PHANTOM LIMBS, THE SELF AND THE BRAIN (THE D.O. HEBB MEMORIAL LECTURE)

RONALD MELZACK
McGill University

ABSTRACT

A phantom limb is universally experienced after a limb has been amputated or its sensory roots have been destroyed. A complete break of the spinal cord also often leads to a phantom body below the level of the break. Furthermore, phantom breasts, genitals and other body areas occur in a substantial number of people after surgical removal or denervation of the body part. The most astonishing feature of a phantom limb (or other body area) is its incredible "reality" to the person. An examination of phantom limb phenomena has led to four conclusions: the experience of a phantom limb has the quality of reality because it is produced by the same brain processes that underlie the experience of the body when it is intact; neural networks in the brain generate all the qualities of experience that are felt to originate in the body, so that inputs from the body may trigger or modulate the output of the networks, but are not essential for any of the qualities of experience; the experience of the body has a unitary, integrated quality which includes the quality of the "self"—that the body is uniquely one's own and not that of any other individual; the neural network that underlies the experience of the body-self is genetically determined but can be modified by sensory experience. A new theory has been developed to explain these conclusions. It is proposed that we are born with a widespread neural network—the "neuromatrix"—for the body-self, which is subsequently modified by experience. The neuromatrix imparts a pattern—the "neurosignature"—on all inputs from the body, so that experiences of one's own body have a quality of self and are imbued with affective tone and cognitive meaning. The theory is presented with supporting evidence as well as implications for research.

The field of psychology is in a state of crisis. We are no closer now to understanding the most fundamental problems in psychology than we were when psychology became a science a hundred years ago. Each of us is aware of being a unique "self," different from other people and the world around us. But the nature of the "self," which is central to all psychology, has no physiological basis in any contemporary theory and continues to elude us. The concept of "mind" is as perplexing as ever: Descartes' 17th century view of a non-physical mind that acts on a physical brain is still the most pervasive theory, despite its inherent inconsistency with contemporary physiological psychology (Hebb, 1980). The stagnation in psychological theory is underscored by the current status of the heredity-environment ("nativist/empiricist") controversy; even though the problem is basic to an understanding of knowledge and what we mean by "reality," we are no further ahead than Locke and Kant were in the 17th and 18th centuries.

Our inability to make any headway in understanding these essential problems reflects the state of psychological theory. There is a profusion of little theories—theories of vision, pain, behaviour-modification, and so forth—but no

---

This paper is based on an invited address to the Canadian Psychological Association, Vancouver, June 1987, as recipient of the 1986 CPA Award for Distinguished Contributions to Psychology as a Science. This paper is part of a book now being written.

The research reported here was supported by grant A7890 from the Natural Sciences and Engineering Research Council of Canada.

Requests for reprints should be sent to Ronald Melzack, Department of Psychology, McGill University, 1205 Dr. Penfield Avenue, Montreal, Quebec, Canada, H3A 1B1.

Editor's note: Comments on this article are especially welcome, and will be considered for publication in the Correspondence/Courrier section along with a rejoinder from Ronald Melzack.

Annotation du rédacteur: nous invitons vos commentaires au sujet du présent article et nous examinerons la possibilité de les publier dans la section Correspondance/courrier avec une réplique de Ronald Melzack.

broad unifying concepts. Recent histories of psychology (e.g. Leahey, 1980) have recorded the rapid decline of behaviourism as a useful theory. Cognitive psychology has recently been proclaimed as the revolutionary concept which will lead us away from the sterility of behaviourism. The freedom to talk about major psychological topics such as awareness and perceptual illusions does, indeed, represent a great advance over behaviourism. But on closer examination, cognitive psychology turns out to be little more than the psychology of William James published in 1890; some neuroscience and computer technology have been stirred in with the old psychological ingredients, but there have been no important conceptual advances. Hebb's theory, proposed in 1949, was a powerful refutation of Skinner's (1938) radical behaviourism but stopped short of providing a conceptual breakthrough in our ideas about mind; basically, it remained true to classical stimulus-response (S/R) behaviourism, even though it added a more complex brain between S and R than had previously been posited. In historical perspective, then, psychological theory is at a standstill. This does not mean that psychologists have not been active; there are masses of new "facts" which continue to pour out steadily in the journals. But there is no conceptual model to provide a coherent framework for the data. We are adrift, without the anchor of neuropsychological theory, in a sea of facts—and practically drowning in them. We desperately need new concepts, new approaches.

New avenues to an understanding of the self, the mind, and reality are provided by the consideration of the "phantom limb" which is experienced after the loss of an arm or leg. A commonly heard statement made by amputees, for example, is: "I continue to feel my leg as vividly as I felt my real leg and I often feel a burning pain in my foot." When a person says "*my* leg," that implies a "self." "I feel a burning pain in my foot" implies awareness. Furthermore, amputees report that the phantom limb has a position in space and feels "normal"; they say that the limb is sometimes sweaty, cold, wet, or itchy in particular places; the majority of them suffer burning, shooting or cramping pains. How can we have such "normal," "real" qualities in the absence of any input? In an attempt to find a new approach to understanding phantom limbs, I will first describe their basic properties and then, because no contemporary theory comes even close to explaining the phenomena, I will propose a new concept of brain function and discuss its implications.

The Nature of Phantom Limbs

There are three kinds of phantom limb phenomena: the experience of a limb (or other body part) after it has been amputated, the experience of an arm after its sensory roots to the spinal cord have been destroyed, and the experience of the legs and body below the level of a complete break of the spinal cord. So much is now known about phantom limb phenomena that I will attempt to synthesize the data and their implications in the form of a series of conclusions. In the next section I will turn to our knowledge of brain function for an explanation of the phenomena.

The Reality of Phantom Limbs

The most astonishing feature of the phantom limb is its incredible "reality" to the amputee (Simmel, 1956). Its vivid sensory qualities and precise location in space, particularly when it is first experienced after amputation, are so real to the person who feels it that he may try to step off the bed onto the phantom foot or lift a telephone receiver with a phantom hand. One's phantom, in fact, may be experienced as more "real" than the real limb because it has a tingling or "pins-and-needles" quality that, initially at least, makes it highly salient. A painful phantom, of course, develops an overwhelming presence in the patient's awareness. The amputee with a painless phantom, however, may find that the reality of the phantom is enhanced by wearing an artificial arm or leg; the phantom usually fills the prosthesis "like a hand fits into a glove"; the prosthesis feels real, "fleshed out." Amputees in whom the phantom leg has begun to "telescope" into the stump, so that the foot is felt to be above floor level, report that the phantom fills the artificial leg when it is strapped on and the phantom foot now occupies the space of the artificial foot in its shoe (Riddoch, 1941).

The remarkable reality of the phantom is reinforced by the experience of details of the limb before amputation. For example, the person may feel a painful corn or bunion that had been on the foot. The phantom of a crippled leg may, after amputation, feel disfigured in the same way the real leg had been. Even minor aspects of the limb are felt, such as a ring on a phantom finger.

More alarming to patients with Parkinson's disease is that, after a limb is amputated, it is felt to have a tremor like that experienced in the real limb before amputation. Still more astonishing is the fact that amputees who receive drugs that produce the tremor of tardive dyskinesia report a tremor in the phantom (Jankovic & Glass, 1985).

Although the majority of patients feel the phantom arm as lying straight down at the side, the phantom usually moves, when the person walks, in perfect coordination with the other limbs; that is, it behaves and feels like a normal limb. Similarly, the phantom leg bends as it should when a person sits on a chair, stretches out when the person lies down on a bed, or becomes upright when the person stands up. In some people, the arm is continuously felt in an abnormal position and cannot voluntarily be moved into a more comfortable one. In one person, the phantom arm was felt to extend straight out at the shoulder and at a right angle to the body; the phantom was so vivid that he turned sideways to walk through a doorway so that the phantom would not hit the wall. Another person, whose phantom arm was felt behind his back, slept only on his abdomen or a side but could not sleep on his back because his phantom arm was in the way (Poeck, 1964, 1969).

Phantoms of other body parts feel just as real as limbs do. Heusner (1950) describes two men who underwent amputation of the penis. One of them, during a 4-year period, was intermittently aware of a painless but always erect phantom penis. The other man had severe pain of the phantom penis; he was "constantly aware of his pain and had often to check...a pressing desire to reach out into extrapersonal space and squeeze the apparition's tip for relief" (p. 129). Phantom bladders and rectums have the same quality of reality (Bors, 1951; Dorpat, 1971). The bladder may feel so real that patients, after a bladder removal, may keep complaining of a full bladder and even report that they are urinating. One woman, after years of pain due to bladder infections, underwent a surgical excision of the bladder but still reported feeling a distended bladder and continued to suffer the same kinds of pain. The same quality of reality is described by people with a phantom rectum, so that they may actually feel that they are passing gas or feces. The painless phantom breast after a mastectomy, in which the nipple is the most vivid part, is usually a pleasant experience because the phantom breast seems to fill out the padded brassiere and feels extremely real. However, pain in the phantom breast becomes distressing (Weinstein, Vetter & Sersen, 1970).

After a brachial plexus avulsion, in which all the sensory roots from the arm are ripped from the spinal cord, the phantom "fills" the totally insensate arm and hand and may feel normal except that movement is not possible (Wynn-Parry, 1980). The painless phantom occupies the arm and is perfectly coordinate with it. Telescoping of the phantom does not occur in these patients (presumably because visual information indicates that the limb is still present) and they may deny having a phantom because, apart from the absence of movement, the arm and hand feel so alive and real. However, dissociation occurs after the arm is moved while the patient's eyes are closed so that, when he opens them, the arm is seen to be in a position other than the one he felt with the eyes closed. People who feel a phantom after an anaesthetic block of the brachial plexus provide further testimony to the reality of the phenomenon. The tendency of the phantom to be felt vividly in one of two positions (at the side or above the chest) makes it a shock to discover that it was moved (when the eyes were closed) to a position above the head and out of sight when the eyes were opened (Melzack & Bromage, 1973). Then the phantom is suddenly felt to reside in the arm—in fact, *is* the arm (even though nothing is felt when the skin is touched or pinched).

Finally, paraplegics and quadriplegics who suffer a complete break of the spinal cord, so that they have no feeling or voluntary movement below the level of the break, usually report that they still feel their legs and lower body (Bors, 1951; Conomy, 1973). The reality of their experience is indicated by their frequent denial that they have a "phantom body." The phantom appears to inhabit the body, is perfectly coordinate with it and, when the person's eyes are open, the experienced body (that is, the phantom) behaves in perfect coordination with the movements of the body. The dissociation between the two is usually realized only when the legs fall off the side of the bed in the dark, or the body is moved without the person being told about it or able to see it. The dissociation also occurs when activity is *felt* to occur in the genitals or rectum but none takes place. A man may feel that he has an erect penis yet find (when he looks) that the penis is lying flaccid; alternatively, he may see the penis to really be erect, but feel nothing whatever (Bors, 1951). Yet, astonishingly, quadriplegics with a complete spinal break may report that erotic dreams are accompanied by the experience of an orgasm (Money, 1960). Furthermore, stimulation of the nipples or other skin tissue above the level of the break, together with erotic fantasy or actual activity with a partner, may produce the experience of an orgasm in the genital area that feels just as an orgasm felt before the spinal injury (Verkuyl, 1969). The multitude of qualities of feelings experienced by amputees and paraplegics reinforces the reality of the phantom.

My conclusion from these data is that the phantom represents our normal experience of the body. It is not a pathological entity due to a psychological abberation, or due to an abnormal functioning of the brain. It is the body we always feel, but without the input that normally modulates the central neural processes that produce the experience. The tingling, strange positions, pain and other abnormal aspects are due to the absence of input to a neural network which I will describe later. But that neural system exists within the brain even when the body input is cut off by amputation, nerve avulsion or spinal break. It is evident that our experience of the body can occur without a body at all. We don't need a body to feel a body. The experience of the body is produced by networks in the brain, which are normally triggered or modulated by inputs from the body. An analogy is the power of a car which derives from the engine, not the gas pedal.

Conclusion 1. The experience of a phantom limb has the quality of reality because it is produced by the same brain processes that underlie the experience of the body when it is intact.

The Qualities of Phantom Limb Experience

Descriptions given by amputees and paraplegics indicate the range of the qualities of experience of phantom body parts (Riddoch, 1941). Touch, pressure, warmth, cold and many kinds of pain are common. There are also feelings of wetness, sweatiness, roughness (as when the artificial foot steps on pebbles). There is itchiness of the foot—which can be extremely distressing and evoke an intense desire to scratch (actual scratching movements may sometimes relieve the itch)—as well as tickle, tingling, pins-and-needles, formication (like ants crawling on the skin of the phantom limb). Male quadriplegics report feeling erections and women describe sexual sensations in the perineal area. Both describe feelings of pleasure, including orgasms. In addition, they often report sensations that characteristically come from the rectum and bladder. Paraplegics may complain of painful fatigue and beg the nurse to stop their legs from making continuous cycling movements even though their legs are lying immobile on the bed (Conomy, 1973).

There is increasing evidence that the sense of effort originates in the brain command and the evidence obtained with amputees and paraplegics makes it clear that the experiences of effort and fatigue are not solely the result of inputs from the body but from the outputs of a brain process that can be modulated by bodily inputs. Powerful supporting evidence is provided by the observation that the brain "knows" (shows a characteristic electroencephalographic pattern) that the incorrect command to perform a particular response in a test situation has been given even before the response is made (Gevins et al., 1987). In other words, feedback is not necessary; all of the relevant activity goes on in the brain.

The incredible range of qualities of experience felt by patients after amputation or denervation of parts of the body indicates that the origin of the qualities of experience is not from peripheral inputs but from central processes that are built into the brain. They produce characteristic patterns that underlie the qualities of experience. Sensory inputs may trigger or modulate the patterns but are not essential for their production.

Conclusion 2. Neural networks in the brain generate all the qualities of experience that are felt to originate in the body; inputs from the body may trigger or modulate the output of the networks but are not essential for any of the qualities of experience.

The Unity of the Phantom Limb Experience

One of the most striking features of the phantom limb or any other body part (including half of the body in many quadriplegics) is that it is perceived as an integral part of the remaining sensate part of the body. Even when a foot is dangling "in mid-air" (without a connecting leg) a few inches below the stump, it is still felt to be part of the body and moves appropriately with the other limbs and torso. When a prosthesis is put on, the dangling phantom foot usually lowers into the shoe and the whole artificial leg is felt as a part of the body. The reality of these experiences derives in large part from the feeling of unity of the phantom part and the real body.

An integral part of the feeling of unity of the phantom limb (or other body part) with the remainder of the body is the feeling that the phantom is part of one's self. The phantom foot, penis or breast is described not only as real but as unquestionably belonging to the person. While this may seem self-evident, there is reason to believe that particular brain processes underlie the experience of the self. Just as extraordinary as the persistent experience of a limb after it has been amputated is the converse—the denial that a part of one's body belongs to one's self (Denny-Brown et al., 1952; Mesulam, 1981). Typically, the person, after a lesion of the right parietal lobe or any of several other brain areas (such as the left parietal lobe, cingulum, thalamus and midbrain) denies that a side of the body is part of himself and even ignores the space on that side. There are several descriptions of patients who topple out of their hospital bed because they believe that a strange leg is in their bed, which they try to throw out of bed with the consequence, of course, that the rest of the body follows the leg. Generally the leg (or arm, or whole side of the body) is treated negatively—as undesirable. On one occasion, however, a patient thought that the leg belonged to an attractive woman and was happy to have it share his bed.

From these cases and many others like them, it is evident that the brain processes that underlie the experience of our bodies must include the signal that says: this is *my* body, it belongs to *me*, is part of my *self.* We take this for granted. But the effects of these lesions indicate that there are parts of the brain which impart a special signal that provides the basis for experience of the self. When these areas are lost, the person denies that a part of the body belongs to the self.

These patients provide powerful evidence that the brain distinguishes between self and not-self. The self is accepted; the not-self is denied. An artist who suffered this kind of brain damage would simply not paint one side of his face in his self-portrait. As he began to improve, he added more details to the previously denied face. However, more than the self is involved. When these people draw the numbers of the hours on a clockface, they crowd all the numbers on one side. Or, if they draw a daisy, they draw the petals on one side only. The self, then, includes the space that surrounds the self (Denny-Brown, Meyer & Horenstein, 1952; Mesulam, 1981).

Furthermore, the not-self is not merely denied; it is rejected outright. The hostility and rejection with which the not-self is regarded is indicated by the instances in which the not-self leg is thrown violently out of bed or the patient desperately asks the nurse or doctor to remove the not-self leg or arm from the bed. The negative feelings are evident. A moment's thought about how each of us would feel if a stranger's leg or arm were placed in our bed and we were told that it belongs to us makes the denial and hostility easy to understand. If a strange leg were put in my bed, no amount of coaxing would convince me that the leg is actually mine—that is, belongs to my "self." Extraordinarily, after particular brain lesions, this denial occurs even though the real limb is intact and is even used in movements such as walking, dressing and eating. If not paralyzed, the limb is used in a natural way to put on clothes, but the arm that is doing the dressing is itself not put through the sleeve of a shirt or other garment; it is ignored as not-self. An elderly woman described as religious and fastidious in her manners showed unusual behaviours after a right parietal lobe lesion: she "modestly adjusted her clothing on the right while parts of the left side of the body were heedlessly exposed" (Denny-Brown et al., 1952, p.438). A part of the body was "disconnected"—not there, ignored—to the extent that the neurologist's insistence that "this is *your* arm (or leg)" brought increasingly angry denials.

Conclusion 3. The experience of the body has a unitary, integrated quality which includes the quality of the "self"—that the body is uniquely one's own and not that of any other individual.

The Innateness of Phantom Limb Experience

There is convincing evidence that a substantial number of children who are born without all or part of a limb feel a vivid phantom of the missing part. The long-held belief that phantoms are experienced only when an amputation has occurred after the age of 5 is not true. Weinstein and his colleagues (1961, 1964) and Poeck (1964, 1969) have made a powerful case that phantoms are experienced by children who are born without a limb (congenital aplasia) or who have lost it before the age of 5.

Phantoms in children missing part or all of a limb were reported by Valentin as long ago as 1836. Valentin's first case was a 19-year old girl born without a hand who consistently had the sensation of possessing a complete hand and five fingers. His second case had no lower arm on one side so that the actual hand was at the elbow, yet (when not looking) he felt his arm to be of normal length. The third case is the most important: the left arm was deformed so that the hand was attached to the shoulder, but the arm was actually felt as though it was half the length of the right arm (which was normal in all respects). It is this description (and others) of a deformed phantom that makes these cases convincing. As Weinstein and his colleagues note, if these people were simply describing a fantasy of a normal arm, they would not describe a partial or deformed limb. A 6-year old child described in Weinstein et al. (1964), for example, reported that her phantom leg consisted of only the upper calf and two toes. Another child felt only the palm and middle finger. Descriptions such as these resemble those of many adult amputees to such an extent that they are completely believable when they are described by children born without part or all of a limb.

The estimated percentage of phantoms reported by people with congenital aplasia is about 18%, much lower than the virtually universal (90% to 100%) phantom reported by adult amputees (Weinstein et al., 1964). However, since the phantom in amputees tends to fade or telescope and disappear as a function of time, it is not surprising that when children with congenital aplasia are able to speak sufficiently well to describe such phenomena, the phantom may have come and gone and been forgotten. It is noteworthy, then, that those children who have worn an artificial limb before the age of 7 have a significantly larger proportion of phantom limbs (81.2%) than children who received a prosthesis after the age of 7 (52.6%) (Weinstein et al., 1964). In other words, just as the artificial limb in amputees reverses telescoping and fading, so too, in children with congenital aplasia, the disappearance of the phantom seems to be impeded by wearing an artificial limb. Inputs from the prosthesis—tactual inputs from the stump as well as visual inputs—maintain the integrity of the body-self by including the experience of the missing part of a whole limb.

Results obtained with animals support the conclusion that the phantom is built-in. In a remarkable experiment (Taub, Perrella & Barro, 1973; Taub, 1977), newborn monkeys, within hours after birth, underwent complete sensory-root deafferentation of both forelimbs and were blinded by suturing the eyelids. Astonishingly, by the age of 3 months, these monkeys had spontaneously developed the ability to walk and clasp objects. They were also trained to make precise hand-to-mouth movements and to discretely extend the arm toward the front after a tap on the upper lip. The only reasonable explanation of such spatially coordinated behaviour in the absence of vision and sensory feedback from limbs after birth is that the monkeys possess built-in brain mechanisms for a phantom body capable of meaningful actions in three-dimensional space.

This does not mean, of course, that experience is irrelevant. Obviously it is relevant. People's phantoms often assume the shape of the prosthesis. People with a deformed leg or a painful corn often report that the phantom is deformed or has a corn. That is, sensory inputs play an important role in the experience of the phantom limb. Heredity and environment clearly act together to produce the phenomena of phantom limbs.

Conclusion 4. The neural network that underlies the experience of the body-self is genetically determined but can be modified by sensory experience.

Sketch for a New Conceptual Nervous System

Phantom limb phenomena confront us with the most challenging problems in psychology: awareness; the self; the qualities of experience; the nature of knowledge and reality. These ancient problems have been debated throughout the centuries and continue to elude us. In recent years we have tended to ignore them, explain them away, even deny their existence. We can no longer evade them if we want to find an answer to phantom limbs.

The Conceptual Nervous System

Before I embark on a search for a new understanding of brain function, it is essential to recognize the importance of Don Hebb's (1955) insight that psychologists who seek global answers to major problems can deal only with a conceptual nervous system. Our present knowledge of the number of brain cells and their connections makes the imagination reel (Hoyenga &

Hoyenga, 1988). There are, it is estimated, 100 billion nerve cells in the brain (a 10-fold increase over the number in most textbooks only 5 to 10 years ago), and the number continues to rise. If we recognize that many neurons in sensory projection systems may have synaptic connections with tens or hundreds of thousands of other neurons, and if we carry our computation through the cortical layers and their projections to deeper levels which may, in turn, project to the cortex again, the number is astronomical. To think that we are even close to an understanding of brain functions and their relation to experience and behaviour is absurd. At this stage, as Don Hebb so wisely told us, we can only speculate and try to build reasonable neural models—in short, a "conceptual nervous system." Our old concepts of the brain are totally inadequate in their ability to explain phantom limb phenomena and it is time to try to sketch out a new one. First, however, let us look at earlier conceptual nervous systems to explain phantom limb phenomena.

Earlier Theories of Phantom Limbs

There is now virtually universal agreement that phantom limb phenomena cannot be explained in terms of peripheral mechanisms such as neuromas or other pathological activity in the stump. Loeser and I (1978) described several patients who underwent complete surgical transection of the spinal cord yet continued to suffer severe pain in the phantom body even though there was no possible route (after bilateral sympathetic blocks) for events in the periphery to reach the brain. Carlin, Wall, Nadvorna and Steinbach (1978) proposed that hyperactive deafferented cells in the spinal cord provide a sufficient explanation for phantom limb pain. However, the output of hyperactive spinal cells does not, by itself, explain the multitude of specific, detailed phenomena such as the urge to urinate after surgical removal of the bladder (Dorpat, 1971) or the onset of tremor in the phantom arms after ingestion of certain drugs (Jankovic and Glass, 1985). Nor can hyperexcited spinal cells explain the phantom's perfect coordination with other limb movements or the coherence and unity of the experience. The answer, I believe, is not to be found in the hyperactive cells in spinal cord (which Loeser and I refer to as a "pattern generating mechanism"); it must be sought in the brain.

Unfortunately, there is no satisfactory theory of brain function to explain phantom-limb phenomena. Simmel (1956) and Weinstein et al. (1964) have equated phantom limbs with Head and Holme's (1911-1912) concept of body schema and then proposed that both are located in the somatosensory cortex which contains a representation of the body surface (the "homunculus" mapped by Penfield and Boldrey, 1937). This theory is unsatisfactory for two reasons. First, the idea of the "body schema" is too vague to provide an explanation of any of the phenomena. Second, there is no postulate by Head and Holmes on the actual neural mechanisms that comprise their postural "body schema," apart from identifying a tactile schema with the somatosensory cortex. They also deny any relation between postural "body schema" and "body image." The latter, they say, is a visual image while the former is a somatic neural mechanism. Thus, the role of vision in the phantom limb is left unexplained even though we know that the phantom limb experience, in terms of position and other qualities, is powerfully influenced by vision. It is clear that, while phantom limbs obviously have a neural substrate, they are not explained by Head and Holmes' conceptual "body schema."

The identification of phantom limb phenomena with the post-central somatosensory cortex is also erroneous. The early reports that a phantom is eradicated by ablating a portion of the post-central gyrus have not been supported; a later evaluation (White & Sweet, 1969) of excisions of the somatosensory cortex for phantom limb pain shows that, with time, the phantom limb and pain both return. In addition, if the phantom limb is to be identified with the somatosensory cortex, we now know that there are at least seven projections of the body surface at the cerebral cortex (Merzenich & Kaas, 1980), which leaves out known additional projections to brainstem areas, the limbic system and the cerebellum. All of these, presumably, play a role in the phantom limb experience. But how? It is evident that a new theory is needed.

A New Approach

The examination of phantom limb phenomena has led to four conclusions which point to a new conceptual nervous system. First, because the phantom limb (or other body part) feels so real, it is reasonable to conclude that the body we normally feel is subserved by the same neural processes in the brain; these brain processes are normally triggered and modulated by inputs from the body but they can act in the absence of any inputs. Second, all the qualities we normally feel from the body, from pain to orgasm, are also felt in the absence of inputs from the body; from this we may conclude that the qualities of experience may be triggered or modulated by inputs from the body but the origins of the patterns that underlie the qualities of experience lie in neural networks in the brain. Third, the body is perceived as a unity and is identified as the "self," distinct from other people and the surrounding world. The experience of a unity of such diverse feeling, including the crucially important recognition of the self as the point of orientation in the surrounding environment, is produced by central neural processes and cannot derive from the peripheral nervous system or spinal cord. Fourth, the brain processes that underlie the body-self are, to an important extent which can no longer be ignored, "built-in" by genetic specification, although this built-in substrate must, of course, be modified by experience. These conclusions provide the basis of the new conceptual model.

Outline of the Theory

I will first present an outline of the theory and then deal with each of the components.

The anatomical substrate of the body-self, I propose, is a large, widespread network of neurons that consists of loops between the thalamus and cortex as well as between the cortex and limbic system. I have labelled the entire net work, whose spatial distribution and synaptic links are initially determined genetically, and are later sculpted by sensory inputs, as a *neuromatrix*. The loops diverge to permit parallel processing in different components of the neuromatrix and converge repeatedly to permit interactions between the output products of processing. The repeated *cyclical processing and synthesis* of nerve impulses through the neuromatrix imparts a characteristic pattern: the *neurosignature*. The neurosignature of the neuromatrix is imparted on all nerve impulse patterns that flow through it; the neurosignature is produced by the patterns of synaptic connections in the entire neuromatrix. Although bursts of growth of synapses are genetically determined, inputs from the body determine whether the synapses will become functional or die, when they will do so, and thereby influence the anatomical pattern of the synapses. In this way, heredity and environment together influence the signature pattern. All inputs from the body undergo cyclical processing and synthesis so that characteristic patterns are impressed on them in the neuromatrix. Portions of the neuromatrix are specialized to process information related to major sensory events (such as injury, temperature change and stimulation of erogenous tissue) and may be labelled as neuromodules which impress subsignatures on the larger neurosignature.

The neurosignature, which is a continuous outflow from the body-self neuromatrix, is projected to areas in the central core of the brainstem—the *sentient neural hub (SNH)*—in which the stream of nerve impulses (the neurosignature modulated by ongoing inputs) is converted into a continually changing stream of awareness. Two signatures are normally always present—one for the body-self and another for three-dimensional space, so that these (in the intact person) are constant qualities in the continuous flow of all experience. Neurosignature patterns that flow through the neuromatrix for the body-self may also activate a neuromatrix to produce movement. The signature patterns bifurcate so that a pattern proceeds to the *sentient neural hub* (where the pattern is converted into the experience of movement) and a similar pattern proceeds through a neuromatrix that eventually activates spinal cord neurons to produce muscle patterns for complex movement.

The four components of the new conceptual nervous system, then, are the body-self neuromatrix, cyclical processing and synthesis in which the neurosignature is produced, the sentient neural hub which converts (transduces) the flow of neurosignatures into the flow of awareness, and neuromodules of the body-self which project command messages to the *sentient neural hub* (to provide awareness of movement) and to the motor system (to provide the *pattern* of movements to bring about the desired goal). We will now deal separately with each of the components of the new conceptual nervous system.

The Body-Self Neuromatrix

The body is felt as a unity, with different qualities at different times and, I believe, the brain mechanism that underlies the experience also comprises a unified system that acts as a whole and produces a neurosignature pattern of a whole body. The conceptualization of this unified brain mechanism lies at the heart of the new theory and I believe the word "neuromatrix" best characterizes it. "Matrix" has several definitions in Webster's dictionary, and some of them imply precisely the properties of the neuromatrix as I conceive of it. First, a matrix is defined as "something within which something else originates, takes form or develops." This is exactly what I wish to imply: the neuromatrix (not the stimulus, peripheral nerves or "brain center") is the origin of the neurosignature; the neurosignature originates and takes form in the neuromatrix. Though the neurosignature may be triggered or modulated by input, the input is only a "trigger" and does not produce the neurosignature itself. Matrix is also defined as a "mold" or "die" which leaves an imprint on something else. The term "matrix," for example, is used for "the electroformed impression of a phonograph record used for mass-producing duplicates of the original." In this sense, the neuromatrix "casts" its distinctive signature on all inputs (nerve impulse patterns) which flow through it. Finally, matrix is defined as "an array of circuit elements...for performing a specific function as interconnected." The array of neurons in a neuromatrix, I propose, is genetically programmed to perform the specific function of producing the signature pattern. The final, integrated neurosignature pattern for the body-self ultimately projects to the sentient neural hub (SNH) in which the signature pattern is transduced into awareness.

For these reasons, the term neuromatrix seems the most appropriate for the functions I attribute to networks of neurons in the brain. The neuromatrix, distributed throughout many areas of the brain, comprises a widespread network of neurons which generates patterns, processes information that flows through it, and ultimately produces the pattern that is felt as a whole body. The stream of neurosignature output with constantly varying patterns riding on the main signature pattern produce the feelings of a whole body with constantly changing qualities.

Psychological Reasons for Postulating the Neuromatrix. It is incomprehensible to me how individual bits of information from skin, joints or muscles can all come together to produce the experience of a coherent, articulated body. At any instant in time, millions of nerve impulses arrive at the brain from all the body's sensory systems, including the vestibular system. How can all this be integrated in a constantly changing unity of experience? Where does it all come together?

I cannot imagine how all these bits are added up to produce a whole. But I can visualize a genetically built-in neuromatrix for the whole body, producing a characteristic neurosignature for the body which carries with it patterns for the myriad qualities we feel. The neuromatrix, as I conceive of it, sends a continuous message for the whole body in which details are differentiated within the whole as inputs come into it. We start from the top, with the experience of a unity of body-self, and look for differentiation of detail within the whole. The neuromatrix, then, is a template of the whole, which provides the characteristic neural pattern for the whole body (the body-self's neurosignature) as well as subsets of signature patterns (from neuromodules) that relate to events at (or in) different parts of the body.

These views are in sharp contrast to the classical specificity theory in which the qualities of inputs are presumed to be inherent in peripheral nerve fibers or some mythical center in the brain. Pain is not injury; the *quality of pain experiences* must not be confused with the physical event of breaking skin or bone. Warmth and cold are not "out there"; temperature changes occur "out there," but the *qualities of experience* must be generated by structures in the brain. There are no external equivalents to stinging, smarting, tickling, itch; the *qualities* are produced by built-in neuromodules whose neurosignatures innately produce the qualities.

We do not learn to feel qualities of experience: our brains are built to produce them. The inadequacy of the traditional peripheralist view becomes especially evident when we consider paraplegics with high-level complete spinal breaks. In spite of the absence of inputs from the body, virtually every quality of sensation and affect is experienced, from excruciating pain to orgasm. It is known that the absence of input produces hyperactivity in spinal cells above the level of the break. But how, from this jumble of activity, do we get the meaningful experience of movement, the coordination of limbs with other limbs, cramping of specific (nonexistent) muscle groups, and so on? This must occur in the brain, in which neurosignatures are produced by neuromatrixes that are triggered by the output of hyperactive cells.

When all sensory systems are intact, inputs modulate the continuous neuromatrix output to produce the wide variety of experiences we feel. We may feel position, warmth, and several kinds of pain and pressure all at once. It is a single unitary feeling just as an orchestra produces a single unitary sound at any moment even though the sound comprises violins, cellos, horns, and so forth. Similarly, at a particular moment in time we feel complex qualities from all of the body. In addition, our experience of the body includes visual images, affect, "knowledge" of the self (versus not-self) as well as the meaning of body parts in terms of social norms and values. I cannot conceive of all of these bits and pieces coming together to produce a unitary body-self, but I can visualize a matrix which impresses a characteristic signature on all the inputs that converge on it and thereby produces the never-ending stream of feeling from the body.

The neuromatrix must clearly undergo changes as a result of sensory inputs and ideas—that is, learning must occur as a result of experience. I propose that the built-in neuromatrix should be called the *phylomatrix*, which, in the course of development and sensory experience, is modified to produce the *ontomatrix*. The phylomatrix is conceived to be a complex network of neurons whose excessive synaptic connections and output pattern (neurosignature) are genetically determined. When particular sensory inputs result in the survival of certain sets of synapses and the death of other sets (that is, convert the phylomatrix to the ontomatrix), the output neurosignature pattern is also changed, producing a modulation of the qualities of experience that are felt. Thus, the basic phylomatrix pattern (which can never be known) would presumably produce the experience of a body. After sensory experience sculpts it to produce the ontomatrix, the body that is felt becomes the unique body of the individual in terms of experience and action.

The experience of the body-self involves multiple dimensions--sensory, affective, evaluative, postural and many others. The sensory dimensions are subserved, in part at least, by portions of the neuromatrix that lie in the sensory projection areas of the brain; the affective dimensions, I assume, are subserved by areas in the brainstem and limbic system. Each major psychological dimension (or quality) of experience, I propose, is subserved by a particular portion of the neuromatrix—*neuromodule*—which contributes a distinct portion of the total neurosignature. To use a musical analogy, it is like the strings, tympani, woodwinds and brasses of a symphony orchestra which each comprise a "module" of the whole; each makes its unique contribution yet is an integral part of a single symphony which varies continually from beginning to end.

In summary, the *neuromatrix* for the body-self comprises a network of neurons which is spatially distributed throughout the brain. The particular spatial distribution and synaptic endowment are genetically determined and produce outputs with particular signature patterns. The time at which the neuromatrix, or any module that is part of it, becomes active (and susceptible to change by sensory inputs) is genetically determined; inputs then determine, in part, the sudden growth, survival or death of particular sets of synapses. The configuration of synapses produced by inputs at a critical time may then become permanent and thereafter inpart new, distinct patterns to the neurosignature, which later evoke predetermined kinds of experience.

Major Properties of the Neuromatrix. Although the neuromatrix is a hypothetical mechanism, the evidence allows us to attribute three major properties to it. First, I have proposed that the neuromatrix for the body-self is, in part, built in. This property derives from the evidence on phantoms in children born without limbs and from research with animals by Levitt and Heybach (1981) and Taub (1977) that permit the same conclusion. Moreover, the built-in aspect of the phantom represents not only the body, but also the quality of the "self" since phantoms are felt as belonging to the self. It is difficult to see how learning could account for such a quality being produced by a distinct set of brain areas; it is far more likely that heredity determines the spatial distribution of this part of the neuromatrix, its neurosignature and the experiential quality of self.

The second property is the widespread distribution of the neuromatrix that produces the neurosignature for the body-self. This is indicated by the multiple areas that receive somatosensory input or are somehow involved in its processing. We now know that there is not a single somatic representation area (the "homunculus") but at least seven representations in the parietal, frontal and temporal cortex (Merzenich & Kaas, 1980.) Furthermore, body experiences such as pain are influenced by lesions or stimulation of the parietal, frontal and temporal cortex as well as a large part of the brainstem, including the hypothalamus, thalamus, superior colliculus and reticular formation (Melzack & Wall 1988). In addition, most of the limbic system contributes to somatic experiences: lesions or stimulation of the amygdala, hippocampus, septum and fornix have an effect on pain (Gloor, 1986; Abbott & Melzack, 1978). It is obvious that the body-self experience involves virtually all of the brain, and the concept of a widespread network—the neuromatrix—with specialized modules is plausible.

The third property is that information processing occurs at the same time in parallel systems. The results of such parallel processing must come together to produce the "final" neurosignature pattern that underlies the body-self experience at a particular moment and which continues in time. Processing undoubtedly goes on simultaneously in all seven of the known cortical somatosensory projection systems. It must also go on in parallel in the sensory-discriminative, motivational-affective and cognitive processing systems (Melzack & Casey, 1968; Dennis & Melzack, 1977). To recognize parallel processing in widely distributed neural systems is a major step forward; the question it inevitably leads to is: how does this go on to produce the final output (at each given moment in time) that then subserves experience and behaviour? I therefore propose the second component of this new conceptual theory: cyclical processing and synthesis (CPS) through the neuromatrix.

Cyclical Processing and Synthesis

The important recent discovery of the columnar organization of the cortex was foreshadowed by Lashley's (1944) and Sperry's (1947) remarkable observations that vertical cuts of the cortex have no effect on sensory discrimination or motor patterns. It was long assumed that fibers from one part of the cortex to another (cortico-cortical fibers) were the basis of all information processing and the resultant experience and behavious. It was, therefore, astonishing to find that deep cuts which criss-crossed the cortex had no effect on perception or response. This result can be explained by the discovery by Mountcastle (1957) and Hubel and Wiesel (1967) of the columnar organization of the somatosensory and visual systems. While there is some lateral transmission in the cortex, vertical transmission up and down (thalamo-cortical, cortico-cortical between different layers, and cortico-thalamic) seems to be the more important form of nerve impulse transmission and information processing. Goldman-Rakic (1984) has recently reviewed substantial evidence to show that this columnar organization is a dominant feature of the activity of *all* cortex—association areas (such as prefrontal cortex) as well as sensory areas.

On the basis of this fact, it becomes possible to envisage the physiological mechanism of action of the neuromatrix (which is an anatomical concept). I propose a mechanism which functions in this manner:

> the brainstem reticular formation is continually active, due partly to intrinsic spontaneous activity and partly to the continual inputs from collateral fibres of all the sensory systems as well as a large portion of the rest of the brain;
>
> this continuous, high level of activity of the reticular formation is projected, in part, to the nuclei of the thalamus which, in the absence of sensory inputs, produce slow, rhythmic waves (Andersen & Eccles, 1962) that act as *carrier waves;* when information arrives from a particular sensory system, the carrier waves change their properties according to the amount and kinds of information they are carrying;
>
> these waves from the thalamus, which carry a continuous flow of sensory information, are projected to the cortex through columns of organized neurons and, after processing, are projected back to the thalamus; they are projected cyclically in this way through large, widespread networks and are returned to the brainstem matrix which I have called the sentient neural hub (SNH);
>
> reticular activity also projects to the limbic system, where the hippocampus (among other functions) also produces distinct carrier waves so that parallel cyclical processing occurs in portions of the neuromatrix that include the thalamus, limbic system and cortex;
>
> cyclical processing also occurs through a portion of the neuromatrix for the body-self which includes the superior colliculi (which are known to receive inputs from the body in addition to visual information and have a highly organized representation of the body surface);
>
> the processing of information through the neuromatrix and its component neuromodules imposes distinct neurosignature patterns on the input patterns that entered the neuromatrix, so that the synaptic properties of the neuromatrix *synthesize* (or create) particular patterns of output; the synthesized product is the result of both the properties of the neuromatrix and the properties of the input;

> after parallel cyclical processing and synthesis (CPS) through all the neuromodules of the neuromatrix, the final neurosignature pattern converges into the areas of the sentient neural hub.

The Sentient Neural Hub (SNH)

There is a growing body of evidence that a localized, fairly extensive area in the central portion of the brainstem plays a critical role in awareness. Cairns (1952), Penfield (1960) and others have noted that a cyst or tumour in this area—which includes portions of the hypothalamus and pons—produces a loss of awareness, and surgical removal of the cyst or tumour produces a return of awareness. Lesions of these brainstem areas are critically important; lesions of the reticular formation may produce loss of awareness but for a different reason: it destroys the source of activity to the thalamus which produces the carrier waves. Lesions of the cortex, as Plum (1972) has pointed out, may affect the *contents* of awareness but not awareness itself. Penfield (1960) has made similar arguments. This area, I propose, comprises the sentient neural hub (SNH) which receives inputs from the body-self neuromatrix.

In the SNH, the body-self neurosignature is transduced into awareness. I propose further that the SNH's built-in properties are such that each of the patterns in the neurosignature produces a particular quality of experience.

In summary, we now have the basis for a new conceptual nervous system in which neuromatrixes, whose synaptic architecture is determined by both heredity and environment, impose (like a die or template) particular patterns on the information that is projected to them from the senses. I conceive of the cyclical processing and synthesis (CPS) which occurs in a neuromatrix as a creative, constructive process in which meaning, structure and pattern are imposed on inputs. Heredity, I believe, anticipates the properties and possibilities of the world into which we are born and, because of the survival value of different discriminations, creates particular synaptic configurations which impose distinctive neural patterns on the input so that the processed output produces particular qualities. It is reasonable to expect that the qualities of experience evolved because they promoted survival. I also conceive of CPS as a process whereby constancy is imposed on inputs so that, for example, if inputs from the body are absent (due to amputation or nerve lesion), the neurosignature continues to provide information about an intact body. It is noteworthy that people whose phantom had faded and disappeared shortly after amputation report that it could still be evoked 30 or 40 years later (Cohen, 1944). CPS also permits "filling in" of missing information on the basis of genetic programming, past experience and expectation. In short, the act of being aware of a body-self in three-dimensional space is a creative process—the product of a brain that took hundreds of millions of years to evolve.

Action Patterns: The Action-Neuromatrix

The output of the body-self neuromatrix, I have proposed above, is directed at two systems: 1) the neuromatrix in the brainstem that produces awareness of the output (the SNH neuromatrix), and 2) a neuromatrix involved in overt action patterns. In this discussion, it is important to keep in mind that just as there is a steady stream of awareness (even during the dream episodes of sleep), there is also a steady output of behaviour (including movements during sleep). Behaviour is rarely a reflex response to a stimulus (unconditional or conditioned) but is generally a smooth flow of action patterns.

It is important to recognize that behaviour occurs only after the input has been at least partially synthesized and recognized. For example, when we respond to the experience of pain or itch, it is evident that the experience has been synthesized by the body-self neuromatrix (or relevant neuromodules) sufficiently for the neuromatrix to have imparted the neurosignature patterns that underlie the quality of experience, affect and meaning. Apart from a few reflexes (such as withdrawal of a limb, eye-blink and so on), behaviour occurs only after inputs have been analyzed and synthesized sufficiently to produce meaningful experience. When we reach for an apple, the visual input has clearly been synthesized by a neuromatrix so that it has three-dimensional shape, colour and meaning as an edible, desirable object, all of which are produced by the brain and are not in the object "out there." When we respond to pain (by withdrawal or even by telephoning for an ambulance), we respond to an experience that has sensory qualities, affect and meaning as a dangerous (or potentially dangerous) event to the body-self.

I propose that after inputs from the body are projected to and undergo transformation in the neuromatrix for the body-self, the appropriate action patterns are activated concurrently (or nearly so) with the neuromatrix for experience. I suggest that inputs in large-diameter, fast-conducting fibers rapidly activate cyclical processing and synthesis (CPS) to begin the quickest possible identification of the "class" of input (that is, the self, others, objects, etc.). This rapidly conducted input, I propose, activates several action-neuromodules for potentially appropriate response patterns and holds them in readiness until CPS completes the synthesis of the neurosignature for experience. As the input becomes better defined and evaluated, the response possibilities are narrowed down until one is chosen. Thus, in the neuromatrix for action patterns, CPS produces activation of several possible patterns and their successive elimination until one particular pattern emerges as the most appropriate for the circumstances at the moment. In this way, input and output are synthesized simultaneously, in parallel, not in a series. This permits a smooth, continuous stream of action patterns.

Thus, whole action patterns are produced by neuromodules which are determined by genetic factors and modified by experience. The command, which originates in the brain, to perform a pattern such as running activates the neuromodule which then produces firing in sequences of neurons that send precise messages through ventral horn neuron pools to appropriate sets of muscles. At the same time, the output patterns from the body-self neuromatrix that engage the neuromodules for particular actions are also projected to the sentient neural hub and produce experience. In this way, the brain commands may produce the experience of movement of phantom limbs even though there are no limbs to move and no proprioceptive feedback. Indeed, reports by paraplegics of terrible fatigue due to persistent bicycling movements (like the painful fatigue in a tightly clenched phantom fist in arm-amputees) indicate that feelings of effort and fatigue are produced by the signature of a neuromodule rather than particular input patterns from muscles and joints.

Implications of the New Conceptual Nervous System for Phantom Limb Pain

The new theory of brain function, proposed on the basis of phamtom-limb phenomena, attempts to provide a physiological basis for the body-self, awareness, and the multitude of qualities perceived in phantom body areas. The implications of this conceptual nervous system for visual perception, learning, thinking and other psychological problems will be dealt with elsewhere. I will deal here only with its implications for phantom limb pain.

Amputees suffer burning, cramping and other qualities of pain. An excellent series of studies (Jensen *et al.*, 1985; Krebs *et al.*, 1984) found that 72% of amputees had phantom limb pain a week after amputation and 60% had pain 6 months later. Even 7 years after amputation, 60% still continued to suffer phantom limb pain, which means that only about 10% to 12% of amputees obtain pain relief. The pain is astoundingly intractable; although more than 40 forms of treatment have been tried, none has proved to be particularly efficacious (Sherman & Sherman, 1980).

Why is there so much pain in phantom limbs? I believe that the active neuromatrix, in the absence of modulating inputs from the limbs or body, produces a signature pattern that is transduced in the sentient neural hub into a hot or burning quality. The cramping pain, however, may be due to messages from the action-neuromodule to move muscles in order to produce movement. In the absence of feedback from the limbs, the messages to move the muscles become more frequent and "stronger" in the attempt to move the limb, just as Lashley's blindfolded subject, who had lost sensation from his leg, felt great fatigue in the effort to keep his leg raised even though his leg was actually resting on the floor (Lashley, 1917). The end result of the *output* message may be felt as camping muscle pain. Shooting pains may have a similar origin, in which action-neuromodules attempt to move the body and send out abnormal patterns that are felt as shooting pain. The origins of these pains, then, lie in the brain.

Surgical removal of the somatosensory areas of the cortex (White & Sweet, 1969) or thalamus (Spiegel & Wycis, 1966) fails to relieve phantom limb pain. However, the new theory conceives of a neuromatrix that extends into widespread areas of the whole brain, including prefrontal, parietal, temporal and visual cortex, the limbic system (including the hypothalamus, amygdala and hippocampus), and extensive areas of the brainstem. Thus, to destroy the neuromatrix for the body-self which generates the neurosignature pattern for pain is impossible. It would mean destruction of almost the whole brain. However, if the neurosignature for pain is generated by cyclical processing and synthesis (CPS), then it may be possible to block CPS by injecting a local anesthetic into a discrete area. Such an injection would be relatively easy and harmless to carry out and could bring relief that extends beyond the duration of the anesthetic.

To make a beginning toward such an approach to a major human pain problem, my students and I (Tasker *et al.*, 1987) have injected the local anesthetic lidocaine into the lateral hypothalamus — an area we considered to be strategic for a neuromatrix for the body-self and pain. We found that freely moving rats which received the injection showed a significant reduction of pain in the formalin test, which produces a moderately intense pain for about two hours and has many of the characteristics of injury-produced pain in humans (Dennis & Melzack, 1979). However, the injection had no effect on tailflick pain, which is primarily a spinally mediated reflex. Moreover, lidocaine injected into adjacent hypothalamic structures (including the medial hypothalamus) had no effect on the formalin-test pain, indicating that the analgesia was produced by local anesthesia of a specific group of neurons. Since the analgesia was bilateral, it is reasonable to assume that the lateral hypothalamus contains neurons that are important for producing the neurosignature for pain in both sides of the body. Furthermore, the analgesia is not due to a simple mechanism such as blocking a pain inhibitory system, which is known to exist in the hypothalamus (Carstens, 1985), because then the local anesthetic should have produced more pain, not less pain.

My doctoral student, Anthony Vaccarino, and I are presently injecting lidocaine into the cingulum, another area which seems to be strategically located in the neuromatrix for the synthesis of the neurosignature for pain. And, as we had hoped, the lidocaine produces striking decreases in pain in the formalin test. We plan to inject lidocaine in other areas, including the somatosensory cortex. It is gratifying that Leriche (1949) observed that local injection of procaine at the somatosensory cortex abolished severe central pain for two months. However, surgical excision of the area generally fails to abolish the pain (White & Sweet, 1969). The return of pain may occur because ablation activates the plasticity of brain tissue so that other areas take over the function of the ablated area, but periodic, temporary anesthetic blocks do not do so.

These exciting results suggest a new approach for the treatment of phantom limb pain (and presumably other forms of chronic pain.) We may hope that neurosurgeons will, in the future, test the technique in people who are suffering terrible phantom limb pain and have not been helped by any other procedures. If the technique relieves pain and suffering, the theory proposed here will have served at least one valuable function.

RÉSUMÉ

Un membre fantôme est une sensation qui est éprouvée d'une façon universelle après qu'un membre est amputé ou que ses racines sensorielles ont été détruites. Une fracture complète de la colonne vertébrale entraîne bien souvent un corps-fantôme en-dessous du niveau de la fracture. De plus, des seins fantômes, organes génitaux et autres parties du corps peuvent se produire chez un nombre substantiel de personnes après l'ablation chirurgicale ou l'énervation de cette partie du corps. La caractéristique la plus étonnante de ce membre fantôme (ou d'une autre partie du corps) est sa "réalité" incroyable pour la personne. L'étude du phénomène du membre fantôme a conduit à quatre conclusions: 1) l'expérience du membre fantôme possède cette qualité de réalité parce qu'elle est produite par le même processus qui est à la base de l'expérience du corps lorsqu'il est intact: 2) les réseaux neuraux dans le cerveau produisent toutes les qualités de l'expérience que l'on croit provenir généralement du corps; les données provenant du corps peuvent déclencher ou moduler la réponse des réseaux mais elles ne sont pas essentielles pour aucune des qualités de l'expérience; 3) l'expérience du corps a une qualité unitaire, intégrée qui comprend la qualité du "soi" — qui fait que le corps est uniquement son propre corps et non pas celui d'un autre individu; 4) le réseau neural qui est à la base de l'expérience du corps-soi est génétiquement déterminé mais peut être modifié par l'expérience sensorielle. On a bâti une nouvelle théorie pour expliquer ces conclusions. Cette théorie veut que l'on soit né avec un réseau neural très étendu — la "neuromatrice" — pour le corps-soi qui est modifié par

par la suite par l'expérience. La neuromatrice transmet un modèle — la "neurosignature" — à toutes les données provenant du corps, de façon à ce que les expériences de son propre corps aient cette qualité du soi et soient remplies de tons affectifs et de signification cognitive. La théorie est présentée avec des preuves à l'appui et aussi des explications de ce qu'elle signifie pour la recherche.

References

Abbott, F.V. and Melzack, R. (1978). Analgesia produced by stimulation of limbic structures and its relation to epileptiform discharges. *Experimental Neurology, 62,* 720–734.

Andersen, P. and Eccles, J.C. (1962). Inhibitory phasing of neuronal discharge, *Nature, 196,* 645–647.

Bors, E. (1951). Phantom limbs of patients with spinal cord injury. *Archives of Neurology and Psychiatry, 66,* 610–631.

Cairns, H. (1952). Disturbances of consciousness with lesions of the brain-stem and diencephalon. *Brain, 75,* 107–146.

Carlen, P.L., Wall, P.D., Nadvorna, H. and Steinbach, T. (1978). Phantom limbs and related phenomena in recent traumatic amputations. *Neurology, 28,* 211–217.

Carstens, E. (1985). Inhibition of rat spinal neuronal responses to noxious skin heating by stimulation in hypothalamus and other diencephalic sites. *Society for Neurosicience Abstracts, 11,* 637.

Cohen, H. (1944). The mechanism of visceral pain. *Transactions of the Medical Society of London, 64,* 65–99.

Conomy, J.P. (1973). Disorders of body image after spinal cord injury. *Neurology, 23,* 842–850.

Dennis, S.G. and Melzack, R. (1977). Pain-signalling systems in the dorsal and ventral spinal cord. *Pain, 4,* 97–132.

Dennis, S.G. and Melzack, R. (1979). Comparison of phasic and tonic pain in animals. In: J.J. Bonica, J. Liebeskind and D. Albe-Fessard (eds.), *Advances in Pain Research and Therapy, Vol. 3,* New York, Raven Press, pp. 747–760.

Denny-Brown, D., Meyer, J.S. and Horenstein, S. (1952). The significance of perceptual rivalry resulting from parietal lesion. *Brain, 75,* 433–471.

Dorpat, T.L. (1971). Phantom sensations of internal organs. *Comprehensive Psychiatry, 12,* 27–35.

Gevins, A.S., Morgan, N. H., Bressler, S.L., Cutillo, B.A., White, R. M., Illes, J., Greer, D.S., Doyle, J.C. and Zeitlin, G.M. (1987). Human neuroelectric patterns predict performance accuracy. *Science, 235,* 580–584.

Gloor, P. (1986). Role of the human limbic system in perception, memory, and affect: lessons from temporal lobe epilepsy. In: B.K. Doane and K.E. Livingston (eds), *The Limbic System: Functional Organization and Clinical Disorders.* New York, Raven Press, pp. 159–169.

Goldman-Rakic, P.S. (1984). Modular organization of prefrontal cortex. *Trends in Neurosciences, 7,* 419–424.

Head, H. and Holmes, G. (1911-1912). Sensory disturbances from cerebral lesions. *Brain, 34,* 102–254.

Hebb, D.O. (1949). *The Organization of Behavior.* New York: Wiley.

Hebb, D.O. (1955). Drives and the C.N.S. (Conceptual nervous system). *Phychological Review, 62,* 243–254.

Hebb, D.O. (1980). *Essay on Mind.* Hillsdale, N.J.: Erlbaum Associates.

Heusner, A.P. (1950). Phantom genitalia. *Transactions of the American Neurological Association, 75,* 128–131.

Hoyenga, K.B. and Hoyenga, K.T. (1988). *Psychobiology: The Neuron and Behavior.* Pacific Grove, CA, Brooks/Cole.

Hubel, D.H. and Wiesel, T.N. (1967). Receptive fields and functional architecture of monkey striate cortex. *Journal of Physiology, 195,* 215–243.

James, W. (1890). *Principles of Psychology.* New York, Holt.

Jankovic, J. and Glass, J.P. (1985). Metoclopramide-induced phantom dyskinesia. *Neurology, 35,* 432–435.

Jensen, T.S., Krebs, B., Nielson, J. and Rasmussen, P. (1985). Immediate and long-term phantom limb pain in amputees: incidence, clinical characteristics and relationship to pre-amputation limb pain. *Pain, 21,* 267–278.

Krebs, B., Jensen, T.S., Kroner, K., Nielson, J. and Jorgensen, H.S. (1984). Phantom limb phenomena in amputees seven years after limb amputation. *Pain Supplement, 2,* S85.

Lashley, K.S. (1917). The accuracy of movement in the absence of excitation from the moving organ. *American Journal of Physiology, 43,* 169–194.

Lashley, K.S. (1944). Studies of cerebral function in learning: XIII. Apparent absence of transcortical association in maze learning. *Journal of Comparative Neurology, 80,* 257–281.

Leahey, T.H. (1980) *A History of Psychology.* Englewood Cliffs, N.J.: Prentice-Hall.

Leriche, R. (1949). *La chirurgie de la douleur.* Third Edition. Paris, Masson.

Melzack, R. and Bromage, P.R. (1973). Experimental phantom limbs. *Experimental Neurology, 39,* 261–269.

Melzack, R. and Casey, K.L. (1968). Sensory, motivational, and central control determinants of pain: a new conceptual model. In: D. Kenshalo (ed.), *The Skin Senses.* Springfield, Illinois, C.C. Thomas, pp. 423–443.

Melzack, R. and Loeser, J.D. (1978). Phantom body pain in paraplegics: evidence for a central "pattern generating mechanism." *Pain, 4,* 195–210.

Melzack, R. and Wall, P.D. (1988). *The Challenge of Pain.* Second Edition. Harmondsworth, Pelican Books.

Merzenich, M.M. and Kaas, J.H. (1980). Principles of organization of sensory-perceptual systems in mammals. *Progress in Psychobiology and Physiological Psychology, 9,* 1–42.

Mesulam, M.-M. (1981). A cortical network for directed attention and unilateral neglect. *Annals of Neurology, 10,* 309–325.

Money, J. (1960). Phantom orgasm in the dreams of paraplegic men and women. *Archives of General Psychiatry, 3,* 373–382.

Mountcastle, V.B. (1957). Modality and topographic properties of single neurons of cat's somatic sensory cortex. *Journal of Neurophysiology, 20,* 408–434.

Penfield, W. (1960). Neurophysiological basis of the higher functions of the nervous system—introduction. *Handbook of Physiology: Section 1: Neurophysiology.* Washington, American Physiological Society, pp. 1441–1445.

Penfield, W. and Boldrey, E. (1937). Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. *Brain, 60,* 389–443.

Plum, F. (1972). Organic disturbances of consciousness. In: M. Critchley, J.L. O'Leary and B. Jennett (eds.), *Scientific Foundations of Neurology.* London, Heinemann, pp. 193–201.

Poeck, K. (1964). Phantoms following amputation in early childhood and in congenital absence of limbs. *Cortex, 1,* 269–275.

Poeck, K. (1969). Phantome nach amputation und bei angeborenem gliedmassenmangel. *Deutsche Medizinishe Wochenschrift, 94,* 2367–2374.

Riddoch, G. (1941). Phantom limbs and body shape, *Brain, 64, 197–222.* .

Sherman, R.A., Sherman, C.J. and Gall, N.G. (1980). A survey of current phantom limb pain treatment in the United States. *Pain, 8,* 85–90.

Simmel, M. (1956). On phantom limbs. *Archives of Neurology and Psychiatry, 75,* 69–78.

Skinner, B.F. (1938). *The Behavior of Organisms.* New York: Appleton.

Sperry, R.W. (1947). Cerebral regulation of motor coordination in monkeys following multiple transection of sensorimotor cortex. *Journal of Neurophysiology, 10,* 275–294.

Spiegel, E.A. and Wycis, H.T. (1966). Present status of stereoencephalotomies for pain relief. *Confinia Neurologica, 27,* 7–17.

Tasker, R.A.R., Choinière, M., Libman, S.M. and Melzack, R. (1987). Analgesia produced by injection of lidocaine into the lateral hypothalamus. *Pain, 31,* 237–248.

Taub, E. (1977). Movement in nonhuman primates deprived of somatosensory feedback. In J.F. Keogh (ed.), *Exercise and Sports Sciences Reviews.* Santa Barbara, Journal Publishing Affiliates, pp. 335–374.

Taub, E., Perrella, P. and Barro, G. (1973). Behavioral development after forelimb deafferentation on day of birth with and without blinding. *Science, 181,* 959–960.

Valentin, G. (1836). Uber die subjectiven gefühle von personen, welche mit mangelhaften extremitaten gebornen sind. *Repertorium für Anatomie und Physiologie, 1,* 328–337.

Verkuyl, A. (1969). Sexual function in paraplegia and tetraplegia. *Handbook of Clinical Neurology, 4,* 437–465.

Weinstein, S. and Sersen, E.A. (1961). Phantoms in cases of congenital absence of limbs. *Neurology, 11,* 905–911.

Weinstein, S., Sersen, E. A. and Vetter, R.J. (1964). Phantoms and somatic sensation in cases of congenital aplasia. *Cortex, 1,* 276–290.

Weinstein, S., Vetter, R.J. and Sersen, E.A. (1970). Phantoms following breast amputation. *Neuropsychologia, 8,* 185–197.

White, J.C. and Sweet, W.H. (1969). *Pain and the Neurosurgeon.* Springfield, Illinois, C.C. Thomas.

Wynn-Parry, C.B. (1980). Pain in avulsion lesions of the brachial plexus. *Pain, 9,* 41–53.