mechanism within the predictive system for motor control, the authors proposed that in fibromyalgia patients, small discrepancies between a sensorimotor expectation and sensory input were enough to trigger an alert in the motor control system that resulted in somesthetic disturbances to warn the individual of an abnormality in information processing. According to the authors, this high sensitivity to sensorimotor discrepancies explains why no additional exacerbation of symptoms was seen during incongruent mirror visual feedback.

Sumitani, Rossetti, Shibata, Matsuda, Sakaue, Inoue, Mashimo, & Miyauchi (2007a) used a different device to further test the hypothesis that sensorimotor incongruence generates pain. They adapted the visual experience of five patients with prismatic goggles that produced a 20-degree displacement of the visual field toward the unaffected side. Patients underwent prism adaptation for 5 to 10 minutes daily during 14 days. Pain was assessed with a numerical rating scale (NRS) before prism exposure, immediately after the first prism exposure, and after a 14-day sequence of prism exposure. The subjective body midline was also assessed at the same moments. The results show a significant displacement of subjective body midline in the direction of the prismatic shift immediately after prism exposure as well as after two weeks of daily exposure. Pain judgements remained the same immediately after the first prism exposure but had decreased after 14-day prism exposure in all five cases. In addition, the authors conducted a longitudinal single case study. Several types of prisms were used in the course of two-month period: a sham neutral prism, prisms that displace vision 20° towards the affected side of the body, prisms that displace

vision 20° towards the unaffected side of the body and a 5° prism towards the unaffected body side. They found that prism adaptation toward the unaffected side of the body had an analgesic effect. The sham prism and the 5-degree produced no effect, and the prism with 20-degree adaptation towards the affected side exacerbated the pain. The authors discuss the possibility that the decrease in pain is the result of a re-establishment of congruent sensorimotor integration induced by the prism adaptation. The authors argue that CRPS-I shifts the subjective body midline, and thus the egocentric body reference frame needed to coherently perform movements and interact with objects. They suggested that the incoherence sensorimotor integration created by this displacement in the body midline leads to the further disruption of sensorimotor feedback loops. The visual field shift induced by the prisms, they suggested, re-establishes congruent sensorimotor integration, thereby easing pathological pain.

Bultitude and Rafal (2009) corroborated Sumitani et al's findings in a single-case study, treating a CRPS I patient with mirror and prism adaptation therapy. The patient's symptoms included pain, hyperalgesia, swelling, temperature changes, and motor and sensory abnormalities on her right hand. The patient recovered the full range of movement and experienced no pain when performing synchronous movements of her hands while viewing the reflected image of her unaffected hand. As soon as the mirror was removed, these effects disappeared. Interestingly, these effects did not occur when the patient looked at the reflected image of the experimenter's hand moving in the mirror but did no move her own unaffected hand, nor if the patient performed synchronous movements with both hands but without the mirror. However, if the patient looked at the reflected image of the experimenter's hand moving in the mirror while she performed the same movements with her unaffected hand, which was hidden from her view, again, the patient's range of movements increased and she experienced no pain. The authors interpreted these results as suggesting that the efficacy of the manipulation with the mirror depends on the execution of synchronous bimanual movements while experiencing the illusion of normal movement in the affected hand. Later, the same patient underwent a prism adaptation protocol that lasted 15 weeks. Prism adaptation was induced using prismatic goggles that produced a 17° displacement towards the left (unaffected side) while the patient was asked to perform 50 alternating pointing movements. The protocol involved a sequence of three weeks of prism treatment, two weeks of 'washout,' another week of prism treatment where pointing was performed with the unaffected hand, and then nine weeks of prism treatment again. Pain and range of movement were measured on a numerical rating scale on nine occasions throughout the 15-week period. The result showed that pain and range of movement were ameliorated over the course of the prism adaptation treatment. This effect disappeared during the washout period and during prism adaptation with the unaffected hand, corroborating Sumitani et al.'s findings.

Using a different approach, Moseley, Zalucki & Wiech (2008d) showed the impact of body awareness on chronic pain. The authors tested whether improvement in tactile acuity decreased pain perception. In their experiment, 17 CRPS-I patients with reduced tactile acuity underwent a four-phase protocol: a phase without treatment, a tactile acuity discrimination phase, a tactile stimulation phase and a three-month follow-up phase.

The first three phases lasted between 11 and 17 days. The main measures recorded were pain intensity as assessed by a visual analogue scale (VAS) and two-point discrimination threshold. They found that tactile discrimination decreased both reported pain and the two-point discrimination threshold; tactile stimulation alone did not have such effects. They suggested that tactile discrimination decreases pain via cortical reorganization.

In summary, devices that modify body awareness such as the 'mirror box' seem to have an impact on pain perception. Based on these findings, Harris hypothesized that pain results from incongruence between motor intentions, visual input and proprioception. McCabe and collaborators developed this hypothesis further, suggesting that sensorimotor incongruence triggers a warning mechanism within the predictive system for motor control, leading to sensory disturbances and pain. Although this hypothesis can explain some of the presented findings, some issues remain unclear.

2.2. Issues with the idea of sensorimotor incongruence

One issue with explanations of pain in terms of sensorimotor incongruence relates to the efficacy of the mirror-box in relieving chronic pain. Although several groups have tested the use of mirrors in pain syndromes (*e.g.,* Ramachandran and Seckel, 2010; Altschuler and Hu, 2008; Chan, Witt, Charrow, Magee, Howard, Pasquina, Heilman & Tsao, 2007; Brodie, Whyte, & Niven, 2007) and "mirror" therapy has been considered as a potential tool to treat phantom limb and CRPS, the efficacy of mirror therapy has been questioned. In a critical review article, Moseley, Gallace & Spence (2008a) point to the fact that a) many studies that show the effective use of mirror therapy are clinical trials that lack statistical power, b) the effect of mirror therapy might be effective in acute phases of CRPS but not in chronic patients (as seen for example in McCabe et al., 2003) and c) that studies that show a positive effect of mirror therapy use protocols that also involve motor imagery, therefore it cannot be establish if the effect is due to mirror therapy, to motor imagery, or to both.

A second issue is illustrated by consideration of the study of McCabe et al. (2005a) and McCabe et al. (2007) presented in section 2.1. In the former study, McCabe et al. tested the Harris's sensorimotor incongruence hypothesis using a bilateral coordination task on the upper and lower limbs of healthy subjects. The results showed that 66% of the participants experienced an 'anomalous' sensation, but only 17% said they experienced pain. This would not seem to be enough to show a true causal relationship. In the latter study, the group used a similar protocol to test whether sensory-motor mismatch increased existing symptoms in fibromyalgia patients. The results showed increased baseline symptoms in fibromyalgia patients, but this increase applied, in both congruent and incongruent sensory-motor situations. The authors suggested that a reduced threshold for sensory-motor discrepancies compared to healthy subjects may explain why no additional exacerbation of symptoms was seen during incongruent mirror visual feedback, but nevertheless it seems that the exacerbation of the symptoms in this case is due to factors other than sensorimotor incongruence. Again this does not argue for a causal role of incongruence in pain, since pain was enhanced in both the congruent and incongruent conditions.

Another issue is raised by the study of Moseley, McCormick, Hudson & Zalucki (2006), which aimed to test whether sensorimotor incongruence that does not involve visual input is sufficient to induce pain. The authors induced sensorimotor incongruence by creating the illusion of perpetual wrist flexion through tendon vibration in healthy subjects. Participants were asked to evaluate several aspects of their experience in five different conditions. Among these, only the "tendon vibration" condition was design to induce the illusion of flexion. The aspects that participants were asked to evaluate were perceived pain/discomfort, feelings of peculiarity, changes of temperature of the limb, feelings of foreignness of the limb, and feelings of swelling. The results showed that, among the participants who experienced the illusion of flexion, the affected limb felt more peculiar, more foreign, and more swollen during the tendon vibration condition than in the control conditions, but no difference in pain/discomfort or perceived temperature was found. These results suggest that disruption of the cortical proprioceptive representation without conflicting visual input is not sufficient to cause pain.

Another issue is that many situations involve sensory-motor incongruence but not pain. Examples include "anarchic hand" syndrome, in which patients have a hand that moves independently of their conscious intentions, delusions of control in which schizophrenic patients experience their actions as caused by some external force (Frith, Blackmore & Wolpert, 2000), or, as pointed out by Moseley and Gandevia (2005), conditions such as focal dystonia and the use of prism glasses. All of these situations involve incongruence between motor intention, proprioception and vision, but not pain.

Taken together, these issues suggest that incongruence between motor intention, visual input and proprioception, although it seems to be present in chronic pain conditions and may even enhance or stabilize some of the symptoms of chronic pain conditions, in itself is not enough to cause pain. It seems that other factors are needed to account for the complexity of chronic pain.

3. Pain and homeostatic regulation

3.1. Pain and stress

In the preceding sections, we have looked at evidence of a bidirectional relationship between pain and body awareness. On one hand, chronic pain conditions affect elements of body awareness including motor control, body perception and cortical reorganization. These observations led researchers to hypothesize pain-related disruptions of the body schema and a crucial role for the central nervous system. Still, the mechanisms that relate pain, motor dysfunction, disruption of body perception and cortical changes remain unclear. On the other hand, evidence from techniques like mirror therapy suggests that there may be a link that runs from body awareness to pain. Here also, however, the link is not simply one of cause and effect.

It is therefore worth considering an aspect of pain that has not yet been discussed in this review, and that Harris's account of pain in particular also did not take into account. This is the relationship between pain and the autonomic nervous system.

It is well established that pain can act as a stressor, disturbing homeostatic equilibrium and activating the sympathetic branch of the autonomic nervous system (ANS) (McEwen and Kalia, 2010; Vierck, 2006; Cohen, Neumann, Shore, Amir, Cassuto & Buskila, 2000). In particular, one of the ways in which pain activates the sympathetic nervous system is through the hypothalamic-pituitary-adrenal (HPA) axis and the locus ceruleus-norepinephrine (LC-NE) system. Both of these systems seem to be affected in chronic pain syndromes. Exaggerated sympathetic activity has been found in fibromyalgia through the heart rate variability tests and tilt table testing (Martinez-Lavin, 2007). Signs of autonomic disruption in CRPS are suggested by patients' abnormal regulation of blood flow and sweating, oedema of skin and subcutaneous tissues and trophic skin changes, and effective pain relief after sympathetic blockage (Schlereth and Birklein, 2008). Based on this type of evidence for a relationship between chronic pain and the autonomic nervous system, it has been suggested that chronic pain syndromes are a result of a deregulation of neurohormonal systems in charge of stress response and homeostasis. For instance, Martinez-Lavin (2007) suggested that patients with fibromyalgia present a hyperactivation of the sympathetic nervous system but then become hyporeactive to stress: constant hyperadrenergic activity leads to a breakdown of the sympathetic regulatory system, which in turn leads to the development of abnormal connections between the sympathetic nervous system and nociceptive fibers.

How do Harris and McCabe's accounts of the causation of pain by sensorimotor incongruence relate to this evidence connecting chronic pain to dysfunction in the autonomous nervous system?

McCabe et al. (2007) suggested that incongruence between sensory and motor systems could act as a stressor and activate the responses of the autonomic nervous system, suggesting a primary causal role for motor control system disturbances.

However, this hypothesis remains to be tested.

3.2. The concept of interoception and internal body awareness

As seen above, the relationship between pain and the autonomic nervous system has usually been viewed in terms of a general stress response. But this relationship could also be viewed in the light of Craig's interoceptive framework (Craig, 2002; 2003). Craig defines interoception as the sense of the physiological state of the whole body. This concept emerged from Craig's functional anatomy studies on the connectivity of the lamina I of the trigeminal and spinal dorsal horns. Craig shows that small-diameter (A and C) primary afferents present in all tissues of the body that carry signals of different physiological parameters, including among others noxious stimuli, the metabolic state of tissues (acidic pH, hypoxia, hypercapnia, hypoglycaemia, hypo-osmolarity and lactic acid), cell rupture, immune and hormonal activity, mast cell activation, and temperature (Craig, 2002), project monosynaptically to the lamina I of the spinal and trigeminal dorsal horns (Craig, 2003). From here, lamina I cells project to the autonomic cell columns, forming a spino-spinal loop for somatoautonomic reflexes and to pre-autonomic sites in the brainstem such as the parabrachial nucleus (PB) and the nucleus of the solitary tract (NTS), a major integration site for homeostatic activity. In mammals, the PB projects to the medial thalamic nuclei and the basal ventral medial nucleus (VMb) and from there to the anterior cingulate (ACC) and insular cortices. This lamina I spinothalamic pathway is viewed as the afferent counterpart of the sympathetic system (Craig 2003). In primates, Craig presents evidence showing that neurons from lamina I have an additional pathway from which they project in a topographic fashion directly to the insular and anterior cingulate cortices via relay nuclei in the thalamus (Craig, 2002). According to Craig, this projection to the insula creates a sensory representation of afferent activity related to the physiological condition of the entire body. Craig views the insula and ACC as limbic sensory and limbic motor cortices respectively (Craig, 2011) and suggests that in primates the direct activation of the insular and anterior cingulate cortices by inputs signalling the internal state of the body corresponds to the simultaneous generation of sensation and motivation triggered by basic needs, which, he says, are at the basis of human emotions (Craig, 2003).

In summary, according to Craig, input from lamina I projects topographically to the insula, creating a sensory representation of afferent activity related to the physiological condition of the entire body. This representation could be seen as a map of the homeostatic condition of the body, which could be the foundation for the experience of subjective sensations and emotions.

This account yields a contrast with the notion of body awareness discussed above. The latter refers mainly to factors that contribute to spatially oriented voluntary body motions, which are thought to depend on a sort of body map or body schema. Interestingly, such aspects of body awareness necessary involve sensorimotor integration between external stimuli and skeletal muscles—that is, muscles that are under voluntary control. Following the distinction of Craig (2011), such forms of body awareness could thus be called *exteroceptive*. In contrast, we may also conceive an *interoceptive* form of body awareness, or 'internal body map', which is more concerned with the integration of sensory signals, allowing the control of visceral systems using smooth muscles.

While little work has thus far been addressed to understanding the mechanisms underlying the connection between exteroceptive and interoceptive body awareness, a line of research that has shown evidence of such a relationship is the work of Moseley and collaborators, which we will review below.

In Moseley, Parsons & Spence (2008c), the investigators asked a group of chronic arm pain patients to evaluate the intensity of their pain after performing a set of standardized movements. When looking through magnifying or minifying binoculars, patients felt respectively more or less pain than when they looked directly at their arm. Interestingly, physically measured swollenness of the hand followed the same pattern (Moseley et al., 2008c). These results show that there is a bidirectional link between pain and autonomic regulation on one hand and body awareness on the other. The authors suggested that the decrease in pain intensity and swollenness found when the patients looked through the minifying binoculars could be due to a reduced sense of ownership of the limb. In another study, Moseley, Olthof, Venema, Don, Wijers, Gallace & Spence

(2008b) showed that the illusion of owning a rubber hand[5] has the effect of decreasing participants' real hand temperature. Body temperature is a physiological parameter regulated by the autonomic nervous system. Thus, this result shows that modification of the sense of body ownership through the illusory incorporation of a rubber hand modifies a physiological parameter, suggesting a bridge between exteroceptive and interoceptive body awareness.

The relationship between exteroceptive body awareness and interoception is exemplified by another study. Moseley, Gallace and Spence (2009) investigated the hypothesis that CRPS-I patients present a bias in tactile processing towards the unaffected side of the body. In order to assess bias in tactile processing, the authors used a temporal order judgements task (TOJ)[6]. In addition to skin temperature, tactile acuity and swelling were measured. These parameters were assessed in two conditions: one in which patients were seated with their arms parallel to each other resting on a table, and a second which differed only in that participants crossed their arms. The results showed that in the uncrossed condition, patients prioritized tactile stimuli from the unaffected hand, but interestingly, in the crossed condition, the opposite was the case: patients prioritized tactile stimuli from the affected hand. In addition, the affected arm was significantly warmer in the crossed condition than it was before crossing the arms. With regard to the point under discussion here, this experiment has two important results: a) pain-related tactile deficits seem to follow a spatial reference frame that is egocentrically centered rather than somatotopically centered and b) temperature deregulation follows this egocentric reference frame. According to the authors, these findings suggest that a spatial reference frame influences the cortical mechanisms that modulate vasoconstriction, again reflecting a link between exteroception and interoception.

One brain structure that might participate in such integration is the insular cortex. The insula is part of the cortex folded deep within the lateral sulcus. It seems to be organized into different functional domains along an antero-posterior axis (Dupont Bouilleret, Hasboun, Semah & Baulac, 2003). Stephani, Fernandez-Baca, Maciunas, Koubeisse, & Lüders (2010) confirmed the existence of clear topographic specificity inside the insular cortex, with visceromotor and viscerosensory sensations elicited mainly by anterior insular stimulations and somesthetic sensations elicited by stimulations in posterior insula. The insula is often viewed as limbic cortex: it is strongly interconnected with the amygdala, the hypothalamus, orbitofrontal cortex, and brainstem homeostatic regions. It is thought to be a structure into which several sensorial inputs converge, contributing to the integration of emotion and behavior (Dupont et al., 2003). Studies also suggest that the insula is involved in the experience of body ownership and agency (Devue, Collette, Balteau, Degueldre, Luxen, Maquet & Brédart, 2007; Farrer and Frith, 2002) and subjective awareness of feelings (Damasio, Grabowski, Bechara, Damasio, Ponto, Parvizi & Hichwa, 2000).

Incorporating the interoceptive dimension into the concept of body awareness may enlarge our view of this issue, notably opening up the way to an integration of the individual's emotional states, which are thought to play a key role in health and disease (*e.g.*, Flor, 2011; Geha, Marwan, Baliki, Harden, Bauer, Parrish and Apkarian, 2008).

4. Conclusion

In this review we have examined evidence for relationships between pain and awareness of the body in relation to voluntary movements and space, and between pain and the body's homeostatic regulation—(un) awareness of the body's internal state and emotions. Rather than a specific directional causal chain, this evidence suggests that interactions between these factors are complex and multidimensional, casting doubt on the assumption that they can be reduced to a single cause and suggesting that future investigations should inquire into the full set of relationships between them. Research on the relationship between the mechanisms underlying exteroceptive and interoceptive aspects of self-bodily awareness, which so far have been kept separate, might shed light on the links between chronic pain, sensorimotor incongruence and the autonomic nervous system.

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[5] In the rubber hand illusion a person is seated in front of a table, looking at a rubber hand that is placed on the table. The rubber hand is aligned to the person's forearm; the person's real hand is hidden from view. If the rubber and real hands are stroked synchronously, 70% of subjects have the impression that the rubber hand belongs to them. There are two conditions for this illusion to be effective: the stroking has to be synchronous, and the rubber hand has to be placed in an anatomically plausible position. The measures traditionally used to assess the presence of the illusion are a questionnaire that assesses the subjective feeling of owning the rubber hand and the perceived location of the participants' index finger: usually in the presence of the illusion participants feel their index finger to be located somewhere in between their actual index finger and that of the rubber hand.

[6] In the experiment, patients were presented with pairs of tactile stimuli, one in each hand, with different time intervals between the two tactile stimulations. Patients were asked to state in which hand they felt the first tactile stimulation. The interval at which patients perceived the two stimuli as occurring at the same time (PSS: point of subjective simultaneity) was used as an indicator of bias in tactile processing.

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