

Review

# The homuncular jigsaw: Investigations of phantom limb and body awareness following brachial plexus block or avulsion

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**Abstract:** Many neuropsychological theories agree that the brain maintains a relatively persistent representation of one’s own body, as indicated by vivid “phantom” experiences. It remains unclear how the loss of sensory and motor information contributes to the presence of this representation. Here, we focus on new empirical and theoretical evidence of phantom sensations following damage to or an anesthetic block of the brachial plexus. We suggest a crucial role of this structure in understanding the interaction between peripheral and central mechanisms in health and in pathology. Studies of brachial plexus function have shed new light on how neuroplasticity enables “somatotopic interferences,” including pain and body awareness. Understanding the relations among clinical disorders, their neural substrate, and behavioral outcomes may enhance methods of sensory rehabilitation for phantom limbs.

**Keywords:** phantom limb, somatotopy, brachial plexus, deafferentation rehabilitation, anesthetic block,

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Deafferentation, or limb loss, has a dramatic impact on the neural representation of the body [1], silencing all sensory and proprioceptive signals that flow in the primary somatosensory and primary motor cortex to enable limb control [2,3]. Deafferentation events often trigger sensorimotor changes in the brain; however, despite such reorganization, the missing limb remains strongly represented. Indeed, experiencing the sensation of a missing body part, which is known as a “phantom limb sensation,” is an extremely common condition in people experiencing any type of deafferentation – i.e., amputation, spinal cord injury, and other neurologic conditions [4]. These types of subjective experiences can sometimes be painful [5]. Symptoms typically emerge within days after an injury and can last for weeks, years, or even for the patient’s entire life [6]. In the best-case scenario, affected people can easily cope with immobilized [7], spatially misplaced, or telescoping limbs [8]. However, their quality of life and psychological health are often deeply compromised. A “side effect” of the challenge in providing relief and rehabilitation protocols for such patients is that clinical treatment effects also improve the scientific understanding of the mind–body (or body–mind) connection.

In some cases, such as those involving upper limb deafferentation, the “phantom” can be actively evoked through tactile stimulation of the ipsilateral cheek [4,9–12]. Phantom limb sensations elicited by the stimulation of body sites neurally adjacent to the affected limb are reported in 60–95% of individuals with amputated limbs [13,14]. Additionally, this phenomenon is frequently reported in cases of an intact limb with a loss of sensory and motor innervation, either due to nerve avulsion

[15] or a spinal cord injury [16]. Thus, the occurrence of phantom limb sensations elicited by the stimulation of body sites adjacent to the affected limb appears caused by interrupted sensorimotor traffic, rather than the absence of a part of the physical body. Sensory referral of the affected (missing) body part onto a preserved body part is regarded as evidence of some persistent and stable representation of the deafferented body part [14], as well as evidence of somatotopically organized modifications [4]. This type of “somatotopic interference” has been widely studied, and it has produced new and advanced—but also controversial—insights into the cortical plasticity of body representations. The debate is related to the central versus peripheral origin of referred sensation leading to maladaptive plasticity taken over somatotopic map remodeling [5] or the altered inter-regional connectivity of the original, stable neural representation [17]. Interactions with neighboring somatosensory areas remain under discussion, and the sensory “homunculus” is not yet completely defined [18,19].

Phantom sensations have primarily been studied in amputees and, to a lesser extent, in patients with spinal cord lesions. However, such sensations can manifest in many other conditions and, interestingly, in a transient manner. Thus far, there is a paucity of research regarding the brachial plexus, which may instead serve as a model to investigate important questions regarding somatotopy, pain, embodiment, and neural reorganization. The brachial plexus, which is a complex network receiving fibers from the cervical and thoracic nerves of the spinal cord, is completely responsible for the entire area of the upper limb [20]. Due to its topographical arrangement, following damage or anesthesia, it has the potential to interrupt permanently or temporarily the motor, sensory, and proprioceptive signals of upper limb. The somatosensory role of the brachial plexus began receiving attention in the 1960s due to the effects of blocking during surgical anesthesia [21]. The importance of this structure within the clinical field of neuropathic pain quickly became clear [22]. A pharmacological block of the plexus was then extended to treat acute pain caused by an avulsion injury or more distal damage, such as upper limb injury or amputation [23]. In healthy adults, a temporary anesthetic block of the brachial plexus can elicit an artificially induced phantom limb sensation [24]. A phantom arm sensation often fades when the effects of the anesthesia wear off [24]; however, in some cases, it can persist for a longer period [25].

An interesting aspect by which an artificial block or lesion of the brachial plexus may guide phantom phenomena is mislocalization. The classic work of Melzack and Bromage [24] showed that an anesthetic block of the upper limbs produces a significantly high rate of phantom arms. Interestingly, there is a different spatial orientation between the real limb and the phantom limb when sensation arises minutes after the injection. Furthermore, despite differences in the actual arm position between subjects, the phantom limb is often felt in a similar position. Specifically, during brachial plexus anesthesia, the phantom arm is experienced, in most cases, as resting on the chest/abdomen, even if it was on the operating table [24]. These observations were recently confirmed [25], and they suggest a highly different spatial localization between natural, pre-traumatic limb postural sensations, and post-trauma phantom sensation. The common experience of the phantom arm resting on the chest suggests common morphological and functional rearrangements after deafferentation, and it provides an important clue to the common bases of phantom phenomena.

Even more relevant are the somatotopic-type changes of phantom sensations observed in cases involving a brachial plexus injury, where patients commonly report a remapping of sensation from the hand to the cheek [4], in the jaw and buccal region [26], or in the ear [18]. Patients with total brachial plexus avulsions reported phantom limbs more frequently than patients whose lesion involved only portions of the brachial plexus [27]. Interestingly, these limb sensations were reported to be evoked by light touch on the surface of the external ear within days of the lesion [18], whereas they were reported on the jaw and buccal region after a number of months [26] and on the cheek area after a number of years [4]. This temporal pattern suggests that sensation from the deafferented limb may undergo a continuous and gradual process of neural reorganization onto a circumscribed region of the facial skin, with each spatial stage of remapping having a characteristic time scale. While many topographical relationships between somatotopical representations have been identified [28,29], the ear images of the sensory and motor homunculi, relative to other facial structures, remain under debate, leaving a hole in the homunculus. A limited number of studies found and confirmed, using

electric stimulation of the ear on three different points, the presence of a specific area in the somatosensory cortex corresponding to the ear [30-32]. Using both magnetoencephalography [30] and functional magnetic resonance [31], the representation of the ear was located in the primary somatosensory cortex in both the neck and face areas. Much less is known about the motor cortical representation of the ear. Yu, *et al.* [33] induced movement of an ear via electrical stimulation of the contralateral posterior portion of the superior temporal gyrus. The authors were highly cautious and suggest the presence in the stimulated structure of a connection with a “ear motor center” in the frontal areas, which has not yet been found in humans but is located in primates [34]. However, clinical observations of ear remapping after a traumatic nerve injury suggest that such sensations can be specific to the upper limb [35], fully compatible with the hypothesis of a collocation of ear contiguous to the upper limb in somatosensory cortical maps. More recently, a single case study on a patient who experienced a brachial plexus avulsion injury was undertaken to define and depict better the hand in the ear [18]. After brachial avulsion, the patient reported that phantom limb sensations in the hand and arm were evoked by stimulating the ear. No effects from stimulation of the face were found. Tactile stimulation by light touch to the aural territory innervated from a branch of the vagus nerve revealed a high spatial specificity of phantom upper limb sensations. Stimulation of different points on a selected ear region evoked clearly delineated phantom digit sensations for either the dorsal or volar skin surfaces of the limb. Different forms of stroking delivered to the ear (e.g., continuous versus intermittent) were felt as the same sensation on the limb. Four weeks after the injury, even if the phantom ear sensation has vanished, the same systematic somatotopic changes can be experimentally re-induced using the rubber hand illusion framework [36]. This spatial specificity of referred sensation is fully compatible with the hypothesis of “somatotopic interferences” in the homuncular map of the somatosensory cortex. This possibility is strongly supported by the study of somatosensory-evoked potential [18]. In patients, stimulation within the vagally innervated territory of the external ear modulated activity within the centro-parietal regions, in accordance with the findings of previous studies [30-32]. The case demonstrates an important contribution to recent medical advances related to the vagus nerve, given its apparent role in bodily awareness [37] and its proven modulation of the centro-parietal cortical regions [38,39]. The phenomena, mechanisms, and neural structures involved in vagal stimulation have been explored in deafferented patients [40,41]. The auricular branch of the vagus nerve projects to the nucleus tractus solitarius. The direct pathways connecting the solitary tract nucleus and thalamus reach the parietal cortex and may initiate loop-like enhanced activity between the body and brain [40]. Although the role of the vagal network in bodily awareness remains unknown, vagus nerve stimulation seems to potentiate the spread of cortical signaling via the re-establishment of the thalamocortical network. Cortical responsiveness can, therefore, be modulated from short- and long-term modifications mediated by neurotransmitter release (e.g., norepinephrine and serotonin) and may evoke cortical reorganization, such as that been reported in the deafferented somatosensory areas of primates [42]. A recent work proposed a cortical multi-determined body model consisting of different representations of the cortical layers of the somatosensory cortex [43]. This interesting theoretical proposal attempted to answer the question, “Is [the] somatosensory cortex a sensory map or an animatable avatar?” Layer 4 of this primary cortical area can be considered a container of the body’s memories, resulting from genetics and experience—a puppet-like body model that goes beyond simply an up-to-date sensory map—it is a more stable and long-lasting model used to evaluate and project motor responses before final action production [43]. Especially in the somatosensory cortex, deafferentation is expected to imbalance this finely tuned interaction and stabilize body representations that cannot be correctly updated. Cortical representations likely do not change, as was previously thought. The stable topography despite the presence of a brachial plexus avulsion [44], even decades after injury, emphasizes the need to determine what happens to the abolished somatosensory territory involving sensory and motor communication between the residual arm and the central nervous system [44].

For the moment, the mechanisms underlying the development of spontaneous or actively elicited phantom sensations remain hypothetical, as are those supporting the embodiment processes

and the plasticity of bodily representations. In amputees, when a hand is deafferented, the neuronal territory that controls that hand in S1 can apparently be remapped to adjacent body representations [45,46]. In monkeys, after prolonged sensory deafferentation, the cortical representation of the body part is reorganized into neighboring areas [47]. Nevertheless, studies on humans did not yield similar results. Human brain does not exhibit the same topographical mapping as the primate brain [48,49]. Recent neural evidence documented the stability of somatosensory topographies and functional organization, despite massive sensory deafferentation [50]. Additionally, a phantom limb is occasionally reassigned to body parts that do not obey the rule of adjacency in cortical topography [51]. Corporeal shifts occur, for example, for the healthy contralateral hand, foot, or chest. The current phantom limb dogma centrally undermines subcortical activity, as well. Reorganization plays a large role in the potentiation and formation of new pathways in subcortical and peripheral structures [50]. The cuneate nucleus in the brainstem is likely a key point for reorganization following deafferentation [52]. Incoming facial projections, which from the trigeminal nucleus of the brainstem sprout and grow into the cuneate nucleus [53], could explain the presence of somatosensory interference between the referred sensations to the face and hand, but not as distinct from the ear.

While referred sensations from the ear/face to phantom limb experiences might well reflect peripheral and central processes, so the comprehension of phantom pain could potentially disentangle the intricate picture. In many accounts, phantom sensations and pain both emerge from altered activity in the central nervous system caused by the loss of peripheral information in a top-down process of perceptual prediction. A different, coexistent, and less-explored approach is the "bottom-up" hypothesis [54]. This view attempts to answer the question, "How do peripheral nervous structures impact perception?" Amputation or nerve lesions activate regenerative processes. This activity often produces tumor-like structures, known as neuromas, in the stump area. The role of these structures in painful sensations has long been known and is well-established in scientific research; both spontaneous activation and active pressure on the stump are highly correlated with the onset of pain [55]. Despite the role of stump neuromas, both acute and chronic treatment of the phantom pain targeting the stump have had limited success. Moreover, specific clinical guidelines do not exist due to the high levels of individual variability. The limited efficacy of distal treatment has led researchers to focus instead on the central nervous system. Vaso et al. [54], however, supported the role of the peripheral nervous system with their study on dorsal root ganglia. An anesthetic block of the roots suppressed painful phantom sensations in many patients. The authors explained that this result reflected the suppression of ectopic neuronal activity. This view contrasts with top-down theories, which consider phantom pain a possible consequence of cortical reorganization induced by the lack of afferent information. Interestingly, non-painful phantom limb sensations were also affected by a peripheral block [54]. However, the possibility of evoking the phantom limb with tactile stimulation of cortically adjacent but not peripherally adjacent body parts and the high variability of non-painful sensations (i.e., telescoping, reference, and unnatural orientations), both suggest a greater involvement of cortical reorganization [54].

As has been briefly shown, many questions remain, and there may be more than one mechanism leading to phantom pain and the remapping of phantom sensations. A better understanding of phantom sensations in body representations will have a great impact on clinical and rehabilitative approaches to motor and somatosensory impairment. Although nerve grafting alone may have led to a resolution of both the phantom pain and the referred sensations, non-invasive interventions, such as mirror therapy [26,56], virtual reality [57], mental imagery [58], and other sensorimotor experiences would be integrated to partially reset the equilibrium. Technologic advancements are proceeding quickly, and they are poised to offer many solutions regarding the maintenance of a functional or physical body. However, the necessary knowledge of both peripheral and central nervous system processes linked to deafferentation is relatively poor. Most advanced experiences with myoelectric and neural interfaces use muscular proprioceptive information [59] or artificial sensory feedback [60] to control active robotic prostheses. The results are encouraging and are already producing positive impacts in daily life [61]. A truly natural experience, however, remains a distant goal. A brachial plexus avulsion injury and brachial plexus anesthesia can represent effective models for studying deafferentation effects on the nervous system. Understanding adaptive brain plasticity

and its impact on the overall perception process may guide the development of multimodal interventions focused on phantom limb control, as well as the exploitation of residual motor ability and sensory afferences [62,63]. Brachial plexus damage has a higher incidence rate, a more selective impact on health, and a greater promise of recovery, relative to other deafferentation conditions, such as amputations or spinal cord injuries. Therefore, studies of brachial plexus damage may be important scientifically to deal with the neural mechanisms of phantom limb sensations and pain, which, having been made in a single clinical case, obviously need to be confirmed to attain further knowledge. To conclude, we support an integrated view of the bottom-up and top-down contributions to the field of phantom sensations, body representations, and post-traumatic reorganization. A more detailed scientific understanding will require new experimental perspectives [54], including a wider range of clinical or artificially induced conditions [18,25] and a lucid theoretical reorganization of experimental results, as proposed by Brecht [43].

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## References

1. Makin, T.R.; Scholz, J.; Henderson Slater, D.; Johansen-Berg, H.; Tracey, I. Reassessing cortical reorganization in the primary sensorimotor cortex following arm amputation. *Brain* **2015**, *138*, 2140–2146, doi:10.1093/brain/awv161.
2. Pazzaglia, M.; Zantedeschi, M. Plasticity and Awareness of Bodily Distortion. *Neural Plast* **2016**, *2016*, 9834340, doi:10.1155/2016/9834340.
3. Lucci, G.; Pazzaglia, M. Towards multiple interactions of inner and outer sensations in corporeal awareness. *Frontiers in human neuroscience* **2015**, *9*, 163, doi:10.3389/fnhum.2015.00163.
4. Ramachandran, V.S.; Hirstein, W. The perception of phantom limbs. The D. O. Hebb lecture. *Brain* **1998**, *121* ( Pt 9), 1603–1630.
5. Flor, H.; Nikolajsen, L.; Staehelin Jensen, T. Phantom limb pain: a case of maladaptive CNS plasticity? *Nat Rev Neurosci* **2006**, *7*, 873–881, doi:10.1038/nrn1991.
6. Ramachandran, V.S. Consciousness and body image: lessons from phantom limbs, Capgras syndrome and pain asymbolia. *Philos Trans R Soc Lond B Biol Sci* **1998**, *353*, 1851–1859, doi:10.1098/rstb.1998.0337.
7. Schott, G.D. Revealing the invisible: the paradox of picturing a phantom limb. *Brain : a journal of neurology* **2014**, *137*, 960–969, doi:10.1093/brain/awt244.
8. Giummarra, M.J.; Gibson, S.J.; Georgiou-Karistianis, N.; Bradshaw, J.L. Central mechanisms in phantom limb perception: the past, present and future. *Brain Res Rev* **2007**, *54*, 219–232.
9. Montoya, P.; Ritter, K.; Huse, E.; Larbig, W.; Braun, C.; Topfner, S.; Lutzenberger, W.; Grodd, W.; Flor, H.; Birbaumer, N. The cortical somatotopic map and phantom phenomena in subjects with congenital limb atrophy and traumatic amputees with phantom limb pain. *The European journal of neuroscience* **1998**, *10*, 1095–1102.
10. Halligan, P.W.; Marshall, J.C.; Wade, D.T. Sensory disorganization and perceptual plasticity after limb amputation: a follow-up study. *Neuroreport* **1994**, *5*, 1341–1345.

11. Ichinose, A.; Sano, Y.; Osumi, M.; Sumitani, M.; Kumagaya, S.I.; Kuniyoshi, Y. Somatosensory Feedback to the Cheek During Virtual Visual Feedback Therapy Enhances Pain Alleviation for Phantom Arms. *Neurorehabilitation and neural repair* **2017**, *31*, 717-725, doi:10.1177/1545968317718268.
12. Ramachandran, V.S.; Rogers-Ramachandran, D. Phantom limbs and neural plasticity. *Archives of neurology* **2000**, *57*, 317-320.
13. Weeks, S.R.; Tsao, J.W. Incorporation of another person's limb into body image relieves phantom limb pain: A case study. *Neurocase* **2010**, *16*, 461-465, doi:Pii 921668417  
10.1080/13554791003730592.
14. Melzack, R. Phantom limbs and the concept of a neuromatrix. *Trends Neurosci* **1990**, *13*, 88-92.
15. Sherman, R.A.; Griffin, V.D.; Evans, C.B.; Grana, A.S. Temporal relationships between changes in phantom limb pain intensity and changes in surface electromyogram of the residual limb. *International journal of psychophysiology : official journal of the International Organization of Psychophysiology* **1992**, *13*, 71-77.
16. Cook, A.W.; Druckemiller, W.H. Phantom limb in paraplegic patients; report of two cases and an analysis of its mechanism. *Journal of neurosurgery* **1952**, *9*, 508-516, doi:10.3171/jns.1952.9.5.0508.
17. Makin, T.R.; Scholz, J.; Filippini, N.; Henderson Slater, D.; Tracey, I.; Johansen-Berg, H. Phantom pain is associated with preserved structure and function in the former hand area. *Nature communications* **2013**, *4*, 1570, doi:10.1038/ncomms2571.
18. Pazzaglia, M.; Galli, G.; Lucci, G.; Scivoletto, G.; Molinari, M.; Haggard, P. Phantom limb sensations in the ear of a patient with a brachial plexus lesion. *Cortex* **2018**, *in press.*, doi:10.1016/j.cortex.2018.08.020.
19. Catani, M. A little man of some importance. *Brain : a journal of neurology* **2017**, *140*, 3055-3061, doi:10.1093/brain/awx270.
20. Leinberry, C.F.; Wehbe, M.A. Brachial plexus anatomy. *Hand Clin* **2004**, *20*, 1-5.
21. Winnie, A.P. Interscalene brachial plexus block. *Anesthesia & Analgesia* **1970**, *49*, 455-466.
22. Parry, C.W. Pain in avulsion lesions of the brachial plexus. *Pain* **1980**, *9*, 41-53.
23. Schley, M.; Topfner, S.; Wiech, K.; Schaller, H.; Konrad, C.; Schmelz, M.; Birbaumer, N. Continuous brachial plexus blockade in combination with the NMDA receptor antagonist memantine prevents phantom pain in acute traumatic upper limb amputees. *European journal of Pain* **2007**, *11*, 299-308.
24. Melzack, R.; Bromage, P.R. Experimental phantom limbs. *Exp Neurol* **1973**, *39*, 261-269.
25. Russell, H.G.; Tsao, J.W. Phantom Sensations Following Brachial Plexus Nerve Block: A Case Report. *Front Neurol* **2018**, *9*, doi:ARTN 436  
10.3389/fneur.2018.00436.
26. Tsao, J.W.; Finn, S.B.; Miller, M.E. Reversal of phantom pain and hand-to-face remapping after brachial plexus avulsion. *Ann Clin Transl Neurol* **2016**, *3*, 463-464, doi:10.1002/acn3.316.
27. Ciaramitaro, P.; Mondelli, M.; Logullo, F.; Grimaldi, S.; Battiston, B.; Sard, A.; Scarinzi, C.; Migliaretti, G.; Faccani, G.; Cocito, D., et al. Traumatic peripheral nerve injuries: epidemiological findings, neuropathic pain and quality of life in 158 patients. *J Peripher Nerv Syst* **2010**, *15*, 120-127, doi:10.1111/j.1529-8027.2010.00260.x.
28. Rasmussen, T.; Penfield, W. The human sensorimotor cortex as studied by electrical stimulation. *Fed Proc* **1947**, *6*, 184.
29. Zeharia, N.; Hertz, U.; Flash, T.; Amedi, A. New whole-body sensory-motor gradients revealed using phase-locked analysis and verified using multivoxel pattern analysis and functional connectivity. *J Neurosci* **2015**, *35*, 2845-2859, doi:10.1523/JNEUROSCI.4246-14.2015.

30. Nihashi, T.; Kakigi, R.; Kawakami, O.; Hoshiyama, M.; Itomi, K.; Nakanishi, H.; Kajita, Y.; Inao, S.; Yoshida, J. Representation of the ear in human primary somatosensory cortex. *NeuroImage* **2001**, *13*, 295-304, doi:10.1006/nimg.2000.0695.
31. Nihashi, T.; Kakigi, R.; Okada, T.; Sadato, N.; Kashikura, K.; Kajita, Y.; Yoshida, J. Functional magnetic resonance imaging evidence for a representation of the ear in human primary somatosensory cortex: comparison with magnetoencephalography study. *NeuroImage* **2002**, *17*, 1217-1226.
32. Nihashi, T.; Kakigi, R.; Hoshiyama, M.; Miki, K.; Kajita, Y.; Yoshida, J.; Yatsuya, H. Effect of tactile interference stimulation of the ear in human primary somatosensory cortex: a magnetoencephalographic study. *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology* **2003**, *114*, 1866-1878.
33. Yu, L.; Terada, K.; Usui, N.; Usui, K.; Baba, K.; Inoue, Y. Ear movement induced by electrical cortical stimulation. *Epilepsy Behav* **2010**, *18*, 488-490, doi:10.1016/j.yebeh.2010.05.016.
34. Lucchetti, C.; Lanzilotto, M.; Bon, L. Auditory-motor and cognitive aspects in area 8B of macaque monkey's frontal cortex: a premotor ear-eye field (PEEF). *Exp Brain Res* **2008**, *186*, 131-141, doi:10.1007/s00221-007-1216-5.
35. Pourrier, S.D.; Nieuwstraten, W.; Van Cranenburgh, B.; Schreuders, T.A.; Stam, H.J.; Selles, R.W. Three cases of referred sensation in traumatic nerve injury of the hand: implications for understanding central nervous system reorganization. *Journal of rehabilitation medicine* **2010**, *42*, 357-361, doi:10.2340/16501977-0526.
36. Pazzaglia, M.; Scivoletto, G.; Giannini, A.M.; Leemhuis, E. My hand in my ear: a phantom limb re-induced by the illusion of body ownership in a patient with a brachial plexus lesion. *Psychological research* **2018**, *in press*.
37. Redgrave, J.; Day, D.; Leung, H.; Laud, P.J.; Ali, A.; Lindert, R.; Majid, A. Safety and tolerability of Transcutaneous Vagus Nerve stimulation in humans; a systematic review. *Brain Stimul* **2018**, *11*, 1225-1238, doi:10.1016/j.brs.2018.08.010.
38. Frangos, E.; Ellrich, J.; Komisaruk, B.R. Non-invasive Access to the Vagus Nerve Central Projections via Electrical Stimulation of the External Ear: fMRI Evidence in Humans. *Brain Stimul* **2015**, *8*, 624-636, doi:10.1016/j.brs.2014.11.018.
39. Komisaruk, B.R.; Whipple, B.; Crawford, A.; Liu, W.C.; Kalnin, A.; Mosier, K. Brain activation during vaginocervical self-stimulation and orgasm in women with complete spinal cord injury: fMRI evidence of mediation by the vagus nerves. *Brain research* **2004**, *1024*, 77-88, doi:10.1016/j.brainres.2004.07.029.
40. Corazzol, M.; Lio, G.; Lefevre, A.; Deiana, G.; Tell, L.; Andre-Obadia, N.; Bourdillon, P.; Guenot, M.; Desmurget, M.; Luaute, J., et al. Restoring consciousness with vagus nerve stimulation. *Curr Biol* **2017**, *27*, R994-R996, doi:10.1016/j.cub.2017.07.060.
41. Hoshida, R.; Jandial, R. Regaining Consciousness: The Effect of Vagal Nerve Stimulation on a Patient in a Permanent Vegetative State. *Neurosurgery* **2018**, *82*, N29-N30, doi:10.1093/neuros/nyx597.
42. Conti, F.; Minelli, A.; Pons, T.P. Changes in glutamate immunoreactivity in the somatic sensory cortex of adult monkeys induced by nerve cuts. *The Journal of comparative neurology* **1996**, *368*, 503-515, doi:10.1002/(SICI)1096-9861(19960513)368:4<503::AID-CNE3>3.0.CO;2-8.
43. Brecht, M. The Body Model Theory of Somatosensory Cortex. *Neuron* **2017**, *94*, 985-992, doi:10.1016/j.neuron.2017.05.018.

44. Kikkert, S.; Kolasinski, J.; Jbabdi, S.; Tracey, I.; Beckmann, C.F.; Johansen-Berg, H.; Makin, T.R. Revealing the neural fingerprints of a missing hand. *Elife* **2016**, *5*, doi:10.7554/eLife.15292.
45. Ramachandran, V.S.; Altschuler, E.L. The use of visual feedback, in particular mirror visual feedback, in restoring brain function. *Brain* **2009**, *132*, 1693-1710, doi:10.1093/brain/awp135.
46. Lotze, M.; Grodd, W.; Birbaumer, N.; Erb, M.; Huse, E.; Flor, H. Does use of a myoelectric prosthesis prevent cortical reorganization and phantom limb pain? *Nature neuroscience* **1999**, *2*, 501-502, doi:10.1038/9145.
47. Pons, T.P.; Garraghty, P.E.; Ommaya, A.K.; Kaas, J.H.; Taub, E.; Mishkin, M. Massive cortical reorganization after sensory deafferentation in adult macaques. *Science* **1991**, *252*, 1857-1860.
48. Jain, N.; Qi, H.X.; Collins, C.E.; Kaas, J.H. Large-scale reorganization in the somatosensory cortex and thalamus after sensory loss in macaque monkeys. *J Neurosci* **2008**, *28*, 11042-11060, doi:10.1523/JNEUROSCI.2334-08.2008.
49. Kaas, J.H.; Qi, H.X.; Burish, M.J.; Gharbawie, O.A.; Onifer, S.M.; Massey, J.M. Cortical and subcortical plasticity in the brains of humans, primates, and rats after damage to sensory afferents in the dorsal columns of the spinal cord. *Exp Neurol* **2008**, *209*, 407-416, doi:10.1016/j.expneurol.2007.06.014.
50. Makin, T.R.; Bensmaia, S.J. Stability of Sensory Topographies in Adult Cortex. *Trends Cogn Sci* **2017**, *21*, 195-204, doi:10.1016/j.tics.2017.01.002.
51. Knecht, S.; Henningsen, H.; Elbert, T.; Flor, H.; Hohling, C.; Pantev, C.; Taub, E. Reorganizational and perceptual changes after amputation. *Brain : a journal of neurology* **1996**, *119* ( Pt 4), 1213-1219.
52. Kambi, N.; Halder, P.; Rajan, R.; Arora, V.; Chand, P.; Arora, M.; Jain, N. Large-scale reorganization of the somatosensory cortex following spinal cord injuries is due to brainstem plasticity. *Nature communications* **2014**, *5*, 3602, doi:10.1038/ncomms4602.
53. Jain, N.; Florence, S.L.; Qi, H.X.; Kaas, J.H. Growth of new brainstem connections in adult monkeys with massive sensory loss. *Proc Natl Acad Sci U S A* **2000**, *97*, 5546-5550, doi:10.1073/pnas.090572597.
54. Vaso, A.; Adahan, H.M.; Gjika, A.; Zahaj, S.; Zhurda, T.; Vyshka, G.; Devor, M. Peripheral nervous system origin of phantom limb pain. *Pain* **2014**, *155*, 1384-1391, doi:10.1016/j.pain.2014.04.018.
55. Henderson, W.R.; Smyth, G.E. Phantom limbs. *J Neurol Neurosurg Psychiatry* **1948**, *11*, 88-112.
56. Agon, F.; Mateo, S.; Servajean, V.; Rode, G. Regression of supernumerary upper limb phantom and pain after left complete plexus brachial avulsion using mirror therapy: A single case study. *Annals of Physical and Rehabilitation Medicine* **2014**, *Volume 57*, n° S1, e105.
57. Ambron, E.; Miller, A.; Kuchenbecker, K.J.; Buxbaum, L.J.; Coslett, H.B. Immersive Low-Cost Virtual Reality Treatment for Phantom Limb Pain: Evidence from Two Cases. *Front Neurol* **2018**, *9*, 67, doi:10.3389/fneur.2018.00067.
58. Raffin, E.; Mattout, J.; Reilly, K.T.; Giroux, P. Disentangling motor execution from motor imagery with the phantom limb. *Brain : a journal of neurology* **2012**, *135*, 582-595, doi:10.1093/brain/awr337.
59. Clites, T.R.; Carty, M.J.; Ullauri, J.B.; Carney, M.E.; Mooney, L.M.; Duval, J.F.; Srinivasan, S.S.; Herr, H.M. Proprioception from a neurally controlled lower-extremity prosthesis. *Sci Transl Med* **2018**, *10*, doi:10.1126/scitranslmed.aap8373.
60. Valle, G.; Mazzoni, A.; Iberite, F.; D'Anna, E.; Strauss, I.; Granata, G.; Controzzini, M.; Clemente, F.; Rognini, G.; Cipriani, C., et al. Biomimetic Intraneural Sensory Feedback Enhances Sensation Naturalness, Tactile Sensitivity, and Manual Dexterity in a Bidirectional Prosthesis. *Neuron* **2018**, *100*, 37-45 e37, doi:10.1016/j.neuron.2018.08.033.



61. Graczyk, E.L.; Resnik, L.; Schiefer, M.A.; Schmitt, M.S.; Tyler, D.J. Home Use of a Neural-connected Sensory Prosthesis Provides the Functional and Psychosocial Experience of Having a Hand Again. *Sci Rep-Uk* **2018**, *8*, 9866, doi:10.1038/s41598-018-26952-x.
62. Pazzaglia, M.; Haggard, P.; Scivoletto, G.; Molinari, M.; Lenggenger, B. Pain and somatic sensation are transiently normalized by illusory body ownership in a patient with spinal cord injury. *Restor Neurol Neurosci* **2016**, *34*, 603-613, doi:10.3233/RNN-150611.
63. Pazzaglia, M. Body and Odors: Non Just Molecules, After All. *Current Directions in Psychological Science*. **2015**, *24*, 329-333.