The Open Journal of Occupational Therapy

Volume 2
Issue 4 *Fall 2014*

Article 7

10-1-2014

# The Significance of Somatosensory Stimulation to the Hand: Implications for Occupational Therapy Practice

Guy L. McCormack
*Samuel Merritt University, Oakland,CA*, gmccormack@samuelmerritt.edu



## Recommended Citation

McCormack, G. L. (2014). The Significance of Somatosensory Stimulation to the Hand: Implications for Occupational Therapy Practice. *The Open Journal of Occupational Therapy, 2*(4). https://doi.org/10.15453/2168-6408.1141

# The Significance of Somatosensory Stimulation to the Hand: Implications for Occupational Therapy Practice

**Abstract**
The hands contain numerous nerve endings that are intimately connected to the brain. Mounting evidence supports the concept that willful manipulation of objects contributes to expansion or reorganization of the somatosensory cortex and can produce therapeutic outcomes. In the past decade, research has demonstrated that cortical plasticity can continue throughout adulthood. Brain plasticity is a core principle that demonstrates the ability of the central nervous system to respond to stimuli and modify its structural organization and function as an adaptive response. Occupation-based interventions, which engage the use of the hands, are conceived in this article as a "mindbody" experience because of the vast potential for perceptual learning and neurologic reorganization. Many types of neuroplasticity have been identified, but "activity-dependent neuroplasticity" is an essential concept for occupational therapy practice. In addition, the concept of "cross-modal plasticity" will also be delineated with regard to implications to clinical practice. Guidelines for tactile or somatosensory stimulation will be derived from a systematic review of the neuroscience literature.

**Keywords**
somatosensory stimulation, activity-dependent neuroplasticity, cross-modal plasticity, attention parallel processing

**Credentials Display**
Guy L. McCormack, PhD, OTR/L


DOI: 10.15453/2168-6408.1141

There is a common belief in occupational therapy (OT) that through the use of our hands, one can influence their state of health (Reilly, 1962). In her 1976 Eleanor Clarke Slagle Lecture, Joy Huss outlined the significance of touch as a therapeutic intervention. Neuroscience evidence supports the premise that the sensory receptors in the fingers generate action potentials that communicate to multiple neural networks and specific neurons in the cerebral cortex that correspond with the hand and face (Bangert & Schlaug, 2006; Kaas, 1991, 1997, 2004b, 2005; Merzenich & Jenkins, 1993; Merzenich et al., 1996; Obretenova, Halko, Plow, Pascual-Leone, & Merabet, 2010). There is also strong evidence that continuous and long-lasting participation in tactile or sensorimotor skills with the hands results in substantial changes (expansion) in the corresponding regions (maps) of the cortex (Burton, Sinclair, & McLaren, 2004; Recanzone, Merzenich, & Dinse, 1992). The evidence on neuroplasticity also suggests that there is an "activity-dependent" type of neuroplasticity that is enhanced through touch and the manipulation of objects (Bly et al., 2003; Doidge, 2007; Frey & Povinelli, 2012; Hallett, 2005; Hlustík, Solodkin, Gullapalli, Noll, & Small, 2001; Jones, 2000; Vance & Wright, 2009).

Activity-dependent neuroplasticity is the nervous system's capacity to change structurally and functionally in response to tactile input that involves participation in an occupation. Studies show that when one engages in specific repeated activities in a routine fashion, the manipulation of objects will alter the boundaries of neuronal maps developed on the surface of the cortex (Burton et al., 2004; Höffken et al., 2007; Recanzone, Merzenich, & Dinse, 1992). As a result of both actively and passively stimulating the hands for as little as two weeks, changes up to 34 percent can be objectively measured in motor skills and spatial tactile discrimination (Ladda et al., 2014). Because occupational therapists are interested in engaging clients in manual tasks, it is prudent to look at the evidence that contributes to this concept. This article will review selected neuroscience evidence to support the premise that somatosensory stimulation to the hands can influence the organization of the brain and promote better outcomes in habilitation and rehabilitation.

## Literature Review

In her 1961 Eleanor Clarke Slagle lecture, Mary Reilly stated, "man, through the use of his hands, as they are energized by mind and will, can influence the state of his own health" (p. 87). This profound statement has had a tremendous influence on the philosophical and founding concepts of OT. Until recently, the evidence to support this claim has been based on clinical observations and anecdotal findings. A review of the elements of the *Occupational Therapy Practice Framework: Domain and Process* (AOTA, 2014) shows that client factors, which include body functions and body structures, are essential to OT practice. In addition, performance skills, which contribute to sensory perceptual skills and the sense of position in space, enable one to conceptualize a sense of "self." When OT practitioners engage clients to use their hands in performing a purposeful manual task, they are evoking a "consciousness of movement" that involves a continuous feedback loop that informs the nervous system about the quality and precision of the movements, which is a high level of adaptation and sensory integration.

Clinical interventions used in the 1960s and 1970s were based mainly on a “bottom up” approach, meaning the interventions were applied “to the client” mainly through somatosensory, proprioceptive, and vestibular stimulation (Ayres, 1973; Huss, 1977; Rood, 1963). More recently, Bundy, Lane, and Murray (2002) identified a number of sensory-based interventions that expanded the sensory integration frame of reference. The Wilbarger Approach is based on the premise that “individuals require a certain quality and quantity of sensory experiences to be skillful, adaptive and organized in their daily lives” (Wilbarger & Wilbarger, 2002, p 339). In a systematic review of the Wilbarger approach, Weeks, Boshoff, and Stewart (2012) found that the evidence so far has been drawn from small sample studies and has limited generalizability. Schaaf, Hunt, and Benevides (2012) suggest that the methodologies for evaluating the effectiveness of sensory-based interventions in randomized, controlled trials is improving through a method called Goal Attainment Scaling, which allows varied goals to be quantified on the same scale. So far, the literature on sensory stimulation in OT has been limited.

**Contributions of Neuroscience**

In the past ten years, neuroscience has informed us that the brain contains more than 100 billion neurons that reach action potentials to communicate with each other for the formation of complex neural networks that enable the performance of task-oriented functions (Bear, Connors, & Paradiso, 2006; Johnson & Soucacos, 2012). Two types of mechanoreceptors are embedded in the skin of the hand. One type is slowly adapting (SA) and another type is rapidly adapting (RA), both of which detect pressure and touch, respectively (Kandel, Schwartz, & Jessell, 2000). In addition, the larger fingers have more widely spaced mechanoreceptors (Wong, Peters, & Goldreich, 2013). The hands contain remarkable discriminative sensory organs that can accomplish amazing manual activities. By manipulating three-dimensional objects, complex pathways are formed in the cortex and are physiologically connected to behavioral outcomes, such as the stress response, emotions, and the immune system (Calero & Navarro, 2007; Doidge, 2007; Fong et al., 2005; Hussain, 2010; Ramachandran & Hirstein, 1998; Tinaazi et al., 2000).

In recent years, neuroscience studies have amassed considerable evidence that shows that there is an intimate relationship between the somatosensory cortex and the surface of the hands and fingers in both primates and humans. Two researchers in particular, Jon Kaas (2004a, 2004b, 2004c, 2005) and Michael Merzenich (1984, 1993, 1996), have conducted neuroscience studies that show that stimulation of the sensory receptors in the hand, either through passively applied stimulation or through the voluntary manipulation of objects, enlarges the boundaries of the neuronal assembles in the cortex. In one study, Merzenich and Jenkins (1993) found that if a digit is amputated in adult


DOI: 10.15453/2168-6408.1141

monkeys, the cortical sensory representation to that digit is taken over by the adjacent digits within two months. In another study, Pons et al. (1991) found that the somatosensory cortex not only undergoes remarkable reorganization after long-term deafferentation, but that the cortical area originally corresponding to the hand is taken over by sensory input to the lower facial region, which is topographically just below the hand on the homunculus.

In 1949, Donald Hebb proposed the concept of nerve assemblies. In Hebb's classic book, *The Organization of Behavior: A Neuropsychological Theory* (1949), he formulated his "dual trace mechanism" theory, whereby interconnected and coactive neuronal circuits permanently modify the efficacy of pathways. According to Hebb, connections between neurons increase in efficacy in proportion to the degree of correlation between pre and postsynaptic activity. In other words, "neurons which tend to fire together, wire together." Drawing on data and concepts from the molecular systems, Hebb also applied this theory to processes of learning and memory (Brown & Milner, 2003).

It has been known for some time that the hand is amazingly over-represented in the somatosensory cortex (Kaas et al., 1995; Penfield & Boldrey, 1937; Penfield & Rasmussen, 1950). Dr. Wilber Penfield conducted pioneering studies by applying a small electrical probe to regions of the cortex to elicit motor responses in the hand and other body regions in preparation to perform neurosurgery on patients with brain tumors and seizure disorders. From studies of over 400 patients, Penfield and Rasmussen (1950) discovered the sensory and motor homunculus, which is used today to depict the representation of neurons to body structures on the surface of the cortex. The hands, lips, and face are abundantly represented to enable assembles of neurons to interact during the performance of highly skilled hand manipulations and speech and facial expressions. Beyond the borders of the somatosensory and motor cortices, Penfield found that if he stimulated areas of the parietal and temporal lobes, his patients reported unusual "mindbody sensations," such as smelling odors, recalling long-lost memories, and experiencing visual and auditory hallucinations and even out-of-body experiences (Penfield & Rasmussen, 1950).

The neuronal cell assembles in the cortex are organized in six layers. Somatosensory integration was believed to begin in the sensory end organs of the hand, transmit to the thalamus, and then move to layer four of the cerebral cortex where neuron assemblies communicate through parallel processing to other regions of the cortex (Bear et al., 2006; Kandel et al., 2000). The primary somatosensory cortex (S1) is subdivided into smaller regions and today neuroscientists know that area S1 is most responsive to somatosensory sensation that is discrete and segregated (Höffken et al., 2007).

**Types of Neuroplasticity**

Different types of neuroplasticity have been identified (Grafman, 2000; Grafman & Litvan, 1999; McCormack, Douglas, Pauley, Schultze, & Volkers, 2009). Cross-modal plasticity is the adaptive reorganization of neuronal networks to integrate the function of two or more sensory systems. For example, in visually impaired individuals, the somatosensory cortex is able to recruit the neurons in the visual cortex to assist with tactile sensation (Bavelier & Neville, 2002). In addition to cross-modal plasticity, the brain is capable of map expansion, which means the regions of the cortex that are normally devoted to receiving and processing sensory information enlarge and recruit neighboring neurons to join the newly formed cell assembles devoted to a new function (Bavelier & Neville, 2002).

Another form of neuroplasticity is called homologous area adaptation, which occurs during the early critical period of development (Goh & Park, 2009; Lane & Schaaf, 2010; Woodruff-Pak & Hansen, 1995). If a particular region of the brain becomes damaged in early life, its normal operations have the ability to shift connections to other brain areas to take over for the damaged area. The function is often shifted to cell assemblies in the matching, or homologous, area of the opposite brain hemisphere (Nudo, 2007; Nudo & Millikin, 1996).

Yet, another form of neuroplasticity is called compensatory masquerade, which can be described as the brain rerouting or figuring out an alternative strategy for carrying out a task when the initial skill set is faulty due to trauma or dysfunction (Grafman & Litvan, 1999; Hodzic, Veit, Karim, Erb, & Godde, 2004). For example, a person who suffers some form of brain trauma and impaired spatial sense may resort to another strategy for spatial orientation and navigation. They may compensate by memorizing landmarks or use a cell phone application to find their way to a destination.

There is also negative neuroplasticity, whereby new pathways emerge that create undesirable sensations or perceptions, often as the result of central nervous system trauma (Vance & Wright, 2009). Chronic pain syndromes or neuropathic pain are examples of negative neuroplasticity (Baldry, 2005; Merighi, Salio, Ferrini, & Lossi, 2011; Tinazzi et al., 2000; Tinazzi et al., 1998).

Activity-dependent neuroplasticity is a positive result of applying tactile stimulation to the hands or the result of intentionally manipulating objects. Take, for example, the process of basket weaving. This is a high level skill that requires intact sensation, good finger dexterity, and attention to the detail of putting the reeds in the correct order. Historically, the reconstruction aides used basket weaving for “shell shocked” soldiers as a diversion technique. Little did they know at the time, the activity was stimulating neuroplastic changes in the brain that had a calming effect on the nervous system (Reed, 2001). In the past decade, the evidence to support the use of somatosensory stimulation as a significant form of intervention has become less controversial in the rehabilitation literature (Smith et al., 2009; Whitall et al., 2011; Woodruff-Pak & Hanson, 1995; Xerri, Merzenich, Peterson, & Jenkins, 1998).

**Contributions of Imaging Studies**

The evolution of imaging studies has advanced the knowledge that somatosensory


DOI: 10.15453/2168-6408.1141

stimulation can improve rehabilitation outcomes (Kerschke & Witas, 2013; Levin, 2006). Neuroscience studies are beginning to unravel the complexity of the somatosensory cortex and its respective pathways through advanced imaging techniques, such as functional magnetic resonance imaging (fMRI) and diffusion tensor imaging (DTI). An fMRI is a non-invasive medical procedure used to procure two-dimensional images of the structures of the brain. An fMRI machine uses a magnetic field and radio waves to create detailed images of the body, whereas DTI is a recently developed MRI technique that can measure the movement of water molecules and the macroscopic organization of the white matter to display images. DTI provides greater image resolution of white matter (pathways or tracts) and is becoming widely available in clinical scanners and in human clinical studies. In both imaging methods—DTI and fMRI—the participant performs a task while computed images depict the areas of the brain that are requiring more oxygen uptake (metabolism) and to which neural pathways in the nervous system are transmitting the signals (Caffarra, Ghetti, Concari, & Venneri, 2008; Mori & Zhang, 2006).

**Imaging the Visually Impaired and Musicians**

It has been known for some time that the visually impaired compensate by developing better hearing, better odor detection, and exquisite tactile discrimination (Bavelier & Neville, 2002; Pascual-Leone & Torres, 1993). Studies on visually impaired individuals learning tactile language communication to read braille show robust activation of the occipital lobes, the post superior temporal lobes, and the inferior frontal lobe areas associated with language (Obretenova et al., 2010). Cross-modal adaptation occurs in the visual cortex independent of language when tactile stimulation is applied to the right index finger (Burton et al., 2004). In research on sighted individuals who were blindfolded for 24 hours a day for 5 days while learning to read braille, the visual cortex became active and the cortex was expanded in the cortical representation of their reading fingers (Bangert & Schlaug, 2006; Obretenava et al., 2010). In fact, in other studies it was found that when a visually challenged person learns to read braille using the index, middle, and ring fingers, there is so much overlap in the receptor fields that, as a consequence, the neuroplastic changes in the cortex cause the sensation to become less localized. Therefore, when investigators stimulate each finger for touch localization, the person cannot discriminate between which finger is being touched (Hodzic et al., 2004; Medina and Branch Coslett, 2010; Recanzone, Merzenich, & Dinse, 1992; Tinaazi et al., 2000). Studies show that in the absence of processing visual information, the occipital cortex is recruited to process tactile information (Bavelier & Neville, 2002; Pascual-Leone, Amedi, Fregni, & Merabet, 2005; Pascual-Leone & Torres, 1993). Furthermore, people who have both vision and hearing loss have superior performance in tactile verbal memory because they recruit neurons in the dorsal visual stream, which is normally active in spatial awareness and the perception of three-dimensional objects (Bavelier & Neville, 2002;

Pascual-Leone & Torres, 1993). In summary, studies show that extensive use of the hands can improve tactile perception in visually impaired people.

Brain imaging studies on musicians show that string players expand different regions of the cortex more than keyboard players (Bangert & Schlaug, 2006). Herdener and colleagues (2014) found that Jazz drummers recruit neurons in language-specific regions of the cortex, in addition to the sensory-motor cortex, to process rhythmic patterns unique to each song. The process of learning to play an instrument early in life and into old age is one way to stave off cognitive decline. In fact, dexterous manual work leads to the acquisition of tactile expertise, and this expertise may delay the age effects on the decline in tactile perception (Höffken et al., 2007). In a study on the age-related changes in the human hand, Bowden and McNulty (2013) found that the hypothenar eminence is a better site than the index finger for testing age-related discrimination loss. Curiously, they also found that skin moisturizers used on the hands helped participants to better discriminate among different sensory stimuli.

In general, there is a vast body of literature on healthy aging that supports the concept of maintaining an active lifestyle and learning new manual skills, such as playing an instrument, learning a craft, and using brain fitness computer games that not only improve the use of the hands, but also cognitive perceptual learning, such as speed of visual processing and useful field of view (Andrade & Radhakrishnan, 2009; Ball et al., 2002; Calero & Navarro, 2007; Goh & Park, 2009; Gunning-Dixon & Raz, 2003; Mahncke, Bronstone, & Merzenich, 2006; Mahncke et al., 2006; Vidovich, Lautenschlager, Flicker, Clare, & Almeida, 2009; Wagner, Hassanein, & Head, 2010; Wolinsky, Vander Weg, Howren, Jones, & Dotson, 2013; Zelinsky & Reyes, 2009). This area of neuroplasticity goes beyond the scope of this article, but supports the mind and body effects associated with intentionally manipulating objects. According to Rakoski and Ferguson (2013), the virtual context plays an important role in computer games. In addition, the process of performing mental rehearsals before performing a manual task is showing benefits for people who have had a completed stroke (Butler & Page, 2006; Page, Murray, Herman, & Levine, 2011).

**Influences of Neurogenesis**

Research has shown that new neurons are being developed in the brain throughout life; a concept called neurogenesis (Riddle & Lichtenwalner, 2007). The most common regions of the brain associated with neurogenesis are the olfactory bulbs, the hippocampus (dentate nucleus), the lateral ventricular zone, and the caudate nucleus (Gould, Reeves, Graziano, & Gross, 1999; Riddle & Lichtenwalner, 2007; Tashiro, Makino, & Gage, 2007). Although new neurons are being produced all of the time, many of the new neurons expire if they are not used or integrated. For instance, the progenitor cells in the hippocampus are integrated through active learning. This suggests that active learning by doing is an important factor in preventing cognitive decline in the older adult


DOI: 10.15453/2168-6408.1141

population (Hodzic et al., 2004; Medina & Branch Coslett, 2010).

The use of olfactory stimulation can also cause states of arousal or inhibition, depending on the odor and on how it is used. Olfactory stimulation can trigger memory or promote learning. In addition, the uses of occupations have been shown to influence neuroplastic changes in the lateral ventricular zone and the caudate nucleus. Imaging studies on the caudate nucleus are related to neuroplastic changes in behavioral studies on obsessive-compulsive disorder (Schwartz & Begley, 2003).

**Somatosensory Interactions**

Much of the early OT somatosensory intervention protocols were based on principles of evolution and the developmental concepts of the nervous system that emerged decades ago. The early neurodevelopmental theorists believed that the brain had some capacity for change through experience, but the scientific evidence was lacking (Mathiowetz, 2011; Rao, 2011). Based on the current evidence, the regions of the cortex associated with the hand and fingers have the capacity to reorganize through the mechanisms discussed earlier (cross-modal reassignment, map expansion, homologous area adaptation, and compensatory masquerade) and, more importantly, through activity-dependent neuroplasticity.

Recently, Bogdanov, Smith, and Frey (2012) used imaging studies to demonstrate that hand amputation induces substantial reorganization of the primary sensory cortex (S1), and the effects of deafferentation increase with time. However, these changes are reversible during representation of an allogeneic transplanted hand and when the fingertips are stimulated to recapture the pre-amputation S1 hand cortical map territory. In another study, McGeoch and Ramachandran (2012) proposed that the somatosensory cortex and the primary motor cortex are not entirely distinct entities but influence the neuronal activity of each other. For example, if the left hand is amputated and the right hand is actively engaged in manipulating objects, there is increased activity of the somatosensory cortex of both cerebral hemispheres. Therefore, active engagement of the intact hand stimulates the territory associated with the amputated hand (Ramachandran, 2005; Ramachandran & Hirstein, 1998; Ramachandran & Rogers-Ramachandran, 1996).

Area 2 of the primary somatosensory cortex is responsive to the sizes and shapes of objects (stereognosis). Area 3a responds to conscious proprioception (position sense) and area 3b transmits the sensation of textures (Bear et al., 2006; Kaas & Florence, 2001). In the sensory-motor strip or homunculus, the hands, lips, and tongue are overrepresented in terms of cortical real estate relative to their skin area on the body (Bogdanov et al., 2012). This over representation is called cortical magnification and is a reflection of extremely dense peripheral innervation. Most of the hand's cortical representations are occupied by the fingertips, where innervation density is the highest. Therefore, the fingertips, lips, and tongue are excellent areas for sensory stimulation. Current research is showing that there is much more overlap of the neurons representing the hands and face than previously understood (Hlustík et al., 2001; Oishi et al, 2003). Imaging studies by Komisaruk et al. (2011) discovered that there are gender differences in the circuitry of the somatosensory cortex and distinct connections to organs of reproduction.

**Concept of Parallel Processing**

New research suggests that stimulation of the hands produces parallel processing, which means the signals from the thalamus are transmitted simultaneously to layer 4 and also to deeper layers of the cortex that seem to connect with more survival functions, such as states of arousal (Bruno & Sakmann, 2006; Bruno & Simons, 2002; Constaninople & Bruno, 2013). This has clinical implications because learning is improved with attention. Studies on the pathways between the thalamus and cortex (Thalomocortical Pathways) show that attention to the task during the performance of the activity facilitates the expansion of cortical maps (Nicolelis, 1995; Shipp, 2004).

The surfaces of the hands have physiological influences on body function and structures (client factors). For example, when heat is released through the hands, it helps to cool the body during aerobic exercise (Grahn, Cao, & Heller, 2005). The receptor fields on the hands are influenced by inhibitory neurons during the process of touching objects of different textures. More important, somatosensory stimulation, which includes participation in functional manual activities, has implications for alleviating pain, relieving psychological stress, and bolstering the immune system (Gillen, 2011; Hussain, 2010).

In experimental studies, when the hands are wrapped and taped to prevent movement and the manipulation of objects, regions of the cortex associated with the hands undergo changes in cortical excitation and representation in a few hours (Kaneko, Murakami, Onari, Kurumadani, & Kawaguchi, 2003; Medina & Branch Coslett, 2010). This raises the concern about using static splinting with persons who have had a stroke. Obviously, the intent of using a resting splint is to prevent deformity in a paralyzed extremity. However, the immobilization may affect the rate of potential recovery. The dynamic splints, which promote movement, appear to be better in preliminary investigations (http://www.otshow.com/?filename=saboflex-lends-a-hand-to-stoke-patients).

**Implications for Practice**

It is important for OT practitioners to recognize that when the hands are engaged in meaningful and functional tasks, the brain can re-route signals that form new neural connections that are directly related to mechanisms of neuroplasticity of the somatosensory cortex (Kaas, 1991; Marangon, Jacobs, & Frey, 2011; Martin, Jacobs, & Frey, 2011; Xerri et al., 1998). No doubt, individuals with neurologic hand/arm weakness have difficulty performing everyday activities, and this becomes a major focus for occupational therapists working in post-stroke acute rehabilitation. Studies are mounting to generate support for the premise that the hands can influence recovery from neurological lesions. At the Frey Lab at the University of Missouri, studies are underway to demonstrate that neuroplasticity occurs in the precentral and postcentral gyrus of the cerebral cortex in conjunction with applied stimulation and/or intentional manipulation of objects when performing a functional task (Shigaki, 2013). Therefore, bilateral activities that engage both hands have a co-activation effect on both hemispheres (Dimou, Biggs, Tonkin, Hickie, & Lagopoulos, 2013).

Ten years ago, the concept of neuroplasticity was not well supported in the neuroscience literature. Today, the concept of "activity-dependent neuroplasticity," the nervous system's capacity to change structurally and functionally in response to somatosensory input, has become widely accepted (Fong et al., 2005; Goh & Park, 2009; McCormack et al., 2009). Occupational therapists are interested in systematic investigations involving hand function and functional outcomes of sensory stimulation to treat conditions of dysfunction (Atchison & Dirette, 2007; Gillen, 2011; Hinojosa, Kramer, & Crist, 2005; Stein, Rice, & Cutler, 2013). Current neuroscience imaging studies are beginning to reveal how the brain processes information while manipulating in real time (Frey & Povinelli, 2012; Philip & Frey, 2013). Other studies have shown that cortical reorganization or neuroplasticity takes place even when the extremities are amputated or when peripheral nerves are severely damaged (Hlustík et al., 2001; Kaas, 2004a, 2004b, 2004c, 2005; Merzenich & Jenkins, 1993; Merzenich et al. 1983; Merzenich et al., 1984; Merzenich et al. 1996; Nudo, 2007; Rhamachandran & Hirstein, 1998). Current neuroscience evidence suggests that the combination of conscious intent—the willful act of performing a motor act—facilitates a cascade of neurochemical and neurophysiological events that "set the stage" for better motor performance and health outcomes (Butler & Page, 2006; Nilsen, Gillen, DiRusso, & Gordon, 2012; Page et al., 2011). The recognition of mental rehearsals and the motivation that goes into performing a manual task suggests the presence of a "top down" mechanism that is important to the process of habilitation and rehabilitation. Furthermore, there also appears to be a "bottom up" process, which involves the application of somatosensory stimulation to the hand while manipulating objects, which contributes to activity-dependent neuroplasticity in the somatosensory cortex. In short, when the client is provided with manual activities, the region of the cortex that is associated with that manual activity shows enhanced enlargement and function on imaging studies, if performed with regularity (Caffarra et al., 2008; Levin, 2006; Mahncke, Bronstone, et al., 2006; Mahncke, Conner, et al., 2006; Nudo, 2007; Recanzone, Merzenich, & Jenkins, 1992; Tashiro, Makina, & Gage, 2007; Tinaazi et al., 2000; Zelinski & Reyes, 2009).

Historically, in OT there has been controversy about the efficacy of somatosensory stimulation as an intervention for both children and adults (Lane & Schaaf, 2010). Somatosensory stimulation may be defined as specific forms of manual manipulations of the soft tissues of the body. Although older adults are more likely to experience some natural decline of sensation in their fingertips, the hands remain excellent targets for applying somatosensory stimulation (Helme & Gibson, 1999). The practice of manual therapy has been limited in OT academic programs and is regulated by different state professional licensure bills (McCormack, 1993; Reed, 2001). In addition, many neurological structures and systems are influenced by the activity of the hands. The organization of the somatosensory cortex, particularly in respect to the hand, is vastly integrated into both sensory and motor systems (Hlustík et al., 2001; Johnson & Soucacos, 2012; Kaas, 2004; Nudo & Milliken, 1996; Whitall et al., 2011). The synaptic connections between neurons in the cortex are changing all of the time, which means the brain is very malleable. This is particularly apparent in the boundaries of the postcentral gyrus or the somatosensory cortex in response to stimulation of the hand (Kaas, 2004; Marangon et al., 2011; Merzenich et al., 1996; Whitall et al., 2011). In addition, the pathways between the thalamus and the cortex are extremely neuroplastic (Bruno & Simons, 2002) and have been shown to undergo considerable reorganization after peripheral sensation is lost in the hand (Ramachandran & Hirstein, 1998).

Somatosensory stimulation can be applied with a small vibrator systematically along the lateral surfaces of the fingers where Merkel disc and Pacinian corpuscles are abundant (see Figure 1). Firm pressure to the hand has been shown to be effective in reducing levels of anxiety using both psychological and physiological measures (Andrade & Clifford, 2008; Cox & Hayes, 1999; Field et al., 1996; Harris & Richards, 2010; Hattan et al., 2002). Although the autonomic pathways in the hand have not been fully studied, sensory stimulation to specific areas of the hands has been reported to have effects on specific organ systems, such as renal blood flow (Sudmeier et al., 1999), symptoms of menopause (Williamson, White, Hart, & Ernst, 2002), intestinal activity (Bonder et al., 2001), and increases in blood flow and neuronal activity in the brain (Cho et al., 1998; Cho, Oleson, Alimi, & Niemtzow, 2002). In respect to therapeutic use of self, hand stimulation has been shown to encourage face-to-face eye contact and better communication (Harris & Richards, 2010; Kim, Cho, Woo, & Kim, 2001).

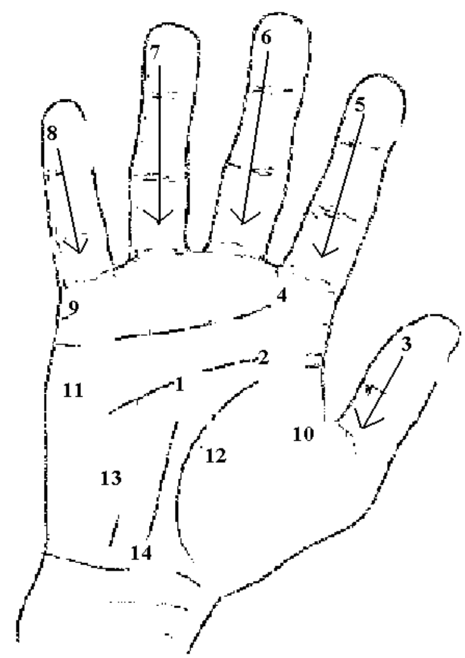


*Figure 1.* Protocol for hand somatosensory stimulation. Shows sequential stimulation on points for the hand for the direction of vibratory stimuli and areas that are sequentially numbered for firm pressure stimulation to the hand.

The concept of a holistic relationship between the mind and body has been the cornerstone of OT practice. Adolf Meyer and William Rush Dunton originally described the mind/body relationship in the early OT literature on moral treatment and the value of occupation (Kielhofner, 2009). The reductionistic view that the brain acts as a separate entity from the body comes from Descartes' concept of Dualism (Rosemond, 2002). The Affordable Care Act (ACA; Pub.L. 111-148) is partial to health and wellness approaches. The ACA is beginning to change health care delivery significantly and occupational therapists are engaging in primary care practices that promote healthy life styles, prevention, habilitation, and mental health (Persch, Braveman, & Metzler, 2013). Neuroscience has informed us that the brain is not entirely "hard wired" to the body (Merighi et al., 2011). Using the somatosensory stimulation and the mind/body paradigm supports the notion that working with the hands to perform functional activities can have a direct influence on the brain, emotions, and immune functions.

**Summary**

Neuroscience has revealed that the hand has vast connections to the cerebral cortex. Depending on how the hand is stimulated or engaged in occupations, the connectivity between the hand and brain are in a constant state of flux. This evidence supports the importance of manual activities in OT practice. For example, treatment plans should include some form of manual manipulation of three-dimensional objects to facilitate the strength of the pathways between the hand and brain. Although there is an emphasis on functional outcomes for documentation and reimbursement, the practitioner should apply task analysis methodology to break down the activity into the anatomical, physiological, and psychological benefits of performing the task. Although OT was conceived to be occupation-based, state and federal guidelines for reimbursement are designed to be quantifiable and do not encourage the use of therapeutic media in rehabilitation environments. However, if the occupational therapist takes the time to explain the rationale for the manual activity and references neuroscience research to support the claim, most insurance reviewers will see the value of the activity and allow the use of therapeutic media. In addition, the practitioner should also elicit "buy in" from the family members who are most intimately involved in the caregiver role. If, for example, the occupational therapist suggests that the client make objects out of clay or a similar media, some mutual goals can be set before the next visit. If the client and caregiver are in agreement with the activity, the therapist can then grade up the intensity or grade down the activity at the next visit or treatment session. Many times, the most successful outcomes in rehabilitation are the result of a team approach.

**Conclusion**

This article has used neuroscience evidence to support the premise that somatosensory stimulation of the hand promotes activity-dependent neuroplastic changes in regions of the somatosensory cortex. There is considerable evidence that engaging the hands in different manipulative functions influences cell assemblies and the connectivity of the brain. Studies show that functional neuroplastic changes best occur when there is a higher degree of attention and motivation during the manual activity. Neuroplasticity continues on into adulthood and is a core principle of brain function and demonstrates that the nervous system can be altered and modified as an adaptive response to functional demand (Doidge, 2007). Neuroscience also suggests that repetition is another important element of neuroplasticity. Extended practice training is for training memory abilities related to attention and sensory discrimination (Bly et al., 2003; Zelinski & Reyes, 2009). However, too much repetition can lead to boredom and will decrease motivation. The task-oriented approach advocated by Gillen (2011) is based on functional skill training rather than achieving some isolated motor response. The OT practitioner should feel confident that promoting repetition of similar movements to accomplish tasks is consistent with the literature (Kerschke & Witas, 2013; Vance & Wright, 2009).

The intensity of somatosensory stimulation is another important factor in neuroplasticity (Hayner, Gibson, & Giles, 2010). As the client achieves competency, the practitioner should step up the level of difficulty (Martin et al., 2011; McCormack et al., 2009; Smith et al., 2009; Vidovich et al., 2009; Wagner et al., 2010; Willis et al., 2006; Zelnski & Reyes, 2009). The goal in any functional activity must be achievable; this is where the concept of the “just right challenge” comes in, so the task poses just enough demand for effort (Bly et al., 2003; Dustman & White, 2006; Levin, 2006). The neuroscience evidence is clear; it does not seem to matter if a client is working with therapeutic media (crafts) or performing an activity of daily living; it is the combination of mental engagement and the somatosensory stimulation derived from the manipulation of objects with the hands that can indeed influence the state of one’s own health.


DOI: 10.15453/2168-6408.1141

## References

American Occupational Therapy Association. (2014). Occupational therapy practice framework: Domain and process (3rd ed.). *American Journal of Occupational Therapy*, *68*(Supp1), S1-S48. http://dx.doi.org/10.5014/ajot.2014.682005

Andrade, C. K., & Clifford, P. (2008). *Outcome-based massage: From evidence to practice*. Philadelphia, PA: Lippincott Williams & Wilkins.

Andrade, C. K., & Radhakrishnan, R. (2009). The prevention and treatment of cognitive decline and dementia: An overview of recent research on experimental treatments. *Indian Journal of Psychiatry*, *51*(1), 12-25. http://dx.doi.org/10.4103/0019-5545.44900

Atchison, B. J., & Dirette, D. K. (2007). *Conditions in occupational therapy: Effect on occupational performance* (3rd ed.). Philadelphia, PA: Lippincott Williams & Wilkins.

Ayres, A. J. (1973). *Sensory integration and learning disorders*. Los Angeles, CA: Western Psychological Services.

Baldry, P. E. (2005). *Acupuncture, trigger points and musculoskeletal pain* (3rd ed.). Amsterdam: Elsevier.

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M. D., Marsiske, M., . . . Willis, S. L. (2002). Effects of cognitive training interventions with older adults: A randomized controlled trial. *Journal of the American Medical Association*, *288*(18), 2271-2281. http://dx.doi.org/10.1001/jama.288.18.2271

Bangert, M., & Schlaug, G. (2006). Specialization of the specialized in features of external human brain morphology. *European Journal of Neuroscience*, *24*(6),1832-1834. http://dx.doi.org/10.1111/j.1460-9568.2006.05031.x

Bavelier, D., & Neville, H. J. (2002). Cross-modal plasticity: Where and how? *Nature Reviews Neuroscience*, *3*(6), 443-452.

Bear, M. F., Connors, B. W., & Paradiso, M. A. (2006). *Neuroscience: Exploring the brain* (3rd ed.). Philadelphia, PA: Lippincott Williams & Wilkins.

Bly, N., Roderick, J., Mohamed, O., Hanny, M., Kotler, J., Smith, A., . . . Abrams, G. (2003). Effectiveness of sensory and motor rehabilitation of the upper limb following the principles of neuroplasticity: Patients stable poststroke. *Neurorehabilitation & Neural Repair*, *17*(3), 176-191. http://dx.doi.org/10.1177/0888439003257137

Bogdanov, S., Smith, J., & Frey, S. H. (2012). Former hand territory activity increases after amputation during intact hand movements, but is unaffected by illusory visual feedback. *Neurorehabilitation & Neural Repair*, *26*(6), 604-615.

Bowden, J. L., & McNulty, P. A. (2013). Age-related changes in cutaneous sensation in the healthy human hand. *Age*, *35*(4),1077-1089. http://dx.doi.org/10.1007/s11357-012-9429-3

Brown, R. E., & Milner, P. M. (2003). The legacy of Donald O. Hebb: More than the Hebb Synapse. *Nature Reviews Neuroscience*, *4*(12), 1013-1019. http://dx.doi.org/10.1038/nrn1257

Bruno, R. M., & Sakmann, B. (2006). Cortex is driven by weak but synchronously active thalamocortical synapses. *Science*, *312*(5780), 1622-1627. http://dx.doi.org/10.1126/science.1124593

Bruno, R. M., & Simons, D. J. (2002). Feedforward mechanisms of excitatory and inhibitory cortical receptive fields. Retrieved from http://www.jneurosci.org/content/22/24/10966.full.pdf

Bundy, A. C., Lane, S., & Murray, E. A. (Eds.). (2002). *Sensory integration*: *Theory and practice* (2nd ed.). Philadelphia: F. A. Davis.

Burton, H., Sinclair, R. J., & McLaren, D. G. (2004). Cortical activity to vibrotactile stimulation: An fMRI study in blind and sighted individuals. *Human Brain Mapping*, *23*(4), 210-228.

Butler, A. J., & Page, S. J. (2006). Mental practice with motor imagery: Evidence for motor recovery and cortical reorganization after stroke. *Archives of Physical Medicine and Rehabilitation*, *87*(12), 2-11. http://dx.doi.org/10.1016/j.apmr.2006.08.326

Caffarra, P., Ghetti, C., Concari, L., & Venneri, A. (2008). Differential patterns of hypoperfusion in subtypes of mild cognitive impairment. *Open Neuroimaging Journal*, *2*, 20-28. http://dx.doi.org/10.2174/1874440000802010020

Calero, D., & Navarro, E. (2007). Cognitive plasticity as a modulating variable on the effects of memory training in elderly persons. *Archives of Clinical Neuropsychology*, *22*(1), 63-72. http://dx.doi.org/10.1016/j.acn.2006.06.020

Cho, Z. H., Chung, S. C., Jones, J. P., Park, J. B., Park, H. J., Lee, H. J., . . . Min, B. I. (1998). New findings of the correlation between acupoints and corresponding brain cortices using functional MRI. *Proceedings of the National Academy of Sciences*, *95*(5), 2670-2673.

Cho Z. H., Oleson, T. D., Alimi, D., & Niemtzow, R. C. (2002). Acupuncture: The search for biologic evidence with functional magnetic resonance imaging and positron emission tomography techniques. *Journal of Alternative and Complementary Medicine*, *8*(4), 399-401. http://dx.doi.org/10.1089/107555302760253577

Constantinople, C. M., & Bruno, R. M. (2013). Deep cortical layers are activated directly by thalamus. *Science*, *340*(6140), 1591-1594. http://dx.doi.org/10.1126/science.1236425

Cox, C., & Hayes, J. (1999). Physiologic and psychodynamic responses to the administration of therapeutic touch in critical care. *Complementary Therapies in Nursing and Midwifery*, *5*(3), 87-92. http://dx.doi.org/10.1016/s1353-6117(99)80026-2

Dimou, S., Biggs, M., Tonkin, M., Hickie, I. B., & Lagopoulos, J. (2013). Motor cortex neuroplasticity following brachial plexus transfer. *Frontiers in Human Neuroscience*, *7*(500), 1-6. http://dx.doi.org/10.3389/fnhum.2013.00500

Doidge, N. (2007). *The brain that changes itself: Stories of personal triumph from the frontiers of brain science*. New York, NY: Penguin Group USA.

Dustman, R. E., & White, A. (2006). Effect of exercise on cognition in older adults: A reexamination of proposed mechanisms. In L. Poon, W. Chodzko-Zajko, & P. Tomporowski (Eds.), *Active living, cognitive functioning, and aging* (pp. 51-74). Champaign, IL: Human Kinetics.

Field, T., Ironson, G., Scafidi, F., Nawrocki, T., Goncalves, A., Burman, R., . . . Kuhn, C. (1996). Massage therapy reduces anxiety and enhances eeg pattern of alertness and math computations. *International Journal Neuroscience*, *86*(3-4), 197-205. http://dx.doi.org/10.3109/00207459608986710

Fong, M. S., Brown, T. L., Wolcott, K. R., Lin, J., Fisher, B. E., & Wu, A. (2005). Evidence for activity-dependent neuroplasticity in an individual with Parkinson's Disease: A transcranial magnetic stimulation study. *Journal of Neurologic Physical Therapy*, *29*(4), 189-217. http://dx.doi.org/10.1097/01.npt.0000282329.80133.de

Frey, S. H., & Povinelli, D. (2012). Comparative investigations of manual action representations: Evidence that chimpanzees represent the costs of potential future actions involving tools. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1585), 48-58. http://dx.doi.org/10.1098/rstb.2011.0189

Gillen, G. (2011). *Stroke rehabilitation: A function-based approach*. St. Louis, MO: Elsevier Mosby.

Goh, J., & Park, D. (2009). Neuroplasticity and cognitive aging: The scaffolding theory of aging and cognition. *Restorative Neurology and Neuroscience*, *27*(5), 391-403. http://dx.doi.org/10.3233/RNN-2009-0493

Gould, E., Reeves, A. J., Graziano, M. S. A., & Gross, C. G. (1999). Neurogenesis in the neocortex of adult primates. *Science*, *286*(5439), 548-552. http://dx.doi.org/10.1126/science.286.5439.548

Grafman, J. (2000). Conceptualizing functional neuroplasticity. *Journal of Communication Disorders*, *33*(4), 345-356. http://dx.doi.org/10.1016/s0021-9924(00)00030-7

Grafman, J., & Litvan, I. (1999). Evidence of four forms of neuroplasticity. In J. Grafman, & Y. Christen (Eds.), *Neuronal plasticity: Building a bridge and perspectives in neurosciences* (pp. 131-139). New York, NY: Springer. http://dx.doi.org/10.1007/978-3-642-59897-5_9

Grahn, D. A., Cao, V. H., & Heller, C. (2005). Heat extraction through the palm of one hand improves aerobic exercise endurance in a hot environment. *Journal of Applied Physiology*, *99*(3), 972-978. http://dx.doi.org/10.1152/japplphysiol.00093.2005

Gunning-Dixon, F. M., & Raz, N. (2003). Neuroanatomical correlates of selected executive functions in middle-aged and older adults: A prospective MRI study. *Neuropsychologia*, *41*(14), 1929-1941. http://dx.doi.org/10.1016/s0028-3932(03)00129-5

Hallett, M. (2005). Neuroplasticity and rehabilitation. *Journal of Rehabilitation, Research and Development*, *42*(4), 17-22. http://dx.doi.org/10.1682/jrrd.2005.07.0126

Harris, M., & Richards, K. C. (2010). The physiological and psychological effects of slow-stroke back massage and hand massage on relaxation on older people. *Journal of Clinical Nursing*, *19*(7-8), 917-926. http://dx.doi.org/10.1111/j.1365-2702.2009.03165.x

Hayner, K., Gibson, G., & Giles, G. M. (2010). Comparison of constraint-induced movement therapy and bilateral treatment therapy of equal intensity in people with chronic upper-extremity dysfunction after cerebrovascular accident. *American Journal of Occupational Therapy*, *64*(4), 528-538. http://dx.doi.org/10.5014/ajot.2010.08027

Hebb, Donald. (1949). *The organization of behavior: A neuropsychological theory*. Mahway, NJ: Erlbaum Associates, Inc.

Herdener, M., Humbel, T., Esposito, F., Habermeyer, B., Cattapan-Ludewig, K., & Seifritz, E.

(2014). Jazz drummers recruit language-specific areas for the processing of rhythmic structure. *Cerebral Cortex*, *24*(3), 836-843. http://dx.doi.org/10.1093/cercor/bhs367

Hinojosa, J., Kramer, P., & Christ, P. (Eds.). (2005). *Occupational therapy evaluation: Obtaining and interpreting data* (2nd ed.). Bethesda, MD: American Occupational Therapy Association.

Hlustík, P., Solodkin, A., Gullapalli, R. P., Noll, D. C., & Small, S. L. (2001). Somatotopy in human primary motor and somatosensory hand representations revisited. *Cerebral Cortex*, *11*(4), 312-321. http://dx.doi.org/10.1093/cercor/11.4.312

Hodzic, A., Veit, R., Karim, A. A., Erb, M., & Godde, B. (2004). Improvement and decline in tactile discrimination behavior after cortical plasticity induced by passive tactile coactivation. *The Journal of Neuroscience*, *24*(2), 442-446. http://dx.doi.org/10.1523/jneurosci.3731-03.2004

Höffken, O., Veit, M., Knossalla, F., Lissek, S., Bliem, B., Ragert, P., . . . Tegenthoff, M. (2007). Sustained increase in somatosensory cortex excitability by tactile coactivation studied by paired median nerve stimulation in humans correlates with perceptual gain. *Journal of Physiology*, *584*(2), 463-471. http://dx.doi.org/10.1113/jphysiol.2007.140079

Huss, A. J. (1977). Touch with care or a caring touch? 1976 Eleanor Clarke Slagle Lecture. *American Journal of Occupational Therapy*, *31*, 11-18.

Hussain, D. (2010). Stress, immunity, and health: Research findings and implications. *International Journal of Psychosocial Rehabilitation*, *15*(1), 94-101. Retrieved from http://www.psychosocial.com/IJPR_15/Stress_Immunity_Health_Hussain.html

Jones, E. G. (2000). Cortical and subcortical contributions to activity-dependent plasticity in primate somatosensory cortex. *Annual Review of Neuroscience*, *23*(1),1–37. http://dx.doi.org/10.1146/annurev.neuro.23.1.1

Johnson, E. O., & Soucacos, P. N. (2012). Proprioception. *International Encyclopedia of Rehabilitation*. http://cirrie.buffalo.edu/encyclopedia/en/article/337/

Kaas, J. H. (1991). Plasticity of sensory and motor maps in adult mammals. *Annual Review of Neuroscience*, *14*(1), 137–167. http://dx.doi.org/10.1146/annurev.neuro.14.1.137

Kaas, J. H. (1997). Topographic maps are fundamental to sensory processing. *Brain Research Bulletin*, *44*(2), 107–112. http://dx.doi.org/10.1016/s0361-9230(97)00094-4

Kaas, J. H. (2004a). Evolution of the large, complex sensorimotor systems of anthropoid primates. *International Journal of Comparative Psychology*, *17*(34-52).

Kaas, J. H. (2004b). Plasticity of somatosensory and motor systems in developing and mature primate brains. In I. J. Stockman (Ed.), *Movement and action in learning development* (pp. 75-91). San Diego: Elsevier Academic Press.

Kaas, J. H. (2004c). Somatosensory system. In J. K. Mai, & G. Paxinos (Eds.), *The human nervous system* (2nd ed., pp. 1074-1109). New York, NY: Elsevier Academic Press.

Kaas, J. H. (2005). The future of mapping sensory cortex in primates: Three of many remaining issues. *Philosophical Transactions of the Royal Society B: Biological Sciences, 360*(1456), 653-664.

Kandel, E. R., Schwartz, J. H., & Jessell, T. M. (2000). *Principles of neural science* (4th ed.). New York, NY: McGraw-Hill.

Kaneko, F., Murakami, T., Onari, K., Kurumadani, H., & Kawaguchi, K. (2003). Decreased cortical excitability during motor imagery after disuse of an upper limb in humans. *Clinical Neurophysiology, 114*(12), 2397-2403. http://dx.doi.org/10.1016/s1388-2457(03)00245-1

Kerschke, S., & Witas, M. (2013). Brain injury rehabilitation for the real world: Intensive, specialized programming targets optimized long-term outcomes at all care levels. *Rehab Management*, *26*(5), 34-39.

Kielhofner, G. (2009). *Conceptual foundations of occupational therapy practice*. Philadelphia, PA: F.A. Davis.

Kim, M. S., Cho, K. S., Woo, H-M., & Kim, J. H. (2001). Effects of hand massage on anxiety in cataract surgery using local anesthesia. *Journal of Cataract Refraction Surgery, 27*(6), 884-890.

Komisaruk, B., Wise, N., Frangos, E., Liu, W-C., Allen, K., & Brody, S. (2011). Women's clitoris, vagina, and cervix mapped on the sensory cortex: fMRI evidence. *The Journal of Sexual Medicine*, *8*(10), 2822-2830.

Ladda, A. M., Pfannmoeller, J. P., Kalisch, T., Roschka, S., Platz, T., Dinse, H. R., & Lotze, M. (2014). Effects of combining 2 weeks of passive sensory stimulation with active hand motor training in healthy adults. *PLoS ONE*, *9*(1), e84402. http://dx.doi.org/10.1371/journal.pone.0084402

Lane, S. J., & Schaaf, R. C. (2010). Examining the neuroscience evidence for sensory-driven neuroplasticity: Implications for sensory-based occupational therapy for children and adolescents. *American Journal of Occupational Therapy*, *64*(3), 375-390. http://dx.doi.org/10.5014/ajot.2010.09069

Levin, H. S. (2006). Neuroplasticity and brain imaging research: Implications for rehabilitation. *Archives of Physical Medicine and Rehabilitation*, *87*(12), 1. http://dx.doi.org/10.1016/j.apmr.2006.09.010

Mahncke, H., Bronstone, A., & Merzenich, M. (2006). Brain plasticity and functional losses in the aged: Scientific bases for a novel intervention. *Progress in Brain Research*, *157*, 81-109. http://dx.doi.org/10.1016/s0079-6123(06)57006-2

Mahncke, H., Connor, B., Appelman, J., Ahsanuddin, O., Hardy, J., Wood, R., . . .Merzenich, M. (2006). Memory enhancement in healthy older adults using a brain plasticity-based training program: A randomized, controlled study. *Proceedings of the National Academy of Sciences*, *103*(33), 12523-12528.

Marangon, M., Jacobs, S., & Frey, S. H. (2011). Evidence for context sensitivity of grasp representations in human parietal premotor cortices. *Journal of Neurophysiology*, *105*(5), 2536-2546. http://dx.doi.org/10.1152/jn.00796.2010

Martin, K., Jacobs, S., & Frey, S. H. (2011). Handedness-dependent and –independent cerebral asymmetries in the anterior intraparietal sulcus and ventral premotor cortex during grasp planning. *Neuroimage*, *57*(2), 502-512. http://dx.doi.org/10.1016/j.neuroimage.2011.04.036

Mathiowetz, V. (2011). Task-oriented approach to stroke rehabilitation. In G. Gillen (Ed.), *Stroke rehabilitation: A function-based approach* (pp. 80-99). St. Louis, MO: Elsevier Mosby.

McCormack, G. L. (1993). *Pain management: Mind-body techniques for treating chronic pain syndromes*. Tucson, AZ: Therapy Skill Builders.

McCormack, G. L., Douglas, B., Pauley, S., Schultze, M., & Volkers, J. (2009). How occupational therapy influences neuroplasticity. *OT Practice*, *14*(17), CE1-CE7.

McGeoch, P., & Ramachandran, V. (2012). The appearance of new phantom fingers post-amputation in a phocomelus. *Neurocase*, *18*(2), 95-97.

Medina, J., & Branch Coslett, H. (2010). From maps to form to space: Touch and the body schema. *Neuropsychologia*, *48*(3), 645-654. http://dx.doi.org/10.1016/j.neuropsychologia.2009.08.017

Merighi, A., Salio, C., Ferrini, F., & Lossi, L. (2011). Neuromodulatory function of neuropeptides in the normal CNS. *Journal of Chemical Neuroanatomy*, *42*(4), 276-287. http://dx.doi.org/10.1016/j.jchemneu.2011.02.001

Merzenich, M. M., & Jenkins, W. M. (1993). Reorganization of cortical representations of the hand following alterations of skin inputs induced by nerve injury, skin island transfers, and experience. *Journal of Hand Therapy*, *6*(2), 89-104. http://dx.doi.org/10.1016/s0894-1130(12)80290-0

Merzenich, M. M., Kaas, J. H., Wall, J. T., Sur, M., Nelson, R. J., & Felleman, D. J. (1983). Progression of change following median nerve section in the cortical representation of the hand in areas 3b and 1 in adult owl and squirrel monkeys. *Neuroscience*, *10*(3), 639-665. http://dx.doi.org/10.1016/0306-4522(83)90208-7

Merzenich, M. M., Nelson, R. J., Stryker, M. P., Cynader, M. S., Schoppmann, A., & Zook, J. M. (1984). Somatosensory cortical map changes following digit amputation in adult monkeys. *Journal of Comparative Neurology*, *224*(4), 591-605. http://dx.doi.org/10.1002/cne.902240408

Merzenich, M. M., Wright, B., Jenkins, W., Xerri, C., Byl, N., Miller, S., & Tallal, P. (1996). Cortical plasticity underlying perceptual, motor, and cognitive skill development: Implications for neurorehabilitation. *Cold Spring Harbor Symposia on Quantitative Biology*, *61*, 1-8.

Mori, S., & Zhang, J. (2006). Principles of diffusion tensor primer imaging and its applications to basic neuroscience research. *Neuron*, *51*(5), 527-539. http://dx.doi.org/10.1016/j.neuron.2006.08.012

Mur, E., Schmidseder, J., Egger, I., Bodner, G., Eibl, G., Hartig, F., . . . Herold, M. (2001). Influence of reflex zone therapy of the feet on intestinal blood flow measured by color Doppler blood sonography. *Forsch Komplementarmed Klass Naturheilkd*, *8*(2), 86-89.

Nicolelis, M. (1995). Computing the thalamocortical ensembles during behavioural states. *Journal of Physiology*, *566*(1), 37-47. http://dx.doi.org/10.1113/jphysiol.2005.083709

Nilsen, D. M., Gillen, G., DiRusso, T., & Gordon, A. M. (2012). Effect of imagery perspective on occupational performance after stroke: A randomized controlled trial. *American Journal of Occupational Therapy*, *66*(3), 320-329. http://dx.doi.org/10.5014/ajot.2012.003475

Nudo, R. J. (2007). Postinfarct cortical plasticity and behavioral recovery. *Stroke*, *38*(2), 840-845. http://dx.doi.org/10.1161/01.str.0000247943.12887.d2

Nudo, R. J., Jenkins, W. M., Merzenich, M. M., Prejean, T., & Grenda, R. (1992). Neurophysiological correlates of hand preference in primary motor cortex of adult squirrel monkeys. *Journal of Neuroscience*, *12*(8), 2918-2947.

Nudo, R. J., & Milliken, G. W. (1996). Reorganization of movement representations in primary motor cortex following focal ischemic infarct in adult squirrel monkeys. *Journal of Neurophysiology*, *75*(5), 2144-2149.

Obretenova, S., Halko, M. A., Plow, E. B., Pascual-Leone, A., & Merabet, L. B. (2010). Neuroplasticity associated with tactile language communication in a deaf-blind subject. *Frontiers in Neuroscience*. Retrieved from http://journal.frontiersin.org/Journal/10.3389/neuro.09.060.2009/full

Oishi, M., Fukuda, M., Kameyama, S., Kawaguchi, T., Masuda, H., & Tanaka, R. (2003). Magnetoencephalographic representation of the sensorimotor hand area in cases of intracerebral tumour. *Journal of Neurology, Neurosurgery and Psychiatry*, *74*(12), 1649-1654. http://dx.doi.org/10.1136/jnnp.74.12.1649

Page, S. J., Murray, C., Herman, V., & Levine, P. (2011). Retention of motor changes in chronic stroke survivors who were administered mental practice. *Archives of Physical Medicine and Rehabilitation*, *92*(11), 1741-1745. http://dx.doi.org/10.1016/j.apmr.2011.06.009

Pascual-Leone, A., Amedi, A., Fregni, F., & Merabet, L. B. (2005). The plastic human brain cortex. *Annual Review of Neuroscience*, *28*(1), 377-401. http://dx.doi.org/10.1146/annurev.neuro.27.070203.144216

Pascual-Leone, A., & Torres, F. (1993). Plasticity of the sensorimotor cortex representation of the reading finger in Braille readers. *Brain*, *116*(1), 39-52. http://dx.doi.org/10.1093/brain/116.1.39

Penfield, W., & Boldrey, E. (1937). Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. *Brain*, *60*(4), 389-443. http://dx.doi.org/10.1093/brain/60.4.389

Penfield, W., & Rasmussen, T. (1950). *The cerebral cortex of man: A clinical study of localisation of function*. New York, NY: Macmillan.

Persch, A. C., Braveman, B. H., & Metzler, C. A. (2013). P4 medicine and pediatric occupational therapy. *The American Journal of Occupational Therapy*, *67*(4), 383-388. http://dx.doi.org/10.5014/ajot.2013.674002

Pons, T. P., Garraghty, P. E., Ommaya, A. K., Kaas, J. H., Taub, E., & Mishkin, M. (1991). Massive cortical reorganization after sensory deafferentation in adult macaques. *Science*, *252*(5014), 1857-1860. http://dx.doi.org/10.1126/science.1843843

Rakoski, D. R., & Ferguson, R. C. (2013). The virtual context of occupation: Integrating everyday technology into everyday practice. *OT Practice*, *18*(9),CE-1-CE-8.

Rao, A. K. (2011). Approaches to motor control dysfunction: An evidence-based review. In G. Gillen (Ed.), *Stroke rehabilitation: A function-based approach* (pp. 117-155). St. Louis, MO: Elsevier Mosby.

Ramachandran, V. S. (2005). Plasticity and functional recovery in neurology. *Clinical Medicine*, 5(4), 368-373. http://dx.doi.org/10.7861/clinmedicine.5-4-368

Ramachandran, V. S., & Hirstein, W. (1998). The perception of phantom limbs: The D.O. Hebb lecture. *Brain*, *121*(9), 1603-1630. http://dx.doi.org/10.1093/brain/121.9.1603

Ramachandran, V. S., & Rogers-Ramachandran, D. (1996). Synaesthesia in phantom limbs induced with mirrors. *Proceedings of the Royal Society B: Biological Sciences* *263*(1369), 377–386. http://dx.doi.org/10.1098/rspb.1996.0058

Recanzone, G. H., Merzenich, M. M., & Dinse, H. R. (1992). Expansion of the cortical representation of a specific skin field in primary somatosensory cortex by intracortical microstimulation. *Cerebral Cortex*, *2*(3), 181-196. http://dx.doi.org/10.1093/cercor/2.3.181

Recanzone, G. H., Merzenich, M. M., & Jenkins, M. W. (1992). Topographic reorganization of the hand representation in cortical area 3b owl monkeys trained in a frequency-discrimination task. *Journal of Neurophysiology*, *67*(5), 1031-1056.

Reed, K. L. (2001). *Quick reference to occupational therapy* (2nd ed.). Austin, TX: Pro-Ed International Publisher.

Reilly, M. (1962). Occupational therapy can be one of the greatest ideas of 20th century medicine. 1961 Eleanor Clarke Slagle lecture. *American Journal of*

*Occupational Therapy*, *16*, 1–9.

Riddle, D. R., & Lichtenwalner, R. J. (2007). Neurogenesis in the adult and aging brain. In D. R. Riddle (Ed.), *Brain aging: Models, methods and mechanisms*. Boca Raton: CRC Press.

Rood, M. (1962). The use of sensory receptors to activate, facilitate, and inhibit motor responses, autonomic and somatic in developmental sequence. In C. Scattely (Ed.), *Approaches to the treatment of patients with neuromuscular dysfunction* (pp. 26-37). Third International Congress, World Federation of Occupational Therapists. Dubuque IA: William C. Brown.

Rozemond, M. (2002). *Descartes's dualism*. Cambridge, MA: Harvard University Press.

Schaaf, R. C., Hunt, J., & Benevides, T. (2012). Occupational therapy using sensory integration to improve participation of a child with autism: A case report. *American Journal of Occupational Therapy*, *66*(2), 1–9. http://dx.doi.org/10.5014/ajot.2012.004473

Schwartz, J. M., & Begley, S. (2003). *The mind and the brain: Neuroplasticity and the power of mental force*. New York, NY: Regan Books.

Shigaki, C. (2013). Rehabilitation Neuroscience Laboratory. Retrieved from University of Missouri, Department of Psychological Sciences website: http://freylab.missouri.edu/

Shipp, S. (2004). The brain circuitry of attention. *Trends in Cognitive Sciences*, *8*(5), 223-230. http://dx.doi.org/10.1016/j.tics.2004.03.004

Smith, G. E., Housen, P., Yaffe, K., Ruff, R., Kennison, R. F., Mahncke, H. W., & Zelinksi, E. M. (2009). A cognitive training program based on principles of brain plasticity: Results from the improvement in memory with plasticity-based adaptive cognitive training (IMPACT) study. *Journal of the American Geriatrics Society*, *57*(4), 594-603. http://dx.doi.org/10.1111/j.1532-5415.2008.02167.x

Stein, F., Rice, M. S., & Cutler, S. K. (2013). *Clinical Research in Occupational Therapy* (5th ed.). Clifton Park, NY: Cengage Learning.

Sudmeier, I., Bodner, G., Egger, I., Mur, E., Ulmer, H., & Herold, M. (1999). Changes of renal blood flow during organ-associated foot reflexology measured by color doppler sonography. *Forschende Komplementaemedizin*, *6*(3),129-34.

Tashiro, A., Makino, H., & Gage, F. H. (2007). Experience-specific functional modification of the dentate gyrus through adult neurogenesis: A critical period during an immature stage. *The Journal of Neuroscience*, *27*(12), 3252-3259. http://dx.doi.org/10.1523/jneurosci.4941-06.2007

Tinaazi, M., Fiaschi, A., Rosso, T., Faccioli, F., Grosslercher, J., & Aglioti, S. M. (2000). Neuroplastic changes related to pain occur at multiple levels of the human somatosensory system: A somatosensory-evoked potentials study in patients with cervical radicular pain. *Journal of Neuroscience*, *20*(24), 9277-9283.

Tinazzi, M., Zanette, G., Volpato, D., Testoni, R., Bonato, C., Manganotti, P., . . . Fiaschi, A. (1998). Neurophysiological evidence of neuroplasticity at multiple levels of the somatosensory system in patients with carpal tunnel syndrome. *Brain*, *121*(9), 1785–1794. http://dx.doi.org/10.1093/brain/121.9.1785

Vance, D. E., & Wright, M. A. (2009). Positive and negative neuroplasticity: Implications for age-related cognitive declines. *Journal of Gerontological Nursing*, *35*(6), 11-17.

Vidovich, M., Lautenschlager, N., Flicker, L., Clare, L., & Almeida, O. (2009). The PACE study: A randomised clinical trial of cognitive activity (CA) for older adults with mild cognitive impairment (MCI). *Trials*, *10*(1), 114-122. http://dx.doi.org/10.1186/1745-6215-10-114

Wagner, N., Hassanein, K., & Head, M. (2010). Computer use by older adults: A multi-disciplinary review. *Computers in Human Behavior*, *26*(5), 870-882. http://dx.doi.org/10.1016/j.chb.2010.03.029

Weeks, S., Boshoff, K., & Stewart, H. (2012). Systematic review of the effectiveness of the Wilbarger protocol with children. *Pediatric Health, Medicine, and Therapeutics*, *2012*(3), 79-89. http://dx.doi.org/10.2147/PHMT.S37173

Whitall, J., McCombe Waller, S., Sorkin, J. D., Forrester, L., Macko, R. F., Hanley, D. F., . . . Luft, A. (2011). Bilateral and unilateral arm training improve function through differing neuroplastic mechanisms: A single-blinded randomized controlled trial. *Neurorehabilitation & Neural Repair*, *25*(2), 118-129. http://dx.doi.org/10.1177/1545968310380685

Wilbarger, J. L., & Wilbarger, P. L. (2002). Wilbarger approach to treating sensory defensiveness: Clinical application of the sensory diet. In A. C. Bundy, S. J. Lane, & E. A. Murray (Eds.), *Sensory integration: Theory and practice* (2nd ed., pp. 335-341), Philadelphia, PA: F.A. Davis.

Williamson, J., White, A., Hart, A., & Ernst, E. (2002). Randomised controlled trial of reflexology for menopausal symptoms. *An International Journal of Obstetrics and Gynecology*, *109*(9), 1050-1055. http://dx.doi.org/10.1016/s1470-0328(02)01504-5

Willis, S. L., Tennstedt, S. L., Marsiske, M., Ball, K., Elias, J., Koepke, K. M., . . . Wright, E. (2006). Long-term effects of cognitive training on everyday functional outcomes in older adults. *Journal of the American Medical Association*, *296*(23), 2805-2814. http://dx.doi.org/10.1001/jama.296.23.2805

Wolinsky, F. D., Vander Weg, M. W., Howren, M. B., Jones, M. P., & Dotson, M. M. (2013). A randomized controlled trial of cognitive training using a visual speed of processing intervention in middle aged and older adults. *PLoS ONE*, *8*(5), e61624. http://dx.doi.org/10.1371/journal.pone.0061624

Wong, M., Peters, R. M., & Goldreich, D. (2013). A physical constraint on perceptual learning: Tactile spatial acuity improves with training to a limit set by finger size. *Journal of Neuroscience*, *33*(22), 9345-9352. http://dx.doi.org/10.1523/jneurosci.0514-13.2013

Woodruff-Pak, D. S., & Hanson, C. (1995). Plasticity and compensation in brain memory systems in aging. In R. A. Dixon, & L. Backman (Eds.), *Compensating for psychological deficits and declines: Managing losses and promoting gains* (pp. 191-217). Hillsdale, NJ: Erlbaum Associates.

Xerri, C., Merzenich, M. M., Peterson, B. E., & Jenkins, W. (1998). Plasticity of primary somatosensory cortex paralleling sensorimotor skill recovery from stroke in adult monkeys. *Journal of Neurophysiology*, *79*(4), 2119-2148.

Zelinski, E. M., & Reyes, R. (2009). Cognitive benefits of computer games for older adults. *Gerontechnology*, *8*(4), 220-235. http://dx.doi.org/10.4017/gt.2009.08.04.004.00