Adding Senses to the Human Body

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***Abstract*—This article is an excerpt from our upcoming textbook on haptic technologies. Here, we discuss early models of the human brain, as well as several studies on brain plasticity. We then focus on the opportunities afforded by the mechanism of neuroplasticity.**

***Index Terms*—neuroscience, human perception, haptics**

I. Early Models of the Brain

Expressive aphasia, also known as Broca's aphasia, is a neurological condition characterized by an individual's inability to produce grammatically correct speech, often due to a physical impact or alteration to the anterior regions of the brain, which impairs the proper function of neurons that would otherwise help construct vocalizations of grammatically correct sentences [1]. In the suburbs of Paris, France in 1861, Paul Broca identified the location of the region responsible for expressive aphasia after he conducted an autopsy of a patient incapable of uttering any word other than "tan" [2]. Though speculations of the structure and function of human consciousness had existed for several centuries, Broca's discovery resulted in a new framework for understanding the brain's role in producing conscious experience. The patient's brain incurred a lesion from injury, and only a small subset of his cognitive function was impaired. Naturally, psychologists concluded that different parts of the brain mediate different cognitive processes. By 1874, Carl Wernicke discovered receptive aphasia (Wernicke's aphasia), which results from damage to posterior regions of the brain [3], and increasing numbers of scientists began exploring which regions of the brain were responsible for different aspects of cognition. Brain science adopted a new goal: mapping the locations of the brain corresponding to each observable function in human consciousness.

For many years, much of neurology and cognitive psychology consisted of research based on assumptions extrapolated from Broca's and Wernicke's conclusions. Since the brains of humans, chimpanzees, rats, and many of our other mammalian cousins did not exhibit much structural change past adolescence, the brain appeared to be a large circuit produced from the blueprint of our DNA. Studies of damage to isolated regions of the brain also revealed damage to isolated cognitive functions. Researchers followed this chain of cause and effect to a seemingly logical conclusion: parts of the brain are hardwired from birth to perform specific tasks. The occipital lobe processes vision. The temporal lobe provides networks for face recognition, emotion, long-term memory, and hearing. The parietal lobe processes taste, touch, pressure sensitivity, and kinesthetics. The frontal lobe is involved in speech, smells, emotions, language, problem solving, and personality. The cerebellum coordinates fine motor skills and balance. The limbic system controls emotional responses. This functional division of the brain, further subdivided into smaller layers and regions, was considered to be an increasingly complete map of the cognitive networks endowed by our DNA.

It took nearly a full century after Broca's discovery before the borders lining the map of the human brain became a bit more fuzzy. By the late 1960's, neuroplasticity became prominently recognized as a possible alternative explanation of the distribution of cognitive functions across neurons [4]. Though genes do influence the structure and function of the brain, they also provide countless homeostatic and adaptive mechanisms that allow the brain to adjust in physical structure to accommodate new kinds of cognitive processes. Learning can not only occur within regions identified as performing a specific task, but also within regions ordinarily dedicated to other tasks. When a region of the brain is not actively used, its neurons are not simply left alone. Sometimes, those neurons are slowly repurposed to perform a different task—direct evidence of the plasticity of the brain.

II. Observations of Brain Plasticity

Countless studies have revealed the effectiveness of the human brain in reorganizing its structure to accommodate for different streams of information as well as the corresponding cognitive processes required to interpret the information effectively. One such study that received significant public attention was VS Ramachandran's successful attempt in 1995 to treat phantom limb pain [5]. When a patient suffering from an injury receives an amputation, they may sometimes experience a confounding feeling that the limb is still attached to their body. Although their visual system perceives that their limb is missing, their somatosensory system continues to provide them with tactile and kinesthetic feedback mimicking the movements and position of the missing limb. Although some patients are able to adjust to the strange sensation, the phantom limb can sometimes result in overwhelming phantom pain from a clenching or tensing of phantom muscles—pain that shouldn't exist, but somehow continues to be perceived despite the limb's absence. Ramachandran's experiment used a mirror box to provide a reflection of the intact limb that wasn't amputated. By looking at the mirror and moving their intact limb, a patient would receive visual feedback that appeared as though they were able to control their phantom limb. Over time, some patients were able to reduce the pain they experienced by tricking their sensory system into perceiving that their phantom limb was no longer in a painful position. Upon examination via brain imaging, the therapy appeared to result in significant cortical reorganization in successful patients, indicating that the approach takes advantage of brain plasticity [6]. Although some patients have benefited from this therapy, a standardized procedure has not yet been established—further experimentation is required to understand the generalizability of the results [7]. Although the mirror box experiment has not yet resulted in an effective and replicable therapy, it was a poignant demonstration of the extent to which our sensory perception is mediated by cognitive processes in the brain—cognitive processes that may be modified with significant effort.

Perhaps the most profound investigations of the human sensory system involve individuals with sensory impairments. In 1996, Sadato et al. demonstrated that blind individuals reading text in Braille utilize neurons in the occipital lobe, a brain region previously believed to be rigidly organized for visual processing [8]. This finding has been replicated, and the plasticity of the occipital cortex may also provide individuals who are blind or visually impaired with a superior ability to process other modalities of sensory information, including tactile or auditory stimuli [9]. A 2006 review of studies on brain plasticity concluded that individuals with visual impairments could greatly benefit from adjustment strategies that target neuroplasticity, including repeated exposure to assistive technologies similar to Braille [10]. A team of researchers from Canada, Denmark, and Belgium noticed a difference in response between blind and blindfolded sighted participants in a study involving the stimulation of the occipital cortex using single-pulse transcranial magnetic stimulation (TMS) [11]. While blindfolded sighted participants reported experiencing phosphenes (rings or spots of light in their vision), blind individuals experienced tactile sensations on their fingertips similar to their experience reading Braille text. Furthermore, the researchers found a correlation between an individual's level of experience with Braille (hours per day of reading, reading speed, and dexterity) and the number of sites on the occipital cortex that produced tactile sensations when stimulated. When the occipital cortex went unused, its neurons were consistently repurposed to aid in the interpretation of stimuli from other sensory modalities.

Although recent studies of brain plasticity have revealed the depth of the human body's adaptive mechanisms, the volumes of research studying neuroplasticity in individuals with visual impairments can unintentionally paint too rosy of a picture. Though found to produce significant results, neuroplasticity occurs after the continuous repetition of a task, and the process of interpreting new streams of information, as is required in learning Braille, requires significant training. Neuroplasticity is far from a miraculous cure. Instead, it is a testament to the indefatigable persistence of individuals attempting to acquire skills and adjust to a disability. Additionally, the human brain does maintain a templated distribution of cognitive processes across its different regions—tasks are not spontaneously reassigned to any available neurons. An exploration of the occipital and somatosensory cortex in blind individuals suggests a possible limit to the types of tasks typically performed by recruited neurons in the occipital cortex. Ordinary touches of the fingers and explorations of surfaces are handled entirely by the somatosensory cortex, while the specific task of reading Braille text was handled by the occipital cortex [12]. This finding suggests something more interesting: instead of processing Braille as a sequence of finger touches, the recruited neurons in the occipital cortex may be providing the individual's conscious experience with a sense of vision entirely separate from the input received from their eyes. Rather than being wholly integrated with the rest of their sense of touch, their interpretation of Braille appears isolated as its own separate sensory stream.

Cross-modal neuroplasticity is not limited to individuals with visual disabilities. Deaf individuals using American Sign Language to communicate demonstrates a similar reassignment of neurons in the auditory cortex. Children who experience deafness at a very young age often cannot benefit from a cochlear implant due to the reassignment of neurons in their auditory cortex to other tasks [13]. Though a cochlear implant would ordinarily stimulate the regions responsible for allowing an individual to hear sounds, implants provided to children after a long period without any assistive hearing device would stimulate neurons repurposed for a different task. Studies of deaf individuals further reveal some of the limitations of neuroplasticity. The extent to which an individual's brain may reassign neurons may be dependent on the extent to which they experience deafness [14]. Children have a much higher likelihood of benefiting from cross-modal plasticity due to a generally increased level of plasticity during childhood. Providing a child with a cochlear implant early will increase the likelihood of their ability to interpret speech through the implant more clearly. This finding suggests that sensory streams are hardwired at birth, and only modified later when an individual is required to adapt [15]. Though the effects of brain plasticity are most visible in children, reorganization still occurs in adults who experience deafness after learning how to speak through childhood [16]. However, further research can reveal the exact differences in neuroplasticity throughout the human lifespan. Studies in mice and humans have demonstrated the possibility of both neurogenesis [17] and cross-modal plasticity in old age, but the full capabilities and limitations have not yet been isolated.

Neuroplasticity can also help improve outcomes for patients recovering from a stroke. When a region of the brain is deprived of oxygen for an extended period of time, its neurons will no longer be able to properly perform their intended function. A treatment plan may be more effective when it includes activities that force the brain to recruit different neurons to perform a task [18]. Through intensive use of a limb impacted by a stroke, a patient can slowly recover motor function due to brain plasticity. Typically administered as a form of constraint-induced movement therapy (the unaffected limb will be restrained or held still), the patient performs repetitive tasks that slowly rebuild their motor function [19].

When administered within 3-9 months after a stroke occurred, constraint-induced movement therapy "produced statistically significant and clinically relevant improvements in arm motor function that persisted for at least 1 year." [20] Functional imaging studies have detected significant reorganization of brain function as a result of constraint-induced therapy [21]. Although such therapeutic regimens are effective, they come at the cost of extreme discomfort and exertion. When attempting to recover motor function in an affected limb, a stroke patient will often need to perform the same repetitive exercise hundreds of times over hundreds of days, experiencing fatigue and even pain along the way.

In addition to researching rehabilitative methods for stroke patients, researchers began exploring other possible rehabilitative applications of neuroplasticity. For patients with Parkinson's disease, a goal-based regimen of aerobic exercise activities appears beneficial. With instruction, feedback, and encouragement, patients are able to perform beyond their own perceived ability, and the process of engaging in such exercise can have a beneficial effect on cognitive and automatic motor control in individuals with Parkinson's [22]. Although further research can reveal the mechanisms underlying these improvements, preliminary studies demonstrate neuroplastic changes in synaptic connections and circuits. And although a firm treatment of Alzheimer's disease has not yet been developed, the underlying mechanism of the disease appears to be related to neuroplasticity. The onset of Alzheimer's appears to be a slow onset of the inability of the brain to restructure itself to accommodate learning [23]. This finding is also consistent with the typical onset of Alzheimer's in old age—the rate and ease of neuroplasticity does decline over time. Regardless, the etiology of Alzheimer's is complicated, and we cannot yet reduce it to a single cause.

Though neuroplasticity provides a basis for several potential treatment and adjustment regimens, its effects can be observed in the performance of ordinary tasks. An exploratory study conducted in 2009 demonstrated that frequent Internet users activate different regions of their brains when conducting a web search on Google [24]. Unlike a new user to the Internet, frequent users did not just rely on the portions of their brain typically used in reading text (left inferior frontal, temporal, posterior cingulate, parietal, and occipital regions), but also portions of the brain typically used in decision making, complex reasoning, and vision (the frontal pole, anterior temporal region, anterior and posterior cingulate, and hippocampus). An exploratory study also demonstrated potential differences between people with and without musical training. In particular, the participants of the brain imaging study who had been trained in music experienced "increased activation in the left fusiform gyrus and prefrontal cortex, and decreased activation in visual association areas and the left inferior parietal lobule during the mathematical task" [25]. Neuroplasticity doesn't just appear to be a mechanism for the brain to recover function, but also a mechanism that underlies learning. For learning motor skills, structural plasticity has been demonstrated to occur in relatively short durations of training. During a study examining the process of learning how to juggle, subjects showed significant changes in the grey matter within the occipitotemporal cortex after only a single week of training [26]. Microstructural changes in the limbic system were detected after only two hours of training in subjects asked to complete a spatial learning and memory task with a complex set of rules and procedures [27]. Again, these discoveries come with a caveat. Nobody can learn to professionally juggle within a week, regardless of the detectable changes in the microstructures of their brain. The aforementioned investigations constitute a small fraction of the growing consensus that the human brain can reorganize itself under the right circumstances. This reorganization has the potential to improve people's quality of life by endowing them with the ability to perform tasks with a greater level of ease and comfort, but the ease and comfort only arrive after long periods of intensive learning and relearning.

III. Conclusion

Neuroscience is a rapidly growing field of research. Investigations into the structure and function of the brain have the potential to uncover truths with profound implications for who we are as humans. Like any other human activity, scientific research must be evaluated by examining its effect on our well-being. Though the thousands of publications describing neuroplasticity can provide us with a foundation to imagine future applications, the research only becomes valuable in its implementation for the benefit of individuals facing a cognitive or sensory impairment, hundreds of whom have contributed their time and selves to make scientific discoveries possible. The science is a starting point—a foundation from which hackers, entrepreneurs, and policy-makers can potentially push for a more equitable future. Though neuroplasticity provides us with an underlying mechanism for understanding how the brain can learn, this book attempts to answer a related pertinent question: what can we teach the brain to do?

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