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# Phantom Limbs and Mirror Therapy: Brain Plasticity and Future Treatment for Brain Disorders and Injuries

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***Abstract:*** *Every thirty seconds globally, a person loses his or her arm or leg due to amputation. Annually, more than one million people around the world undergo amputation surgery. In the United States alone, 185,000 people lose their limbs due to this type of surgery each year. Amputation may cause many problems in patients' daily lives since they have lost one or more of their limbs, which means that their motor ability will be significantly reduced. Interestingly, after the amputation, many patients report that they can still feel their amputated limb, which, of course, does not exist physically.*

***Keywords:*** *Phantom Limbs, Mirror Therapy, Brain Plasticity, Brain Disorders and Injuries*

## 1. Introduction

Every thirty seconds globally, a person loses his or her arm or leg due to amputation. Annually, more than one million people around the world undergo amputation surgery. In the United States alone, 185,000 people lose their limbs due to this type of surgery each year (Owings, Kozak, 1998). Amputation may cause many problems in patients' daily lives since they have lost one or more of their limbs, which means that their motor ability will be significantly reduced. Interestingly, after the amputation, many patients report that they can still feel their amputated limb, which, of course, does not exist physically. This phenomenon of having an imagined limb after amputation is called Phantom Limb Syndrome (PLS). In fact, PLS occurs in approximately 90 percent of amputees (Katz, 2020), which means that it is very frequent among patients. Some patients report that they feel that their phantom limbs are “frozen” and fixed in a “block of cement,” or they experience pain from these fixed limbs (Ramachandran 2012, p31). This phenomenon has long baffled scientists. One of the most renowned neuroscientists, V. S. Ramachandran, discovered a possible cause of this phenomenon, subsequently developing a treatment that has proven effective to reduce phantom limb pain: the mirror box. The cause of phantom limbs among amputees, the symptoms and logical reasoning behind phantom limb pain, and the principle of mirror therapy, together suggest that humans have an unbelievably large capacity for brain plasticity, which broadens scientists’ view on the prospect of future plausible treatments for brain disorders.

## 2. Fundamentals of Phantom Limb Syndrome

Phantom limb is a phenomenon in which a limb is amputated but the amputee still feels the sensation of the pre-existing limb (Manchikanti, Singh, et al., 2019). The phantom limb was first described in 1552 by the French surgeon Ambroise Paré after he heard complaints from the wounded and amputated soldiers (Rugnetta, nd). The term “phantom limb” was originally created by the American physician Silas Weir Mitchell in 1871. Between 1871 and the late 1980s, the main hypothesis for explaining phantom limb was irritation of the peripheral nervous system at the amputation site, which creates a neuroma (a painful nerve tumor) that causes the sensation of a phantom limb. However, researchers later discovered that newborn babies who were born without intact limbs have the sensation of phantom limb, thus detracting from the explanatory power of the neuroma hypothesis. (*Canadian Psychology,* 1989).

Phantom limb pain (PLP) may arise from the phantom limb of a patient after amputation. However, only a relatively small percentage of phantom limb amputees experience painful sensations (Manchikanti, Singh, et al., 2019). These pain sensations usually ease and disappear after approximately 2-3 years after amputations in most PLP patients (Manchikanti, Singh, et al., 2019), but some patients report persistent pain over a longer period. There are different treatment options for PLP, such as antidepressants, vibration therapy, acupuncture, and spinal cord stimulation (Alviar, Hale, et al., 2016). However, most of these treatment methods are not very effective. The most famous treatment which has caught the medical field's interest is mirror therapy (MT), which requires the use of a mirror box developed by the neuroscientist V. S. Ramachandran. Many recent peer-reviewed studies suggest that "MT seems to be effective in relieving PLP, reducing the intensity and duration of daily pain episodes" and "it is a valid, simple, and inexpensive treatment for PLP" (Campo-Prieto, Rodr ǵuez-Fuentes, 2018).

Ramachandran's hypothesis of the cause of phantom limbs is one of the most plausible and biologically logical ones: He believes that phantom limb sensations in humans may be due to the reorganization of the brain's somatosensory cortex. This reorganization is the central idea that helped Ramachandran formulate the mirror box and MT. All the evidence and logical reasoning behind the reorganization of the brain supports the idea that the human brain has a large capacity for plasticity.

## 3. Diagnosis and Treatment for PLP and Future Application

Phantom limb patients experience the sensation of their amputated limb at the original site of their missed limbs. However, this is not the only location in which patients have phantom limb sensation. Ramachandran surprisingly found that patients can also feel a sensation in their phantom limbs when he uses a Q-tip to touch the patients' faces while blindfolding them, a phenomenon named referred sensations (RS) (Ramachandran 2012, p25). The patients can feel the actions Ramachandran does to their faces on the phantom limb location (Ramachandran 2012, p25). For example, if there is a water droplet flowing down the patients' cheeks, they will feel that water is flowing downward on their phantom limbs (Ramachandran 2012, p25). One of the patients stated that "he could relieve itching [on the phantom limb area] by scratching the corresponding location on his face. (Ramachandran 2012, p26)" In 2017, Collins, et al discovered that RS- "experience feelings in the missing limb when a different body part is stimulated"- occurs in 42.1% (eight of 19) of the amputees in their experimental group (Collins et al.). The researchers confirmed Ramachandran's findings and delineated a hand-to-face remapping (as shown in Figure 1).

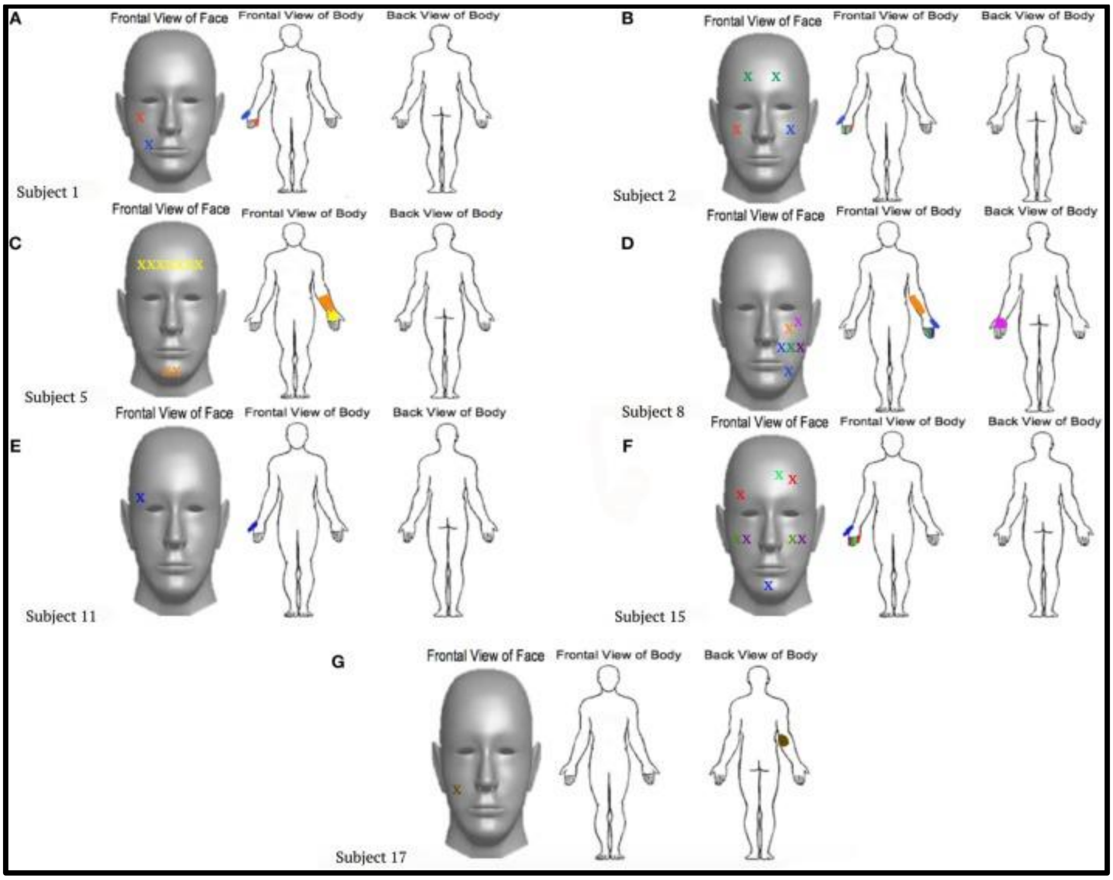

*Figure 1. Locations touched on the faces that were reported to also elicit sensations within the phantom limb.*

This interesting phenomenon occurs because of the complicated layout and function of the human brain. There is a brain map, which is called the cortical homunculus, that represents our sensations of different body parts on sensory areas inside our brain. The continuity of homunculus is broken into several pieces, a mapping that does not correspond to the body's actual layout (Ramachandran 2012, p26). For example, the map of the face is "next to the hand instead of near the neck" (Ramachandran 2012, p26) where it should be in our actual body (as shown in Figure 2). The arrangement of the brain map may explain the RS phenomenon. After an amputation, the patient has no actual limb. However, the location of the specific part of the body from the sensory neurons used to connect to each other still exists in the cortical homunculus of the patient. Therefore, the brain map still represents the missing body parts but the brain is not receiving any inputs from the amputated limbs, and is in expectation of signals (Ramachandran 2012, p28). Signals received from the "face sensory area" of the brain start to actively invade the nearby hand and arm sensory area. Neurons start to form new synapses and connections, making the signals from the face not only stimulate the face map but also the limb map. There is another explanation that even before amputation, sensory input from the face not only reaches the face sensory area but also "creeps" * into the arm and hand sensory area (Ramachandran 2012, p28). Patients could not feel this before amputation because this phenomenon is "silent" *, but they can feel the sensation right after they get amputated (Ramachandran 2012, p28).

* These words are more metaphorical than explanation.

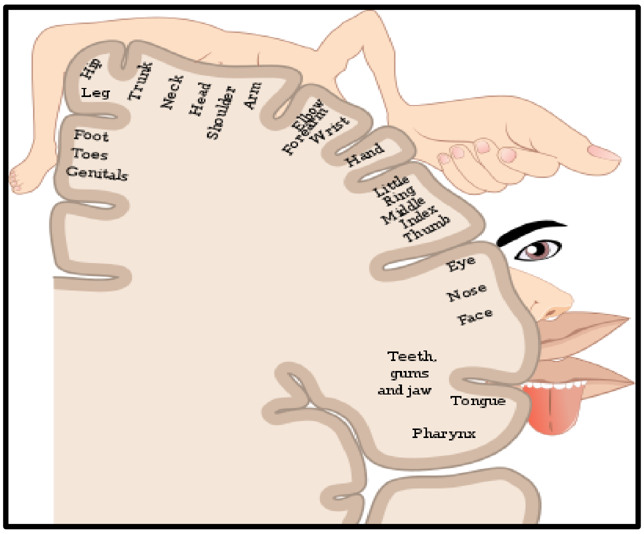

*Figure 2. A 2-D cortical sensory homunculus (brain map)*

In fact, there are more examples of differences between sensory input and actual sensation other than the arms-face connection. For example, there are cases in which after patients get amputated, their phantom feet receive sensation from their penises (Ramachandran 2012, p29). This phenomenon is also easy to understand because according to the homunculus model, the map of the genitals is right next to the map of the foot (Figure 2), and therefore signals from the genitals actively invade the sensory area of the feet. All these examples support the idea that brain maps can change and the brain is highly plastic, with the ability to form new synapses and connections and duplicating signals from one sensory area to another.

Some patients report that they can vividly "move" their phantom limbs after they get amputated, which is a very interesting phenomenon that relates to the sensory input and motor output of the brain. It is known that the motor output is not only sent to the specific body part that is being instructed to move but also sent to the parietal lobe where the brain will compare the signals it sends and the actual movement of the muscle (Ramachandran 2012, p30). If the body does not move as the command, the brain will make corrections next time when it makes motor signals (Ramachandran 2012, p30). In the situation in which the limb is amputated, the brain does not know that the limb is missing but instead keeps sending commands to the parietal lobe. When the parietal lobe receives the copies of these signals, patients misinterpret these signals as the actual movement of the phantom limb. This happens because the patient's parietal lobe does not give back any "veto signals" from his sensation since his limb does not physically exist and there are no sensory signals from his eyes, muscles, or nervous system that tells the brain that the limb is not moving (Ramachandran 2012, p31). Instead, in a normal human being in which the limbs are intact, even if the brain sends motor signals, the sensory signals from his eyes, muscles, and skin confirm and tell the parietal lobe that his limb is not moving. (Ramachandran 2012, p31) (as shown in Figure 3).

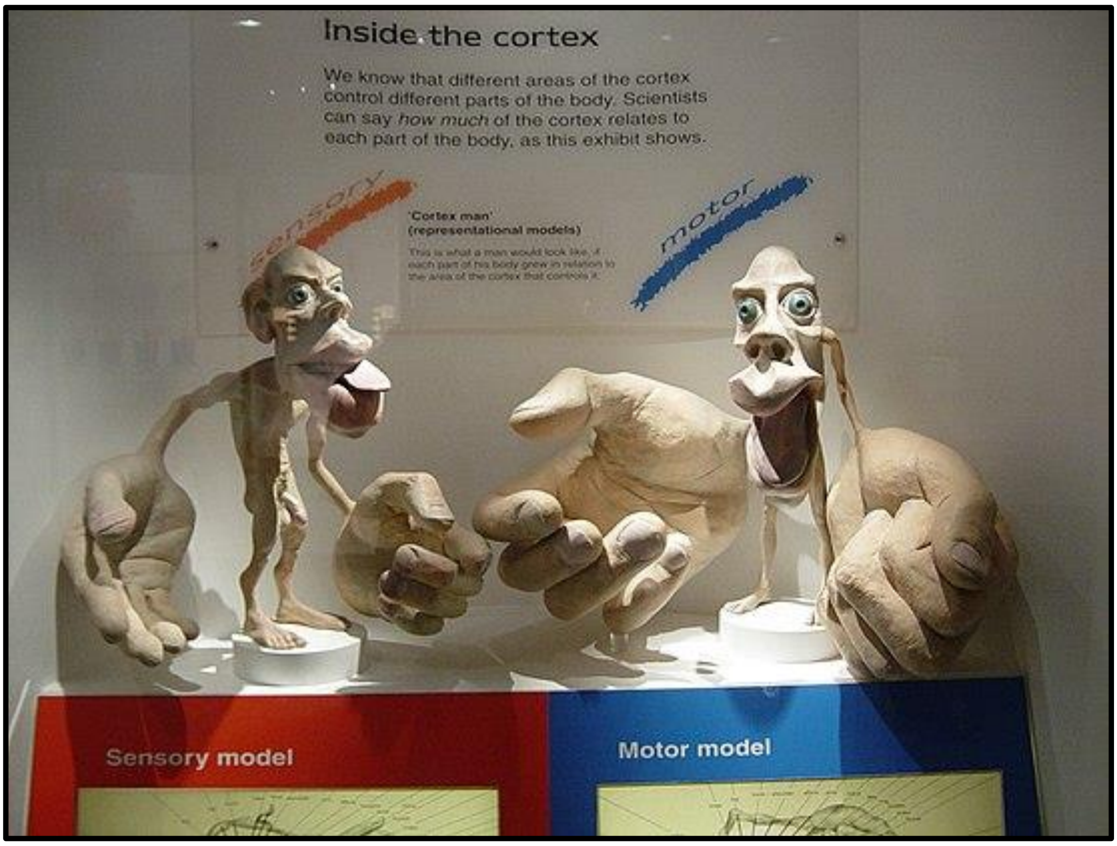

*Figure 3. 3-D Sensory and Motor homunculus models at Natural History Museum, London*

Although many patients report that they perceive they can move their phantom limbs, some others report that they are not able to move them but instead sense that their phantom limbs are "frozen" and fixed in a "block of cement." (Ramachandran 2012, p31) They also report painful sensations since they are not able to move their phantom limb, a phenomenon known as Phantom Limb Pain (PLP). PLP has long baffled researchers who want to develop a plausible and effective treatment- including Ramachandran. However, after careful research and observation, Ramachandran discovered that there is a condition common in many PLP patients: Prior to amputation, many PLP patients experience peripheral nervous system injuries, which cause them to have an intact, but paralyzed limb, meaning that although their limbs physically exist, the patients are not able to feel any sensations from them (Ramachandran 2012, p31).

Ramachandran suspects that "this period of real paralysis could lead to a state of learned paralysis. (Ramachandran 2012, p31)" In the nervous system, if patterns between motor output and sensory input are reinforced, which means that the output and input happen simultaneously, the connection between synapses of the neurons will strengthen. Conversely, if there is no sensory input following motor output, which means there is not an apparent connection between command and sensation, the neurons will shut down their synapses and stop working. For PLP patients before amputation, their arms are intact and paralyzed, which means that every time the brain sends a "move signal," the sensory cortex will receive a veto from the eyes, the muscles, and the skin. After this happens multiple times, the neuron will shut down connections and the synapse will become moribund and cause a "learned paralysis." (Ramachandran 2012, p32) This "learned paralysis" will be carried on by the patients after the amputation, which results in the perception that the phantom limbs cannot be moved.

According to this explanation, there is one effective way that PLP can be improved or cured: Get rid of the "learned paralysis" and reinforce synapse connections. The phantom limb is no longer physically intact, so therefore it is not possible for the patient to receive any real sensory signals from muscles, skins, or joint sections. However, if it were possible for them to receive visual cues and if the patient's vision confirms the movement of the phantom limb after a motor output is sent, there will be positive reinforcement, and synapses between neurons will start to reform. This will lead the patient to get rid of "learned paralysis" and pain may ease or disappear.

In order to create these visual cues and fool the brain, Ramachandran developed a device called a mirror box (Figure 4). This device allows amputees to see the reflection of their intact limbs at the position of their phantom limbs. According to Ramachandran, the patient will "see the reflection of one hand precisely superimposed on the *felt* location of [his] other hand"(Ramachandran 2012, p32).

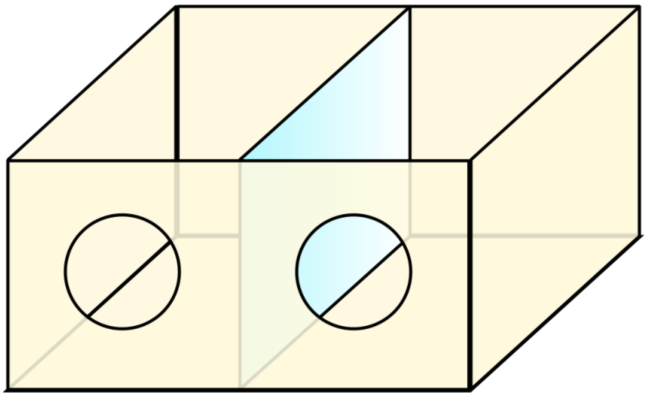

*Figure 4. A diagram of a mirror box*

*Figure 5. A PLP patient with phantom left arm using the mirror box while having mirror therapy*

Ramachandran thus constructed the idea of mirror therapy and then conducted an experiment on one of his PLP patients with an intact right arm and a phantom left arm. After positioning his right intact arm into the mirror box, the patient is able to see the superimposition of the arm in the position of his phantom limb (Ramachandran 2012, p34). The patient is then asked to perform mirror-symmetric movements while looking into the mirror (Ramachandran 2012, p34). While performing these actions, the patient immediately feels that his arm is "plugged back in "(Ramachandran 2012, p34). After using the mirror box for a few more weeks, PLP eventually eases and disappears (Ramachandran 2012, p34). More encouraging, some other patients report that their pain, along with phantom limb, completely vanishes after taking mirror therapy for several weeks (Ramachandran 2012, p34)(as shown in Figure 5).

Ramachandran's mirror therapy caught researchers' focus and they began to test the efficacy of this therapy: Most results come back with positive feedback. A 2018 review found 15 peer-reviewed research articles on mirror therapy and concluded that "MT seems to be effective in relieving PLP, reducing the intensity and duration of daily pain episodes. It is a valid, simple, and inexpensive treatment for PLP. (Campo-Prieto, Rodrǵuez-Fuentes, 2018)"

*Figure 6. V. S. Ramachandran (right) with his original mirror box*

Researchers were surprised after they discovered that mirror therapy can be applied to treat and cure disorders other than PLP. They found that mirror therapy can also ease or treat symptoms of hemiparesis in post-stroke patients and limb pain in patients with Complex Regional Pain Syndrome (CRPS). Hemiparesis usually results in past-stroke patients, who are unable or experience difficulties moving one side of their bodies. CRPS is a disorder in which patients experience prolonged pain and inflammation after an injury in their limbs (NIH). Mirror therapy can ease pain or foster recovery in both of these two disorders, following the same logic behind the mirror therapy treatment for PLP (as shown in Figure 6).

The referred sensations in post amputees and mirror therapy for various disorders together show that the human brain is extraordinarily plastic. The ability for the brain structure to “change” and neurons to form new synapses or disconnect from each other is an important feature in humans. These features have significant clinical importance because they allow researchers to logically analyze the cause of different brain disorders and develop new and plausible treatment methods such as mirror therapy. There are many other nervous system diseases or brain disorders that lack effective treatment methods. However, with the concept of highly plastic brains and advances in science and medications, treatments for these disorders may become available.

## 4. Refutation

Researchers and medical students in the mid to late 1900s believed that the brain's neural connections are “laid down in the fetus and during early infancy.” Some use this as an excuse to “tell patients to expect to recover little function after stroke.” Even now, many people have a stereotype that only children have the ability to reshape their brains but adult brains lose their ability to form neural connections. This stereotype lacks support and people of all ages have the ability to “reform” their brain and form new connections, which can be demonstrated by the change of brain map after amputation and the effectiveness of the mirror therapy in past-stroke patients.

Magnetoencephalography (MEG) scans, which are scans that identify brain activities (usually used to find the area of the brain which indicates eplipsy), confirm Ramachandran’s statement that human brains will form new connections. In Figure 7, a significant difference is shown between the basic sensory map of control group adults and adult amputees. This demonstrates the idea that several centimeters change of neural connection in an adult’s brain can change sensory inputs and again reinforces the statement that phantom limb sensations are caused by a change in the brain map and neural connections.

In 2009, researchers Ezendam, Bongers, and Jannink conducted a review that gives an “overview of the current state of research regarding the effectiveness of mirror therapy in upper extremity function” (MJ, Ezendam, et.al.). The researchers carefully identified and reviewed fifteen studies, including five studies focused on mirror therapy after stroke, and six studies focused on CRPS (MJ, Ezendam, et.al.). In their report, the researchers came to the conclusion that “The present review showed a trend that mirror therapy is effective in upper limb treatment of stroke patients and patients with CRPS” (MJ, Ezendam, et.al.). This proves that patients are able to recover through mirror therapy to reshape the brain after a stroke, even though the patient is an adult.

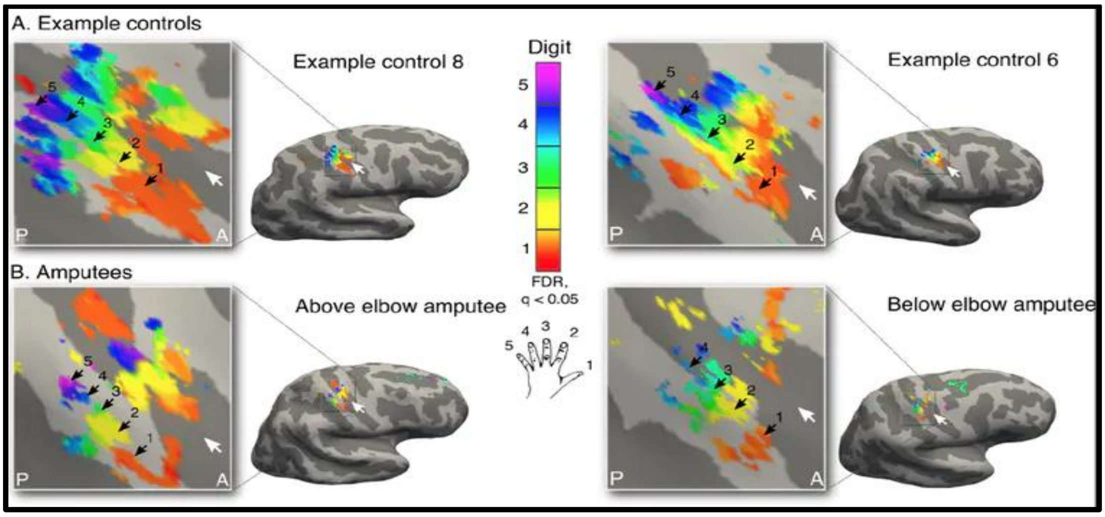

*Figure 7. Change of the basic sensory maps in the adult human after amputation, causing phantom limb sensations*

Multiple other pieces of research and studies regarding brain plasticity completely overthrow the idea that adult brains can not form new connections, but instead show that human brains, one of the most complex and interesting biological systems, have unlimited plasticity.

## 5. Conclusion

According to the work and experiments done by neuroscientist V. S. Ramachandran and other researchers on phantom limb and mirror therapy, a strong conclusion can be stated: human brains have an extraordinary level of plasticity, enabling the brain to form new connections and synapses, disconnect different neurons when there is negative feedback, and remain the ability to reform and reconnect through visual cues. These features have significant clinical importance and may help researchers discover new ways to treat nervous system diseases or brain disorders.

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