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COGNITIVE SOCIAL AND AFFECTIVE NEUROSCIENCE OF PATIENTS WITH SPINAL CORD INJURY

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Libertà di pensiero,

è libertà di movimento

Freedom of thinking,

is freedom of moving.

Lorenzo Amurri

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ABSTRACT

A successful human-environment interaction requires a continuous integration of information concerning body parts, object features and affective dynamics. Multiple neuropsychological studies show that tools can be integrated into the representation of one's own body. In particular, a tool that participates in the conscious movement of the person is added to the dynamic representation the body – often called "Body schema" – and may even affect social interaction. In light of this the wheelchair is treated as an extension of the disabled body, essentially replacing limbs that don't function properly, but it can also be a symbol of frailty and weakness.

In a series of experiments, I studied plastic changes of action, tool and body representation in individuals with spinal cord injury (SCI). Due to their peripheral loss of sensorimotor functions, in the absence of brain lesions and spared higher order cognitive functions, these patients represent an excellent model to study this topic in a multi-faceted way, investigating both fundamental mechanisms and possible therapeutic interventions.

In a series of experiments, I developed new behavioral methods to measure the phenomenological aspects of tool embodiment (Chapter 3), to study its functional and neural correlates (Chapter 4) and to assess the possible computational model underpinning these phenomena (Chapter 5). These tasks have been used to describe changes in tool, action and body representation following the injury (Chapter 3 and 4), but also social interactions (Chapter 7), with the aim of giving a complete portrait of change following such damage.

I found that changes in the function (wheelchair use) and the structure (body brain disconnection) of the physical body, plastically modulate tool, action and body representation. Social context and social interaction are also shaped by the new configuration of bodily representations. Such a high degree of plasticity suggests that our sense of body is not given at once, but rather it is constantly constructed and adapted through experience.

OVERVIEW OF THE THESIS

The aim of this dissertation is to address functional and plastic properties of body and action representation, as well as changes in tool embodiment process, in patients with spinal cord injuries. Due to their peripheral loss of sensorimotor functions, in the absence of brain lesions and spared higher order cognitive functions, these patients represent an excellent model to study this topic in a multi-faceted way, investigating both fundamental mechanisms as well as possible therapeutic interventions. These patients show significant changes in peripheral sensorimotor processing, as well as important cortical reorganization in sensorimotor areas (Henderson et al., 2011), which are thought to be basic for the bodily self and related cognition. Such changes are thus likely to evoke disturbances in the body schema (Curt et al., 2011), the body image (Fuentes et al., 2013); tool embodiment (Papadimitriou, 2008) or action representation. Clinical characteristics of the spinal cord and consequences of its damage have been reviewed in Chapter 1.

Nonetheless, little is known about the perceptual changes in the embodiment process and its underlying neural mechanisms in these patients. Even less is known about how these changes influence higher-level embodied cognitions such as social interaction. In order to successfully interact with people and objects in the world the brain requires to continuously integrating information concerning body parts, object features and socio-affective dynamics in the environment. Two different models are thought to support this function: a dynamic representation of the body, i.e. Body Image (BI), and an online, constantly updated, action-orientated multisensory representation of the body schema (BS) that is critical for action. One of the critical features of these representations is that both BI and BS are not fixed, but they dynamically change depending on different types of experience. The connection of the self to the body (often termed "embodiment") is one of the most essential aspects of human consciousness and has been the subject of various influential philosophical (e.g., Descartes, James, Merlot-Ponty) and, more recently, neuroscientific theories (e.g., Damasio). These recent theories converge in term of their emphasis of the great relevance of bodily sensorimotor processes (i.e. the non-conceptual representations and processing of body-related information) in higher-level cognition and self-consciousness, as well as in the interactions with external objects and people. These basic sensorimotor processes are peripherally and profoundly disturbed in patients with spinal cord injuries, leading also to important structural and functional cortical reorganization in the respective cortical areas (Henderson et al., 2011). Properties and features of these processes and representations, as well as the theoretical background inspiring my research, have been reviewed in Chapter 2.

In the experimental section of this dissertation, behavioral and functional properties of these plastic representations have been investigated using different methods. In particular, in Chapter 3 the bodily assimilation of a relevant external tool as a consequence of altered sensory and motor inputs from the body and of prolonged confinement in the wheelchair has been studied, while in Chapter 4 I presented a new matching-to-sample auditory discrimination paradigm specifically developed to investigate whether profound alterations in sensorimotor traffic between the body and brain influence audio-motor representations. Moreover, as suggested by a new computetional model, in order to compute the decision process for auditory recognition, individuals integrate information considering both the memory of a motor-action repertoire and the memory of the perceptual features of the sound repertoire. In Chapter 5 I presented an experiment run to test this computational hypothesis.

In a second series of experiments I focused on the way in which the dramatic change in body representation that occur after a sudden transformation in the structure of the physical body, such as the spinal cord injury, assume a role in social and affective dynamics as a function of different types of experiences. Particularly, in Chapter 6 I investigated how our perception of individuals on wheelchair is shaped by social experience. I firstly explored the presence of implicit stereotypes toward wheelchair-bound patients with spinal cord injury by means of an ad hoc devised version of the Implicit Association Test. Subsequently, I focused on a possible attenuation of the strength of the implicit disability prejudice through a personal interaction with an individual with SCI. Finally, in Chapter 7 I will try to give a general portrait of social cognitive and affective neuroscience of this particular clinical population.

CHAPTER 1

PHENOMENOLOGY OF SPINAL CORD INJURIES: A BRAIN BODY DISCONNECTION

The spinal cord is the traditional starting point for a detailed consideration of the central nervous system (CNS). It is a uniformly organized part of the CNS, extraordinarily important in the day-to-day activities we tend not to think about. In it reside all the motor neurons supplying the muscles we use to move our body around, as well as major populations of autonomic efferents. It also receives all the sensory input from the body and some from the head and performs the initial processing operations on most of these input.

Spinal cord injuries (SCI) are among the most dramatic causes of immobility also because they often affect young people who expect to live for decades in a state of massive sensory de-afferentation and motor de-efferentation. Approximately between 180,000 and 250,000 people is currently living with such injuries in the United States (58% of them aged between 16 and 30 years) (Cole, 2004). A similar figure is found in Europe although both the incidence and prevalence are possibly underestimated (Wyndaele & Wyndaele, 2006). Importantly, although these patients have no brain lesions and higher order cognitive functions are largely spared, they show significant changes in peripheral sensorimotor processing, as well as important cortical reorganization in sensorimotor areas (Henderson et al., 2011), which are thought to be basic for the bodily self and related cognition.

1.1 Spinal cord anatomical organization

An adult human spinal cord appears surprisingly small on first inspection, being only about 42 to 45 cm long and about 35 g. It begins at the neck and extends down to the low back, supported and protected by the vertebral column; it connects the brain to the nerves throughout the body and it is anatomically segmented by the nerve roots attached to it. A continuous series of dorsal (posterior) rootlets enter the cord in a shallow longitudinal groove (the posterocentral sulcus) in its posterolateral surface; and a continuous series of ventral (anterior) rootlets leaves from the poorly defined anterolateral sulcus. The dorsal and ventral rootlets from discrete sections of the cord coalesce to form dorsal and ventral roots, which in turn join to form spinal nerves. Each dorsal root bears a dorsal root ganglion just proximal to the junction between dorsal and ventral roots; it contains the cell bodies of the primary sensory neurons whose processes travel through that particular spinal nerve. Each dorsal root ganglion remains at the level of the appropriate foramen. Proceeding from the cervical to the sacral levels, the dorsal and ventral roots become progressively longer because they have longer and longer distances to travel before reaching their sites of exit from the vertebral canal. A portion of the cord that gives rise to a spinal nerve constitutes a segment, which supplies the upper and lower extremities and therefore contains increased numbers of motor neurons and interneurons. The sensory nerves leave the cord and the motor ones enter it through nerve roots at each vertebral level. These levels are broadly divided into: the neck or cervical (with eight vertebrae and eight root levels); chest, or thoracic (twelve roots); low back, or lumbar (five roots); and pelvic area, or sacral (five roots). In cross section the spinal cord consists of a roughly H-shaped area of gray matter that floats in a surround of white matter. The gray matter can be divided into horns and the white matter into funiculi. Each spinal nerve retains its relationship with a somite during the development, with the results that spinal cord segments are related systematically with to areas of skin, to muscles, and to vertebrae. A group of muscles innervated through a specific part of the spine is called a myotome, while a section of the skin innervated through a specific part of the spine is called a dermatome. This dermatomal arrangement is particularly apparent in the trunk, where pairs of dermatomes form bands that encircle the chest and abdomen. Similarly, the innervation of the skeletal muscles is related systematically to spinal segments. Knowledge of the segmental innervations of muscles and cutaneous areas can be extremely helpful in diagnosing the site of damage in or near the spinal cord. In addition the highest level of a sensory or motor deficit may allow deductions about the segmental level of a suspected spinal cord lesion.

1.2 Phenomenology of spinal cord injuries

A spinal cord injury (SCI) refers to any damage to the spinal cord that is caused by trauma instead of disease. Depending on where the spinal cord and nerve roots are damaged, the symptoms can vary widely (Lin et al., 2002; Kirshblum et al., 2001). The level of an injury is described in terms of its roots level. An injury in the cervical area will lead to loss of use of arms, trunk, and legs: tetraplegia if complete, or a tetra-paresis if some movement remains. Injury to the thoracic, lumbar, and sacral cord leads to loss of movement of the legs but spares the arm: paraplegia if complete, or a para-paresis if incomplete.

Classification of the injury

Spinal cord injuries are described at various levels as "incomplete", which can vary from having no effect on the patient, or "complete", which mean a total loss of function. Retaining sensation and functions in the very lowest region of the spine, the sacral region, indicates that the spinal cord is only partially damaged. An incomplete spinal cord injury involves preservation of motor or sensory function below the level of injury in the spinal cord (Ho et al., 2007). This includes a phenomenon known as sacral sparing which involves the preservation of cutaneous sensation in the sacral dermatomes, even though sensation is impaired in the thoracic and lumbar dermatomes below the level of the lesion (Lafuente et al., 1995). Sacral sparing has been attributed to the lamination of fibers within the spinal cord and to the idea that the sacral spinal pathways are not as likely as the other spinal pathways to become compressed after injury (Lafuente et al., 1995). While the prognosis of complete injuries are generally predictable since recovery, the symptoms of incomplete injuries can vary and it is difficult to make an accurate prediction of the outcome.

The American Spinal Injury Association (ASIA) first published an international classification of spinal cord injury in 1982, called the International Standards for Neurological and Functional Classification of Spinal Cord Injury. Now in its sixth edition, the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) is still widely used to document sensory and motor impairments following SCI (Marino et al., 2003). It is based on neurological responses, touch and pinprick sensations tested in each dermatome, and strength of the muscles that control ten key motions on both sides of the body, including hip flexion (L2), shoulder shrug (C4), elbow flexion (C5), wrist extension (C6), and elbow extension (C7). Traumatic spinal cord injury is classified into five categories on the ASIA Impairment Scale:

• A indicates a "complete" spinal cord injury where no motor or sensory function is preserved in the sacral segments S4-S5.

• B indicates an "incomplete" spinal cord injury where sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-S5. This is typically a transient phase and if the person recovers any motor function below the neurological level, that person essentially becomes a motor incomplete, i.e. ASIA C or D.

• C indicates an "incomplete" spinal cord injury where motor function is preserved below the neurological level and more than half of key muscles below the neurological level have a muscle grade of less than 3, which indicates active movement with full range of motion against gravity.

• D indicates an "incomplete" spinal cord injury where motor function is preserved below the neurological level and at least half of the key muscles below the neurological level have a muscle grade of 3 or more.

• E indicates "normal" where motor and sensory scores are normal. Note that it is possible to have spinal cord injury and neurological deficits with completely normal motor and sensory scores.

Dimitrijevic (1988) proposed a further class, the so-called discomplete lesion, which is clinically complete but is accompanied by neurophysiological evidence of residual brain influence on spinal cord function below the lesion (Sherwood et al., 1992).

Phases of the injury

Any spinal cord injury may be temporary or permanent. Most injuries involve some initial swelling as well as more serious damage. Then some recovery may occur, which is one reason why prognosis can initially be difficult. According to the arrangement of the cord in cross section (with nerve fibers involved in touch and movement sensation in its upper half and fibers involved in movement, pain and temperature sensation in the lower half) it is possible to have a cord syndrome with loss of movement and pain/temperature sensory loss but some touch sensation remaining, or one in which movement remains but touch and position sense are lost. Usually, though, the impairment is not so neat as this, and some or all of both are affected to varying amounts. Despite this, it is possible to identify a typical sequence of clinical events resulting from the trauma. The muscles may contract uncontrollably, become weak, or be completely unresponsive. The loss of muscle function can have additional effects if the muscle is not used, including atrophy of the muscle and bone degeneration. Spinal cord transection eventually leads to spastic (upper motor neuron) paralysis below the level of the damage. This is preceded by a stage of spinal shock that may last for weeks, characterized by more or less completely flaccid paralysis. Deep tendon reflexes then begin to return and finally become hyperactive. Lesser degrees of spinal shock may occur even in cases of contusion of the spinal cord. The mechanism of spinal shock is not completely understood but the whole sequence of the events is thought to been a consequence of interruption of fibers from the brainstem and cerebellum descending to spinal cord motor neurons and interneurons. Multiple mechanisms contribute to the transition from spinal shock to spasticity. Early on, spinal cord neurons probably upregulate their complements of transmitter receptors and become abnormally sensitive. Later stages of the transition are thought to involve the formation of new synaptic connections. The degeneration of the endings of descending fibers leaves vacant synaptic sites at various places on motor neurons and interneurons, adjacent to intact reflex connections. Multiplication of these reflex connections to fill up the vacated sites would be expected to increase the sensitivity and magnitude of reflexes. Spinal shock followed by long-term hyperreflexia affects autonomic functions as well.

Spinal cord damage causes predictable deficits

The functions of the cord are reflected in the neurological impairments following damage to it. Determining the exact "level" of injury is critical in making accurate predictions about the specific parts of the body that may be affected by paralysis and loss of function (see Table 1.1). Signs recorded by a physician and symptoms experienced by a patient will vary depending on where the spine is injured and the extent of the injury. Impairments may be divided into movement and motor function, to voluntary muscles as well as to the breathing system, gut, bladder, and blood vessels, and sensory function to skin, muscles, and internal organs. Because different sensory and motor nerves pass in and out at each level and because the cord is the relay of fibers to and from the brain, the level of injury is crucial. Individuals injured at C1 and C2 will have no movement and sensation below the head. They will be dependent on a respirator because the nerves controlling breathing exit at C3. C3 tetraplegics may be able to control an electric wheelchair via a head control, but will still need assistance with the breathing. People with a C4 lesion may be able to breathe unaided using the diaphragm, though they will still have lost chest wall movement and have reduced expansion of the lungs. A C5 lesion will allow some movement of the shoulders and of biceps, allowing elbow flexion, but no power to straighten the elbow. C6 adds movement of the wrist upwards, though still not use of the hands. A person may be able to transfer in and out of a wheelchair. A C7 level allows independence with elbow extension aiding transfers, though finger movements that are controlled by C8 and T1 are still not normal. For a C8 tetraplegic independence might be expected. Additional signs and symptoms of cervical injuries include: inability or reduced ability to regulate heart rate, blood pressure, sweating and hence body temperature; autonomic dysreflexia or abnormal increases in blood pressure, sweating, and other autonomic responses to pain or sensory disturbances.

In thoracic injuries and below people are paraplegic. In T1 to T8 lesions, trunk muscles as well as chest wall breathing are lost, leading to difficulties in balance in a wheelchair, which are shared with all tetraplegics. Lesions around T8 and below have effects mainly on leg and hip muscles.

To conclude, the cord damage may differ in completeness, duration and most importantly in level. The neurological impairment confronts each person with a huge loss, however, each person’s response to it varies hugely.

Additonal clinical information can be found in Appendix A.

RELATIONSHIP BETWEEN THE NERVE LEVEL OF THE SCI AND MOVEMENT	
SPINAL ROOT LEVEL	**MOVEMENT**
C3 C4 C5	Diaphragm
C5 C6	Shoulder out
C5 C6	Elbow flexion
C6 C7 C8	Elbow straightening
C6 C7	Wrist bending
C7 C8	Wrist straightening
C7 C8	Finger straightening
C7 C8 T1	Finger bending
C8 T1	Hand muscle
L1 L2 L3	Hip bending
L3 L4	Knee extension
L4 L5 S1	Hip straightening
L4 L5 S1	Foot lifting
L5 S1 S2	Toe extension

Table 1.1 Relationship between the nerve level of the SCI and movement.

1.3 Brain plasticity after spinal cord injury

Reorganization of brain function in people with CNS damage has been identified as one of the fundamental mechanisms involved in the recovery of sensory-motor function. Unlike cortical injuries, the brain remains largely intact after SCI, providing a unique opportunity to use mapping techniques to examine cortical and subcortical reorganization in an intact brain after a distal CNS neurotrauma. The impact of traumatic spinal cord injury on structural integrity, cortical reorganization and ensuing disability is variable and may depend on a dynamic interaction between the severity of local damage and the capacity of the brain for plastic reorganization. Intuitively, greater damage to the spinal cord induces greater cortical reorganization that relates quantitatively to disability. Several studies have demonstrated that functional and structural cortical reorganization occurs following deafferentation (Bruehlmeier et al., 1998; Freund et al., 2011a; Freund et ale 2011b; Henderson et al., 2011; Moore et al., 2000; Wrigley et al., 2009). Specifically, subjects with SCI who recover functionally (Jurkiewicz et al., 2006) or who undergo surgical decompression (Duggal et al., 2010) show increases in the volume of activation in primary motor cortex. Increased cerebral activation during lower limb movement is correlated with spinal atrophy and impairment assessed by the American Spinal Injury Associations score (Lundell et al., 2011b). Analogously, subjects with SCI who do not recover show a reduced volume of activation in primary motor cortex (Jurkiewicz et al., 2010).

Reorganization of cortical networks in the brain can occur spontaneously after neurological injury. Several aspects of reorganization of brain function following SCI resembled those reported in stroke. Although SCI does not involve direct injury to cortical neurons, a spinal cord lesion affects primary sensorimotor areas connected to the damaged area and can result in reorganization of these and surrounding regions in order to compensate for sensorimotor loss (Jain et al., 1997; Donoghue et al., 1990). The brain reorganization that occurs can be dependent on both structural and functional changes. Structural changes may include synaptic alterations, such as the change in length and diameter of existing dendritic branches or the growth of new branches, providing the opportunity for new synapses (Bayona et al., 2005). Functional, changes may include modification of neuronal activity, synaptic efficacy (Dunlop, 2008), or increases in astrocyte activity (Kolb et al., 1995). Moreover, it appears that cortical reorganization is particularly associated with the growth of new intracortical connections (Pons et al., 1991). Henderson et al (2011) found that a primary somatosensory cortex (S1) reorganization of the hand area, towards the deafferented leg area, was associated with grey matter preservation and decreased fractional anisotropy. This expansion may be related to rewiring of axotomized hind limb neurons onto cervical motor circuits (Ghosh et al., 2010), driven by compensatory use of a less affected part of the body, similar to that seen following rehabilitative training after stroke (Nudo et al., 1996) or overuse (Elbert et al., 1995). However, an alternative interpretation could be that greater disability induces greater cortical reorganization but that this does not translate into functional gain.

These changes in cortical organization may occur secondary to altered spinothalamic and spinocerebellar input, and presumably reflect the adaptation of cortical maps to altered inputs (Bruehlmeier et al., 1998). Spinal cord atrophy represents the endpoint of neurodegeneration resulting from an accumulation of multiple pathophysiological events, such as axonal degeneration and demyelination, axonal dieback and neuronal loss (Dusart and Schwab, 1994). Overall, the reduction of subcortical white matter volume in the corticospinal tract and cortical grey matter volume and cortical thinning in primary motor cortex is indicative of atrophy due to retrograde degeneration (Hains et al., 2003; Beaud et al., 2008), but could also arise from decreased cortical connectivity due to a reduction in dendritic spine density (Kim et al., 2006) or a reduction in angiogenesis (Fields, 2008). Atrophy of neurons in primary sensory cortex may be induced through reduced cellular activity, triggered by trans neuronal degeneration (Jones, 2000).

It is incredibly important to understand if this well documented brain plasticity finds its functional correlate in different aspects of cognition, affection and social behavior. Although sensory information clearly influences body image (Gandevia & Phegan, 1999; Paqueron et al., 2003) the conscious body model may be only indirectly linked to primary sensory areas. Instead, this body representation is thought to predominately arise from the posterior parietal cortex (PPC) and to depend strongly on visual input. Phantom limb studies in amputees, for example, show that perceived movement of the phantom limb is associated with increased activity in PPC (Kew et al., 1994) and other non-painful phantom sensations are more linked to changes in PPC than SI (Flor et al., 2000). Furthermore, in some cases, lesions in the PPC can suppress the experience of phantom limbs (Melzack & Bromage, 1973) and can induce asomatognosia, a condition in which parts of the body feel as though they have disappeared

(Salanova et al., 1995; Wolpert et al., 1998). Other studies have shown that the left PPC is involved with processing spatial information about bodies (Corradi-Dell'Acqua et al., 2008; Corradi-Dell'Acqua et al., 2009; Felician et al., 2009). Patients with damage to the left PPC can exhibit autotopagnosia, an inability to localize and orient different parts of the body while maintaining the ability to identify body parts (Buxbaum et al., 2001; Pick, 1922). Despite cortical reorganization of primary somatosensory areas, chronic sensorimotor loss may in fact not affect the body image, as higher level areas such as the PPC are generally unaltered following SCI. Indeed, a patient with total large fiber deafferentation below the neck was assumed to rely on a (visual) body image to compensate for the complete absence of proprioceptive or body schema input (Gallagher & Cole, 1995). It is critical to note that reorganization will be different in individuals with paraplegia compared to tetraplegia during upper limb movement. Brain activation with upper limb movements in individuals with paraplegia involve the intact arms/hands, which are above the level of lesion, whereas brain activation in individuals with tetraplegia will involve attempted or imagined movement below the level of lesion.

If brain networks involved in different demands of motor control remain responsive even in chronic paralysis, therapeutic strategies aiming for restoring spinal cord function even in people with chronic SCI should be shaped on a preserved competent brain control.

CHAPTER 2

THEORETICAL BACKGROUND

Spinal cord injuries (SCI) are among the most dramatic causes of immobility also because they often affect young people who expect to live for decades in a state of massive sensory de-afferentation and motor de-efferentation. From a neuroscientific point of view, although these patients have no brain lesions and higher order cognitive functions are largely spared, they show significant changes in peripheral sensorimotor processing, as well as important cortical reorganization in sensorimotor areas (Henderson et al., 2011), which are thought to be basic for the bodily self and related cognition. Such changes are thus likely to evoke disturbances in the body schema (Curt et al., 2011); the body image (Fuentes et al., 2013), and tool embodiment (Papadimitriou 2008; Standal 2011; Arnhoff & Mehl 1963; Higuchi et al., 2006; Higuchi et al., 2009; Olsson 2012; Winance 2006a; Winance 2006b). Nonetheless, little is known about these perceptual and cognitive functions and their underlying neural mechanisms in these patients. Even less is known about how these changes influence higher-level embodied cognitions such as e.g. empathy and social interaction. The aim of this dissertation is to give a portrait of the complex changes occurring in different aspects of cognition, affection and social behavior in these patients after such damage, trying to consider both structural and functional adaptation, as well as social and psychological dynamics.

2.1 Nomenclature of body representations

Sensory signals from receptors in the skin, muscles, and joints provide information about body position (Burgess et al., 1982). This sense of body position – termed proprioception (Sherrington, 1906) – helps form a mental representation of the body. However, since no afferent information specifies shape and size of the body, a model of the body must exist beyond sensory information. The characteristics of this body model have only recently begun to be explored. There is little agreement in literature about the number and types of body representations in the brain. The first distinction was proposed by Head and Holmes (1911), by studying impairments in tactile perception in a brain damaged patient suffering from a surgical ablation of part of the precentral gyrus. Head and Holmes found that the brain lesion affected patient's ability to localize the position of his hand in space, leaving unaffected the ability to localize, by naming it, a tactile stimulus at the hand. Head and Holmes introduced a dyadic distinction between a Postural Schema, a representation of the position of the body parts in space, used for action execution and updating of postural changes, and Superficial Schema, a model of the skin surface used for localizing bodily and tactile sensations. After this seminal paper, different taxonomies of body representations have been proposed, based on the different kinds of body-related information. The currently most accepted taxonomy poses a dyadic distinction between Body Schema and Body Image. Body Schema is generally defined as a constantly updated representation of the position of different body parts in space in relationship with each other, derived from multiple sensory (proprioceptive, vestibular, tactile, visual, auditory, kinesthetic) inputs. It is commonly accepted that Body Schema interacts with the motor system in the genesis of actions. The Body Image instead is an abstract and stable representation of the body for perception, more related to semantic or affective processes, and mainly influenced by visual inputs (de Vignemont, 2010; Gallagher, 2005; Schwoebel & Coslett, 2005). This action-perception duality reminds that originally shown in the visual domain (Goodale & Milner, 1992; Mishkin & Ungerleider, 1982), and more recently in the auditory (Belin & Zatorre, 2000) and somatosensory domains (Kammers et al., 2009; see Dijkerman & De Haan 2007 for a review).

More recently, Longo and colleagues (2010) proposed a general body model that distinguishes between two major classes of high-order body representations, named somatoperception and somatorepresentation. The first term refers to the process of perceiving the body itself, while the second one is more related to abstract knowledge, beliefs and attitudes towards one's own body. Some studies have established that conflicting cross-modal information (e.g., proprioceptive and tactile information) can alter one's body model such that illusions of body shape and size are perceived (Lackner, 1988). Interestingly, a recent study found that conflicting sensory information within one modality (in this case, proprioception) can also affect one's body model: simultaneous extension and flexion signals at a joint can cause perceived shrinkage of the limb (Longo et al., 2009). In addition to having a body model that reflects our first-person perception of our body, we also maintain a cognitive representation of our bodies, which can be thought of as a body image. As opposed to what the body is "felt" to be like, this body image reflects what the body is "believed" to be like (Longo et al., 2010). While more studies are exploring this area, how sensory information is integrated into one's body model is still not well understood. Studying the effects of sensory loss on body representations provides a glimpse into the role played by afferent information. Anaesthetizing digits in healthy adults, for example, results in increased perceived size of the digit (Gandevia and Phegan, 1999) and size of objects held between digits (Berryman et al., 2006). The perception of phantom limbs (i.e., the presence of the missing limb) after traumatic amputation, on the other hand, often results in shrinkage and telescoping of the perceived limb (Henderson and Smyth, 1948).

Our bodies are our instruments and most of us pay little attention to them. They are usually absent from our awareness, just allowing us to do what we like. After spinal cord injury, the body is absented, insentient and unmoving, and yet has to be looked after, because it no longer functions automatically. Moreover, a sense of agency (or will), as well as feedback of movement, seems to be essential to feel at one with one's body. We also have a conscious sense of our appearance, seen in our relations with others and in developing our self-esteem. What we look like and how we move, as well as what we say, play a large part in how we are perceived. In our emotional life, as Merleau-Ponty (2002) wrote, “the body is more than a means, it is our expression in the world”. For those with spinal cord injury, their bodies and hence their worlds might change. The injury may alter the relation to their own body and to others in huge and unimagined ways, from knowledge of the body itself to the will to move and psychological integrity. Moreover, a tool that extends or restores movement (such as the wheelchair) may become part of the identity of the person to whom it belongs. Many physiological and psychophysical studies suggest a highly complex relationship between body representations and relevant extracorporeal objects (Maravita & Iriki, 2004; Cardinali et al., 2009; Tsakiris, 2010).

2.2 Wheelchair embodiment

The extent of body representation is dynamically shaped as a function of subjects’ action in the space, with or without the use of external objects (Gallese & Sinigaglia 2010). Some authors (Iriki et al., 1996; Maravita & Iriki, 2004) have proposed that the flexibility after tool-use reflects a modification in body representations, which indeed should be plastic enough to update accordingly to slow and fast changes the body undergoes with time. In humans, tool use induces plasticity after both short- and long-term learning and practice (Longo & Serino, 2012), and therefore, perceptual, motor, and cognitive capacities (De Preester, 2011) are reformed based on the mode of use (Bassolino et al., 2010). Specifically, if a tool extends the able body’s movement potential, the object becomes part of the body (a process known as “embodiment”) (Longo & Serino, 2012), distorts the perceived body dimension (Fuentes et al., 2013), and alters the sensorimotor state that guides actions (Cardinali et al., 2009; Cardinali et al., 2012).

These bodily changes may result in either a conscious, visual representation of the manner in which the body is perceived, known as “body image” (Fuentes et al., 2013) or, on the other hand, potentially update unconscious sensorimotor representations to enable motor control, as referred to as “body schema” (de Vignemont, 2010). Behavioral studies have specified that, although seeing and touching a tool affirms its embodiment, movement may not be necessary (e.g., a rubber hand can be embodied without moving it) (de Vignemont, 2011). However, the ability to control movement enhances the feeling of embodiment (Newport & Preston, 2010), whereas the inability to control movement prevents it (Tsakiris et al., 2006). When a prosthetic device is used for action and constrains the injured physical body to a new position, the appropriate extracorporeal tool may be assimilated as a corporeal structure (Cardianli et al., 2012; de Vignemont, 2011), influencing the body schema and body image (Fuentes et al., 2013). For example, patients paralyzed because of spinal cord injury (SCI) may lose movement and sensation permanently, thus becoming dependent on a wheelchair for mobility and changing their body posture drastically. Influential theoretical models (Papadimitriou 2008; Standal 2011) and empirical studies (Fuentes et al., 2013; Arnhoff & Mehl 1963; Higuchi et al., 2006; Higuchi et al., 2009; Olsson 2012; Winance, 2006a; Winance, 2006b) have suggested that, in these cases, the body schema and body image are rearranged to incorporate the wheelchair. The experience of wheelchair embodiment has not been evaluated using quantitative measurements but, rather, through systematic descriptions of patient experiences. No definitive conclusions have been drawn from these studies and reports concerning wheelchair embodiment are controversial. Although some patients with SCI experience the wheelchair as a corporeal structure, others regard it as an artificial device. For example, a male patient who had a complete lesion at the fifth cervical vertebra was able to flex his elbow but was completely paralyzed from the chest down and had no hand movement, reported, “[The wheelchair] is not a part of me. It might need to fit me like a pair of trousers; it might need to be there when I want it to do what I want to do, but it is not a part of me” (Cole, 2004). Conversely, a 27-year-old male patient with a thoracic lesion, complete paralysis of the lower half of the body, and spared hand movement and sensation said: “It is a part of me... I forget it" (Papadimitriou 2008). In these two cases, patients with upper and lower SCI reported differences in the corporeal experiences with the wheelchair.

Generally, injury to the upper level of the spinal cord results in greater deficits than injury to the lower level. Cervical spine lesions induce legs and trunk paralysis as well as a variable degree of sensory loss and partial paralysis of the upper limbs. In contrast, lesions of the thoracic and lumbar spine cause paralysis of only the lower limbs. Given the preservation of cognitive functions in SCI patients, the mobility-impaired wheelchair-bound patients offer a unique opportunity to characterize the inherently plastic nature of the body schema and body image as a result of tool use. In particular, sensorimotor deprivation and the specific use of a wheelchair may modulate the development of the corporeal awareness of a tool. Since bodily representation can change because of temporary (regional anesthesia) (Gimbel, 1975; Jauregui-Renaud et al., 2008) or permanent (amputation and peripheral nerve lesions) (Murray, 2004; Navarro, 2009) modification of sensorimotor signals, it is logical to expect that the proportion of the body that is "isolated" from the brain may have an impact on the embodiment of a tool. Along the same lines, the systematic adaptation to an assistive device requires a change in the body's center of mass (Fuentes et al., 2013). Thus, long-lasting distortions of the body morphology may reflect a new state of the body image, leading to a coherent modification of corporeal awareness.

2.2 Wheelchair actions sound

The functional imbalance of perceptual motor states may be partially restored with active tool use (Pereira et al., 1996). A body-held tool, for example, may become essential to the user if it facilitates mobility or other essential functions (Serino et al., 2007, Papadimitriou, 2008). As previously mentioned, the tool may be processed as a part of one's own body (Longo and

Serino, 2012, Lenggenhager et al., 2013; Farne and Ladavas, 2000) and guide visual-motor (Iriki et al., 1996) but also audio-motor (Serino et al., 2007, Bassolino et al., 2010) interactions. Each human action produces a characteristic sound that may permit its unequivocal recognition. For example, hearing hands clapping may allow an individual to draw several inferences about a given event (Aglioti & Pazzaglia, 2010). Similarly, for patients with spinal cord injury hearing the sound of a wheelchair approaching may provide precise (e.g., specific identity) as well as general (e.g., sex or mood) information about an individual. In principle, this patient population may be ideal for testing two fundamental, largely unaddressed simulation and embodiment issues: (i) how a relevant extracorporeal tool producing a typical sound (e.g. wheelchairs) may affect auditory action representations; and (ii) how motor afference/efference may influences the functional integrity of audio-motor mapping.

The notion of embodied cognition postulates that knowledge is grounded on actual bodily states and that higher-order processes, such as mind- and intention- reading or action- and perception- understanding, can be mapped onto modal sensorimotor cortices (Barsalou, 2008). The bodily instantiation of cognitive operations (or "embodiment") and the perceptual-motor state (or "simulation") are thought to enable the inter-individual sharing of experiences (Gallese, 2007). Based on the results of single-cell recordings in monkeys (Gallese et al., 1996, Fogassi et al., 2005), many neuroimaging and neurophysiological studies have proposed that the adult human brain is equipped with neural systems and mechanisms that affect the perception and execution of actions in a common format (Rizzolatti and Craighero, 2004, Van Overwalle and Baetens, 2009, Hommel et al., 2001, Schutz-Bosbach and Prinz, 2007). Direct action perception strengthens motor representation (Stefan et al., 2005), and short-term motor experiences with a particular action may influence its visual recognition (Casile and Giese, 2006) and facilitate action prediction (Pazzaglia, 2013).

Both visual and auditory channels participate in perception-action coupling (Aglioti and

Pazzaglia, 2010). The mechanisms and neural structures involved in the motor coding of action-related sounds have been explored in able individuals using correlative and causative approaches (Aziz-Zadeh et al., 2004, Alaerts et al., 2009, Ticini et al., 2012, Gazzola et al., 2006, Lahav et al., 2007, De Lucia et al., 2009). These studies indicate that the perception of sounds from body part specific actions (e.g. ripping a sheet of paper) activates the left fronto-parietal network (Aglioti and Pazzaglia, 2011) in a somatotopic arrangement (Gazzola et al., 2006, Schubotz et al., 2003). Moreover, greater involvement of the left vs. right inferior parietal lobe has been reported when an observer's attention is explicitly directed toward action sounds (Lewis et al., 2006).

The inability to perform or perceive a given motor action may impact on the structural integrity of that action representation. Individuals with spinal cord injury (SCI) who are unable to move their lower limbs, have a reduced ability to discriminate between different observed movements, suggesting that action mapping may be fully determined by immediate motor signals (Pernigo et al., 2012, Arrighi et al., 2011). In patients with apraxia, impairment in specific actions execution (e.g. inability to clap the hands) greatly reduces the individual's capacity to acoustically recognize the corresponding motor event. However, the inadequate discrimination critically depends on a properly functioning left fronto-parietal network (Pazzaglia et al., 2008), spared in patients with SCI. Individuals with congenital blindness and deafness who have total perceptual loss rely on less implicit motor representations when perceiving human actions (Ricciardi et al., 2009, Alaerts et al., 2011, Lewis et al., 2011). Blind people, however, may still rely on the coding of aural tool action via simulation, which could reflect the activity of inherent motor systems (Ricciardi et al., 2009, Lewis et al., 2011).

However, it is unclear whether lifelong (mobility by lower limbs) and newly acquired (mobility by WHC) perceptual and motor experiences differently impact the integrity of action perception mapping.

2.3 Wheelchair stereotype

Despite the possibility of independence in most or all activities, individuals with paraplegia face multiple challenges that are common to people with disabilities. From rehabilitation tool with striking possibilities, the wheelchair may become the symbol of disability and the physical marker of the newly acquired bodily condition. The incorporation process described above points also to new ways of being in the world, i.e. to the relations between self and other and self and world (Winance 2006a, 2006b; Papadimitriou 2008), which extend beyond the oppositional distinction able-bodied/disabled. Considering our cultural influences, personal experiences, and normative expectations, simply being a wheelchair user is enough to be considered an outgroup member and to attract implicit negative stereotyping (Coleman, 2006). The visibility of a disability (in this case the chair) contributes significantly to producing a damaged identity (Goffman,1963). Empirical data are emerging that support the importance of the social context for shaping perceptions of quality of life after a spinal cord injury (Fuhrer; 1996).

Although people tend to consider themselves and others as single individuals, there are many circumstances in which they think, feel, and act largely as group members. Even if empathy is thought to play a critical role in social interactions motivating pro-social behavior (Dovidio et al., 1991), people often fail to empathize to the same extent with outgroup members as ingroup members (Chiao & Mathur, 2010; Batson & Ahmad, 2009; Stephan & Finlay, 1999). The failure of empathy has many practical repercussions for behavior in every day life. In this regard, it has been repeatedly demonstrated that people are less likely to help outgroup than in-group members in need (Gaertner et al., 1982; Saucer et al., 2005; Kunstman and Plant, 2008) and less likely to value the lives of outgroup members as much as in-group members (Pratto and Glasford, 2008). Furthermore, also response to other's pain depends on the social relationships between the parts. For example, affective links (Singer et al., 2004), perceived similarities (Perry et al., 2010), social memberships (Xu et al., 2009) and racial origin

(Avenanti et al., 2010) are likely to modulate the level of empathy experienced by the observer toward agent's pain (Chiao and Mathur, 2010, for a review).Failures of empathy are especially likely if the sufferer is considered as socially distant. There are specific prejudice-based attitudes about disability built on social and cultural norms in every society. Recent research in social cognition has indicated a way to predict prejudices, grounding on social and cultural dimensions (Cuddy, Fiske, & Glick, 2007; Fiske, Cuddy, & Glick, 2007; Fiske, Cuddy, Glick, & Xu, 2002). The core assumption behind stigma is that one can infer internal worth from an external sign or characteristic. In the case of the wheelchair user the chair becomes both the symbol and the object of stigmatization.

There is also a rapidly growing literature on the relationship between implicit and explicit attitudes and the effect of each on behavioral outcomes (Nosek 2005; Nock and Banaji 2007; McConnell and Liebold 2001; Greenwald et al., 2009). Concerning the racial bias, the evidence suggests that implicit attitudes predict race-related behaviors (Dovidio 2002, Towles-Schwen and Fazio, 2006; Rooth; 2010). A recent meta-analysis of attitude-behavior linkages (Greenwald et al., 2009) found not only that implicit racial attitudes reliably predicted relevant behavioral outcomes, but also that the predictive validity of explicit attitudes was compromised in socially sensitive attitude domains. On the contrary other authors found that explicit and implicit measures of racial attitudes appear to measure distinct concepts.

Since empathy is such a potent predictor of helping behavior (Decety & Ickes, 2009; Batson, et al., 2003), studying its failure as well as its plasticity could be a first stage toward the positive promotion of this particular aspect of the pro-social attitude. Although this theme has become an important research topic, two essential related matters continue to be largely unaddressed. The first concerns the question of whether is there any dissociation in explicit/implicit prejudice-based attitudes about disability according to the group-membership. The second relates to whether we can actively counteract the presence of implicit/explicit bias.

CHAPTER 3

A FUNCTIONALLY RELEVANT TOOL FOR THE BODY FOLLOWING SPINAL CORD INJURY

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3.1 Aims and Hypothesis

A tool that extends or restores movement may become part of the identity of the person to whom it belongs. For example, some individuals with spinal cord injury (SCI) adapt their body representation to incorporate their wheelchairs. However, it remains unclear how the bodily assimilation of a relevant external tool develops as a consequence of altered sensory and motor inputs from the body. Generally, injury to the upper level of the spinal cord results in greater deficits than injury to the lower level. Given the preservation of cognitive functions in SCI patients, the mobility-impaired wheelchair-bound patients offer a unique opportunity to characterize the inherently plastic nature of the body schema and body image as a result of tool use. In particular, sensorimotor deprivation and the specific use of a wheelchair may modulate the development of the corporeal awareness of the tool. It is logical to expect that the proportion of the body that is "isolated" from the brain may have an impact on the embodiment of a tool. Along the same lines, the systematic adaptation to an assistive device requires a change in the body's center of mass (Fuentes et al., 2013). Thus, long-lasting distortions of the body morphology may reflect a new state of the body image, leading to a coherent modification of corporeal awareness. To explore such relationships in this study, we collected structured reports on the introspective experiences of regular wheelchair use in patients with SCI. Our aim was to determine, after SCI at different levels, how the degree of spared sensorimotor function or the prolonged confinement by sitting in a wheelchair modulates the introspective experiences of instantiation of a wheelchair as captured by a standard principal component analysis (PCA).

3.2 Materials and Methods

Participants

Fifty-five wheelchair-bound patients were recruited from the Santa Lucia Hospital in Rome, where they were undergoing treatment in the Spinal Cord Rehabilitation Unit. All patients navigated autonomously in their wheelchair, using their arms for control. Three patients with complete cervical injuries (patients 1, 2, and 17) operated an electronic wheelchair. The remaining 52 patients propelled a wheelchair manually. The patients utilized their wheelchairs for approximately 13 h/day. Written informed consent was obtained from all participants. The study protocol was approved by the local ethics committee (IRCCS Ethics Committee at Fondazione Santa Lucia, Rome) in accordance with the ethical standards of the Declaration of Helsinki.

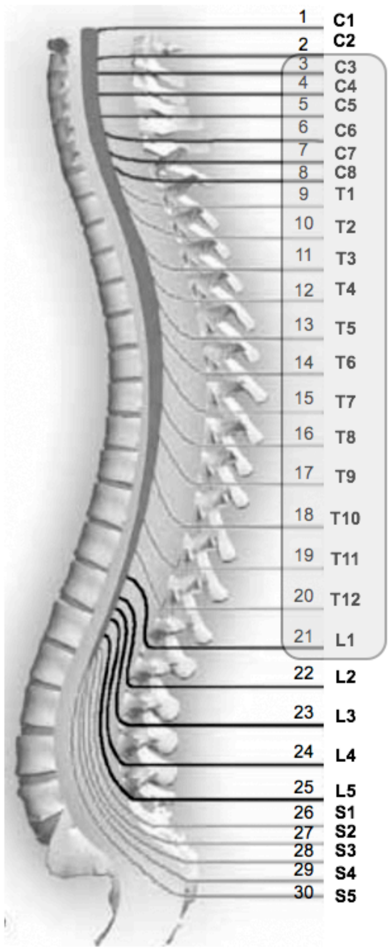
Assessment of individuals with SCI

The SCI lesions ranged from C3 to L1, as shown in Figure 1. Lesions were at 92.2 ± 84.6 months post-SCI (range: 6.2 to 340.6 months), which is within the chronic injury phase. None of the patients had experienced head or brain lesions associated with their SCI, as documented by magnetic resonance imaging (MRI). A neurologist (G.S.) examined each patient after admission to the study. The international standards of the American Spinal Injury Association (ASIA) for the classification of SCI were used to document the sensory and motor impairments following SCI (Marino et al., 2003). The third version of the Spinal Cord Independence Measure (SCIM III) was used to quantify the functional status of each patient (Catz et al., 1997; Anderson et al., 2011). For the purposes of this study, the Self-care and Mobility subscales were used. The Self-care subscale consists of six items with scores ranging from 0 to 20. The Management and Mobility subscale consists of nine items with scores ranging from 0 to 40. Grades of 0 to 8 (requiring higher ability) are assigned for each item according to increasing difficulty. The neurological and clinical data are presented in Appendix A, Table 3.1.

The relationship between injury location and functional disorder

After spinal cord injury, the body parts located below the point of the lesion are insentient and unmoving. The various degrees of sensory and motor impairment are expressed mainly by neurological status, which is determined by the level and severity of the damage to the spinal cord.

Accordingly, the spinal cord vertebrae were numbered from the top, beginning at the neck and extending downward through the back. Lower numbers indicate upper cervical vertebrae (Figure 3.1). The lesion level was converted to a numerical value of the corresponding numbered vertebral column level. The neurological status determines the number of body segments that are "isolated" from the brain and the functional activity or potential ability. Indeed, significant positive correlations were observed between the lesion level and the Self-care subscale scores (Spearman $r_{(53)} = 0.68$, $t = 6.71$, $p < 0.0001$) and Management and Mobility subscale scores (Spearman $r_{(53)} = 0.59$, $t = 5.30$, $p < 0.0003$), indicating a direct relationship between the level at which the spinal cord lesion occurred and the degree of body functional capacity. Although the patients with upper spinal cord lesions included in our study retained partial upper-body function, injury in the upward-extending region of the spinal cord reflects a higher degree of sensory loss and partial paralysis, which consequently modulates the overall ability to act in a wheelchair.



SPINAL ROOT LEVEL	MOVEMENT
C3-C5	The most severe of the spinal cord injuries. Limited shoulder and elbow movement depending on muscle strength. Complete paralysis of arms, hands, trunk and leg.
C6-C8	Normal shoulder movement. Complete paralysis of upper and lower body. Partial finger movement and elbow wrist extension/flexion.
T1- T6	Full use of shoulders, arms, fingers movement with normal muscle strength. Injuries usually affect the trunk control. Complete paralysis of lower body and legs.
T7-T12	Full use of shoulders, arms, fingers movement with normal muscle strength. Complete paralysis of lower body and legs.
L1	Full use of upper body. Paralysis of lower body and legs.

Figure 3.1 Relationship between the nerve level of the SCI and movement. Among all patients with SCI recruited for this study, the level of lesions ranged from C3 to L1, as highlighted in the figure.

Questionnaire

Using a rating scale ranging from 0 (“completely disagree”) to 7 (“completely agree”), participants evaluated questions designed to capture the implicit and explicit tool and body experiences. The questions, including previously adapted hypothesized constructs with prosthetic devices (Murray, 2004), were selected on the basis of a previous analysis of the transcripts from informal interviews with 13 patients with SCI who reported wheelchair-related feelings (unpublished). Six of the questions concerned the implicit (items BI_1–BI_6), and five questions explored the explicit (items BE_1–BE_5) bodily experiences of wheelchair use. The following questions translated from Italian were investigated:

[BI_1] Diet: Do you follow a controlled diet to prevent changes to your body shape and to avoid problems with the wheelchair?

[BI_2] Maintenance: Do you think of ways to prevent problems with the wheelchair? That is, do you pay particular attention to its maintenance?

[BI_3] Defense: Do you protect your wheelchair from dangerous situations?

[BI_4] Awareness: Did you experience any change in your attention and/or awareness while being in a wheelchair (after 1, 3, and 6 months)?

[BI_5] Tool: Do you perceive the wheelchair as an external tool?

[BI_6] Affect: Do you feel emotionally attached to your wheelchair?

[BE_1] Entire body: Do you perceive the wheelchair as part of your entire body?

[BE_2] Lower limbs: Do you perceive the wheelchair only as part of your lower limbs?

[BE_3] Substitution: Do you perceive the wheelchair as a “substitute” for your body?

[BE_4] Extension: Do you perceive the wheelchair as an “extension” of your body?

[BE_5] Action: Do you perceive the wheelchair as a form of compensation for your actions?

Having defined implicit and explicit body experiences with the wheelchair, we next specifically targeted the presence or absence of corporeal awareness of the wheelchair by using the following two questions:

[BI] Image: Close your eyes and imagine yourself [pause for 3 s]. Do you see the wheelchair?

[BE] Frame: When thinking about your body frame, do you feel that the wheelchair is an internal part of your body?

Statistical analyses

Wheelchair embodiment among SCI patients was determined based on 11 different questionnaire statements. A PCA with an orthogonal varimax rotation was conducted to reduce the dimensionality of the data by computing new variables called principal components, which were obtained as linear combinations of the original items.

Certain indicators are traditionally used to draw conclusions regarding the appropriateness of a PCA. The strength of the linear relationship between items has been represented by a correlation coefficient greater than 0.3 (Hair, 1998). Although the ratio of patients to items was 5:1, as recommended (Bryant & Yarnold, 1995; Gorsuch, 1983; MacCallum, 1999; Everitt, 1975; Arrindell & Van der Ende, 1985), we also used the Kayser–Meyer–Olkin (KMO) measure to test the adequacy of the sample and the Bartlett test of sphericity to verify the extent of correlation allowable between items. Scree plots and eigenvalues greater than 1 were used to determine the appropriate number of components. Only items that loaded strongly (above 0.5) were considered, in accordance with the standard PCA approach (Jolliffe, 2002) and psychometric evaluations of embodiment (Longo et al., 2008).

Briefly, the different steps involved in a PCA include the calculation of the correlation matrix, the extraction of the initial principal components, the application of the varimax rotation, the calculation of factor scores assigned to components, and the generation of factor loadings weighted for each component extracted. On each principal component axis, we also computed a single score to which all normalized measurements contributed for each patient.

We then analyzed the factor scores addressed in the PCA using a multiple regression analysis to explore the embodiment facets that are related to the clinical data (i.e., lesion level or exposure to/experience with the wheelchair).

3.3 Results

We will first report a brief summary of the results obtained for each question regarding the presence or absence of a corporeal attribution of the wheelchair. Among the 55 participants, 67% experienced the feeling that the wheelchair was integrated with their body [BE question], and 72% viewed the wheelchair in their corporeal image [question BI]. The percentage of responses indicating the presence of the wheelchair within the boundaries of the physical body in answer to at least one of the two questions described above (BE and BI) was higher than the percentage of responses indicating its absence (binomial test, $p < 0.04$). These percentages of wheelchair assimilation served as a "phenomenon check." We then analyzed the questionnaire statements using the PCA (Figure 3.2).

With the exception of two items (BE_4 and BI_4) all other correlations were significant at the 5% level and entered in the PCA analysis. The KMO test yielded values (KMO = 0.68) above the acceptable limit of 0.5 (Field, 2011). Moreover, Bartlett's test of sphericity indicated that correlations between items were large enough for the PCA $\chi^2_{(36)} = 119$; $p < .0001$). Analyses of eigenvalues and scree plot converged in the extraction of three components that, together, accounted for 66.3% of the variance. Figure 3.2 shows the statement scores for each of the three principal components. The means and standard deviations and communalities for the statement scores are given in Appendix A, Table 3.2.

Principal component 1 accounted for substantially more variance than the other two components (variance = 31.01%; eigenvalue = 2.8) and included items BI_5, BI_6, BE_2, BE_3, and BE_5, which exhibited the highest loadings (magnitude of 0.5 or more). A major difference was observed in the positive loadings for “action,” “lower limb,” “substitution,” and “affect” and in the negative loadings for “tool,” suggesting that two separate processes load on the first component. The wheelchair appeared to be processed as if it were a part of the patients’ limbs as opposed to a tool that reflects a more substitutive process linked to actions. This is consistent with the concept of functional embodiment. Although the positive loading for “affect” may seem to be a functionally less relevant point, this may partly explain the association between the level of wheelchair use and satisfaction of patients with their tool.

Principal component 2 (variance = 20.6 %; eigenvalue = 1.85) included items BI_1, BI_2, and BI_3, which captured the burden of assistive tool care. The new corporeal state leads to the management of body weight, and the safety, risks, and dangers that redefine the person in terms of “body plus wheelchair” gain more focus.

Principal component 3 (variance = 14.4%; eigenvalue = 1.3) included items BI_5 and BE_1. These statements are related to the perception of the wheelchair as a body part (positive loading) as opposed to a tool (negative loading). Item BI_6 loaded moderately (0.40) on the component 3 providing convergent evidence that a lower emotional attachment to the wheelchair selectively influences the sense of embodiment of the tool.

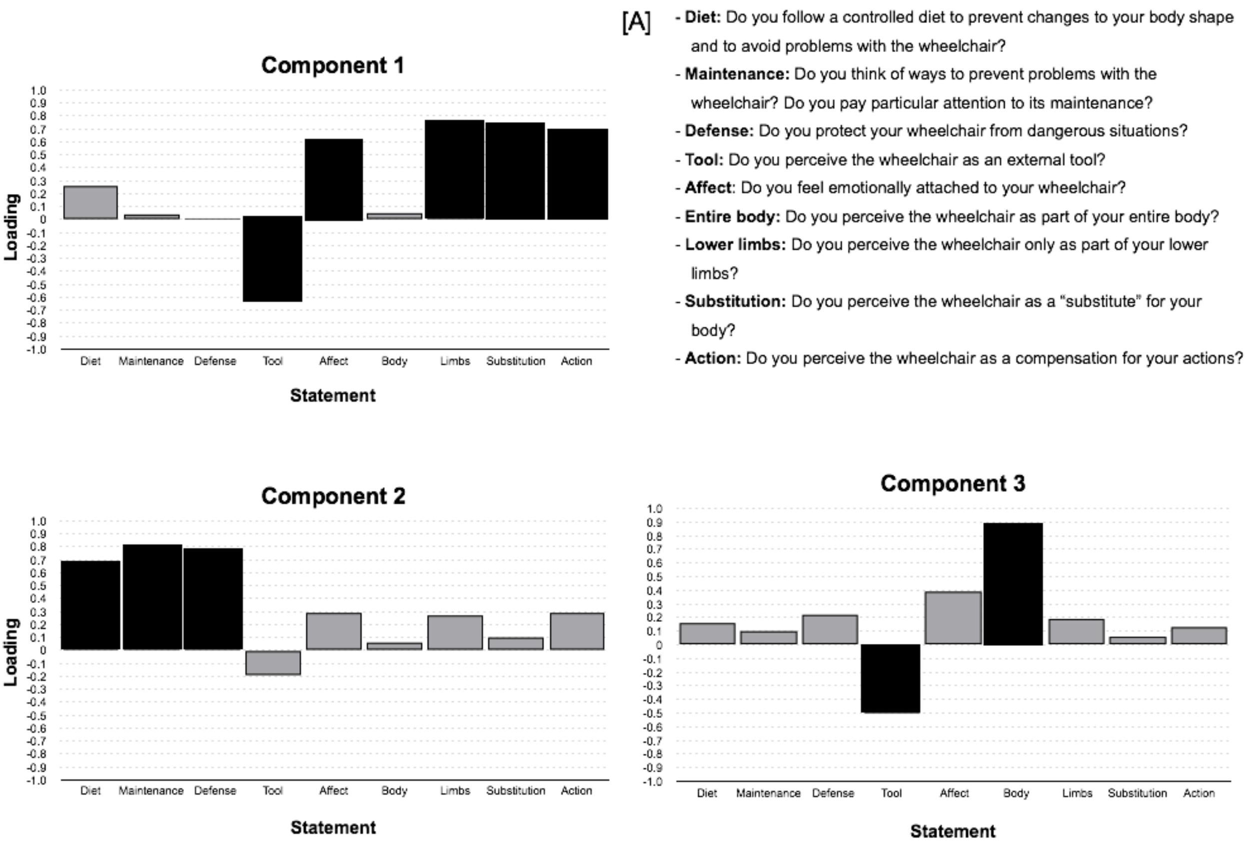


Figure 3.2 Loadings of the statements on the three principal components extracted. The labels on the x-axis refer to the statements shown in panel A. Black bars indicate the statements with the highest loadings (≥ 0.5) for each component. **A.** Statements used to assess wheelchair embodiment.

We also computed the 55 individual component scores, using a single composite measure created for each patient on each orthogonal dimension. A factor score represents a participant's standard score on each specific component.

To identify the potential predictors of the three components, we investigated the relationship between the factor scores of each component and the clinical data: the lesion level, the time since the lesion, and exposure to (daily hours) and experience (time since use) with the wheelchair. The multiple linear regression analysis revealed that a lower lesion level predicted a larger value for principal component 1 ($\beta = 0.48$, $F_{(4,50)} = 4.4$, $p = 0.004$). Lesion level was not a significant predictor of components 2 ($\beta = 0.19$, $F_{(4,50)} = 1.01$, $p = 0.40$) or 3 ($\beta = -0.06$,

$F_{(4,50)} = 0.95$, $p = 0.44$). Among all SCI patients, neither the time since injury nor exposure to/experience with the wheelchair predicted the individual component scores for each of the three principal components (β = n.s. for all). The model indicated that having a lower lesion enhanced the positive factor (limb, action, and substitution) linked to the functional aspect of the embodiment. However, this relation was reversed for the tool factor, which exhibited a negative score. This linear relationship suggests that the feeling of functional embodiment regarding the wheelchair should be substantially enhanced in relation to active body segments.

The sensory-motor control of a wheelchair imposes considerable demand on the upper extremities. In particular, a precise balance occurs between the full use of the upper limbs and the strength or endurance of the trunk muscles to guarantee stability (Kulig et al., 2001).

All SCI patients in the study had complete paralysis of the legs but had various degrees of upper body impairment, such as hand/arm and trunk deficits. To more fully determine the demands on the specific upper body segment, we categorized patients with complete (grade A) injuries into tetraplegia (T: C_3–C_7), high paraplegia (P_H: T_2–T_7), and low paraplegia (P_L: T_8–L_1) groups. The first group included patients with extensive deficits in the entire body (in the arms as well as the trunk). The second group included patients with full use of hands/arms but limited strength, balance, and use of the trunk. The last group comprised patients who had more full use of the upper body (arms and trunk).

A mixed-model ANOVA with significant items in principal component 1 (BI_5, BI_6, BE_2, BE_3, and BE_5) × group (high-paraplegia, low-paraplegia and tetraplegia) revealed a significant effect for the items type ($F_{(4,164)} = 6.7$; $p < 0.001$) which was explained by the higher ratings for BE_5 ($p < 0.01$ for all) compared with the other items (BI_5, BI_6, BE_2, BE_3). No significant differences were observed between groups ($F_{(2,41)} = 2.14$; $p = .13$).

However, we did observe a significant group × item interaction ($F_{(8,164)} = 2.8$; $p < 0.006$). Fisher's post-hoc test revealed that individuals with low and high paraplegia had a significantly higher rating when perceiving their wheelchair as part of their lower limbs (P_L = 4.41 and P_H = 4.11) than those with tetraplegia (T = 2; $p < 0.04$ for all). Interestingly, patients with tetraplegia tended to regard the wheelchair more as an external device (T = 4.7) compared with individuals with low paraplegia (P_L =2.6; $p < 0.01$) but not compared with those with high paraplegia (P_H = 3.2; $p > 0.11$). Patients with low paraplegia (P_L =5.94; $p < 0.04$) tended to regard the wheelchair more as a compensation for their actions compared with individuals with tetraplegia (T = 4.3) but not with those with high paraplegia (P_H = 5.5; $p > 0.68$); the two latter groups did not differ from one another ($p > 0.21$). Upper extremity interaction with the wheelchair enhances the feeling of embodiment. The trunk, which functions to maintain posture and partially govern wheelchair movement, appears to modulate the flexibility in the integration of the tool.

We observed no relevant effects of the other statements (affect and substitution), which indicates that the three groups considered these aspects of the embodiment experience with a wheelchair in a similar way, despite their different lesions and body capacities (Figure 3.3).

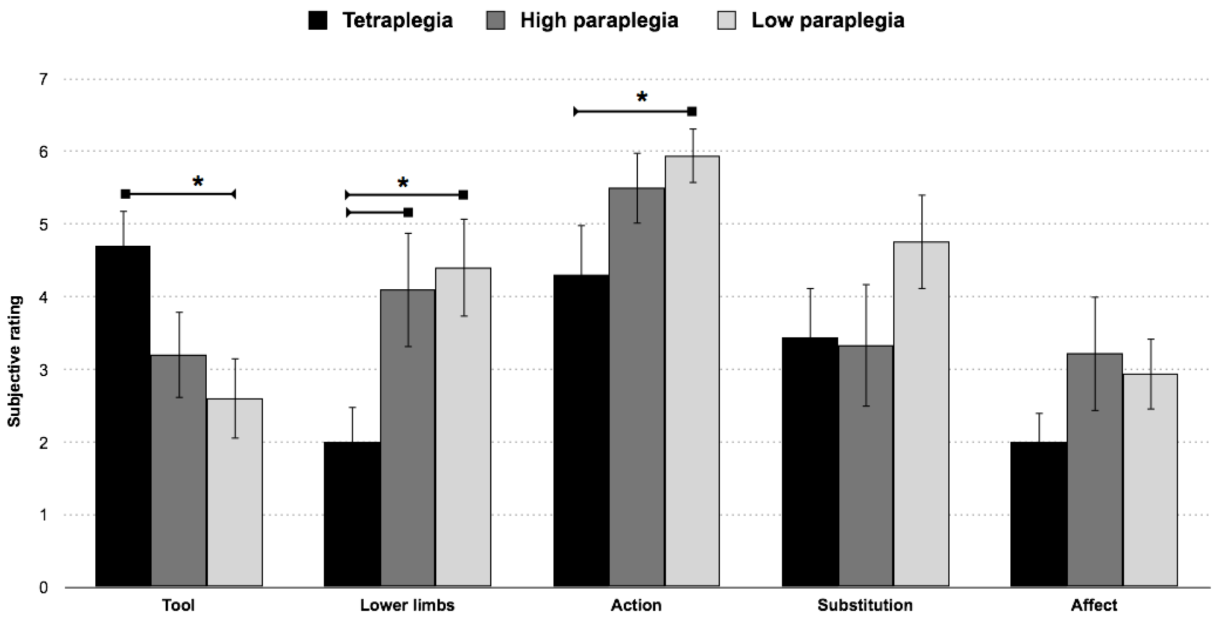


Figure 3.3 Functional aspect of the sense of embodiment concerning the wheelchair. The mean subjective ratings for the statements with the highest loadings in Component 1 in the three subject groups with complete injuries (tetraplegia, high paraplegia and lower paraplegia). The error bars indicate the standard error of the mean (SEM). The asterisks (*) indicate significant results from the post hoc comparisons ($p < .05$).

3.4 Discussion

Most patients with SCI perceive that their legs are still their own (Lenggenhager et al., 2012), despite their inability to use or feel them (Cole, 2004). Although the patients do not confuse their body parts with their wheelchair (Nizzi et al., 2012), some do consider themselves to be “individuals with a wheelchair,” whereas others regard themselves as “enwheeled individuals” (Papadimitriou, 2008; Cole, 2004). This identity or “wholeness” discrepancy prompted us to investigate whether the somatomotor deafferentation/deefferentation of disconnected body segments and the exposure to/experience with the tool, affects corporeal awareness of the wheelchair. To explore the presence of any such relationships, we developed a novel questionnaire regarding wheelchair-related feelings.

Among all participants included in the present study, a significant number experienced the wheelchair as being internal to the corporeal boundary, suggesting a revision in their body image. The perception of the body's edges does not appear to be fixed; rather, the body is plastic and flexible to assimilate the tool. As captured by component 1, the corporeal awareness of the tool emerges not merely as an extension of the body but as a substitute for (and part of) the functional self. This assistive device offers the possibility, at least in principle, to partially "repair" the motor functionality of the damaged body part (Murray 2004; Pereira et al., 1996) and appears conceived not as an object to move but as a mediator of the limbs' action. This reorganization of body model is consistent with the positive inclusion of the wheelchair to accommodate physical impairment and restore mobility (Papadimitriou, 2008; Standal, 2011; Arnhoff & Mehl, 1963; Higuchi et al., 2004, Higuchi et al., 2009; Merleau-Ponty, 2002). The perceived bodily experience is that of being functionally whole, and the system reorganizes itself to achieve its original balance, which enables the immobile user to act in the world. Amputees who use prostheses, which are less efficient and less safe than a wheelchair, report that the object became "part of them," and they feel as though they have a normal, complete body (Murray, 2004; Andre et al., 2001). Importantly, the emotional and physical acceptance of and adaptation to the wheelchair occurs over a period of years (Avillion, 1986; Bates et al., 1993). It also appears to affect the new corporal state whereby the tool feels like "part of" the user. The wheelchair requires the regulation of weight and a great deal of effort and control (maintenance and defense) to achieve reliable usage. The burden of assistive tool care appears to be indirectly processed considering the safety, risks, and danger to the body.

Given the prolonged history of immobility, the bodily attribution may refer to confinement in the wheelchair. However, no effects of either exposure to or experience with the wheelchair on the embodiment of this tool were observed. In contrast, we found that chronic sensorimotor loss specifically predicted the individual's corporeal awareness of his/her wheelchair.

A more unconscious body model, the body schema, which enables motor control and reflects the proprioceptive, tactile inputs of how the body is "felt", may regulate the functional aspects of embodiment considerably. Indeed, the compensatory flexibility of wheelchair embodiment observed in patients with SCI is linearly linked to their ability to feel and move the superior extremities, the trunk and arms in particular.

Accordingly, it has been suggested that the embodiment of an object is modulated by tactile interaction (Ehrsson et al., 2005), and objects that have been in contact with the body (Aglioti et al., 1996; Berlucchi & Aglioti, 1997) and are actively used (Bassolino et al., 2010) become part of the bodily representation (Longo & Serino 2012; Bassolino et al., 2010). The online information regarding movement in a wheelchair is a prerequisite for the capacity to feel that the event is generated by one's own body and one has control over it. The different modes of wheelchair use (from placing the hands on the wheels to steering a knob in more severe cases) may reflect a different attribution or evaluation of being the author of the movement, affecting how the retrospective sense of agency is perceived. This prediction might be tested in future research by comparing patients with SCI who operate their wheelchair manually with those who operate it electronically.

In the case of an upper spinal cord lesion, much more than in the case of a lower spinal cord lesion, there is a more pronounced reduction of strength and functionality in the entire body as well as an overall lack of feeling of touch. Such impairment interferes with the feeling of the wheelchair in direct contact with the body and with other objects and mainly with the regular status that updates the enwheeled body in motion. This failure to "capture" the somatic, proprioceptive, and motor information continuously being exchanged with the "body plus wheelchair" hinders the processes that are essential for creating an abstract reference of the body frame (Gandevia & Phegan, 1999; Paqueron et al., 2003), leading to the feeling of the wheelchair as a corporeal assimilation. This concept is in line with the particular aberration of corporeal detachment and distance observed in patients with higher SCI (Lenggenhager et al., 2012) as well as in individuals with locked-in syndrome (Nizzi et al., 2012).

Neuroanatomically, such distorted sensorimotor input presumably induces adaptive or maladaptive cortical reorganization (Kokotilo et al., 2009). After SCI, the loss of afferent/efferent information related to the body parts located below the lesion leads to the structural and functional reorganization of the cortex, particularly in somatomotor areas (Freund et al., 2011a; Freund et al., 2011b; Henderson et al., 2011), and affects complex intracortical connections (Kokotilo et al., 2009; Freund et al., 2011b; Freund et al., 2012). Decreased frontal and frontoparietal cortical connectivity by the alteration of ascending and descending neural information flow is most pronounced in individuals with upper SCI (Truccolo et al., 2008). Conversely, in patients with lower SCI, an expansion of the primary somatosensory and motor-cortex hand area into the output-deprived primary-cortex leg area was observed (Curt et al., 2002; Henderson et al., 2011), which translates into a functional gain for the internal sensorimotor body representation (Kokotilo et al., 2009).

Moreover, atypical connectivity plays a prominent role in neuronal activity within the parietal cortex, which is the dominant structure for bodily representation (Blanke & Metzinger, 2009). Indeed, recent clinical and neuroimaging data suggest that temporoparietal junction (TPJ) activity reflects the multisensory integration of bodily instantiation (Arzy et al., 2006) as well as feelings of spatial unity related to the body (Blanke & Arzy, 2005). Moreover, the TPJ is thought to rely on the combination of tactile and proprioceptive information in a coordinated reference frame (Blanke et al., 2004; Lenggenhager et al., 2006). Dysfunction in this area may lead to a modified body experience, which is felt to be spatially disconnected (Blanke, 2012). Nevertheless, without further data, we cannot discern whether the modulation of embodiment results from effects on brain networks, the periphery, or both. This should be investigated in future studies, for example, by investigating changes of the BOLD signal in brain areas of bodily representation in both injured and healthy subjects using paradigms eliciting self-referential activity during the observation of an avatar engaged in dynamic actions with tools.

One potential study limitation was the use of introspective data and PCA, which, although an elegant and powerful tool (Longo et al., 2008), needs to include empirical measures. Therefore, we aimed to establish the effect of sensorimotor loss, and the specific use of this tool, on wheelchair embodiment. It is important to note that previous SCI studies have already demonstrated the physical adjustment to (Fuentes et al., 2013; Arnhoff & Mehl, 1963; Higuchi et al., 2006; Higuchi et al., 2009), and brain representation of (Olsson, 2012), the "body plus wheelchair" being perceived as one. We also capitalized on the fact that 12 of the patients recruited for this study were tested in a separate experiment that indicated patients with SCI embody functionally relevant wheelchair action sounds (unpublished data, presented in Galli et al., Concepts, Actions, and Objects; Functional and Neural Prospective Meeting Abstract, 2012).

Altogether, our data suggest that the subjective experience of the embodiment of an external tool in patients with SCI is a complex, multifarious process that requires the following: a feeling of ownership over the tool (including a long-lasting coherent and accurate representation); online multisensory integration, referenced on the state of the body (including the effective regulation of sensorimotor information flow); and, finally the self-attributed control of the physical body and its movement.

The phenomenal reports from SCI individuals cannot be generalized to all occurrences of corporeal awareness of a tool but offer an initial step towards the determination of clearly dissociable subcomponents of prosthetic device embodiment. Indeed, the objective and quantitative evaluation of changes in patients with spinal cord lesions help identify the cause that may preclude the experience of self-attribution and embodiment of a tool. United harmony between the body and the tool may be key for the embodied experience of success or rejection of an assistive device. Embodying a wheelchair may enhance the efficiency and safety of movement, thereby reducing bodily effort and the damage produced by its use. This ease of use may lead to greater autonomy and self-organization, thus allowing patients to benefit from the opportunities offered by the environment in which they move.

CHAPTER 4

EMBODYING FUNCTIONALLY RELEVANT ACTION SOUNDS IN PATIENTS WITH SPINAL CORD INJURY

[This research has been submitted in: Pazzaglia M, Scivoletto G, Galli G, Lewis JW, Molinari M, Aglioti SM. Embodying functionally relevant action sounds in patients with spinal cord injury. Cortex.]

4.1 Aims and Hypothesis

Growing evidence indicates that perceptual-motor codes may be associated with and influenced by actual bodily states. The inability to perform or perceive a given motor action may impact on the structural integrity of that action representation. In the visual domain, individuals with spinal cord injury (SCI) who are unable to move their lower limbs, have a reduced ability to discriminate between different observed movements, suggesting that action mapping may be fully determined by immediate motor signals (Pernigo et al., 2012, Arrighi et al., 2011). However, a dearth of direct evidence exists about whether profound alterations in sensorimotor traffic between the body and brain influence audio-motor representations. In principle, this patient population may be ideal for testing two fundamental, largely unaddressed simulation and embodiment issues: (i) how motor afference/efference influences the functional integrity of audio-motor mapping; and (ii) how relevant extracorporeal tools (e.g. wheelchairs) affect action representations. We hypothesize that the perceptual and motor experiences induced by the sounds of a wheelchair and lower limb activity should differ substantially between subjects with different levels of exposure to wheelchair- and limb-related sounds. To test this hypothesis, we examined audio-motor mapping in three groups of participant. Wheelchair-bound patients with SCI have extensive motor and auditory experience of wheelchair sounds, but do not have motor use of their legs. Physical therapists with normal limb function have extensive perceptual experience of wheelchairs, but are not personally dependent on them. The third group consisted of able-bodied controls who had no previous experience of wheelchairs. We devised a novel psychophysical task that evaluated the auditory discrimination ability of sounds originating from actions produced by wheelchair use, the upper and lower limb, and animals. Listening to sounds of various actions performed by a tool or lower limbs allowed us to dissociate the perceptual and motor contributions of biological or artificial mobility entities (De Lucia et al., 2009). Furthermore, the given task allowed us to investigate the inverse relationship between movements that the patients had previously possessed, lost, and then regained with wheelchair use.

4.2 Materials and Methods

Participants

At the Santa Lucia Hospital in Rome, Italy, we recruited 14 subjects with established lumbar or thoracic SCI (12 men; mean age, 38.6 years; range, 19–56 years), 15 able-bodied participants who had worked exclusively with SCI patients as physical therapists (nine men; mean age, 40 years; range, 27–54 years), and 15 able-bodied subjects who were not physical therapists (eight men; mean age, 38.1 years; range, 20–66 years). The three groups did not differ in age and level of education ($p > .23$). The physical therapists were employed full-time and had an average of five years experience in SCI patient rehabilitation (range, 1–25 years). All of the subjects were right-handed, as determined by the 10-item version of the Edinburgh Handedness Inventory (Oldfield, 1971). Written, informed consent was obtained from each participant for all procedures, and the local ethics committee of Santa Lucia Hospital, Rome, approved the study.

Assessment of individuals with SCI

All of the patients had a traumatic lesion at the thoracic or lumbar level of the spinal cord that caused paralysis of the lower limbs while sparing upper limb function. Lesions were located between T3 and L1, and the patients ranged from 6.3 to 219 months post-SCI (mean, 65 ± 75 months). Each patient was examined by a neurologist (G.S.) with specific, long-standing expertise in treating SCI patients. The neurological injury level was determined using the American Spinal Injury Association (ASIA) for the classification of SCIs (Marino et al., 2003). A standardized ASIA examination protocol was used to determine the most caudal level of the spinal cord with normal sensory and motor functions on both sides of the body. Functional ability was quantified using the third version of the Spinal Cord Independence Measure (SCIM III) (Catz and Itzkovich, 2007). For the purposes of the experiment, the Self-care and the Management and Mobility subscales were considered. All patients were manual wheelchair users and recruited from physiotherapy programs of Spinal Cord Unit. None of the patients had experienced head or brain lesions, as documented by an MRI. No patient presented auditory discrimination deficits or signs of psychiatric disorders, and none of the patients had a history of substance abuse. The demographic and additional clinical data of the patients are presented in Table 4.1.

DEMOGRAPHIC AND CLINICAL DATA OF THE PARTICIPANTS												
Case	Age	Time since injury (days)	Gender	Lesion level	Etiology	AIS grade	SCIM		Motor level		Sensory level	
							Self Care	Mobility	Right	Left	Right	Left
P_1	19	589	M	T10	Traumatic	A	20	19	T10	T10	T10	T10
P_2	36	190	M	L1	Traumatic	D	20	18	L1	L1	L1	L1
P_3	42	760	M	T10	Traumatic	A	20	19	T10	T10	T10	T10
P_4	42	970	M	T9	Neoplastic	A	20	18	T9	T9	T6	T9
P_5	42	4745	M	T8	Traumatic	A	20	19	T8	T8	T8	T8
P_6	35	6570	M	T7	Traumatic	A	20	19	T7	T7	T7	T7
P_7	56	320	M	L1	Traumatic	C	17	13	L1	L1	L3	L3
P_8	35	390	M	T10	Traumatic	A	20	19	T11	T11	T11	T11
P_9	49	240	F	T12	Traumatic	A	18	15	T12	T12	T12	T12
P_{10}	22	365	M	T12	Traumatic	D	20	22	T12	T12	T12	T12
P_{11}	42	970	M	T3	Traumatic	A	18	15	T6	T6	T6	T6
P_{12}	38	1825	M	T12	Traumatic	A	20	19	T12	T12	T12	T12
P_{13}	44	5840	M	T5	Traumatic	A	20	19	T5	T5	T5	T5
P_{14}	39	3650	F	T5	Traumatic	A	20	19	T5	T5	T5	T5

Table 4.1 Clinical and demographic data of the spinal cord injury patients. The clinical neurological level of the lesion (T, thoracic; L, lumbar) was reported for the subjects with spinal cord injury (SCI). The neurological and functional levels of the injury were determined using the American Impairment Scale (AIS) and the third version of the Spinal Cord Independence Measure (SCIM III). The motor/sensory level indicates the most caudal segment of the spinal cord with normal motor/sensory function.

Sound-into-action translation test

Because the auditory system is an intact sensory channel to individuals with paraplegia, we used a sound-into-action translation task to explore the effects of a massive loss of motor function in the lower extremities on the ability to distinguish between different action-sounds. In a two-choice, matching-to-sample auditory action discrimination task, the participants were asked to determine which of two probe sounds matched the previously heard single sample sound (for a schematic representation see Figure 4.1). The sounds used included upper (U_{RAS}) and lower (L_{RAS}) limb-related action sounds, wheelchair-related action sounds (W_{RAS}), and animal action-related sounds (A_{ARS}).

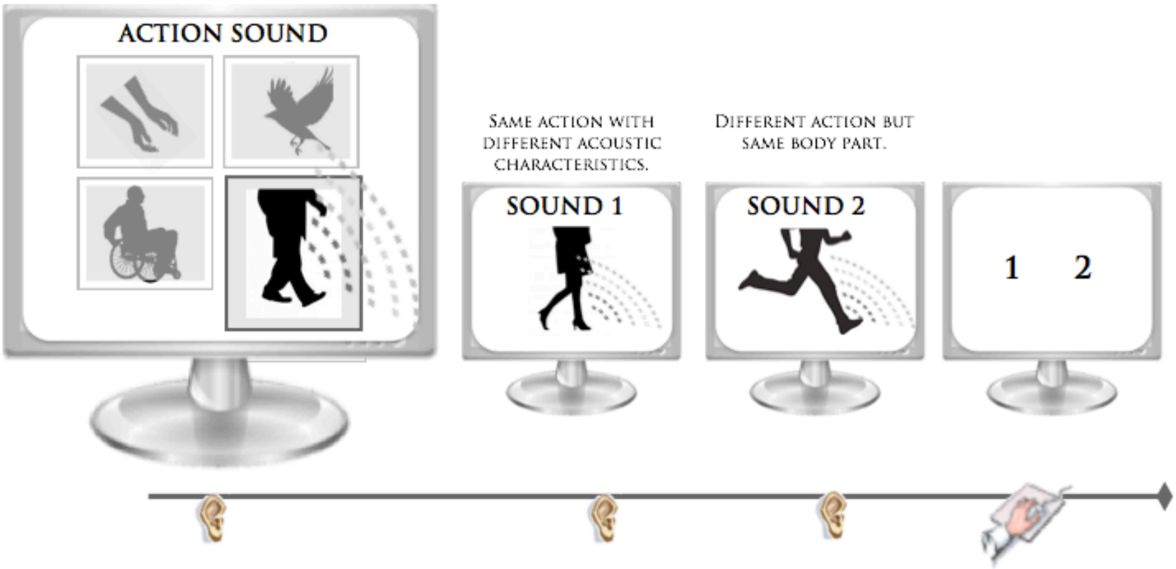


Figure 4.1 Action sound discrimination task. In each trial, following the presentation of a sample sound, two subsequent probe sounds were presented. Only one of the two probe sounds was specifically related to the sample sound. In the set of lower limb actions (e.g. “male footsteps on a glass surface” [the sample sound]), one probe sound represented the same action as the sample sound but was produced using a different source (e.g. “female footsteps on a wood surface”), whereas the other probe sound represented a totally different action produced using the same body part (e.g. “running”). No image associated with an aural action was provided.

Stimuli and task

The auditory stimuli (44.1 kHz, 16 bit, and monophonic) included 120 real-world sounds compiled by a sound engineer using professional collections (Sound Cinecittà, Rome, Italy, and Sound Ideas, Richmond Hill, Ontario, Canada). Many of these sounds were identical to those used in our previous studies (Pazzaglia et al., 2008, Lewis et al., 2011). The sounds were trimmed to an average duration of 4sec (range, 3–6.5 s) and presented to the participants at a comfortable decibel level through Sennheiser PC165 earphones, using the Presentation software (version 12.2, Neurobehavioral Systems, Inc.) on a Windows operating system.

Each sound belonged to one of the following four categories:

(1) Upper limb actions: a group of 10 sets of three different sounds. In this category, the sample, the matching and the non-matching stimuli were sounds of meaningful actions executed by the hands (e.g. knocking on a door).

(2) Lower limb actions: a group of 10 sets of three different sounds. In this category, the stimuli were three sounds of meaningful actions executed by the feet (e.g. descending footsteps on stairs).

(3) Wheelchair actions: a group of 10 sets of three different sounds. In this category, the stimuli were sounds of meaningful actions executed by manual (WHC_M) or electronic (WHC_E) wheelchair actions (e.g. WHC braking) and manual/electrical vehicle motion (e.g. bicycle).

(4) Non-human animal actions: a group of 10 sets of three sounds related to animal physical actions, excluding vocalizations (e.g. a bird flying).

A list of the auditory stimuli and information on the preliminary psychophysical studies are provided in Appendix A, Table 4.2.

Procedures

Each participant was tested in a single experimental session that lasted approximately 20 minutes. During this period, the subjects wore earphones and sat approximately 50 cm from a 17-inch computer monitor. Each trial was initiated by the presentation of a sample action sound that was selected randomly from one of the four categories (i.e. U_{RAS}, L_{RAS}, W_{RAS} or A_{ARS}). At the end of the sample sound presentation, two subsequent matching and non-matching action-sound stimuli were presented in quick succession, separated by an approximate interval of 100 msec. The matching action-sound represented the same motor act as the sample, but with different acoustic features. The non-matching action-sound was acoustically similar to the sample, but linked to a different action within the same category. The sequence of matching and non-matching sound stimuli was counter balanced. For example in the U_{RAS} category, a brief sample sound of an individual clapping three times was presented, after which the subjects listened to two additional sounds, one of which represented the same action as the sample sound, but was produced using a different source (e.g. group applause) and the other sound represented a completely different action produced by using the same body part, which was acoustically similar (e.g. knocking on a door three times).

The subjects were asked to choose between the two auditory stimuli to identify the sound that evoked the same action heard in the sample sound. To better discriminate among the three different sounds, the words “action sound” (for the sample sound) and the numerals 1 (for the first probe sound) and 2 (for the second probe sound) appeared on the black screen while each respective sound was played. No image associated with an aural action was provided. After all three sounds were presented, the final screen prompted the subject to choose a response by pressing a button. The participants were instructed to answer as accurately and quickly as possible, and their accuracy and response times after the prompt (i.e. latency) were recorded and analyzed. Before beginning the test, the participants were given four practice trials, after which performance feedback was provided. The practice auditory stimuli differed from those used in the experimental phase, after which no feedback was provided.

To evaluate the subjective rating of each sound category, a post-test session was conducted, in which the same participants were instructed to rank each sound in terms of familiarity and perceived motor intensity on a vertical 10-cm visual analog scale (VAS). The first question was intended to assess their experience with each sound category (“How familiar is this sound to you?”), while the second investigated a subject’s experience with the amount of movement sensations triggered by each sound (“To what degree do you feel your own movement is based on the action you have just heard?”). With regard to the first question, the lower and upper extremes of the VAS were “no familiarity” and “high familiarity,” respectively, whereas for the second question, these extremes indicated “no perceived movement” and “maximum perceived movement,” respectively. The participants were explicitly asked to rate the sounds, which were presented randomly, in a counterbalanced order. Finally, we collected structured reports on the implicit and explicit introspective experiences of regular wheelchair use in patients with SCI.

Data analyses

The accuracy (raw data) and mean latency were calculated for each participant in each experimental condition (10 trials per category). Trials in which the reaction times (RTs) were two or more standard deviations above the mean for each subject were eliminated prior to the analysis (2% of the trials) (Ratcliff, 1993). Half of the eliminated trials were associated with U_{RAS} actions. Only the RTs for the correct response were considered. The individual accuracy, mean latency values and subjective ratings were entered into separate mixed-model analyses of variance (ANOVAs), with group (healthy subjects, patients with SCI, and physical therapists) as the between-subjects factor and sound category (U_{RAS}, L_{RAS}, W_{RAS}, and A_{ARS}) as the within-subjects factor. All pair-wise comparisons were performed using the Duncan post hoc test. The partial eta-squared (ηp^2) measure of variance was selected as the index of effect size (Cohen, 1973). A significance threshold of $p < .05$ was set for all of the statistical analyses. The data are reported as mean ± standard error of the mean (SEM).

4.3 Results

Patients with SCI

Sound discrimination performance in patients with SCI was > 80% for all conditions. The ANOVA of accuracy revealed a significant main effect of sound category ($F_{3,123} = 7.60$, $P < .001$, $\eta p^2 > .19$), which was explained by the reduced accuracy observed in the L_{RAS} condition

(8 correct trials) compared with the U_{RAS} (8.5 correct trials), W_{RAS} (8.8 correct trials), and A_{ARS} (8.5 correct trials) conditions (all p < .04). No significant effects of group ($F_{2,41}$ = .51, p = .59) and no group × sound category interactions ($F_{6,123}$ = 1.15, p = .34) were observed, indicating that the three groups had comparable performance in the four different sound categories.

The ANOVA of latency (Figure 4.2) revealed no significant main effects of group ($F_{2,41}$ = 058, p = .56) or sound category ($F_{3,123}$ = .63, p = .59) but a significant group × sound category interaction ($F_{6,123}$ = 2.7, p = .02, $\eta p^2 > .17$).

Importantly, the post hoc comparisons revealed that the patients with SCI discriminated the W_{RAS} earlier (608 ms) than the able-bodied individuals with comparable auditory experience (physical therapists: 706 ms, p < .04) and those with no comparable perceptual experience (healthy subjects: 814 ms, p < .0001). The latency difference in RTs between the physical therapists and healthy subjects was also statistically significant (p < .04). Notably, in patients with SCI, the RTs for W_{RAS} were comparable to the RTs elicited by upper and lower limb action sounds (L_{RAS} = 716.0 ms, U_{RAS} = 708.1 ms). Regular wheelchair use contributed to a specific and significant readiness to recognize the sounds produced by a wheelchair. Latency improvements were not accompanied by changes in accuracy, thereby ruling out potential speed/accuracy trade-off effects.

Importantly, SCI patient performance was similar for sounds related to actions of the lower (L_{RAS} = 716.0 ms) and upper (U_{RAS} = 708.1ms) limbs (p = .87), suggesting that audio-motor mapping can be retained even when the effector limb is no longer functional.

No significant latency differences were observed between the lower and upper limb sounds in any of the three groups: healthy subjects (L_{RAS} = 711.4 ms, U_{RAS} = 727.3 ms), physical therapists (L_{RAS} = 662.9 ms, U_{RAS} = 761.8 ms), and patients with SCI (L_{RAS} = 716.0 ms, U_{RAS}

= 708.1 ms; all p > .30). There were also no differences between the three groups with regard to their responses to animal body action sounds (p > .24). Moreover, no differences were observed in discrimination latency between the WHC_M and WHC_E sounds or with regard to the order of the presentation of the correct probe (all p > .80).

We also examined whether the time since the injury influenced RTs for sound discrimination. No significant correlations were found between the SCI lesion-testing interval and latency in the discrimination of each sound category (Spearman correlation analyses; L_{RAS}, r_{14} = -0.16, t_{12} = -.57, p < .58; U_{RAS}, r_{14} = -.27, t_{12} = -.99, p < .33; W_{RAS}, r_{14} = -.01, t_{12} = -.05, p < .95). All patients were in the chronic injury phase (at least six months post-injury), and the time since injury did not appear to play a major role in sound discrimination related to wheelchair action, suggesting that plastic changes could occur rapidly and lead to behavioral gain.

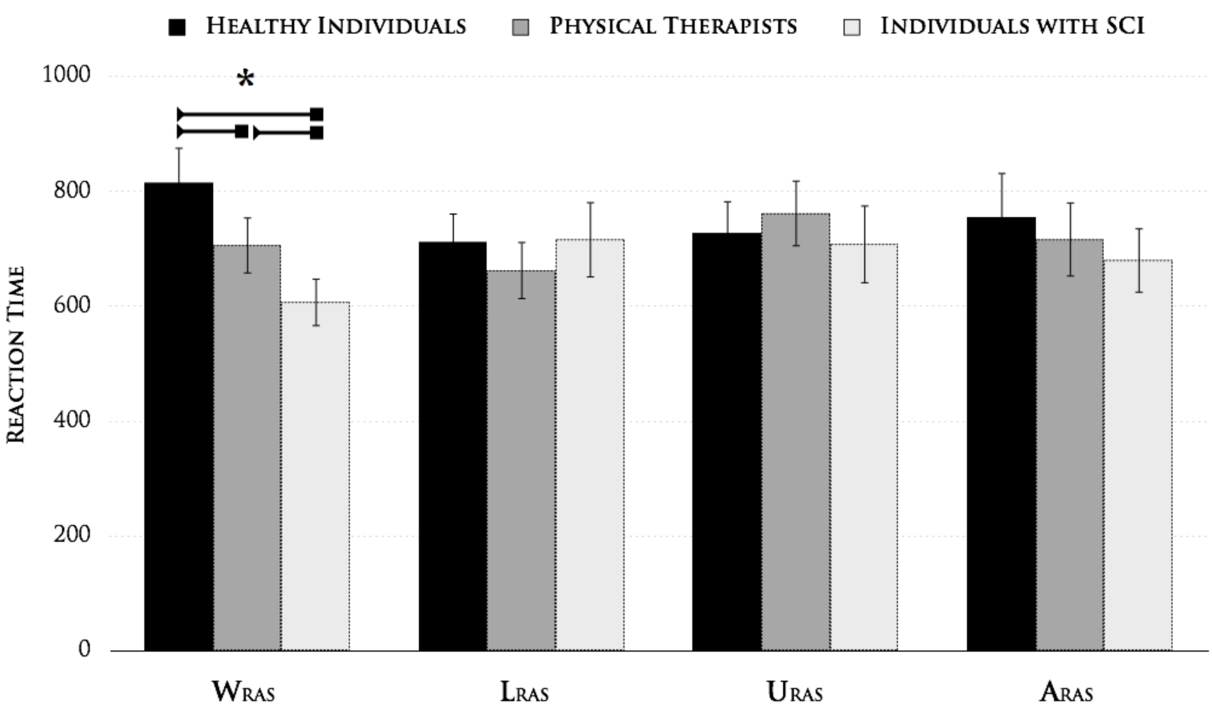


Figure 4.2 Latency in action-sound discrimination. The mean latency for each sound category (upper (U_{RAS}) and lower (L_{RAS}) limb-related action sounds, wheelchair-related action sounds (W_{RAS}), and animal action-related sounds (A_{ARS})) in the three subject groups (healthy individuals, physical therapists and individuals with spinal

cord injuries). The error bars indicate the standard error of the mean (SEM). The asterisk (*) indicates significant results from the post hoc comparisons ($p < 0.05$).

Because three of the patients with SCI included in our study had incomplete injuries, we performed additional analyses that only considered the performance of patients with complete lesions. Consistent with the results of the original analysis of the entire sample, the ANOVA revealed a significant group × sound category interaction ($F_{6,114} = 2.24$, $p < .04$).

The ANOVA confirmed that in the patients with SCI there were no differences in the mean latencies for the different human action sounds (L_{RAS} = 661 ms, U_{RAS} = 640 ms; all $p > .10$) and the faster discrimination of WHC sounds (W_{RAS} = 587 ms; all $p < .01$) when compared with the able-bodied controls.

Altogether, these findings suggest that active use of a sound-producing device, as opposed to mere exposure to the sounds, modulates readiness to recognize associated sounds. The inability of patients with SCI to move their lower limbs did not influence their ability to discriminate sounds of lower limb movement.

Subjective ratings of familiarity and perceived motor reactivity when listening to sounds

At the end of the test, a VAS was used to measure each participant's perceived motor reactivity and auditory familiarity ratings for each of the four sound categories. The mean VAS ratings are shown in Figure 4.3.

The ANOVA of perceived reactivity motor ratings for each sound (Fig. 3) yielded significant effects of sound category ($F_{3,123} = 7.45$, $p < .0001$, $\eta p^2 > .32$). *Post hoc* testing revealed that the subjectively perceived motor reactivity during passive listening was higher for human action sounds (L_{RAS} = 6.3, U_{RAS} = 5.5; $p = .14$) than for W_{RAS} (4.02; $p < .004$) or A_{ARS} (4.48; p

= .03). No significant differences were observed between groups ($F_{2,41}$ = .87, p = .42). Crucially, the ANOVA revealed a significant group × sound category interaction ($F_{6,123}$ = 8.76, p < .0001, $\eta p^2 > .40$). In patients with SCI, the perceived motor reactivity to sounds that implied lower limbs movement (2.8 ± 2.7; p = .0005) consistently received lower ratings than in able-bodied individuals (healthy individuals: L_{RAS} = 7.2 ± 1.9; physical therapists: L_{RAS} = 6.4 ± 2.8) and was significantly lower when compared with W_{RAS} sounds (6.4 ± 2.3) and U_{RAS} sounds (5.6 ± 3.15). These results suggest that the absence of motor signals reduces the reactivity with which actions can be perceived from an associated sound (de Vignemont, 2011). Instead, the perceived motor reactivity to WHC sounds received higher ratings in the patients with SCI (p < .01) than in able-bodied individuals (healthy subjects: W_{RAS} = 1.9 ± 2.1; physical therapists: W_{RAS} = 3.9 ± 2.7) and was comparable to the perceived motor reactivity to U_{RAS} sounds (5.6 ± 3.15; p = .43).

Despite the aural expertise of physical therapists, their perceived motor reactivity to W_{RAS} sounds was significantly lower than their reactivity to human (U_{RAS} = 6.97 ± 2.7, L_{RAS} = 6.4 ± 2.8; p = .0001) and A_{ARS} (5.3 ± 3.4; p = .002) action sounds. Unsurprisingly, healthy subjects were unaccustomed to the W_{RAS} sounds, and their perceived motor reactivity to them was significantly lower than their reactivity to the human (U_{RAS} = 6.3 ± 2.7, L_{RAS} = 7.2 ± 1.9; p = .0001) and was comparable to A_{ARS} (3.3 ± 2.8; p = .16) action sounds. No significant differences in perceived motor reactivity were observed between the two groups of able-bodied individuals (p > .24).

The ANOVA of subjective familiarity ratings (Figure 4.3) revealed a significant main effect of sound category ($F_{3,123}$ = 17.13, p < .0001, $\eta p^2 > .26$). Specifically, higher VAS ratings were found for human action sounds (L_{RAS} = 8.2, U_{RAS} = 8.4) than for non-human action sounds (W_{RAS} = 5.49, A_{ARS} = 6.8; p < .003). No significant differences in familiarity were observed between participant groups ($F_{2,41}$ = .66, p = .42). However, we did observe a significant group

× sound category interaction ($F_{6,123} = 8.3$, $p < .001$, $\eta p^2 > .32$). Physical therapists (7.2 ± 1.9) and SCI patients (7.02 ± 3.1) had similar levels of familiarity with regard to W_{RAS} actions sounds ($p > .85$), and this level of familiarity was not significantly different from the familiarity with human lower limbs (physical therapists: $L_{RAS} = 8.23 \pm 1.98$; SCI patients: $L_{RAS} = 7.7 \pm 2.3$) and upper limbs (physical therapists: $U_{RAS} = 8.25 \pm 2.4$; SCI patients: $U_{RAS} = 7.4 \pm 2.4$) action sounds and non-human action sounds (physical therapists: $A_{ARS} = 7.7 \pm 1.7$; SCI patients: $A_{ARS} = 6.7 \pm 2.9$; all $p > .05$).

As expected, in the group of healthy subjects, the familiarity ratings for W_{RAS} action sounds (2.4 ± 2.3) were significantly lower than the familiarity ratings for the human ($U_{RAS} = 8.8 \pm 1.4$, $L_{RAS} = 9.1 \pm .9$; $p = .0001$) and non-human ($A_{RAS} = 6.2 \pm 1.9$; $p = .0001$) action sounds. The familiarity rating for W_{RAS} was significantly different from those measured in the physical therapists and SCI patients (all $p < .0001$).

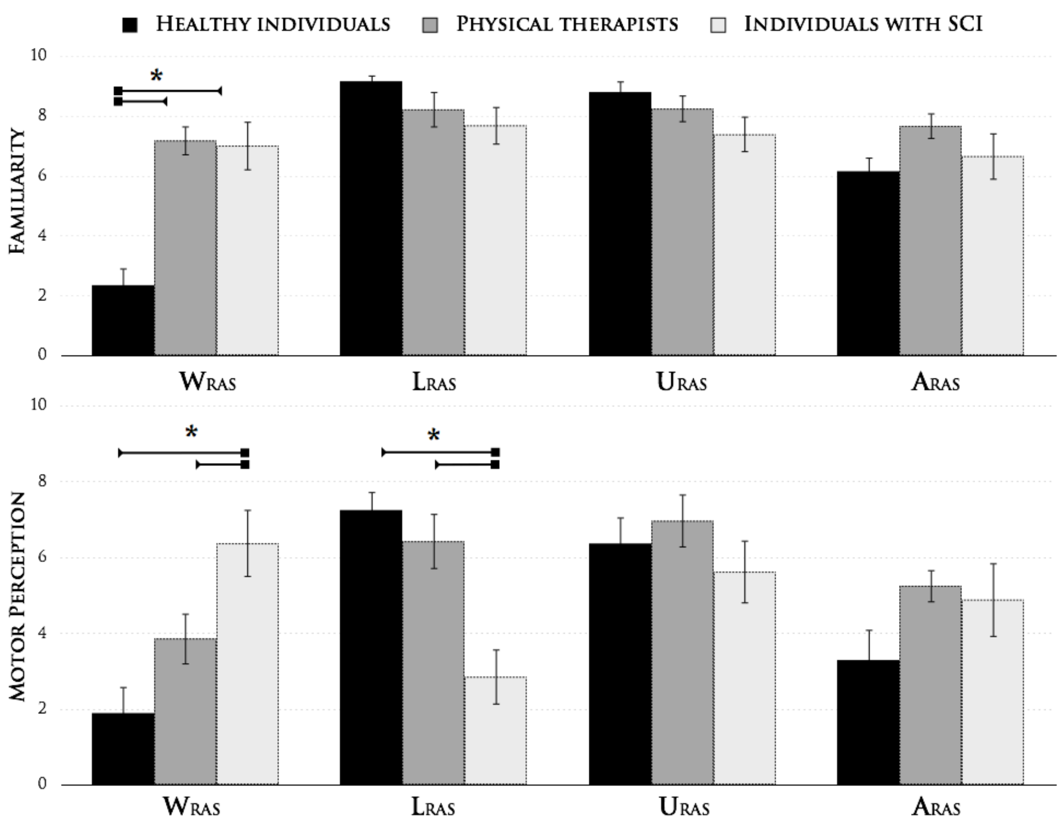


Figure 4.3 Subjective ratings of action-sound familiarity and perceived motor intensity. The mean subjective Visual Analog Scale (VAS) ratings for auditory familiarity and perceived movement for each sound category (upper (U_{RAS}) and lower (L_{RAS}) limb-related action sounds, wheelchair-related action sounds (W_{RAS}), and animal action-related sounds (A_{ARS})) in the three subject groups (healthy individuals, physical therapists and individuals with spinal cord injuries). The error bars indicate the standard error of the mean (SEM). The asterisks (*) indicate significant results from the post hoc comparisons ($p < 0.05$).

The subjects were also briefly interviewed with regard to their feelings about the auditory stimuli. A "yes" or "no" response was required for the following questions: (1) "Do you pay more attention to a specific category of auditory stimuli?" and (2) "Do you feel more emotional participation when hearing a precise sound category?" In the case of a "yes" response, the subject was asked to explain the answer. All subjects stated that they did not pay particular attention to the specific sound category. Four SCI patients declared an increase in emotional participation when hearing lower limb sounds, while another three reported greater emotional participation when hearing animal sounds. Only one SCI patient and one physical therapist (who was married to an individual with SCI) experienced more emotional involvement when hearing the WHC sounds compared with the other sound categories. Sound discrimination does not appear to be explained by category-specific, attention-driving tendencies. Presenting the auditory stimuli in a random order may have prevented the subjects from focusing their attention on a particular auditory stimulus category.

Together, these findings suggest that although the SCI patients and auditory experts (i.e. physical therapists) demonstrated the same degree of familiarity with the WHC sounds, the greatest differences between the three groups occurred with regard to the subjective motor experiences associated with WHC and lower limb action sounds.

Subjective reports of the embodiment experience of wheelchair use

We also used nine question statements (adapted from Pazzaglia et al., 2013) to obtain subjective reports of the corporeal awareness of the wheelchair in SCI patients. The questionnaire consisted of nine statements (listed in Figure 4.4) that described implicit and explicit tool experiences linked to actual bodily states. The first two components (WCH adjusting and WCH awareness) were designed to capture the implicit experience linked to wheelchairs. Tools require a considerable deal of effort from their users (diet, maintenance and protective behavior) to achieve reliable and smooth usage, as well as a reduced need for awareness and attention over time. The remaining components explored the corporeal awareness of tools, including the issue of incorporating the wheelchair into the body as a substitute for the motor architecture of the limbs. For each statement, the numbers of "true" and "false" responses were compared using a binomial test. The responses from 12 patients were available for analysis (cases 2 and 10 were patients with incomplete SCIs and did not return their questionnaires).

In the components "adjusting" and "awareness" and incorporating the wheelchair into the body as a "substitute" for the motor architecture of the "lower limbs" (Figure 4.4), the number of "true" responses was greater than the number of "false" responses (binomial test, $p < .01$). In contrast, the number of "true" and "false" responses did not differ when considering the wheelchair as part of the entire body (binomial test, $p = .2$). This pattern of responses suggests that some wheelchair properties are implicitly processed in the same manner as properties of the body (de Vignemont, 2011). It also seems that the sense of corporeal wheelchair awareness is much more hardwired to the motor architecture of the lower limbs than to the motor architecture of the entire body.

PARTICIPANT RATINGS OF INTROSPECTIVE EXPERIENCES OF WHEELCHAIR EMBODIMENT

Response Count	Statement: Wheelchair Adjustment			Wheelchair Awareness	Wheelchair Tool	Wheelchair Body	Wheelchair Lower Limb Action		Corporal Structure
	diet	maintenance	defense				lower limbs	sub/ext	
true	10	11	11	12	2	5	10	9 (sub.)	10 (in)
false	2	1	1	0	10	7	2	1 (ext.)	2 (out)
binomial test p-value	0.01	0.003	0.003	0.0006	0.01	0.2	0.01	0.01	0.01

Adapting to a wheelchair:

1) **[diet]** Do you follow a controlled diet to prevent changes in your body shape to avoid problems with the wheelchair?
2) **[maintenance]** Do you think of ways to prevent problems with your wheelchair, that is do you pay particularly attention to its maintenance?
3) **[defense]** Do you protect your wheelchair from dangerous situations?

Awareness of the wheelchair

(4) Did you experience any change in your attention and/or awareness while being in a wheelchair (after 1 -3 - 6 months)?

Wheelchair as a tool or body structure

(5) Do you perceive the wheelchair as an external tool?

Wheelchair as part of the body structure

(6) Do you perceive your wheelchair as part of your entire body?

Wheelchair as a lower limb structure

(7) Do you perceive the wheelchair only as part of your lower limbs?

(8) Do you perceive the wheelchair as an "extension" of or a "substitute" for your limbs?

Wheelchair in a corporal structure

(9) When thinking about your body frame, do you feel that the wheelchair is an internal or external part of your body?

Figure 4.4 Participant ratings of introspective experiences of wheelchair embodiment. The first four questionnaire statements were designed to capture the implicit perceptual experience, and the other statements explored the explicit perceptual experience of wheelchair use. For each statement, the numbers of "true" and "false" responses were compared using a binomial test.

4.4 Discussion

Many theories have proposed an association between the perception and execution of actions, suggesting that both are coded according to a common representational format (Prinz, 1997, Brass et al., 2001, Brass et al., 2000, Craighero et al., 2002, Kilner et al., 2003, Sturmer et al., 2000, Repp and Knoblich, 2007). Neural studies in healthy (Gazzola et al., 2006, Rizzolatti et al., 1996, Doehrmann et al., 2010) and brain-damaged (Pazzaglia et al., 2008) individuals indicate that action perception and execution rely on largely overlapping neural substrates. Importantly, it is unclear whether lifelong (mobility by lower limbs) and newly acquired (mobility by WHC) perceptual and motor experiences differently impact the integrity of action-perception mapping.

The present study investigated action-sound mapping in SCI patients and revealed three key findings. First, SCIs that have induced a total loss of lower limb function do not lead to a general reduction of the perceptual-motor mapping of lower limb action sounds. Second, a wheelchair can be integrated as part of the body, thus modifying audio-motor interaction. Third, the effect of "learning by doing" leads to plastic changes that are distinct from the impact of "learning by perception."

Is action audio-motor mapping disembodied?

Alteration of the action network involved in the perception of human motor acts may occur in the absence of a cortical lesion, such as in blind (Ricciardi et al., 2009, Lewis et al., 2011), deaf (Alaerts et al., 2011) and SCI (Arrighi et al., 2011) individuals. This result prompted us to investigate whether the somatosensory deafferentation and motor deefferentation of specific body parts alters the audio-motor mapping of actions generated by the affected body part. Thoracic and lumbar SCI lead to a loss of movement in the legs while sparing arm function. Consequently, this type of injury provides an ideal experimental approach for exploring how sound actions associated with upper and lower limbs are processed in the same individual. As mentioned previously, patients with SCI exhibit reduced perceptual sensitivity in the visual domain when compared to the biological motion of the point-light displays of the entire body (Arrighi et al., 2011) and specific impairments in the visual perception of form and action in the disconnected body parts (Pernigo et al., 2012). In this study, we expected that the processing of sounds depicting upper limb actions would be unimpaired while the processing of sounds depicting lower limb actions might be degraded. However, we obtained psychophysical evidence that paraplegic patients recognize lower and upper limb actions as efficiently as able-bodied individuals. The inability to move and feel the lower limbs did not lead to a deficit in the sound discrimination of actions, even several years after the initial injury.

Several mechanisms may explain the preservation of perceptual signaling referred to the paralyzed portion of the body following SCI. Although speculative, this scenario may recall pathology studies which demonstrate that a small portion of the spinal cord remains intact, even in cases of severe and complete spinal cord lesions (Bunge et al., 1993, Bunge et al., 1997, Guest et al., 2005, Anderson et al., 2004). After injury, spared axons sprout and make new connections. Although these projections are insufficient to restore any motor function, they can support perceptual-motor interaction, even in cases of complete thoracic lesions (Cariga et al., 2002).

However, the use of the legs for a long period of time prior to injury could be a determining factor with regard to the audio motor discrimination of lower limb actions. With a long history of absent sensation and movement after injury, accurate perceptual discrimination may be mediated by long-term motor representations that were learned before the injury. Studies in amputee patients revealed that perceptual sensitivity associated with the missing limb remains accurate (Nico et al., 2004), a process that requires motor simulation (Fiorio et al., 2006). Moreover, neuroimaging studies have suggested that motor mirroring is activated during the observation of limb movements independently of the subject's actual motor and perceptual abilities (Costantini et al., 2005).

The sounds utilized in the present study were highly relevant to the everyday motor functions that the patients had regularly performed prior to injury. These representations could, however, be updated and reinforced through visual and acoustic experiences involving ambulatory individuals encountered in daily life. Action-related networks may be activated to mediate the motor limb sound representation, despite the fact that motor plans have not been utilized for years. Accordingly, the brain regions involved in foot movements appear to remain relatively preserved and active even years after the body has been massively deafferented⁄deefferented (Corbetta et al., 2002, Cramer et al., 2005, Cramer et al., 2007, Hotz-Boendermaker et al., 2011, Hotz-Boendermaker et al., 2008, Alkadhi et al., 2005).

All of the patients recruited in our study were also involved in a motor program at a rehabilitation center. As part of this program, they attempted daily movements and exercise training, including attempts at moving the foot and (to a lesser degree) walking. Such programs require the use of numerous motor functions (including motor imagery) that prompt natural and ecological actions. Accordingly, recent neuroimaging studies demonstrated that a common observation-execution network, including the ventral premotor cortex, parietal cortex and cerebellum, is activated at a normal level through attempts to move a given body part and observations of the movements of other individuals, long after the onset of complete SCI (Hotz-Boendermaker et al., 2011, Hotz-Boendermaker et al., 2008, Mattia et al., 2009, Mattia et al., 2006, Truccolo et al., 2008).

Defects in the audio-motor mapping of actions have been reported in brain-damaged patients. The preservation of the perceptual ability in SCI patients suggests that the cortical regions involved in action simulation could play a compensatory role and facilitate the maintenance of intact audio-motor resonance in patients with impaired lower limb motor functions. Therefore, studies of either virtual (via transcranial magnetic stimulation) or natural lesions probe the essential role of the fronto-parietal regions in mediating the auditory and visual processing of body actions (Aziz-Zadeh et al., 2004, Ticini et al., 2012, Moro et al., 2008, Fazio et al., 2009). Instead, the presence of intact audio-motor mapping in patients with profoundly impaired body-brain communication may conflict with studies of visual-motor action translation in SCI patients. One way to reconcile this potential discrepancy concerns the quality of the experience of actions mediated through visual vs. auditory inputs. Indeed, whereas vision allows one to directly simulate a specific action (e.g. grasping an object), auditory input may elicit the simulation of more than one action related to the sound that was heard (e.g. clapping different hands), thus enabling the simulation of the heard action in multiple, indirect ways as well as higher degrees of compensatory flexibility. Importantly, although we used ecologically relevant sounds of daily human actions, perceptual alterations in SCI studies appear only when a somewhat unnatural task (e.g. the direction of motion point-light (Arrighi et al., 2011) and a humanoid form that assumes a sports posture (Pernigo et al., 2012) is presented.

The ability to properly discriminate everyday action-sound after spinal cord injury led to the development of rehabilitation programs based on the notion of using audio-motor interactions to improve the function of immobile patients. Accordingly, auditory virtual walking may be a viable intervention for neuropathic pain following SCI (Moseley, 2007).

Action-sound mapping highlights the plastic nature of novel object embodiment: a portrait of SCI

The present study investigated action-sound mapping in individuals with SCI with functioning upper limbs and non-functioning lower limbs who had regained mobility using a wheelchair. We provided the first psychophysical evidence that patients with SCI can distinguish WHC sounds from other distracting sounds more rapidly than individuals with no direct perceptual or motor wheelchair experience. Patient DT, a 22-year-old paraplegic, illustrated this process well. He spontaneously reported that he might be able to recognize not only the wheelchair but also the identity of other known wheelchair-bound individuals just by hearing the WHC sound. Notably, the ability of the audio-motor system to distinguish wheelchair actions recalls the greater perceived motor reactivity present when listening passively to WHC sounds. Accordingly, the subjective data also reveal an implicit mechanism of adjustment to the tool, as occurs with artificial limb in amputees (de Vignemont, 2011, Murray, 2004). It also seems that the sense of corporeal wheelchair awareness is much more related to a sense of substitution of the affected body part than to the motor architecture of the entire body (Pazzaglia et al., 2013).

This finding indicates that SCI patients probably redefine or modify their motor abilities, appropriating the action schema to include the actual features of the wheelchair. Therefore, when a tool extends the movement potential of a physically impaired individual, it may be included in the internal representation of the body schema to meet the novel demands of immobile limbs. As posited by theoretical studies, the acquisition of wheelchair skills by SCI patients alters their body representation by adding corporeal awareness of the device (Papadimitriou, 2008, Standal, 2011).

The experience of wheelchair embodiment has not been directly evaluated using systematic quantitative measurements, but has been commonly reported. However, almost five decades ago, Arnhoff and Mehl suggested that body image distortion in paraplegia was attributable to changes in the dimensions of the "body-wheelchair" combination (Arnhoff and Mehl, 1963). More recently, a behavioral study indicated that the altered images of "body-plus-wheelchair" in SCI patients enables them to calculate the accurate spatial requirements for their wheelchair to pass through a space (Higuchi et al., 2009). This scenario is also consistent with the findings of a recent neuroimaging study that compared the motor imagery of tool locomotion (i.e. the wheelchair slalom) with the motor imagery of movement without the wheelchair (i.e. stair walking). An increased blood oxygen level-dependent signal in the dorsal premotor cortex was found during wheelchair movement in a SCI subject (Olsson, 2012). Therefore, objects that have been in contact with the body become part of the bodily representation (Aglioti et al., 1996, Berlucchi and Aglioti, 1997) and induce short- and long-term neuroplastic changes in the motor system (Giraux et al., 2001) following active (rather than passive) use of the body (Cardinali et al., 2009, Cardinali et al., 2012). The incorporation of an external tool into the body representation, together with updating and modifying internal action representations, indicates the inherently plastic nature of the body schema. Therefore, recent studies of tool integration in the corporeal representation revealed bodily changes in experienced identity in both patients with SCI (Lenggenhager et al., 2012) and individuals with locked-in syndrome (Nizzi et al., 2012). Specifically, the capacity to embody new objects may extend an individual's physical impaired ability and remains a potentially unexploited resource for the growing population of those who are severely disabled.

Physical and perceptual practices to forge new learning opportunities

These findings highlight the unique role of motor practice in learning ability. Individuals with SCI, when compared with auditory experts, can closely match aural perception with wheelchair-executed motion, enabling these patients to quickly extract and discriminate relevant WHC sounds. Visual and auditory wheelchair familiarity, although not fundamental, certainly plays a role in the discrimination of its sound. Although the physical therapists did not demonstrate the same ability as the wheelchair-bound subjects in recognizing the WHC sounds, the mere "observation/audition" ability of the wheelchair-bound subjects enhanced their WHC sound discrimination ability when compared with healthy subjects. However, the RT readiness in audio-motor interaction with the tool is revealed when the wheelchair is used actively, rather than passively. The acquisition of motor skills through physical vs. perceptual practice may imply a highly selective coupling of perceptual-motor information. The striking effects of perceptual-motor practice with specific objects induce long-term structural changes in monkey (Quallo et al., 2009) and in human (Bassolino et al., 2010, Aglioti et al., 2008) body representations. The exclusive plastic effect of physical (as opposed to perceptual) learning on the development of new action perception abilities suggests that it is essential for people to experience close sensorimotor associations in order to forge new learning opportunities (Serino et al., 2007, Bassolino et al., 2010).

CHAPTER 5

A COMPUTATIONAL MODEL ON PERCEPTUAL-MOTOR PROCESS OF ACTION-RELATED SOUND

In the previous chapters we provided further evidence of tool and action representation plasticity after spinal cord injury. Nevertheless, the underlying neural mechanisms of these plasticity processes are still largely unknown. The pioneering work of Iriki and colleagues (1996) specifically demonstrated that after tool use, visual receptive fields (RFs) of bimodal neurons at the level of the intraparietal sulcus elongated and became responsive to stimuli presented at the tip of the tool. Few neurophysiological studies in recent years suggest that these effects of tool-use training on the extension of the visual RFs could be explained by morphological changes at the level of synapses connection within the parietal lobe. More specifically, Ishibashi and colleagues (Ishibashi et al., 2002) suggested that the mechanism underlying this phenomenon could be the creation of new synaptic connections from the visual related areas cortex in the parietal cortex with the somatosensory neurons in the intraparietal sulcus (Ishibashi et al., 2002; Hihara, et al., 2006). However, much is still unknown about higher order phenomena such as embodiment and decision-making.

In this chapter, a tentative has been made in order to create a theoretical model describing these neural mechanisms, taking advantages of computation neural network modeling. Neural network models are information elaboration systems aimed at simulating neuron behavior in a realistic way. In this case neural network models and computer simulation techniques represent a useful tool to investigate the mechanisms underlying decision-making processes responsible for different performance in sound of action recognition.

5.1 Elements of neural networks

The term "computational" refers to the use of computer and mathematical principles for the calculation of responses and the simulation of behavior, of a given system. A neural network implemented in the computer is a mathematical model that simulates the behavior of neurons, or groups of neurons, connected between each other. This type of structure is particularly suitable to capture specific aspects of the human brain capacities, such as parallel processing, generalization, and reconstruction of a stimulus or a memory from a partial set of information. Neural networks also allow simulating the processes of various forms of learning, for example associative, supervised, conditional, or with reinforcement. A neural network is composed of units connected between each other. The network activates its own output in function of the values received at input. The activation of the output of the units can be modeled through a function. The connections between the units have associated weights that modulate the contribution of the respective unit of origin. The weights can be changed depending on the output values of the network by simulating the process of learning. Groups of units can be organized to form functional layers of a network such as the input one, the intermediate processing one and output one, as shown in Figure 5.1.

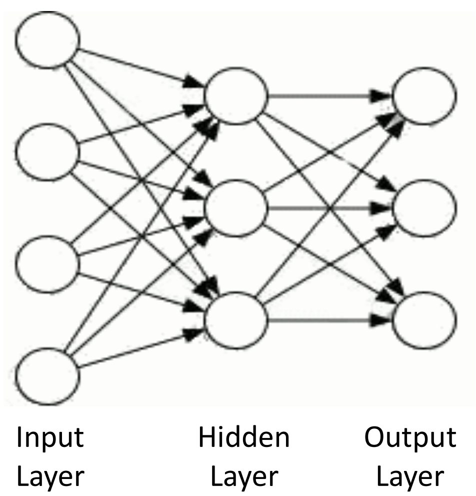


Figure 5.1 Schematic representation of a simple neural network.

There are multiple networks to model the various types of learning. Here I will briefly describe three of them, highlighting their strengths and limitations:

1. **Hopfield network:** this network (Hopfield, 1982) has a generic structure in which each unit is connected with each other except with itself. The weights of the connections are all equal to each other (Figure 5.2). The input stage also corresponds to the output one. This structure allows to model the Hebbian learning process, characterized by the strengthening of the connections in which the units of input and output are both active within a specific time window. In the neural networks this condition is realized considering the simultaneity of activations. The formula describing this process is:

$$\Delta w_{ji} = \eta * y_j * x_i$$

The information storage, and then the learning, is represented by the reinforcement of the connection w_{ij} in terms of increase of Δw, between the input unit and the output one, while η represents the learning coefficient. The set of all weights of the network can be summarized in a matrix with *j* columns and *i* rows. The process to calculate the variations of weights in the connections needs the calculation of the learning formula, multiplying the value of the activated units, for each column and each row of the matrix. The algorithm is:

```
for j = 1: N
    for i = 1: N
        W (j, i) = W (j, i) + 1 / T * q (j) * q (i)
```

where q is the activation of the unit and W (j, i) as second member is the value of the connection before updating.

This network is able to provide a maximum output response in case of input corresponding to memorized stimuli. In case of noise or partial impairment of the input stimulus, the network will be able to reconstruct the output. The stored stimuli become stable states, called attractors. A limitation of this type of network is that non-learned attractors can be accidentally created. Furthermore, the storage memory of these networks is limited.

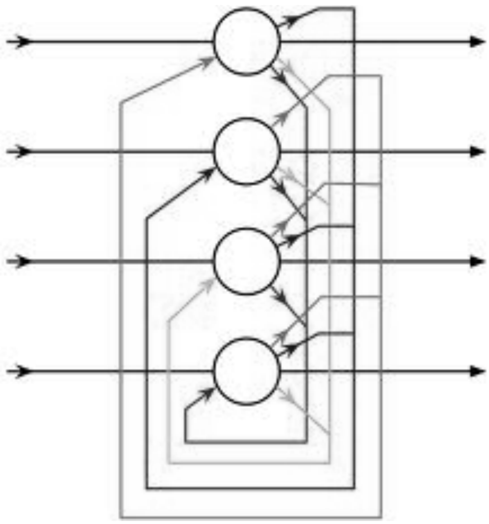


Figure 5.2 Schematic representation of a Hopfield network.

2. **Kohonen network**: this network (Kohonen & Teuvo, 1982) is constituted of one input layer and one processing layer. Each input unit is connected with those of the second layer and the units of the second layer are all connected together. When an input stimulus is presented, the unit of the second layer with the maximum response is able to inhibit the other, with gradually growing force at the increasing of the distance from it (Figure 5.3).

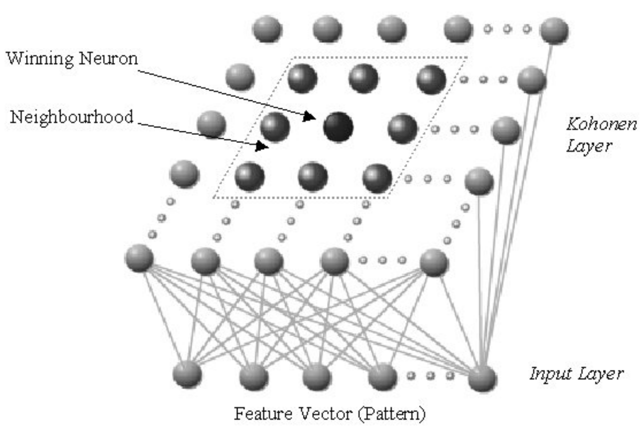


Figure 5.3 Schematic representation of a Kohonen network.

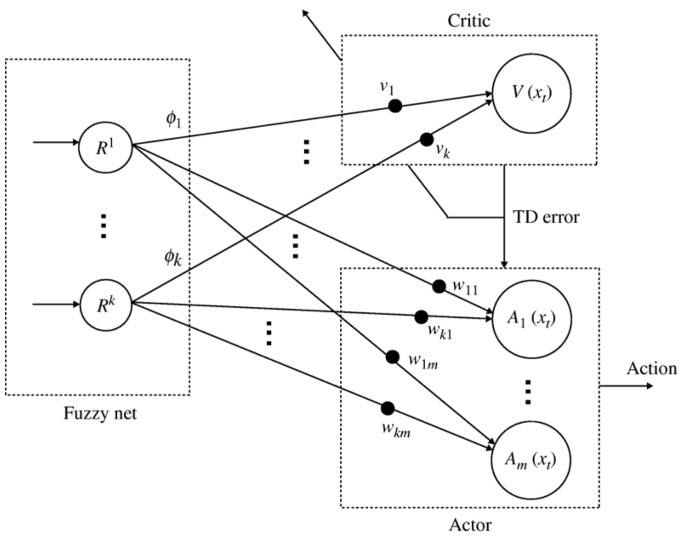
This network is suitable for modeling a type of unsupervised competitive learning, in which the units of the second layer are specialized in the recognition of a particular input pattern. As the pattern changes, the network reorganizes itself and changes its structure. The formula describing the competition between adjacent units, also known as Ojas' rule (Oja, 1982), is:

$$\Delta w_{ji} = \eta * y_j * (x_i - w_{ji})$$

$$\Delta w_{ji} = \eta * y_j * x_i - \eta * y_j * w_{ji}$$

The second row shows how both a part of Hebbian learning and a part able to contain the variation around the activated unit, constitute this computation.

3. **Actor-Critic network**: this type of structure includes a network responsible for the execution of an action, according to established rules, and a control network to evaluate the difference between the obtained result and the expected one, through a specific function (Figure 5.4).



Notes: Actor generates an action of an agent according to a stochastic policy which concerning with the output of Fuzzy net; critic calculates TD-error using the reward of the states from the environment

Figure 5.4 Schematic representation of an actor critic network.

The formula for the calculation of the weights matrix is now more complicated.

$\Delta w_{ji} = \eta * \epsilon * f(x)$

Without going into the details, we just note the presence of a further modulation element of the weight of the connection, ε, linked to the error gradient, i.e. to the direction of its trend. The more is the distance from the desired value, the more is the increasing of the coefficient. This type of network allows to solve discrimination problems and to simulate non-linear processes of learning by reinforcement.

5.2 Embodiment and neural networks: a proposal for a model

In order to choose the best-suited configuration for our neural network model, I will briefly summarize the salient aspects of data and considerations shown in Chapter 4.

We previously showed that:

- Reaction times performance of patients with SCI for wheelchair related action sounds (W_{RAS}) is significantly than the one showed by the other groups. This latency improvement is not accompanied by changes in accuracy, ruling out any potential speed/accuracy trade-off effects.
- SCI patients show similar performances for sounds related to actions of the lower (L_{RAS} = 716.0 ms) and upper (U_{RAS} = 708.1ms) limbs (P = 0.87), suggesting that audio-motor mapping can be retained even when the effector limb is no longer functional.
- SCI patients have both perceptual and motor experiences with the wheelchair, physical therapists have only the perceptual one, and healthy controls don't have any kind of knowledge with this tool.
- To accomplish the test individuals express a form of decision, discriminating not only the target sound but also its relation with the probe sounds.

- At the end of the process there must be a motor action to express the decision by pressing a button.

In order to integrate all these aspects in the model, we prefigure the presence of the following blocks:

- An input block with perceptual stimuli;
- A memory block that stores the sound repertoire (perceptual experience).
- A memory block that stores the action repertoire (motor experience);
- A decision block that compute the decision process;
- An output block that execute the choice;

The complete neural network is shown in the Figure 5.5.

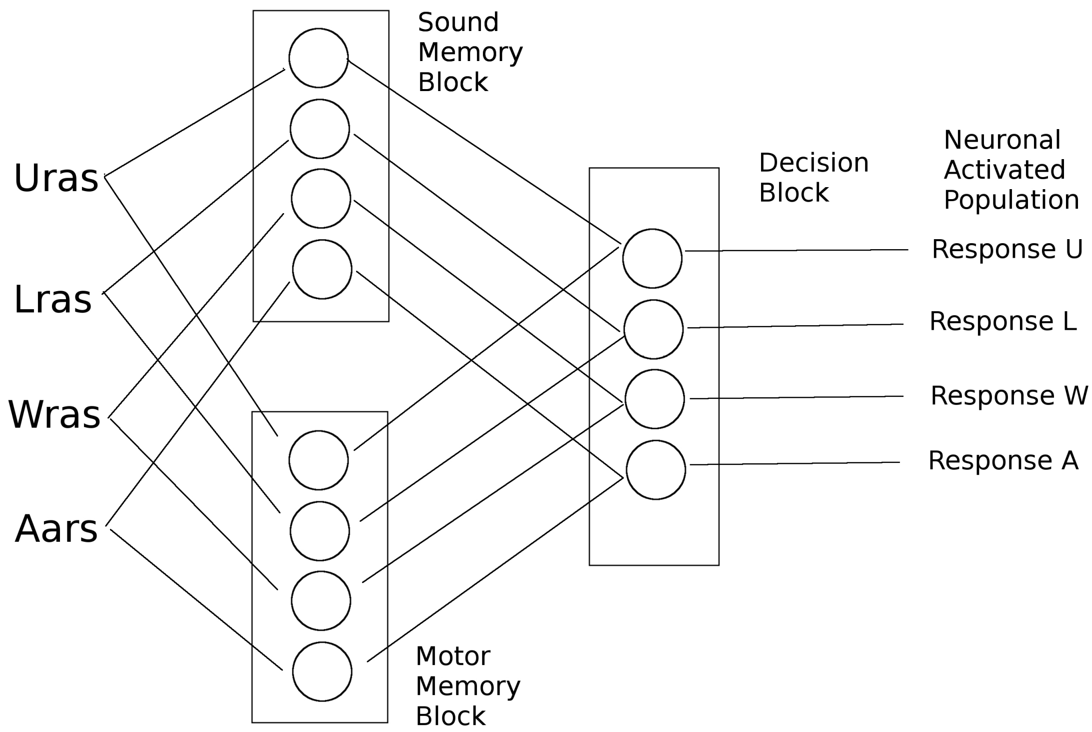


Figure 5.5 Schematic representation of the proposed neural network model.

This schema is common and replicated for every group. The information contained in the memory blocks differentiates the groups. In order to discriminate and store the information, an encoding process is required. Thereby, a unique code will be associated to every single stimulus. We will use a sequence of four numbers: the value "1" will indicate the presence of the corresponding sound category and "0" will indicate its absence. Organizing the digits in a vector, the stimuli will be encoded in the following way:

URAS [1 0 0 0], LRAS [0 1 0 0], WRAS [0 0 1 0], AARS [0 0 0 1].

These vectors are orthogonal to each other, as none of them shows the symbol "1" in the same position. This simplifies the calculation of the behavior of the network and its representation. In case of absence of information, (i.e. no stimulus) we will use the null vector [0 0 0 0].

Sound Memory Block

Recognizing an acoustic stimulus means that it has been experienced before and it is possible to compare the actual perception with the stored representation in our memory. In computational terms, this means that there is a memory block that maintains the information to compare through a learning process in order to recognize this stimulus. Table 5.1 summarizes the stored information for every group.

INFORMATION STORED IN THE SOUND MEMORY BLOCK

	SCI Patients	Physical Therapists	Healthy Controls
U_{RAS}	Yes	Yes	Yes
L_{RAS}	Yes	Yes	Yes
W_{RAS}	Yes	Yes	**No**
A_{RAS}	Yes	Yes	Yes

Table 5.1 Action auditory representation stored in memory, for every group and each sound category.

In the column relative to the control group, we have the presence of the representative vector for the U_{RAS}, L_{RAS} and A_{ARS} stimuli, but not of W_{RAS}, in place of which we have the null vector.

The vectors of the stimuli will be represented synthetically through an array of stimuli, called Q. For the control group we will have:

Q_{CO} =

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

while for the other groups we will have:

Q_{SCI} = Q_{TH} =

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

At this stage, we will omit the dynamic aspects of memory formation. Instead we analyze the general characteristics required by this type of long-term learning, a key element for the implementation of the block, considering the presence of competition and supervision. If the acoustic memory was purely competitive there would be an overwriting of the most recent (or most used) stimuli on the oldest or less used ones. For example, avoiding knocking at a door for a certain period of time should be replaced by the sound of the bell used in substitution. As regards the necessity of a supervised learning we can consider that the storage of a certain sound can be simply explained through an associative, Hebbian-like, learning process, without involving additional mechanisms.

With this background, the sound memory block can be simply modeled by a Hopfield network, described by a W matrix obtained as a product of the Q matrix of the stimuli for its transpose Q ', divided by the number of possible patterns T to learn. In our case the pattern correspond to the four stimuli:

Ws = 1/T*Q*Q' =

$$1/4 * \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Since we chose a base of orthogonal vectors the transposed matrix coincides with the original one, so that the product of matrices is reduced to the product of a matrix for itself, which gives as result the starting matrix. We compute a different Ws matrix for every group, so that we have three different matrices describing the sound memories:

WS_{SCI}, WS_{TH}, WS_{CO}.

Data collected on individuals with SCI are in line with the modeling of Hopfield network. After 6 months from the beginning of wheelchair use, all individuals express the same performance of recognition of W_{RAS}, and this result is independent from the total amount of time spent on the wheelchair. The crucial element seems to be the time window from the onset of tool use and not the absolute time of its use. This is consistent with a classic learning process in which a plateau can be reached after a certain period of learning.

Motor Memory Block

We have to highlight some differences between this block and the Sound Memory Block. This part of the model represents the memory of a specific motor-action and not the repertoire of the actions that individuals can express in a specific moment. In fact, referring to L_{RAS} recognition performances, there are not significant statistical differences among groups, indicating that what is relevant for the task is the previous knowledge of a specific motor action and not its actual execution. One possible explanation could be to postulate the existence of two different memory blocks, one for “innate” actions and another one for “acquired” actions, interacting together. However, this hypothesis is difficult both to verify and to falsify. Moreover, it introduces in the model a level of complexity, without adding any further relevant information to the description of the phenomenon. The simplest explanation is to consider the time at which the trauma occurred and the repertoire of motor actions already acquired from the individual at that moment. Also in this case, as in the sound memory block, a competitive learning mechanism seems to be unsuitable to describe the phenomenon, as it should occur at least one of the following situations:

- None of the individuals with SCI should respond to the L_{RAS} stimuli;
- The performance of individuals with SCI to the L_{RAS} stimuli should be well below the performance of controls and therapists in the same category.

Both of these cases are in contrast with the empirical data collected. Therefore, we discard the use of a Kohonen network and we use a Hebbian network. This model, added in the scheme described before, is able to explain the "re-activation" of the motor memory, through a cross-modal process involving both vision and hearing (Alaerts et al., 2009). Table 5.2 shows the content of the motor memory block. In this case we have the presence of the lower limbs information for all groups and the absence of information related to the action sounds produced by animals.

INFORMATION STORED IN THE MOTOR MEMORY BLOCK

	SCI Patients	Physical Therapists	Healthy Controls
U_{RAS}	Yes	Yes	Yes
L_{RAS}	Yes	Yes	Yes
W_{RAS}	Yes	No	No
A_{RAS}	No	No	No

Table 5.2 Action motor representation stored in memory, for every group and each sound category.

The procedure for the calculation of the matrix describing the Hopfield network for the motor memory block is the same as in the sound memory block, so that we will have:

WM_{SCI}, WM_{TH}, WM_{CO}.

Decision Block

The final stage of our neural network must be able to carry out the computation of a decision-making process, solving the competition between different options, which arise from different possible input stimuli. The basic model selected to solve this task is a biological neural network for optimal selection, introduced by Bogacz (Bogacz et al, 2005). The structure of the network and its behavior is reported in Figure 5.6.

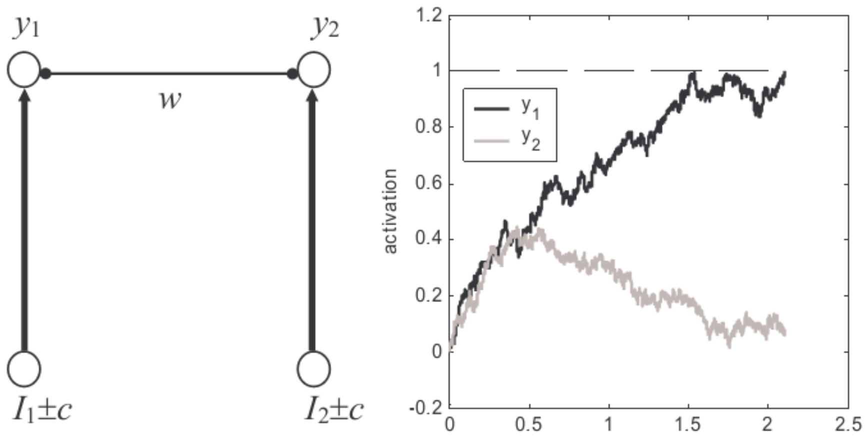


Figure 5.6 Schematic representation of Bogacz network.

The output units individually receive their input and are mutually linked through an inhibitory connection. In this way just one connection will prevail as function of the force of the input signal, making simultaneously silent the others. The "c" factor represents a bias element and is able to polarize the model towards a choice rather than the other. The formula for the calculation of the unit activation is:

$$unit_N = unit_N + (\delta/\tau) * (-\kappa * unit_N - w * unit_{(J \neq N)} + Input_N + Noise_N);$$

The parameters of the formula are:

- Δ is the integration time, i.e. the time interval used to calculate the result of the formula, expressed in milliseconds (ms);

- T is the speed of the activation process between the units;

- K is a parameter that expresses negative autocorrelation;

- W is a parameter corresponding to a mutual inhibition between the units;

- InputN is the input signal of the unit N;

- NoiseN is a noise factor.

The generalization to N-dimensions uses an expression in which each element becomes a parameter array, allowing the simultaneous computation of N units at one time.

$$U = U + (\Delta / T) * (-K * U - U * W + I + N)$$

In this case, K is a diagonal matrix, a matrix of autocorrelations, while W has all the elements on the diagonal equal to 0, since each unit can inhibit the others but not itself. I is the contribution from the two memory blocks examined previously, and N is the matrix of the noise elements.

To test the behavior of the model we prepared three neural networks, one for each group, triggered by the four categories of stimuli. For the computation of the behavior of the neural network unit we can use both the synchronous or asynchronous method. With the synchronous method all the values of the variables are updated at a specific time, and the relative value of the output units is calculated. In this way all the variables remain stationary until the next calculation moment. With the asynchronous method the variables are updated one at a time. In our case we used the first method.

The levels of activation of the output units for each group are shown in the following figures, as function of the input stimulus. The horizontal line shows an arbitrary threshold value in order to compare the points of intersection of the curve: the more the activation is high, the more the intersection is shifted to the origin, indicating a shorter time to reach the threshold and, therefore, the expressed choice.

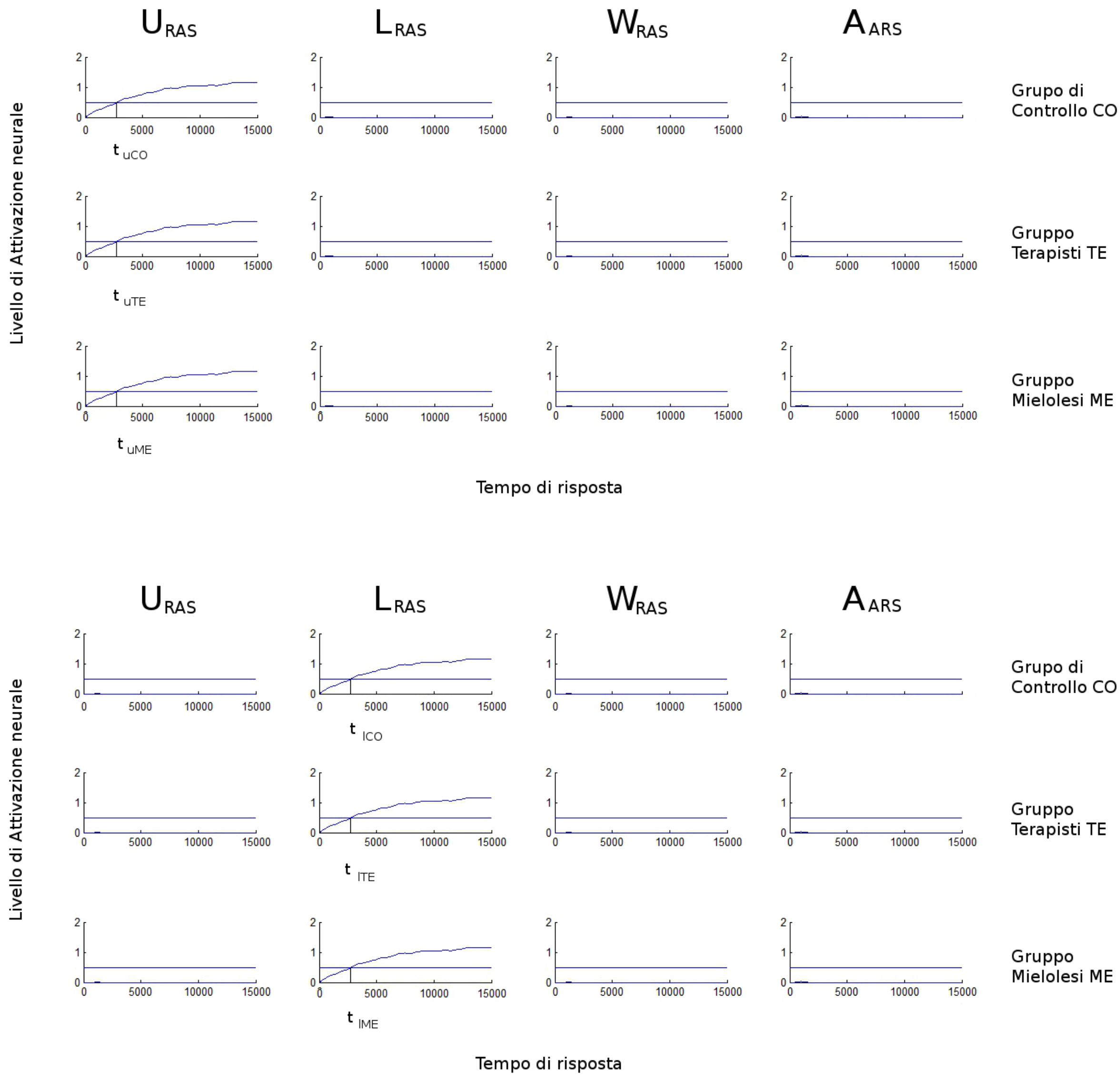


Figure 5.7 Activation levels of the neural network with U_{RAS} and L_{RAS} input stimuli, for each group.

In the case of W_{RAS} we have three different activations, in line with the requirements and the structure of the model. Consequently, the level of activation will be:

$T_{wSCI} > T_{wTH} > T_{wCO}$

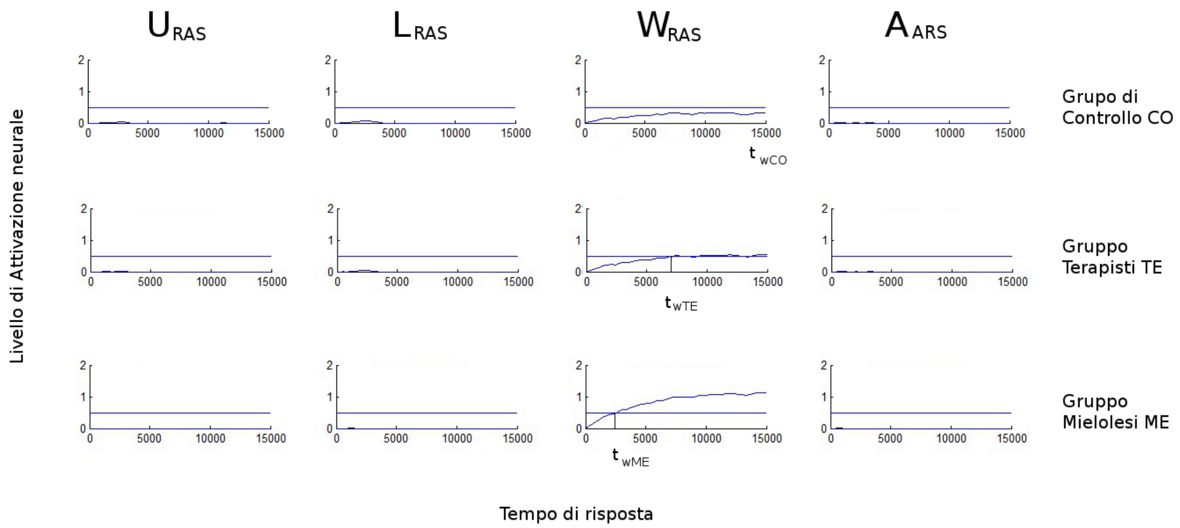


Figure 5.8 Activation levels of the neural network with W_{RAS} input stimuli, for each group.

In the end, we have the graph of the performance relative to the sounds produced by animals. In this case, as for the stimuli relative to the limbs, the performance is equal in the three groups, but with less activation due to the absence of the active motor component.

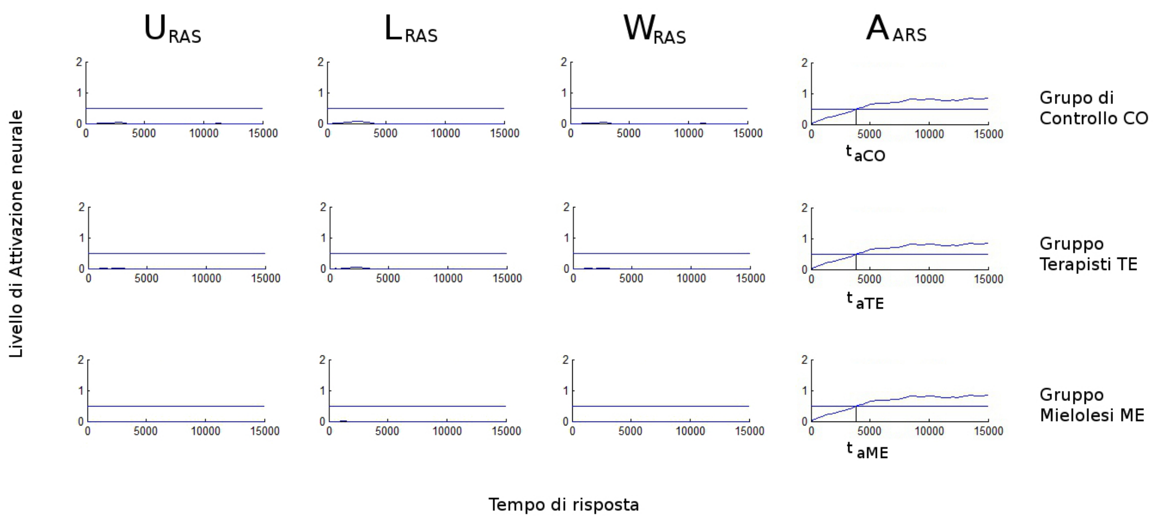


Figure 5.9 Activation levels of the neural network with A_{RAS} input stimuli, for each group

The figure below shows all the responses from the various units of the different groups in order to compare immediately the different cases.

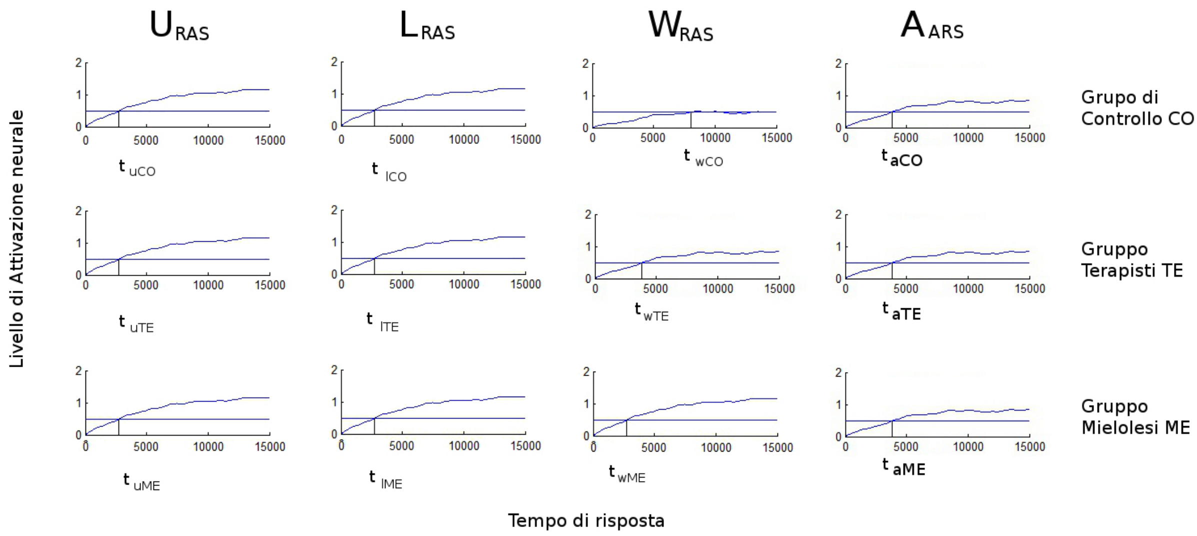


Figure 5.10 Comparison of activation levels of the neural network for all input stimuli in each group.

5.3 Limitations and Considerations

Although able to explain many aspects of the behavioral data collected, the present model is currently limited by three main points:

- Aspects of learning and salience are expressed by a single parameter;

- The computational aspect of dynamic integration of the information relative to the sound-action association is still absent.

- The ability to implement the principles identified in the phenomenon to a virtual embodied level is still lacking.

The last point is most challenging for the implementation. It would allow to realize a model as close as possible to the reality. In this model, a robotic motor system affected by a lesion could potentially reorganize the underlying neural network, depending on the tool replacement.

We demonstrate that this model can simulate the process underlying the performances expressed by different individuals exposed to different auditory stimuli. We assumed that the physical experience of an action can produce different performances when perceiving a related sound, but we reported some evidences that this phenomena changes depending on tool embodiment. It is still possible that different tools have different “salience level”. An alternative explanation could refer to the concept of “salience of the action” (i.e. to what extent the action is important for the individual). From this point of view SCI individuals may respond faster at the W_{RAS} simply because is “highly salient”. In this case we can think to a different model where all individuals share a structure and the difference among them is in terms of action salience. This is a very different hypothesis from what we considered as far. How can we model the salience of an action? We can think of salience as a reinforcement process, where what is useful and create advantage for the individual is preferred and strengthened. Given this, if using a wheelchair gives more opportunities than other options, it becomes very relevant for the individual and increases the valence of all elements related to it.

The question then becomes: Do SCI individuals respond faster at the W_{RAS} because is “salient” or because of the “embodiment”? And how to explain the different performances between TH and SCI groups? To what extent is the wheelchair salient for TH group?

There is a further option we can consider, trying to reconcile these different points of view. What is salient for SCI is something related to autonomy and interaction with the environment. These aspects, in terms of adaptation, may lead to an increased probability of survival and success and to a concrete advantage for the fitness. It is possible that through the action that causes motor memory by embodiment, the individual system checks the consequent advantage and increases the “level of salience” of the action itself. For physical therapist, because of the nature of their job, wheelchair sounds are salient but not so relevant for their lives, as for SCI group. In this light “salience” and “embodiment” could be two parallel aspects of two interacting processes, feed forward one each other. To investigate this issue we can either empirically create some tests to dissociate salience and motor memory of the action; or virtually model different structures that predict our results. A better understanding of these aspects can lead to create new physical therapies and training programs, based on both natural "embodied" and "salient" processes.

5.4 Operating Environment and Code

The model has been implemented using Matlab© 2012a V7.14 for students, on Windows 7 operating system. The code is shown below. The usual conventions of programming in Matlab are shown, where green represents the code comments. The beginning of the listed code contains all the variables with their initialization values. In case you want to run the simulation with different values, such as changing the learning rate of the network, it is possible to change only the variable at the beginning of the code, avoiding updating it in all instances in which it is used.

```
%%% EMBODIMENT MODEL %%%

% Clear all
clear all %Delete variables from work memory
clc   %Delete previous outputs and commands from command window
close all %Closes opened windows, e.g. of previous figures

% Constant parameters. Note: base time unit is the second

SIMU_LENG = 30;         %In seconds
SIMU_TIME_UNIT = 500; %Simulation time unit is milliseconds
DELT = 1;               %Integration time step, in milliseconds
DELT_SECO = DELT/SIMU_TIME_UNIT; %Integration time step, in seconds
```

```
MAX_STEP = (SIMU_LENG * SIMU_TIME_UNIT)/DELT; %Steps of simulation

Ni=4; %input unit

No=4; % output unit

T=Ni;


TAU  = 1000; % Speed of processes within units

K     = 0.2     % K is the first Bogacz's key parameter, corresponding to negative self-recurrency

%W    = K    % W is the second to Bogacz's key parameter, corresponding to mutual inhibition. If = K, efficient decision process

 W = ones(Ni) * K;

 W = W.* ( 1 -eye(Ni));


 smooth=0.5;


q1 = [ 1 0 0 0 ]'; % Upper limb stimulus

q2 = [ 0 1 0 0 ]'; % Lower limb stimulus

q3 = [ 0 0 1 0 ]'; % Wheelchair stimulus

qhalf = [0 0 0.8 0]'; %used for simulating the CO's training in recognizing wheelchair sound

q4 = [ 0 0 0 1 ]'; %Animal stimulus

no = [0 0 0 0]';


Q = double([q1 q2 q3 q4]); %Stimulus Matrix%

Cs = double([q1 q2 no q4]); %Sound Stimulus Matrix CO%

Ps = double([q1 q2 q3 q4]); %Sound Stimulus Matrix ML%

Ts = double([q1 q2 q3 q4]); %Sound Stimulus Matrix TE%


Cm = double([q1 q2 no no]); %Motor Stimulus Matrix CO%

Pm = double([q1 q2 q3 no]); %Motor Stimulus Matrix ML%

Tm = double([q1 q2 no no]); %Motor Stimulus Matrix TE%


WCs = (1/T)*Cs*Cs'; %Hopfield Sound Matrix CO%

WPs = (1/T)*Ps*Ps'; %Hopfield Sound Matrix ML%

WTs = (1/T)*Ts*Ts'; %Hopfield Sound Matrix TE%
```

```
WCm = (1/T)*Cm*Cm'; %Hopfield Motor Matrix CO%

WPm = (1/T)*Pm*Pm'; %Hopfield Motor Matrix ML%

WTm = (1/T)*Tm*Tm'; %Hopfield Motor Matrix TE%


WsInpu = ones(4)*0.5;

WmInpu = ones(4)*0.5;

WS=[WCs; WTs; Wps]; %We use one matrix of matrix to compute once all the activations%

WM=[WCm; WTm; WPm];



TIME_FOR_NOIS_RESE = 1; %= DELT_SECO;

NOIS_SIZE = 0.1;

STEP_FOR_NOIS_RESE = (TIME_FOR_NOIS_RESE * SIMU_TIME_UNIT)/DELT;


% Variables of model

step = 0;



% Variables Matrix

 nois = zeros(1,4);

unit = zeros(1,4);

unitC =  unit;

unitT =  unit;

unitP = unit;


% Variables for collecting data to be plot

unitHist = zeros(4, MAX_STEP);

unitHistC = unitHist;

unitHistT = unitHist;

unitHistP = unitHist;

scrsz = get(0,'ScreenSize');

figure('Position',[scrsz(1)/2 0 scrsz(3) scrsz(4)/2]);
```

```
%for index = 1:4
     stim = Q(:,3)'*1;%*rand(); smooth

    perc=stim*WTs;
    motor=stim*WTm;
        INPU = perc+motor;
        INPU2=(WS+WM)*stim';

% Program step and initialization of units
      unit = unit.*0;
      unitC = unitC.*0;
      unitT = unitT.*0;
      unitP = unitP.*0;
for step = 2:MAX_STEP

 if mod(step, STEP_FOR_NOIS_RESE) == (STEP_FOR_NOIS_RESE-1)
      nois = (rand(1,4)*2-1) * NOIS_SIZE;
    end

unit = unit + (DELT/TAU) * (-K * unit - unit*W + INPU + nois);

unitC = unitC + (DELT/TAU) * (-K * unitC - unitC*W + INPU2(1:4)' + nois);

unitT = unitT + (DELT/TAU) * (-K * unitT - unitT*W + INPU2(5:8)' + nois);

unitP = unitP + (DELT/TAU) * (-K * unitP - unitP*W + INPU2(9:end)' + nois);

    % Activate these if you want to keep units > 0
    if unit(1) < 0
        unit(1) = 0;
    end
    if unit(2) < 0
        unit(2) = 0;
```

```
end
if unit(3) < 0
    unit(3) = 0;
end
if unit(4) < 0
    unit(4) = 0;
end
 if unitC(1) < 0
    unitC(1) = 0;
end
if unitC(2) < 0
    unitC(2) = 0;
end
if unitC(3) < 0
    unitC(3) = 0;
end
if unitC(4) < 0
    unitC(4) = 0;
end
if unitT(1) < 0
    unitT(1) = 0;
end
if unitT(2) < 0
    unitT(2) = 0;
end
if unitT(3) < 0
    unitT(3) = 0;
end
if unitT(4) < 0
    unitT(4) = 0;
end
if unitP(1) < 0
    unitP(1) = 0;
```

```
    end
    if unitP(2) < 0
        unitP(2) = 0;
    end
    if unitP(3) < 0
        unitP(3) = 0;
    end
    if unitP(4) < 0
        unitP(4) = 0;
    end
    %Collect data

    unitHistC(:, step) = unitC';
    unitHistT(:, step) = unitT';
    unitHistP(:, step) = unitP';

end

% Graphics

xs=0; xe=15000; ys = 0.5; ye = 0.5;

x = 1:MAX_STEP;

subplot(3,4,1);
line([xs xe], [ys ye]);
hold on
plot(x,unitHistC(1, :));
hold on

axis([0 MAX_STEP 0 2])
title('Control stimulus 1')
```

```
subplot(3,4,2);
line([xs xe], [ys ye]);
hold on
plot(x,unitHistC(2, :));
hold on

axis([0 MAX_STEP 0 2])
title('Control stimulus 2')

subplot(3,4,3);
line([xs xe], [ys ye]);
hold on
plot(x, unitHistC(3, :));
hold on

axis([0 MAX_STEP 0 2])
title('Control stimulus 3')

subplot(3,4,4);
line([xs xe], [ys ye]);
hold on
plot(x, unitHistC(4, :));
hold on

axis([0 MAX_STEP 0 2])
title('Control stimulus 4')

subplot(3,4,5);
line([xs xe], [ys ye]);
hold on
plot(x,unitHistT(1, :));
hold on
```

```
axis([0 MAX_STEP 0 2])
title('Therapist stimulus 1')

subplot(3,4,6);
line([xs xe], [ys ye]);
hold on
plot(x,unitHistT(2, :));
hold on

axis([0 MAX_STEP 0 2])
title('Therapist stimulus 2')

subplot(3,4,7);
line([xs xe], [ys ye]);
hold on
plot(x, unitHistT(3, :));
hold on

axis([0 MAX_STEP 0 2])
title('Therapist stimulus 3')

subplot(3,4,8);
line([xs xe], [ys ye]);
hold on
plot(x, unitHistT(4, :));
hold on

axis([0 MAX_STEP 0 2])
title('Therapist stimulus 4')

subplot(3,4,9);
line([xs xe], [ys ye]);
hold on
```

```
plot(x, unitHistP(1, :));
hold on

axis([0 MAX_STEP 0 2])
title('Patient stimulus 1')

subplot(3,4,10);
line([xs xe], [ys ye]);
hold on
plot(x, unitHistP(2, :));
hold on

axis([0 MAX_STEP 0 2])
title('Patient stimulus 2')

subplot(3,4,11);
line([xs xe], [ys ye]);
hold on
plot(x, unitHistP(3, :));
hold on

axis([0 MAX_STEP 0 2])
title('Patient stimulus 3')

subplot(3,4,12);
line([xs xe], [ys ye]);
hold on
plot(x, unitHistP(4, :));
hold on

axis([0 MAX_STEP 0 2])
title('Patient stimulus 4')
```

CHAPTER 6

DON'T LOOK AT MY WHEELCHAIR: CHANGING PEOPLE'S BIAS THROUGH SOCIAL INTERACTION

[This research has been submitted in: Galli G, Lenggehager B, Scivoletto G, Molinari M, Pazzaglia M. Don't look at my wheelchair: changing people's bias through social interaction. Cognitive, Affective and Behavioral Neuroscience.]

6.1 Aims and Hypotheses

The dramatic change in body representation that occur after a sudden transformation in the structure of the physical body, such as the spinal cord injury, surely assume a role in social and affective dynamics as a function of different types of experiences. Considering our cultural influences, personal experiences, and normative expectations, simply being a wheelchair user is enough to attract negative stereotyping. Although this theme has become an important research topic, two essential related matters continue to be largely unaddressed. The first concerns the question of whether is there any dissociation in explicit/implicit prejudice-based attitudes about disability according to the group-membership. The second relates to whether we can actively counteract the presence of implicit/explicit bias.

To this purpose, in this study we sought to explore the presence of stereotypes toward wheelchair-bound patients with spinal cord injury (SCI), determining whether an in-group/out-group bias was present in healthy subjects (who have had no past experience with paraplegic patients) compared with physical therapists (who have had extensive experience with paraplegic patients) and paraplegic patients (Experiment 1). Based on the notion that stereotypes and prejudices are more readily observed at implicit rather than explicit levels, we asked participants both to perform an ad-hoc modified version of the Implicit Association Test and to express their opinion explicitly. More importantly, we sought to investigate, if such hardwired biases can be modified by a personal interaction with an individual with SCI (Experiment 2).

6.2 Materials and methods

6.2.1 EXPERIMENT I:

Participants

Fifteen subjects with established SCI (13 men; mean age, 38.07 years; range 19–56 years), 15 healthy control subjects without SCI (11 men; mean age, 37.3 years; range 23–50 years), and 15 physical therapists working with paraplegic patients (11 men; mean age, 37.8 years; range 25–58 years) were recruited at Fondazione Santa Lucia Hospital in Rome, Italy. All therapists were employed full-time and had an average of five years' experience with in-patient rehabilitation (range: 1 to 25 years).

The neurological injury level of the 15 SCI subjects (Table 6.1) was determined by experienced neurologists using the American Spinal Injury Association (ASIA) international standards for the classification of spinal cord injury. All patients were recruited from physiotherapy programs for SCI patients and were in the chronic injury phase (6 months post-injury). None of the SCI patients had suffered a head or brain lesion associated with the trauma leading to the injury.

No participant presented signs of psychiatric disorder, and none had a history of substance abuse. All subjects were right-handed as determined using the 10-item version of the

Edinburgh Handedness Inventory (Oldfield, 1971). Informed written consent was obtained for all procedures, and the study was approved by the local ethics committee of Fondazione Santa Lucia, Rome.

DEMOGRAPHIC AND CLINICAL DATA OF THE PARTICIPANTS

Case	Age	Gender	Time since Injury (days)	Lesion Level	AIS grade	Etiology
P1	42	M	960	T10	A	Traumatic
P2	42	M	1170	T3	A	Traumatic
P3	30	M	220	T3	A	Traumatic
P4	35	M	6770	T7	A	Traumatic
P5	38	M	5840	T8	A	Traumatic
P6	36	M	70	L1	D	Traumatic
P7	19	M	789	T10	A	Traumatic
P8	49	F	450	T12	A	Traumatic
P9	38	M	4945	T8	A	Traumatic
P10	42	M	1170	T9	A	Traumatic
P11	56	M	10220	T4	A	Traumatic
P12	56	M	600	L1	C	Traumatic
P13	19	F	395	T6	A	Traumatic
P14	35	M	590	T10	A	Traumatic
P15	22	M	365	T12	D	Traumatic
Range	19-56	13 M - 2 F	70-10220	T3 - L1	-	-
Mean	37.26		2303.6			
SD	11.56		3102.7			

Table 6.1 Clinical and demographic data of the spinal cord injury patients. The clinical neurological level of the lesion (T, thoracic; L, lumbar) was reported for the subjects with spinal cord injury (SCI). The neurological and functional levels of the injury were determined using the American Impairment Scale (AIS).

Stimuli and Test description

We adapted the classical IAT test (Greenwald et al. 1998) in order to reveal implicit associations between concepts that often reflect the strength to which a person holds a particular societal stereotype. In each IAT trial, a single stimulus is presented on the screen. The task of the participant is to classify it as quickly and accurately as possible into its respective category (for a detailed description of the task and its analysis please see Greenwald et al. 2003). For the current IAT variant, the stimuli consisted of 8 paraplegic-related pictures and 8 non paraplegic-related pictures. Pictures were created using a 3D creation software (Poser 9, SmithMicro Software). All samples were depicted as seated, but paraplegic samples seated on a wheelchair, while non-paraplegic models seated on an armchair. Eight negative common words (ugly, evil, failure, terrible, agony, discomfort, horrible, pain), and eight positive common words (glory, peace, wonderful, laugh, joy, happiness, love, pleasure) were chosen. A schematic representation of stimuli and procedure is displayed in Figure 6.1.

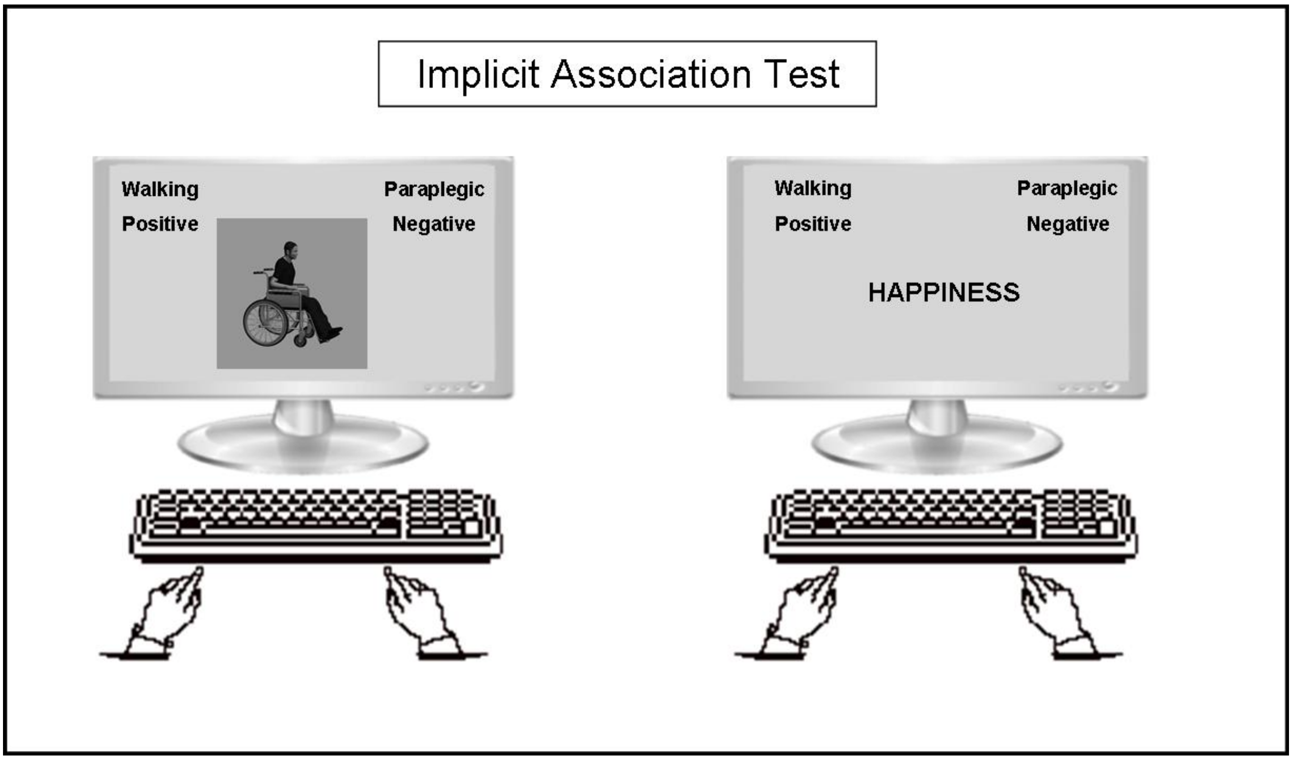


Figure 6.1 Schematic representation of the Implicit Association Test. In each IAT trial, a single stimulus is presented on the screen. The task of the participant is to classify it as quickly and accurately as possible into its respective category.

Procedure

Participants were seated at a distance of approximately 50 cm from a 17-inch monitor (resolution: 1024x768 pixels). Presentation of the stimuli and registration of answers were controlled using the E-Prime software version 1.0 (Psychology Software Tools, INC). Answers were given pressing the appropriate left-hand (Q) or right-hand (P) key, according to the sorting choice of the subject. We instructed subjects to answer as fast and accurate as they could, since IAT scores ground both on accuracy rating and reaction times. Instructions were repeated before starting every new block and category cues on the left/right hand corner remained on the screen for the entire duration of the block. Following the procedures of Greenwald et al. (2003), we mixed up pictures and words in seven blocks, as follows: (a) a 20-trial target picture discrimination block (the Italian word "Paraplegico" ("Paraplegic") appeared in the top left-hand corner and the Italian word "Deambulante" ("Walking") appeared in the top right-hand corner); (b) a 20-trial attribute discrimination block (the Italian word "Buono" ("Pleasant") appeared in the top left-hand corner of the screen and the Italian word "Cattivo" ("Unpleasant") in the top right-hand corner); (c) a 20-trial ''practice'' combination block with both pictures and attributes (the words "Paraplegic/Pleasant" appeared in the top left-hand corner while the words "Walking/Unpleasant" appeared in the top right-hand corner); (d) a 40-trial congruent test block of the same combination in (c); (e) a 20-trial target discrimination block in which the target categories were reversed ("Paraplegic" now appeared in the top right-hand corner of the screen and "Walking" in the top left-hand corner); (f) a 20-trial practice reversed combination block ("Paraplegic/Unpleasant" now appeared in the top right-hand corner and "Walking/Pleasant" now appeared in the top left-hand corner); and (g) a 40-trial congruent test block of the same combination in (f).

The stimuli for the target picture and attribute discrimination blocks were presented randomly, as the stimuli for the combination blocks. Incorrect responses resulted in a red 'X' being presented on the screen. A 250-ms interval separated each trial after a response was made in all blocks.

Questionnaires

Explicit preference

Next to the implicit bias we evaluated explicit preference toward healthy or paraplegic individuals. Participants were instructed to rate how much they prefer one out of these two categories on a visual, vertical 10-cm analogue scale (VAS). Participants were asked to indicate their explicit preference with a sign along the VAS line. The position was then converted into a numerical value.

Empathy

Participants were asked to fill the Interpersonal Reactivity Index (IRI, Davis, 1996), a self-report measure on empathic dispositions, comprising 28 mixed positive and negative statements. Using a 5-point Likert scale (ranging from 1 ["Does not describe me very well"] to 5 ["Does describe me very well"]), participants rated each statement. The questionnaire comprises 4 subscales, each with 7 items: Empathetic Concern (EC i.e. the tendency to experience feelings of sympathy and compassion for unfortunate others), Perspective Taking (PT i.e. the reported tendency to spontaneously adopt the psychological point of view of others in everyday life), Fantasy Scale (FS i.e. the measure of tendency to imaginatively transpose oneself into fictional situations) and Personal Distress (PD i.e. the tendency to experience distress and discomfort in response to extreme distress in others).

Data Handling

Performance on the IAT was scored using the algorithm proposed by Greenwald et al. (1998). Data from the IAT, the IRI and the VAS were analyzed with one-way analysis of variance

(ANOVAs) in which group (controls C, paraplegics P, or therapists T) was the between-subject variable. All pair-wise comparisons were performed using the Duncan's post hoc test. A significance threshold of $p < .05$ was set for all statistical analyses. The data are reported as the mean ± standard error of the mean (SEM). Moreover, Pearson's correlations tests were run for subjective ratings and the IAT scores. All behavioral data from Experiment 1 are reported in Figure 6.2, Figure 6.3, Figure 6.4 and Figure 6.5.

6.2.3 EXPERIMENT II:

Participants

The study included the participation of 40 healthy subjects (20 women, mean age 28.07 years ± 7.37 SD, range 19–48). They were different from those involved in the previous task, and all were unaware of the specific aim of the study. No participant presented signs of psychiatric disorder, and none had a history of substance abuse. All subjects were right-handed as determined using the 10-item version of the Edinburgh Handedness Inventory (Oldfield, 1971). Informed written consent was obtained for all procedures, and the local ethics committee of Fondazione Santa Lucia, Rome, approved the study.

Procedure

This experiment was done in three different sessions: 1) a pre manipulation session, 2) an interaction session and 3) a post manipulation session, all in the same day and lasting approximately 90 minutes in total.

Pretest session

The pre-manipulation session included the completion of the Interpersonal Reactivity Index (IRI, Davis, 1996), the explicit measurement and the first version of the Implicit Association Test (both described in 6.2.1). Since we administered the IAT test two times we created two parallel versions of the test (one with the paraplegic and positive combination first, version A; and one with the paraplegic and negative combination first, version B). Order effects are commonly reported in studies using the IAT and do not appear to impact the reliability and validity of this measure (Nosek et al., 2005). Nevertheless, the IAT versions were counterbalanced across participants in two ways to prevent methodological confounds. Participants who showed a positive bias toward walking people were randomly grouped into two groups, according to different experimental manipulation. Groups didn't show any difference in terms of age, gender and education (all ps > 0.5). Participants who did not show the bias ($n=10$) were excluded from the study, and did not take part to the other sessions of the experiment.

Manipulation

The interaction session was different for the two groups. Group 1 (i.e. social interaction group)'s interaction included a 45 min discussion session with a paraplegic patient (G.Z.) who participated in the study. G.Z., male, 42 years old, was recruited at Fondazione Santa Lucia Hospital in Rome, Italy. He had a traumatic spinal cord injury 760 days before the beginning of the study. The neurological injury level was determined using the American Spinal Injury Association (ASIA) international standards for the classification of spinal cord injury. An expert neurologist examined G.Z. and ascribed to him the AIS grade A. The interaction was built on a semi-structured plot conducted by G.Z. Different topics were treated along the talk, and time-to-time G.Z., had to show, or talk about, some limitations due to the disability.

Group 2 (i.e. passive interaction)'s interaction consisted in 45 minutes listening to an audio registration about some limitations due to the disability. The recording included 4 different topics. In particular, some clinical aspects of paraplegia (etiology, phases of spinal shock, sexual functioning), the use of technological tools (special cars, public transportation, home automation, the exoskeleton), and some examples of possible discomfort (the problem of architectural barriers and the social reintegration and employment) have been addressed in the recording. To ensure that subjects paid constant attention to the recording a short questionnaire about the topics was administered.

Post-manipulation session

The post interaction session included the second version of the IAT.

Data Handling

Performance on the IAT was scored using the algorithm fully described in 2.1.5 (Greenwald et al., 1998). Data were analyzed with a 2x2 analysis of variance (ANOVA) in which group (Group 1 vs Group 2) was the between subject variable and session (Pre manipulation vs. Post manipulation) was the within subject variable. A significance threshold of $p < .05$ was set for all statistical analyses. All pair-wise comparisons were performed using the Duncan's post hoc test. All behavioral data are reported in Figure 6.6.

One-way ANOVAs, with group as the between-subject variable, were conducted to test the group differences for the IRI and VAS subjective results. Moreover, correlations test were run to verify the influence of the subjective ratings on the IAT scores.

6.3 RESULTS

6.3.1 EXPERIMENT I

Difference in implicit biases between healthy, patients and therapists

The ANOVA for the IAT score (Figure 6.2) revealed significant differences across groups ($F_{(2,42)} = 12.41$; $p < .001$). The Duncan's post hoc test for multiple comparisons showed no differences in mean IAT scores between paraplegic patients and healthy controls (P = 0.34, H = 0.48; p = 0.81); meaning that both groups have an implicit positive bias for walking people.

Crucially, in therapists group IAT values (T = -0.11) were significantly different both from paraplegic patients (p <0.001) and healthy controls (p =0.002). This means that physical therapists showed an opposite implicit behavior compared to paraplegic patients and healthy subjects; i.e. they showed a strong implicit and positive bias towards paraplegic patients.

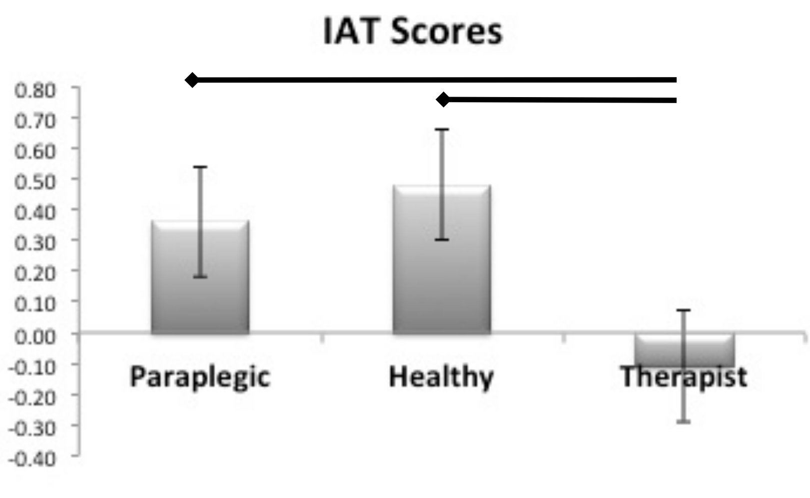


Figure 6.2 Difference in implicit bias between the groups. The IAT scores in three groups of subjects

(individuals with spinal cord injuries, healthy individuals and physical therapists) are reported. The error bars indicate the standard error of the mean (SEM). The black bars indicate significant results from the post hoc comparisons ($p < 0.05$).

Association between implicit bias and years of group-membership

Interestingly, we found a significant inverse correlation between the IAT scores of physical therapists and their years of working experience with SCI patients (mean = 8.7 years, $r = -0.63$; $p = 0.01$); meaning that the more they worked with patients the less they show the bias (Figure 6.3).

On the contrary there was no significant correlation between the IAT scores of SCI patients and the time since injury (mean = 7.7 years, $r = -0.28$; $p > 0.3$).

Figure 6.3 Association between implicit bias and years of group-membership in physical therapists. The IAT scores in physical therapists are negatively correlated with years of group's membership.

Difference in the explicit preference between the groups

The ANOVA for the explicit walking/paraplegic (Figure 6.4) preference revealed a significant effect of group ($p < 0.001$). In particular the Duncan's post-hoc test revealed that the group of physical therapists was the only one who did not show any kind of explicit preference (T = 0). This result differed both from healthy subjects, who showed the highest explicit preference for walking people (H = 4.6, p = 0.009), and from patients with SCI, who explicitly declared to prefer paraplegic patients (P = -4.6, p = 0.01). Moreover patients with SCI and healthy subjects differed from each other (p < 0.001) showing the opposite direction of explicit preference.

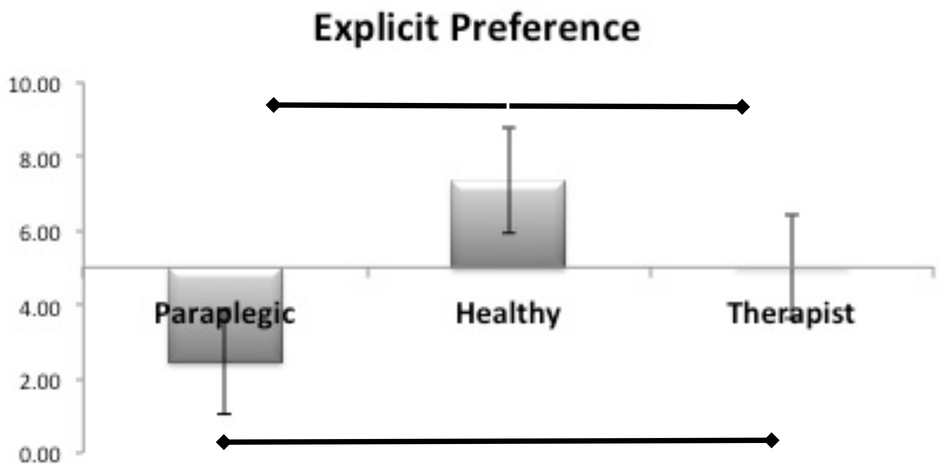


Figure 6.4 Difference in the explicit preference between the groups. The explicit preference score in three groups of subjects (individuals with spinal cord injuries, healthy individuals and physical therapists) is reported. The error bars indicate the standard error of the mean (SEM). The black bars indicate significant results from the post hoc comparisons (p < 0.05).

IRI

Concerning the IRI questionnaire results (Figure 6.5), the ANOVAs revealed a significant effect of interaction ($F_{(6,123)} = 4.23$, $p < 0.001$). In particular Duncan's post hoc test revealed that in Perspective Taking (P = 15.8, H = 20.7, T = 19.3) patients with SCI obtained significantly lower scores than healthy controls (p =0.003) and therapists (p =0.03), which did not differ from each other (p =0.4). Similarly, in Empathy Concern (P = 15.3, H = 19.8, T = 18.8) patients with SCI showed lower scores than healthy controls (p =0.006) and therapists (p =0.03), which again did not differ from each other (p =0.5). Differently, in the Fantasy

Scale (P =13.5, H =16.0, T=12.2) paraplegic patients showed similar scores both compared to healthy controls ($p = 0.14$) and therapists ($p = 0.36$), which differed from each other ($p = 0.02$). In the Personal Distress subscale (P =12.1, H =9.6, T =7.1) patients with SCI showed comparable scores with healthy controls ($p = 0.11$), but differed from physical therapists ($p = 0.001$), which did not differ from healthy controls ($p = 0.09$).

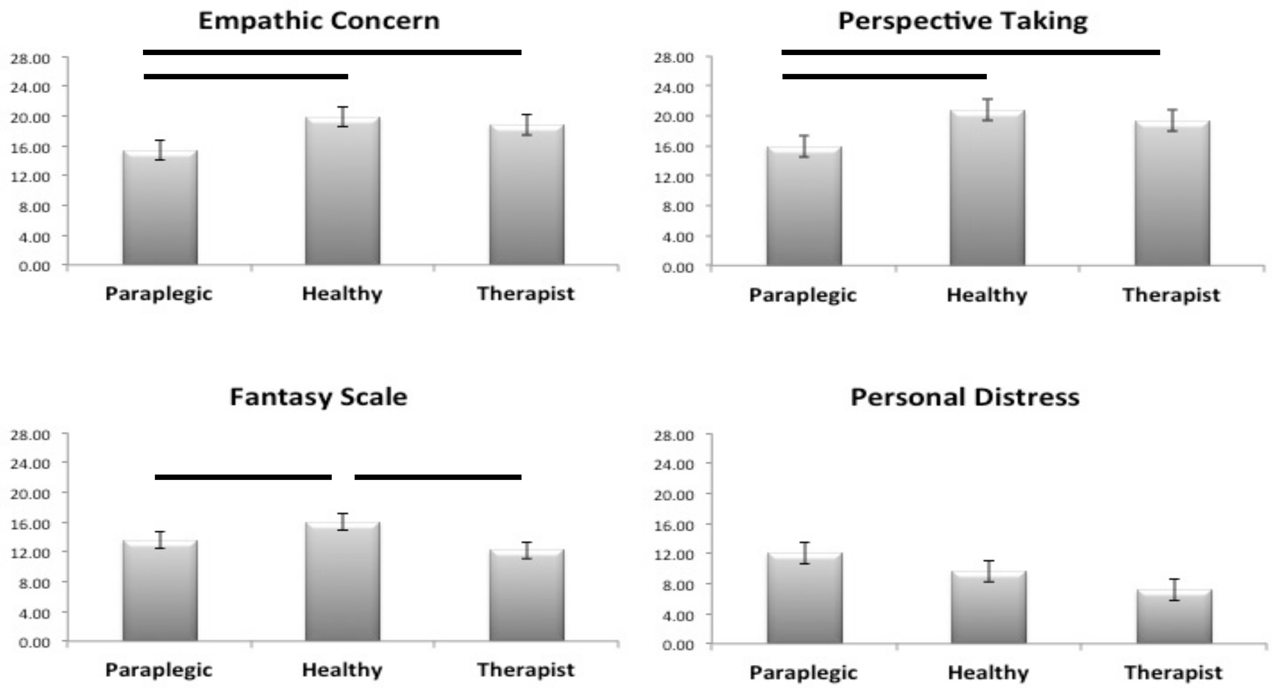


Figure 6.5 Difference in the Interpersonal Reactivity Index between the groups. The IRI scores in three groups of subjects (individuals with spinal cord injuries, healthy individuals and physical therapists) are reported, for the 4 subscales. The error bars indicate the standard error of the mean (SEM). The black bars indicate significant results from the post hoc comparisons ($p < 0.05$).

6.3.2. EXPERIMENT 2

IAT Scores

The ANOVA for the IAT scores (Figure 6.6) revealed a main effect of group ($F_{(1,28)} = 5.7$; $p = 0.02$) and a main effect of session ($F_{(1,28)} = 7.9$; $p = 0.008$) as well as a significant effect of interaction ($F_{(1,28)} = 4.65$; $p = 0.03$). The Duncan's post-hoc test for multiple comparisons, showed that in the pre test session the two groups did not differ from each other, showing the same implicit positive bias toward walking people (Group1 = 0.46, Group2 = 0.59; p = 0.51). Crucially, in the post session test, subjects who underwent the social active interaction showed a significant decreasing of their bias (Group1 = 0.05), which was different both from their bias in the pre test session (p = 0.001) and from the post session bias of subjects who underwent just the passive listening (Group2 = 0.54, p = 0.01). Moreover, subjects who underwent just the passive listening did not show any difference between the pre and the post session test (p = 0.64) confirming their bias.

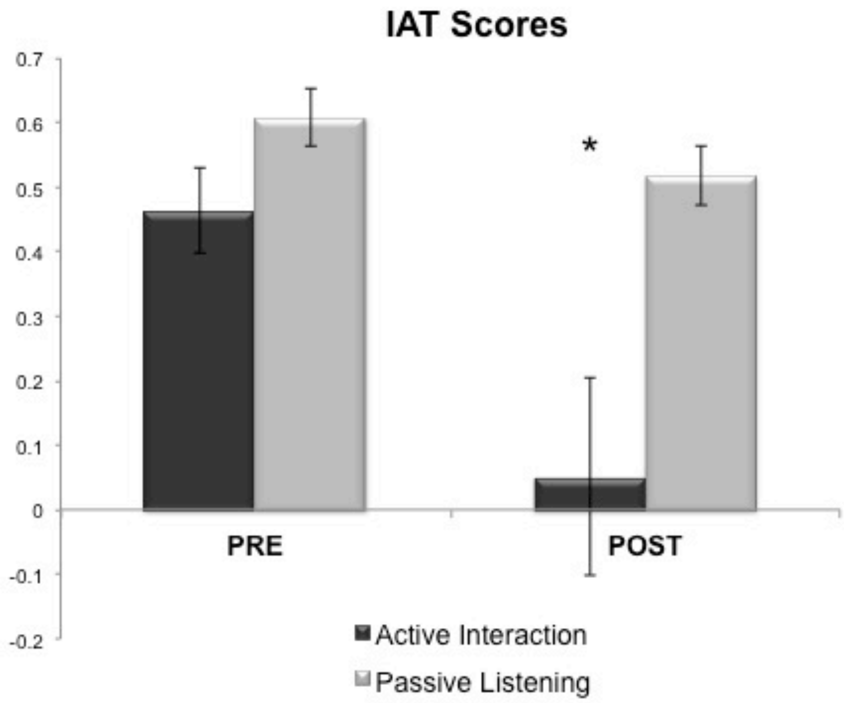


Figure 6.6 Difference in implicit bias between the two groups. The IAT scores in two groups of subjects (active interaction vs. passive listening groups) are reported. The error bars indicate the standard error of the mean (SEM). The asterisk indicates significant results from the post hoc comparisons ($p < 0.05$).

IRI & Explicit preference

IRI scores and VAS subjective ratings on explicit preference didn't show any significant difference between the two groups in both pre- and post manipulation session (all $p > 0.5$). No correlations were found between any of these variables and the IAT scores in the pre or the post session test.

6.4 DISCUSSION

The present study explored the presence of bias toward wheelchair-bound patients with spinal cord injury (SCI) and revealed four key findings, which importantly contribute to the implicit versus explicit manner of biases as well as to their plasticity. First, healthy participants do indeed show an implicit and explicit preference towards healthy subjects. Second, there is a dissociation between implicit and explicit in-group behavior in patients with SCI: while they explicitly declared an in-group preference they implicitly showed an out-group (i.e. healthy) preference. Third, physical therapists do not show any implicit or explicit bias and this effect is modulated by their actual experience with patients. Fourth, real and active social interaction leads to drastic changes of the bias, which has important real-life applications.

Together, our results suggest that thinking about disability is very different from the feelings we actually experience during interactions with individuals on a wheelchair. The opportunity to overcome disability prejudice through the promotion of pro-social inter/intra-group relationships is a challenging issue that can be used to promote the development of specific form of pro-social behavior.

Difference between implicit and explicit attitudes

Implicit (unconscious) and explicit (conscious) modes of thought have been often theorized as separate mental entities. The idea that the two constructs are essentially dissociated so that one component may drive in opposition to the other can be found in Freud's (1933) and in psychodynamic proposals about prejudice (Adorno et al., 1950; Bettelheim & Janowitz, 1949), but also in cognitive psychology and modern neuroscience. Unconscious cognitive processes have been deeply examined in the light of implicit and explicit mental processes (Kihlstrom, 1987; Schacter & Tulving, 1994). Theoretical and methodological developments have supported the interest in implicit social cognition, including implicit stereotyping and prejudice (Bargh, 1994; Devine, 1989; Greenwald & Banaji, 1995). Derived from models of the cognitive psychology, implicit prejudice can be defined as the automatic cognitive association between a social group and negative evaluation (Fazio, Jackson, Dunton, & Williams, 1995). A great deal of work has repeatedly supported the notion of dissociation between implicit and explicit attitudes, showing that implicit socio-cognitive processes have the ability to be qualitatively and quantitatively discrepant from explicit ones. These results suggest that although explicit attitudes are usually reflecting no bias, implicit attitudes are negative toward out-groups.

In our experiment healthy individuals who scored high in explicit preference, also scored high on the implicit one; similarly physical therapists which did not show any explicit preference, behaved consistently and coherently also in the implicit task. These data suggests that implicit and explicit attitudes may not be as dissociated as once thought. Recent findings have shown correlations between these types of measures (Cunningham et al., 2001; Gawronski, 2002; Kawakami et al., 1998; Lepore & Brown, 1997; Wittenbrink et al., 1997). Interestingly, these correlations can be highly variable depending on the particular attitude being measured (Nosek et al., 2002), the degree to which the attitude is elaborated (Nosek, 2004), motivation to control prejudiced reactions (Devine et al., 2002; Fazio et al., 1995), or the degree to which societal norms allow for the explicit expression of prejudice toward the group (Franco & Maass, 1999). In this sense, claim to have an explicit preference for walking people may be socially acceptable for our healthy participants, who have not felt the need to control their answers and to hide this preference when measured in a non-discriminatory way, free of negative connotations towards the out-group. Interestingly, this is not the case of studies on racial bias, where usually people feel very high motivations to consciously control their prejudice and a big difference between implicit and explicit is usually found.

On the other hand, patients with SCI behaved in a completely different way. They showed dissociation between implicit and explicit in-group behavior. In particular they explicitly declared to prefer paraplegic individuals (in-group preference) but implicitly showed a preference for walking ones (out-group preference). This might be due to the fact although it is well established that paraplegia results in dramatic lifestyle changes, little is understood about living in the community as an individual with SCI, especially from the first person perspective (O'Connor et al., 2004). Even if speculative we can draw some explanation to this dissociation. Although from the explicit and cognitive point of view most patients with SCI know to be in a new life condition (i.e. part of a new in-group) and consider themselves to be "individuals with a wheelchair" or "enwheeled individuals" (Papadimitriou, 2008); some may still consider themselves to be more close to the previous in-group (namely the walking people), if not from a physical point of view, at least from a psychological one. Moreover, despite their new physical condition, most patients with SCI continue to attend the environments and to meet the people who were used before the injury, which would help to strengthen the implicit and prior preference for walking people.

Our data suggest that although implicit and explicit attitudes may be dissociated when directly compared and may be discrete systems, a greater permeability between these systems of prejudice may exist. The bidirectional link between implicit and explicit attitudes may indicate that both implicit and explicit prejudices are part of a more general system of preference for one's own group relative to out-groups. Two plausible theories regarding the correlation between implicit and explicit attitudes claim (a) that implicit and explicit attitude measures tap the same attitude construct (single-factor hypothesis) and (b) that implicit and explicit attitudes are completely dissociated (full dissociation hypothesis). Further studies are still needed in this direction to evaluate the specific loading of both implicit and explicit aspects in the creation and extinction of the prejudice.

Experience-dependent effects on biases

Although health care professionals' negative attitudes toward disability may affect successful rehabilitation outcomes and reintegration into the community (Chubon, 1982; Paris, 1993), very little as been written about their personal perception on disability. A study from White & Olson (1998) showed that the majority of the healthcare professionals had positive attitudes toward people with disabilities. Despite this, people with disability often detect inappropriate staff attitudes and behaviors as the biggest obstacle to health services (Carter & Markham, 2001; Byron & Dieppe, 2009). The majority of these studies involved occupational therapy students but the literature on the influence of actual experience in shaping physiotherapists' attitudes is more restricted (French, 1994, 1995, 2000a, b, c; French and Swain, 1997). As part of the validation of the Interaction with Disabled Persons scale, Gething (1993) studied the attitudes of practicing physiotherapists towards disabled persons and emphasized the importance of the first interaction, highlighting that it is not the prior contact per se that is the critical factor, but the nature and dynamics of this interaction. Moreover, while practice setting, age and educational level has no significant effect on healthcare professionals' attitude scores, their actual experience seemed to be correlated with higher attitudes values (White & Olson, 1998).

To our best knowledge our study is the first one that allows an evaluation of both implicit and explicit attitude of physiotherapists towards people with disabilities. Different than normal healthy participants, physical therapists do not show an implicit or explicit bias towards their patients. Interestingly, the lack of bias is dependent on the amount of time working with these patients; the more they worked with patients the less they show the bias. Congruently, a recent study (Tervo et al., 2004) reported that years of experience and hours per week employed predicted comfort with challenging rehabilitation situations.

This finding supports the hypothesis that contact with disabled individuals influences attitudes in a positive way (Stachura and Garven, 2003; Vargo and Semple, 1988; Lyons, 1991; Gething, 1992; Oermann and Lindgren, 1995; Paris, 1993). Interestingly, a positive attitude refers also to the belief that people with disability can be productive community members. This expectation seems to be in the opposite direction compared to the SCM (Cuddy et al., 2007; Fiske et al., 2007; Fiske et al., 2002), which classified disabled people as low in the competence dimension. In this sense, physical therapists seem to be impermeable to the influence of the SCM.

A concrete application of the social contact hypothesis.

We are all influenced by social stereotypes (Devine, 1989). The first step toward a positive modification is to recognize negative thoughts and feelings and make a conscious effort to change them without being influenced.

Some studies inquired the behavioral effects of completing the IAT: being informed about our potential bias through a direct and concrete personal experience, such as that provided by the

IAT, may contribute to improve the consciousness of people toward their implicit behavior. Making people aware of their intergroup bias is a good first step toward reducing it (Devine, 1989; Monteith & Mark, 2005). Many discussions on prejudice reduction suggest that enhancing people's awareness of bias and of their limited control over their responses could cause them to better regulate their intergroup behavior, which in turn could have a beneficial effect on the signals they transfer to out-group members. Even if this is possible, it seems more likely that some other factors intervene.

The active contact between in-group and out-group members and the perception of a common identity have been indicated as useful strategies for the reduction of prejudice (Brown & Hewstone, 2005). Under some conditions, direct contact between members of different groups can reduce stereotyping, prejudice and discrimination. Allport (1954) has firstly described this phenomenon in his social contact hypothesis. When a member of a majority group meets with a minority group member and the experience is a positive one, an attitude change on two levels will result: a target-specific approach change and a new positive and generalized attitude toward the group as a whole. Initial assumptions about the other, which arise from the (negative) stereotypes, are replaced by more positive perceptions of the individual and its original group.

The contact hypothesis contains a long list of conditions for a successful contact (Amir, 1969, 1976). However, Pettigrew and Tropp (2000), in their meta-analysis of contact studies, have found that it is not necessary that all of Allport's conditions be present simultaneously for bias to be reduced. In our study the effect of a real, active, social interaction leads to drastic changes of the bias. Importantly, passively increasing knowledge about the disability did not lead to a similar result.

The hypothesis of the social contact has a great practical importance for interventions in the promotion of cross-categorical contact and the reduction of bias. Not only the positive and direct contact between members of different groups can reduce stereotyping, but also indirect contact can have positive effects on this reduction (Wright et al., 1997). Knowing that a member of our group has a contact with a member of the out-group seems to be sufficient to reduce prejudice. One of the limits of this theory is that individuals may activate mechanisms to neutralize the influence of dissonant and unexpected information arising from the positive contact (i.e. the use of cognitive explanations, the attribution of positive effects to external factors or the reduction of future interaction) making the positive contact with out-group members not effective or insufficient in the reduction of the negative attitude. Additionally organizing meetings among members of opposing groups raises both logistical and financial issues.

Despite these questions remain yet unanswered, we believe that the advantages of using the social interaction for an out-group contact are exceptionally promising. We have shown how even a short intervention, has the power of changing implicit bias and we advocate the introduction of inter/intra-group relationships as a vital part of both health care and social contexts. Interestingly, it remains still to investigate how stable and durable are these effects. This should also be investigated from a neuroanatomical point of view, for example, by exploring possible changes of the BOLD signal in brain areas of pain representation during observations of in-group/out-group members.

CHAPTER 7

GENERAL DISCUSSION

The impairment of the motor, sensory and autonomic systems in SCI can have a devastating effect on function (Yu, 1998) and tremendous efforts are undertaken to identify the clinically most important mechanisms involved in recovery after SCI. Studying the effects of sensory loss on body, action and tool representations, as well as social interactions, provides a glimpse into the role played by afferent information on the bodily self and related cognition. The general aim of this project was to explore the relation between the actual bodily states of patients with spinal cord injury and the possible changes in different aspects of cognition, affection and social behavior. We provided evidence that bodily states, such as the lesion level and the extensive wheelchair use, affect both the subjective experience of tool embodiment and the motor auditory mapping. Moreover, we showed that social preferences and personal interactions could be modulated by new interpersonal social dynamics. Taken together our results allow some important considerations.

7.1 Embodiment, disembodiment, re-embodiment

Most patients with SCI perceive that their legs are still their own (Lenggenhager et al., 2012), despite their inability to use or feel them (Cole, 2004). Although the patients do not confuse their body parts with their wheelchair (Nizzi et al., 2012), some do consider themselves to be “individuals with a wheelchair,” whereas others regard themselves as “enwheeled individuals” (Papadimitriou, 2008; Cole, 2004). This identity or “wholeness” discrepancy prompted us to investigate whether the somatomotor deafferentation/deefferentation of disconnected body segments and the exposure to/experience with the wheelchair, affects corporeal awareness of embodiment. To explore the presence of any such relationship, in Chapter 3 we presented a novel developed questionnaire regarding wheelchair-related feelings. We used a principal component analysis (PCA) to estimate the factors that are involved in the sub-aspects of tool embodiment in relation to lesion level. PCA revealed the presence of three major components. Among all participants included in the study, a significant number experienced the wheelchair as being internal to the corporeal boundary, so that the regular use of a wheelchair induces the perception that the body's edges are not fixed, but are instead plastic and flexible to include the wheelchair, suggesting a revision in the body image. Patients with lesions in the lower spinal cord, and loss of movement and sensation in the legs but spared upper body movement, showed a higher degree of functional embodiment than those with lesions in the upper spinal cord and impairment in the entire body. In the case of an upper spinal cord lesion, much more than in the case of a lower spinal cord lesion, there is a more pronounced reduction of strength and functionality in the entire body as well as an overall lack of feeling of touch. Such impairment interferes with the feeling of the wheelchair in direct contact with the body and with the regular status that updates the enwheeled body in motion. The corporeal awareness of the tool emerges not merely as an extension of the body but as a substitute for (and part of) the functional self. This assistive device offers the possibility, at least in principle, to partially "repair" the motor functionality of the damaged body part (Murray 2004; Pereira et al., 1996) and appears conceived not as an object to move but as a mediator of the limbs' action. This reorganization of the body model is consistent with the positive inclusion of the wheelchair to accommodate physical impairment and restore mobility (Papadimitriou, 2008; Standal, 2011; Arnhoff & Mehl, 1963; Higuchi et al., 2004, Higuchi et al., 2009; Merleau-Ponty, 2002). Since body representations take into account every perceptual input related to the body, it is reasonable to think that it should be plastic enough to update accordingly to slow and fast changes the body undergoes with time. A series of studies demonstrated a relationship between changes in the physical body structure and body representations at different levels (Serino & Haggard, 2010; Ramachandran et al., 1992; Farnè et al., 2002; Di Russo et al., 2006; Taylor-Clarle et al., 2004; de Vignemont et al., 2005; Tajadura-Jimenez et al., 2012; Tsakiris, 2010; Gandevia & Phegan, 1999). However, one of the best examples revealing a direct link between primary cortical activity at the level of the primary somatosensory cortex and body representation is indeed represented by deafferentation (Dijkerman & De Haan, 2007).

Altogether, data presented in Chapter 3 suggest that the subjective experience of the embodiment of an external tool in patients with SCI is a complex, multifarious process that requires the following: a feeling of ownership over the tool (including a long-lasting coherent and accurate representation); online multisensory integration, referenced on the state of the body (including the effective regulation of sensorimotor information flow); and, finally the self-attributed control of the physical body and its movement. One potential study limitation was the use of introspective data and PCA, which, although an elegant and powerful tool (Longo et al., 2008), needs to include empirical measures. Therefore, in the study presented in Chapter 4, we aimed to establish the effect of sensorimotor loss and specific use of wheelchair, on embodiment processes.

Many theories have proposed an association between the perception and execution of actions, suggesting that both are coded according to a common representational format (Prinz, 1997, Brass et al., 2001, Brass et al., 2000, Craighero et al., 2002, Kilner et al., 2003, Sturmer et al., 2000, Repp and Knoblich, 2007). Neural studies in healthy (Gazzola et al., 2006, Rizzolatti et al., 1996, Doehrmann et al., 2010) and brain-damaged (Pazzaglia et al., 2008) individuals indicate that action perception and execution rely on largely overlapping neural substrates. However, it is still unclear whether lifelong (mobility by lower limbs) and newly acquired (mobility by WHC) perceptual and motor experiences differently impact the integrity of action-perception mapping. In the study presented in Chapter 4, we address this issue by testing aural discrimination ability in different samples of participants using sounds that arose from wheelchair, upper limb, lower limb, and animal actions. Our results indicate that an inability to move the lower limbs in patients with SCI did not lead to impairment in the discrimination of lower limb-related action sounds. Importantly, patients with SCI discriminated wheelchair sounds better than individuals with comparable auditory experience (i.e. physical therapists) and inexperienced, able-bodied subjects.

Alteration of the action network involved in the perception of human motor acts may occur even in the absence of a cortical lesion, such as in blind (Ricciardi et al., 2009, Lewis et al., 2011), deaf (Alaerts et al., 2011) and SCI (Arrighi et al., 2011) individuals. These results prompted us to investigate whether the somatosensory deafferentation and motor deefferentation of specific body parts alter the audio-motor mapping of actions generated by the affected body part. In the visual domain patients with SCI exhibit reduced perceptual sensitivity when compared to the biological motion of the point-light displays of the entire body (Arrighi et al., 2011) and specific impairments in the visual perception of form and action in the disconnected body parts (Pernigo et al., 2012). However, data presented in Chapter 4 gave psychophysical evidence that paraplegic patients recognize lower and upper limb actions as efficiently as able-bodied individuals. Several mechanisms such as brain plasticity (Bunge et al., 1993; Bunge et al., 1997; Guest et al., 2005; Anderson et al., 2004; Cariga et al., 2002), motor mirroring (Costantini et al., 2005), reinforced memory (Nico et al., 2004), training exercises and motor imagery (Fiorio et al., 2006), may explain the preservation of perceptual signaling referred to the paralyzed portion of the body following SCI. The preservation of the perceptual ability in SCI patients suggests that the cortical regions involved in action simulation could play a compensatory role and facilitate the maintenance of intact audio-motor resonance in patients with impaired lower limb motor functions. Moreover, findings shown in Chapter 4 highlight the unique role of motor practice in learning ability. Individuals with SCI, when compared with auditory experts, can closely match aural perception with wheelchair-executed motion, enabling these patients to quickly extract and discriminate relevant WHC sounds. Visual and auditory wheelchair familiarity, although not fundamental, certainly plays a role in the discrimination of its sound. Although the physical therapists did not demonstrate the same ability as the wheelchair-bound subjects in recognizing the WHC sounds, the mere "observation/audition" ability of the wheelchair-bound subjects enhanced their WHC sound discrimination ability when compared with healthy subjects. The acquisition of motor skills through physical vs. perceptual practice may imply a highly selective coupling of perceptual-motor information. The striking effects of perceptual-motor practice with specific objects induce long-term structural changes in monkey (Quallo et al., 2009) and in human (Bassolino et al., 2010, Aglioti et al., 2008; Canzoneri et al., 2013) body representations. We believe that this action-dependent embodiment phenomenon is triggered from the changes in tool, action and body representations, documented by the present experiments. This proposal has been recently introduced by our group in the context of a neural network model designed to account for the decision process in the sound matching process, presented in Chapter 5.

The evidence that patients with SCI can distinguish WHC sounds from other distracting sounds more rapidly than individuals with no direct perceptual or motor wheelchair experience gives the empirical measure that was lacking in Chapter 3. SCI patients probably redefine or modify their motor abilities, appropriating the action schema to include the actual features of the wheelchair, so that the subjective personal experience of wheelchair embodiment descripted in Chapter 3, finds in Chapter 4 its functional translation. In individuals with SCI, the brain does not lose its perceptual ability to function properly. Instead, audio-motor associations appear to be modified and enhanced to incorporate external salient tools that now represent extensions of their body schemas. This particular example of neural plasticity is a formidable opportunity to forge novel treatments that intervene with new essential objects to regain and extend the potentiality of physically impaired individuals. The exclusive plastic effect of physical (as opposed to perceptual) learning on the development of new action perception abilities suggests that it is essential for people to experience close sensorimotor associations in order to forge new learning opportunities (Serino et al., 2007, Bassolino et al., 2010).

7.2 The importance of intergroup contact

Embodied accounts of social cognition argue that body representations play a causal role in sociocognitive processing (Gallese et al., 2004). These shared bodily representations for self and other may be particularly important for empathy and other core sociocognitive processes such as stereotype, as they can afford us a unique, first-person understanding of the experiences of others. People often report empathizing with the trials and tribulations of others. While some accounts characterize empathy as a general tendency that individuals possess to differing degrees, an alternative, understudied view is that empathy emerges out of similarity-driven matches between potential targets and empathizers. Actually, the activation of shared bodily representations for self and other has been shown to be modulated by whether the other person being observed is a member of in-group or out-group. The project presented in Chapter 6 examined whether these matches, even when not explicitly identified, influence social experiences, and whether this social relationship has consequences for implicit stereotyping toward people with disabilities. In two different experiments we explored the presence of stereotypes toward patients with spinal cord injury (SCI) and we then investigated if such hardwired biases could be modified by a personal interaction with an individual with SCI. Our findings revealed that SCI patients and healthy subjects showed an implicit preference toward healthy individuals and that the opposite was true for the therapists. In addition, we found that subjects who underwent a significant active social interaction showed a weaker and non-significant bias.

The effects of implicit bias have important implications for social cognition, sociocognitive processes, empathy, mental simulation and prosocial behavior. Results from our studies shows that social interaction is not only sensitive to the presence of stereotypes but is also shaped by actual interactions with others and, more specifically, by active social exchange with other people during the interaction. While previous work has shown that empathy can arise out of the dispositional tendencies that individuals possess, the current study demonstrates that previous social experience between individuals of different groups can influence social relations with- and evaluations of- out-group members. Active social contact between groups not only reduces the disability bias, but may also influence expectations for future relationship. Philosophical considerations as well as neurophysiology, neuropsychology, and behavioral evidence converged in showing that body representation is of fundamental importance for the individual, being the medium for every social interaction. It is worth noting, however, the relevance of emotional and motivational significance, such as previous experience, behaviors and knowledge about others. Our study opens up several lines of future research. First, it will be interesting to replicate the effect with different social groups and stereotypes. Second, our findings would be strengthened by replication using alternative measures of both implicit and explicit stereotype. Further research is also needed to investigate in more depth the nature of the implicit attitudes modulated by self-other bodily representation.

7.3 Concluding remarks

In order to entirely account for the different aspects of body experience involved in interaction with the environment, complex higher-level multimodal representations of the body in the brain must exist, supporting perceptual, motor and emotional functions, and, ultimately, underlying the experience of having a body and the ability of using that body to interact with the external world.

An unconscious body model, the body schema, which enables motor control and reflects the proprioceptive, tactile inputs of how the body is “felt”, may regulate the functional aspects of embodiment considerably. Indeed, the compensatory flexibility of wheelchair embodiment observed in patients with SCI is linearly linked to their ability to feel and move their body in the space again. The online information regarding movement in a wheelchair is a prerequisite for the capacity to feel that one’s own body generates the event and one has control over it. Indeed, an objective and quantitative evaluation of changes in patients with spinal cord lesions help identify the cause that may preclude the experience of self-attribution and embodiment of a tool. United harmony between the body and the tool may be key for the embodied experience of success or rejection of an assistive device. Embodying a wheelchair may enhance the efficiency and safety of movement, thereby reducing bodily effort and the damage produced by its use. This ease of use may lead to greater autonomy and self-organization, thus allowing patients to benefit from the opportunities offered by the environment in which they move.

The finding of preservation of audio motor representation after complete SCI has important implications for basic science research. A variety of experimental therapies are emerging to promote regeneration of the injured spinal cord, including the application of neurotrophic factors (Kwon et al., 2002), drug therapy (Baptiste and Fehlings, 2006), and cell-based therapies (Guest et al., 2005). If regeneration of the injured spinal cord, and thus reconnection of the brain to the muscles, is possible, it is vital that the brain must still be able to activate in a way that will generate movement. Specifically, the capacity to embody new objects may extend an individual’s physical impaired ability and remains a potentially unexploited resource for the growing population of those who are severely disabled.

Most of the studies presented in this dissertation investigated how the representation of action and body changes as a function of interaction with an artificial object. Critically, in everyday life the distinction between successful and unsuccessful exchange is meaningful not only in terms of object interaction, but mainly in terms of social interaction. The hypothesis that social contact decreases implicit negative stereotype has great practical importance for interventions in the promotion of cross-categorical contact and the reduction of bias. Not only the positive and direct contact between members of different groups can moderate stereotyping, but also indirect contact can have positive effects on this reduction (Wright et al., 1997). Negative implicit attitudes towards out-groups are formed at an early age, and remain relatively stable throughout adulthood (Baron & Banaji, 2006). We have shown that inducing intergroup contact may attenuate these persistent implicit social biases, altering the perceived boundaries between in-group and out-group. Our results begin to 'bridge the gap' between the basic, perceptual representation of self and other, and the complex social mechanisms underlying much of our everyday social interaction.

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APPENDIX A

Additional clinical information about spinal cord injury

In all complete spinal cord lesions, sensation is lost below the level, and because people do not feel they can injury themselves without awareness. They have to be aware of skin care to prevent burns and, especially, pressure ulcers. In addition there are a number of other functions altered or lost because of spinal cord injury. Temperature regulation can be a problem, because patients cannot shiver, sweat, or control blood vessels' dilatation and constriction below their level. The latter may also be the reason for autonomic dysreflexia. Cervical spinal cord injury leads to a brief initial period of hypertension, caused by the release of epinephrine and norepinephrine from the adrenal medulla. This is followed by the autonomic equivalent of the spinal shock, in which sympathetic activity is greatly reduced. Cardiovascular manifestations include hypotension and bradycardia, as a result of demised sympathetic outflow from thoracic segment. Over a longer time, spinal sympathetic reflexes become hyperactive, and autonomic dysreflexia commonly develops. Noxious stimuli that would normally cause a moderate sympathetic response lead instead to massive vasoconstriction and potentially life-threatening hypertension (Vaccaro & Fehlings, 2010). A large increases in blood pressure can suddenly occur, which present as severe headache and sweating over the forehead caused by dilatation of the normally controlled blood vessels of the head and neck, connected to the brain by the intact cervical cord, in response to a rise in blood pressure following a problem in the area of body below the level of the lesion. Bladder dilatation is a potent cause of this but some people have dysreflexia during rehabilitation when they are first raised to the vertical. This is a medical emergency, with stroke a real possibility if the blood pressure is not immediately reduced. The rise in blood pressure is all the worse because tetraplegics normally live with lower blood pressure than able-bodied people. Also muscle spasms can be a real problem in those with lesions above the lumbar cord. Initially after spinal injury there is a loss of all reflex activity, known as “spinal shock”. But then, over months, reflexes become abnormally active, which can lead to huge spasms in response to relatively innocuous stimuli. Lastly, people with spinal cord injury have to live with a variety of pain. Roughly 60-65 percent of people have pain, and in 20-25 percent is severe. This may reflect damage to the nerve roots at the site of the lesion, or elsewhere. Later it may also be the result of shoulder arthritis after years of transfers to and from the chair, for example. Lastly, among the most troubling types of pain are “neuropathic pain” and “phantom pain”, perceived in the area of the body below the level of the cord damage in an area that cannot be usually felt.

TABLE 3.1

DEMOGRAPHIC AND CLINICAL DATA OF THE PATIENTS										
Case	Age	Gender	Time since Injury (days)	Time since wheelchair utilization (days)	Daily wheelchair use (hours)	Lesion Level	AIS grade	Etiology	SCIM Self-Care (0-20)	SCIM Mobility (0-40)
P1	26	F	3350	3260	10	C3	A	Traumatic	0	3
P2	30	M	2550	2450	10	C4	A	Traumatic	0	3
P3	40	M	730	715	15	C4	D	Traumatic	20	20
P4	24	M	1654	1530	11	C4	B	Traumatic	1	6
P5	30	M	4015	3960	15	C5	A	Traumatic	18	14
P6	35	M	258	195	10	C5	A	Traumatic	4	6
P7	29	F	8395	8310	10	C5	C	Traumatic	-	-
P8	29	M	540	450	12	C5	A	Traumatic	13	13
P9	40	M	980	920	10	C5	A	Traumatic	4	5
P10	25	M	975	900	15	C5	A	Traumatic	12	11
P11	22	M	420	350	11	C5	A	Traumatic	11	11
P12	31	M	3650	3600	14	C6	A	Traumatic	14	16
P13	40	M	6570	6500	15	C6	A	Traumatic	18	16
P14	54	F	8230	8160	12	C6	A	Traumatic	11	11
P15	29	M	4015	3920	15	C6	C	Traumatic	18	14
P16	31	M	530	495	13	C6	A	Traumatic	11	11
P17	29	F	750	690	10	C6	C	Traumatic	5	6
P18	52	F	3650	3550	10	C6	A	Traumatic	9	10
P19	61	F	9000	8930	14	C6	A	Traumatic	15	14
P20	40	M	400	310	10	C6	A	Traumatic	0	3
P21	41	M	3900	3825	15	C6	A	Traumatic	18	16
P22	36	F	4000	3940	14	C6	A	Traumatic	13	14
P23	22	F	3900	3830	14	C6	A	Traumatic	-	-
P24	65	M	230	190	10	C7	C	Traumatic	5	6
P25	22	M	290	230	10	C7	D	Traumatic	20	19
P26	47	M	1095	995	10	C7	D	Neoplastic	5	6
P27	62	F	300	260	10	T2	A	Myelitis	12	9
P28	34	M	240	215	13	T3	A	Traumatic	17	15
P29	42	M	1170	1140	11	T3	A	Traumatic	18	15
P30	47	M	2400	2330	11	T4	A	Traumatic	19	16
P31	56	M	2100	2020	13	T4	A	Traumatic	19	16
P32	53	M	10220	10160	14	T4	A	Traumatic	14	9
P33	72	F	188	160	11	T5	C	Traumatic	12	9
P34	44	M	6040	5985	15	T5	A	Traumatic	20	19
P35	63	M	4000	3880	10	T5	A	Neoplastic	20	15
P36	39	F	3850	3710	14	T5	A	Traumatic	20	19
P37	35	M	6770	6700	16	T7	A	Traumatic	20	19
P38	31	M	450	380	12	T7	A	Traumatic	20	17
P39	42	M	4945	4885	16	T8	A	Traumatic	20	19
P40	39	M	5840	5760	15	T8	A	Traumatic	19	16
P41	42	M	1170	1070	14	T9	A	Neoplastic	20	18
P42	42	M	4380	4320	15	T9	A	Traumatic	20	19
P43	19	M	789	750	14	T10	A	Traumatic	20	19
P44	42	M	960	925	15	T10	A	Traumatic	20	19
P45	35	M	590	520	11	T10	A	Traumatic	20	19
P46	27	M	1200	1170	14	T10	A	Traumatic	20	16
P47	40	M	4015	3865	15	T11	A	Traumatic	20	19
P48	47	M	2190	2140	15	T11	A	Traumatic	20	15
P49	39	M	3256	3195	14	T11	A	Traumatic	20	19
P50	49	F	450	410	11	T12	A	Traumatic	18	15
P51	38	M	2057	2000	15	T12	A	Traumatic	20	19
P52	29	M	2190	2160	16	L1	A	Traumatic	20	21
P53	56	M	600	540	10	L1	C	Traumatic	17	13
P54	34	M	1100	1055	12	L1	D	Neoplastic	20	21
P55	68	M	4745	4685	10	L1	A	Traumatic	17	17
Range	19 - 72	12 F - 43 M	188 - 10220	160 - 10160	10 - 16	C3 - L1	A - D	-	0 - 20	3 - 21
Mean	39.92		2768.76	2701.72	12.67				14.84	13.88
SD	12.65		2540.82	2533.73	2.15				6.42	5.17

Table 3.1. Clinical and demographic characteristics of patients with SCI. The neurological levels of the lesion and injury, as determined by the American Impairment Scale (AIS), are indicated. Spinal Cord Independence Measure (SCIM) scores were not available for patient nos. 12 and 25.

Statement	Scores		Communalities		
	Mean	Standard deviation	1° component	2° component	3° component
[BI1] Diet:	3.18	2.15	0.11	0.57	0.58
BI2] Maintenance	4.45	2	0.004	0.71	0.71
BI3] Defense	4.03	2.37	0.0001	0.62	0.63
[BI4] Awareness:	5.6	1.98	0.03	0.06	0.35
[BI5] Tool:	3.2	2.38	0.27	0.28	0.50
[BE1] Entire body	2.6	2.34	0.005	0.03	0.33
[BE2] Lower limbs	3.38	2.58	0.45	0.48	0.62
[BE3] Substitution	3.74	2.77	0.57	0.57	0.60
[BE4] Extension	1	1.74	0.21	0.21	0.77
[BE5] Action	5.12	2.24	0.11	0.40	0.49
[LL] Lesion Level	10.89	5.68	0.42	0.43	0.44

Table 3.2: Scores and Communalities to questionnaire statements

LIST OF SOUNDS

Upper Limb	Lower Limb	Wheelchair	Animals
Clapping hands, single human	Footsteps, man	WHCM being rolled down a hallway	Pigeon flying
Clapping hands, group	Footsteps, woman	WHCM being rolled, solid ground	Insects flying
Knocking on door	Running, hard surface	Keys opening door	Dog walking
Writing on chalkboard, quick	Running, solid ground	WHCM braking 1	Horses galloping, slow
Writing on chalkboard, slow	Running, group	WHCM braking 2	Horse galloping, solid ground
Scratching, quick	Footsteps, solid ground	Bicycle	Herd passing
Typing on computer keyboard	Going down wooden stairs, quick	WHCM rattle, cement surface	Horses trotting, soil
Typing on computer keyboard, fast	Going down stairs, hard surface	WHCM rattle, wooden surface	Horse trotting, quick
Drumming fingers	Footsteps, quick	Film projector	Cows moving
Scratching	Dancing, tapping fast	WHCM movement, slow	Birds flying
Scratching, fast	Dancing, tapping slow	WHCM rattle, wooden surface	Bird flying
Writing with chalk	Going up the stairs, quick	Zip fastener	Rattle snake rattling
Snapping fingers	Marching, group	WHCM rolling, indoor	Dog digging 1
Snapping finger	Marching, single human	WHCM rolling, hard uneven surface	Dog digging 2
Cracking fingers	Dancing, flamenco	Bowling ball	Dog footstep
Drumming fingers	Running, outdoor	WHCE braking 1	Horse galloping, slow
Drumming finger	Running, indoor	WHCE braking 2	Horse galloping, indoor
Typing on computer keyboard	Dancing, tip tap	Elevator	Dog running around
Cracking finger	Going up stairs, indoor	WHCE moving changing from high to lower speed.	Horses galloping, solid surface
Cracking knuckles	Going up stairs, outdoor	WHCE moving changing from a low to a higher speed	Horse gallop, solid surface
Snapping finger	Marching, slow	Coffee machine	Hoofed animal stampede
Hands drumming, quick	Footsteps, broken glasses	WHCE moving, solid ground	Bird flapping
Hands drumming	Footsteps, wooden surface	WHCE going back and forth	Butterfly flapping wings
Hands clapping	Going up stairs, man	Scooter	Horse trotting slow
Applause, medium crowd	Running, wet surface	WHCE turning on and accelerating fast	Horse galloping, indoor
Hands clapping, single human	Running, gravel	WHCE turning on and moving	Horses galloping, soil
Tapping fingers, multiple	Footsteps, wet surface	Hairdryer	Zebra trotting
Knocking on wooden door	Going up stairs, quick wearing tennis shoes	WHCE moving, solid ground	Bat flapping wings
Knocking on metal door	Going up wooden stairs, quick	WHCE accelerating	Hen flapping
Tapping fingers	Running, wearing tennis shoes	Scooter	Dog panting

Table 4.2 List of the sounds of the auditory discrimination action task described in Chapter 4. A complete list of the category of 10 sets of three sounds used in the matching-to-sample auditory discrimination action task described in Chapter 4 is provided. Each sound depicts upper (U_{RAS}) and lower (L_{RAS}) limb-related action sounds, wheelchair-related action sounds (W_{RAS}), and animal action-related sounds (A_{ARS}). In each category, the sample, the matching and the non-matching sound stimuli are indicated in the first, second and third rows of each of the 10 sound sets, respectively. The sounds were chosen on the basis of two psychophysics studies. During the test-creation phase, healthy subjects who did not subsequently participate in the study listened to each sound and assessed how easily it could be identified. The selection of the auditory stimuli was based on the results of a preliminary psychophysics study involving 20 healthy participants (11 men, 22–34 years of age). Each

participant listened to each sound and chose between two verbal tags. Only one tag correctly described the sound; the other tag was used as a realistic distractor. Only the sounds that were correctly matched by at least 80% of the participants were used in the subsequent study. Ten groups of three sounds formed every trial set for each sound action category that was chosen for use in the final test. The test performances of 10 healthy participants (3 men; mean age, 23.6 ± 4.8 years) were assessed. No differences were observed in the recognition rate of the U_{RAS} (mean, 88%; range, 70–100%), L_{RAS} (mean, 85%; range, 75–91%), W_{RAS} (mean, 80%; range, 70–100%), or A_{RAS} (mean, 90%; range, 75–100%) action sounds ($P > 0.8$).

Overview of Publications Status

Chapter number	Original text (Not published Before)	Submitted: No Feedback Received	Submitted: Revision Requested or Revision Submitted	Accepted or Published
Chapter 1 Phenomenology of spinal cord injuries: a brain body disconnection	X			
Chapter 2 Theoretical background	X			
Chapter 3 A functionally relevant tool for the body following spinal cord injury				X (Plos One)
Chapter 4 Embodying functionally relevant action sounds in patients with spinal cord injury		X (Cortex)		
Chapter 5 A computational model on perceptual-motor process of action-related sound	X			
Chapter 6 Don't look at my wheelchair: changing people's bias through social interaction		X (Cognitive, Affective and Behavioral Neuroscience)		
Chapter 7 General discussion	X			

Other Papers:

1) **Galli G**, Noel Cue JP, Blanke O, Serino A. The role of spatial exploration and tool use in full body peripersonal space representation. *In prep.*
2) **Galli G,** Scivoletto G, Molinari M, Pazzaglia M. Body part mental rotation in patients with spinal cord injury. *In prep.*
3) **Galli G**, Scivoletto G, Felici L, Molinari M, Pazzaglia M. Verbal markers of pain in patients with spinal cord injury. *In prep.*
4) Salomon R, **Galli G**, Bello Ruiz J, Blanke O. Full body illusion modulates access to visual consciousness in a continuous flash suppression task. *In prep.*
5) Pozeg P, **Galli G**, Blanke O. Crossmodal congruency effect and first person point of view as measures of virtual leg illusion. *In prep.*
6) Pazzaglia M, **Galli G**, Aglioti SM. Body part-specific emotions influence action recognition in apraxic patients. *In prep.*
7) Pazzaglia M & **Galli G**. Crossmodal correspondences as a cue for neglect rehabilitation. 2013. *In prep.*