Recovery Potentials Following CNS Lesions: A Brief Historical Perspective in Relation to Modern Research Data on Neuroplasticity

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This article begins with a brief historical account of our attempts to understand the brain by endlessly mapping out discrete structural and functional territories. These territorial or classical maps are then contrasted with the new metabolic maps, which show brain function and plasticity as it has never been conceptualized or visualized before. The new maps, along with more recent research in such areas as neuroplasticity, synaptogenesis, parallel processing, holistic brain functioning, sexual dimorphism, and individual differences, are giving our profession a solid scientific foundation upon which to base many of the rehabilitation techniques used today in pediatrics, geriatrics, psychiatry, and physical disabilities.

About 400 years B.C. human beings made their first attempts to relate brain structure and function. However, it was not until the 17th century that detailed mappings began (1, 2). By the late 1800s Brodmann, von Economo, and others published cytoarchitectural maps, while Broca, Werneck, Jackson and associates argued about functional areas in relation to brain lesions (1, 2). Since that time Sherrington, Penfield, Adrian, Berger, Matthews, Luria, Eccles, Lund, Sperry, and many others have added a wealth of scientific data on structure, function, and dysfunction, including the little-understood phenomenon of neuroplasticity and recovery of function following a central nervous system (CNS) lesion. Since World War II and especially in the last 10 years there has been an explosion of knowledge in all areas of the neurosciences, not only in relation to macrostructure, function, and recovery of function, but more so in ultrastructural, biochemical, neurobehavioral and neuropharmacological research.

Territorial Versus Metabolic Brain Maps

Perhaps it is the result of this tremendous growth of knowledge that some individuals appear to be reluctant to accept the research data on neuroplasticity and the recovery potentials of the CNS following a brain lesion. However, there may be other reasons for people’s reluctance to change their thinking than the fact that the research data seem to conflict with what they have been taught. Several noted neuroscientists have expressed the belief that the human mind may not be capable of understanding the vast complexity of its own brain (3, 4, 5). However, another reason may be that human beings are makers of maps. For over 2,300 years we have been subdividing the brain into neat little structural and functional units. In so doing we are expressing a fundamental way in which the brain functions, that is, the mind understands things best when it can deal with boundaries and defined territories, known values and measurements, labels, and concrete facts. Overlap of structural areas and especially functional overlap appear to be extremely difficult to grasp. An example of this appeared on a 1981 cover of Science. The title of the article to which the cover referred was "Metabolic Mapping of the Brain's Response to Visual Stimulations: Studies in Humans" (6). The authors chose to ignore (or not discuss) the metabolic activity in other parts of the brain which were just as active, if not more so, than the visual cortices. Their previous education in territorial maps of the brain may have prevented them from seeing the true extent of the functional visual cortices. Yet it is known that much of the prefrontal, frontal, parts of the temporal and parietal lobes, as well as the occipital lobes, are integral parts of the functional visual cortices or what might be called the physiological unit that enables us to see and understand what we...
see (7-11). This idea of a physiological unit of vision may appear contrary to many theories that have been taught concerning structural and functional brain maps and circuitry. However, it is known from electrophysiological research that different regions and levels of the CNS, such as the prefrontal lobes, basal ganglia, inferior olivary nuclear complex, cerebellum, thalamus, and sensorimotor and associative cortices all function as an anticipatory and preparatory circuit, firing 300 to 800 milliseconds prior to the onset of muscle contractions (12-15). Knowing these facts, one can continue to hold to the traditional brain maps and state that the primary motor cortex is the area of the brain governing fine motor coordination, speed, and precision of movement (6, 11, 16, 17)? Is this not analogous to saying that walking is only that part of the gait pattern which occurs with push-off from the left hallux?

This analogy may be unacceptable initially. However, ever since cerebral blood flow (CBF), positron tomography (PT), brain electrical activity mapping (BEAM), magnetic resonance imaging (MRI) scans, and electroencephalographic-evoked potential research data began to appear in the literature, traditional concepts had to be questioned concerning structural and functional territories of the brain. These new metabolic maps are incongruent with traditional teachings and the way in which the brain has been perceived, especially in relation to function and even more so in relation to dysfunction and functional recovery (5, 18-29). Sherrington, Penfield, Luria, Eccles and others have indicated that all structural and functional areas of the CNS are intricately and endlessly overlapping, yet their concepts have been difficult to grasp, and even more difficult to express in a manner that everyone could understand (1, 3-5, 30-32). In reality, it is more comforting to the human mind to discuss the 1st somatosensory cortex or the 1st auditory area and their adjacent association cortices and functions (or dysfunctions) than to look at the brain holistically and try to understand how various areas overlap and interact in millisecond sequences. These new functional maps appear to violate the way in which the human mind likes to think, organize, and compartmentalize information. However, for those in the field of rehabilitation, these new metabolic maps are demonstrating neuroplasticity and functional recovery potentials that have never been visualized before (5, 19, 20-23, 28, 29, 33). These scans illustrate the tremendous potential that the CNS has for using billions of circuits and trillions of synapses for tapping into thousands of overlapping functional patterns or “holograms” and recombining these into new functional units to meet the demands of the environment. Positron emission tomography (PET) and BEAM scan research with mental patients and individuals with multiple personalities has already shown how plastic each individual's brain can be in relation to his or her disease process and/or drug therapy (5, 24, 34-40). Recent research is demonstrating interesting brain patterns in patients with Alzheimer's disease, or those with other degenerative disorders, and comparing these with scans of normal brains (5, 19, 24, 35-37, 41, 42). New sequential scans, operating at split second intervals are being developed along with much higher resolution capabilities and color technology. These will help researchers visualize subtle shades of functional differences occurring in various areas of the CNS as an activity is performed by an individual (5, 20). These new technologies will be a blessing to those in rehabilitation, because they will give us the opportunity to investigate the injured brain and then visualize and quantify reorganization as it occurs in the recovering CNS. In the not too distant future new atlases may be compiled from scans that will picture the entire CNS. These will be functional maps as well as sequential maps showing normal brains involved in specific tasks. These atlases may be the next generation of maps, which will demonstrate how the brain functions and/or recovers following a lesion.

Just as these new maps will be incorporated into our understanding of how the nervous system functions holistically, individuals in rehabilitation will have to revise their previous knowledge to bring it in line with the new theories, which are giving researchers and therapists valuable insight into the recovery potentials of the CNS following a lesion. For instance, there is no question that functional recovery can occur following brain injury. There are too many validated cases to deny this fact. Granted, some persons never recover and many recover to varying degrees, but some appear to recover almost their full potential even among matched groups of patients with very similar lesions (43-51). The question is—why the difference?

**Individual Differences**

The fact is that individual differences play a major role in functional recovery, just as they show up rather dramatically in PET and BEAM scans and EEG studies of normal individuals who are involved in the same task during controlled conditions (5, 6, 21, 22, 25, 34, 36, 41, 43, 44, 52). Moreover, no two brains are structurally or functionally alike, not even in their vascular patterns, just as the two hemispheres of a single brain are structurally and functionally different. Likewise the female brain is known to be different, developmentally as well as structurally and functionally, from the male brain (8, 22, 36, 53, 54). Above all, each brain has been genetically and environmentally “programmed” entirely differently from every other brain on earth. These facts need to be accepted as well as the fact that neuroscientists may never be able to map out the functional unit of the brain which endows each individual with motivation or the drive...
to survive and succeed. Yet it is well known that motivation plays a major role in functional recovery, for without it, there may be no recovery (3, 36, 43, 46, 55).

In the same light, Harlow's (56) work and that of many others has presented significant data on the tremendous importance of the need for love, touching, holding, caring, and communication, in regard to survival and normal brain functioning (3, 5, 36, 56). Although the cells of the nervous system that are dependent on these needs may never be located, there is no question but that these same potentials exist for man's brain, especially when that brain is trying to recover function in an excellent rehabilitation environment.

Alternate Pathways
Other factors that need to be considered in regard to recovery potentials concern the concept of utilizing alternate pathways and/or the unmasking of synapses following a CNS insult (9, 14, 15, 43, 45, 46, 59–61). Many of these alternate pathways may be concerned with the vast number of bilateral tracts that are known to exist in the CNS, not only from brain stem levels and the cerebellum, but also from neocortical levels (7, 8, 10, 11, 13, 15, 60–66). For example, many of the secondary sensorimotor centers of the neocortex are now known to send (or receive) input to and from both sides of the body via bilateral pathways (7, 8, 11, 65). Even PET research is demonstrating that these bilateral systems exist (18, 25). In the past too much emphasis has been given to the classical concept that the majority of pathways (exclusive of the autonomic nervous system circuits) were either contralateral or ipsilateral. Today, emphasis needs to be given not only to the classical pathways but also to the bilateral systems and the potential of these systems in functional recovery.

Unmasking of Synapses and Polysensory Neurons
Almost all neuronal processes of the CNS collateralize (ascending, descending branches, or both, for long or short distances) not only contralaterally, but in many cases ipsilaterally. In a normal functioning (mature) nervous system some of these fiber systems may be dampened or inhibited. Yet following a lesion they may be unmasked or released from inhibition (13, 43, 46). With repeated meaningful and purposeful use, these released neurons may be able to regain their functional potentials. In other cases, research has shown that there are numerous cell populations that are polysensory; many kinds of sensory or even motor types of neurons from motor centers within the CNS synapse on these cells (8, 10, 11, 13, 15, 43). Loss of one or possibly two types of input to these polysensory cells, due to a lesion, results in an abnormal balance of stimuli. This change, which may be excitatory or inhibitory, prevents these cells from acting in their usual pattern of firing. However, with repeated functional use, coupled with an increase (or decrease) in signal strengths from the remaining types of stimuli synapsing on these polysensory cells, these cells may remain viable and eventually, over time, once again fire optimally (or more normally) during functional movement patterns.

Concurrent with the discovery of polysensory cell populations is the finding that a single neuron can have more than one kind of a neurotransmitter substance. Paley's (68, 70) research and that of many others has documented this fact (50, 67–69). It can be theorized that it is the delicate balance of several different neurotransmitters per neuron which makes for an optimally functioning nervous system. Following CNS pathology there may be a need within the CNS to reestablish this delicate balance between the various amounts of different neurotransmitters impinging on the remaining polysensory neurons before functional recovery can begin to occur (59, 69–73).

Parallel Processing
Another important concept concerns the theory known as parallel processing (corollary discharge or comparator systems) and feed-forward/feed-back loops or mechanisms (7, 8, 11, 13, 61). It has been known for decades that the awake nervous system constantly receives tens of thousands of sensory signals concerning ongoing events, from a multitude of receptors located all over the body. These signals are relayed over several different but parallel pathways to a variety of nuclear areas located at all levels of the CNS. Some of these parallel pathways have one or two (or more) synaptic relay centers interspersed along the way. These various centers not only feed forward newly integrated signals but they also feed back this integrated information to the same centers from which the original signals were generated. In this way there is (a) a constant reaffirmation of incoming data both from primary sensory and from reafferent signals; (b) correlation of this data at each feed-forward and feed-back center, including enhancement and/or dampening of the summed signals at each synaptic center (depending upon the circumstances of the moment); and (c) comparison of similar types of signals, not only at each synaptic nucleus, but also in major functional centers (such as the basal ganglia, red nuclei, cerebellar cortex and deep nuclei, vestibular and collicular centers, and limbic areas, as well as various centers of the neocortex). All of these
centers, functioning together in a synchronous sequence, are believed to endow the nervous system with synergy, kinetics, dynamic postural tone and emotional tone, and memory, as well as an appreciation of the environment and various talents and skills. Comparator systems or parallel processing of information also enables the nervous system to anticipate or plan ahead and program the moment-to-moment sequences of individualized behaviors and at the same time modify these behaviors, depending on the multitude of incoming signals which inform the system that the most appropriate responses are being made. Brain pathology interrupts this delicate interplay of feed-forward/feed-back signals between various nuclear centers. At the same time there is a concomitant loss of thousands of parallel signals that cannot be relayed in their proper timing sequences or stimulus strengths to various nuclear areas for comparison with other types of incoming stimuli. Thus parallel processing is another one of the important functional substrates of the nervous system, along with others already noted, that endow the system with its potential for functional recovery (9, 10, 13, 30, 43, 46, 60, 61). If a sufficient number of parallel pathways remain viable, providing that certain critical nuclear areas are not completely destroyed by a massive lesion, then theoretically the remaining parallel circuitry should be available to be retrained to function in a more appropriate way and/or in a compensatory manner.

Conclusion

All of these factors, and many more which have been reported in the research literature, provide a foundation on which to build and substantiate our theories concerning neuroplasticity and the potentials for recovery of function following CNS pathology. Moreover, the new research techniques, such as the different kinds of brain scans, horseradish peroxidase (HRP) tracing methods, electrophysiological microprobes, and biochemical assays are substantiating the importance of individual differences as well as the vast complexity and potentials of the human nervous system. Therapists need to be cognizant of the new functional or metabolic maps of the brain and begin to question many of the older concepts that were based on the traditional territorial maps and a static or “hard-wired” nervous system. The new metabolic maps demonstrate how different nuclear areas of the entire CNS function in unison and at the same time have overlapping functions with other nuclear centers, especially when a subject is involved in a prescribed task, or more important, recovering function following brain injury.

References

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