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The Need for Theory to Guide Concussion Research

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Abstract

While the focus on concussion research has expanded greatly over the past decade, progress in identifying the mechanisms and consequences of head injury, the recovery path and the development of potential interventions to facilitate recovery have been largely absent. Instead, the field has largely progressed through an accumulation of data without the guidance of any systematic theory to guide the formulation of research questions or generate testable hypotheses. As part of this special issue on sports concussion, we advance a theory to describe the evolution of a neural network during the development of a cognitive process as well as the breakdown in that network following injury to the brain. The theory emphasizes the importance of changes in spatial and temporal distributions of the brain's neural networks during normal learning throughout the lifespan and the disruptions of these networks following concussion or mild traumatic brain injury (mTBI). Specific predictions are made regarding both the development of the network as well as the breakdown of that network following injury.

Keywords

Concussion; Theory; Brain; Neuroplasticity; mTBI

Hebb (1949) was the first to describe the notion of neural networks. Such networks were thought to be trained with successive presentations of a stimulus to the point where processing becomes virtually automatic, requiring only partial exposure to an event in order to be correctly activated. Parallel and distributed processing approaches reinforced this view (Andersen, 1983; Hinton, Osindero, & Teh, 2006; McClelland & Rumelhart, 1986). We propose a modification to this classic view, one designed to characterize brain processing that emphasizes the importance of dynamic changes in both the spatial and temporal distributions of the brain's neural networks during normal learning across the lifespan. Disruptions or alterations in the development of these networks would result in learning problems (e.g., learning disabilities) or result in cognitive impairments following traumatic brain injury (TBI), or genetic or environmental factors (e.g., malnutrition).

It is our contention that in the earliest stages of skill acquisition, neural activation is widely distributed across and within multiple brain regions that communicate with each other initially in a spatially and temporally unstable manner. Such instability is inherent to the

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development of the system as it continuously seeks to develop more efficient ways to process information. In this initial phase, the order in which brain areas communicate is continuously in flux. As a cognitive process develops, these temporal and spatial components of a neural network begin to change in the following manner: (1) the number of areas engaged decline; (2) a decreasing number of areas are reliably activated from one time to the next; (3) with skill mastery the order in which these areas communicate stabilizes such that (4) maximally efficient processing is carried out by a more restricted set of neural regions that communicate with each other in both a temporally and a spatially stable manner. This developmental process that spans moments, days or years, results in increasing success in learning and utilizing material more rapidly while requiring fewer neural resources to support these processes.

There are a number of converging studies comparing younger with older populations that support such a view of more focused cortical involvement as development and skills progress. Casey, Giedd, and Thomas (2000) in an fMRI study of children and adults engaged in memory and attention tasks, noted that the magnitude of activation engaged larger neural areas in children than adults as indexed by the more extensive volume of activation in the middle frontal gyrus and superior frontal gyrus in children than in adults. Blakemore and Choudhury (2006) found a similar result in their study investigating an older population. They noted larger activation patterns in adolescents relative to adults during an emotion task in the regions of the anterior cingulate cortex, the left and right orbital frontal cortex, and the amygdala. Thus, across different tasks and different cortical regions, more cortical areas were activated in younger than older populations. These larger and more diffuse activation patterns in the younger populations occur in spite of the developmental trend in which synaptic and cortical development increase with age (Sowell, Trauner, Gamst & Jernigan, 2002; Toga, Thompson, & Sowell, 2006). Studies of brain injury where one expects the neural network to break down and revert to requiring more brain activation provide complimentary findings that support our view of neural processing. For example, Maccotta et al (2007) during a memory task reported widespread dynamic recruitment of additional brain areas following unilateral medial temporal lobectomy. Finger, Walbran & Stein (1973) reviewed an extensive set of papers addressing the “serial lesion” phenomenon in which a series of successive lesions result in less impairment than a single lesion that ablated the same areas at one time. This effect was noted for lesions across diverse brain areas engaged in activities involving motor movement, eating, motivation, emotion, sensory (e.g., tactile, vision), and learning. Furthermore, this effect occurred in regions of the frontal cortex as well as the brainstem, suggesting that this phenomenon could be a general property of the neural system. Finger et al went on to suggest that this phenomenon is directly related to cortical plasticity.

We believe that such spatial and temporal neural changes are both intrinsic to and critical for successful neurocognitive development and functioning. In this model, during the acquisition of a skill, neural activation is widely distributed across multiple brain sites that communicate with each other initially in a temporally and spatially unstable manner. In this phase, the order in which brain areas communicate is continuously in flux, with one neural area activating first upon representation of a stimulus while in the next instant a different area may be activated that is then followed temporally and spatially by yet a third area, etc..

From trial to trial, there is a shift in the order in which different areas are activated. However, as a skill matures, these spatial and temporal relationships and the order in which neural areas areas communicate with each other begin to stabilize while the number of involved areas declines. As a consequence, processing becomes more efficient and proceeds more rapidly as fewer neural regions are engaged, linkages between areas become more direct, and as the temporal order in which areas communicate stabilizes and become routinized. The end result is that this neural-functional restructuring moves processing from being dependent on widely distributed, unstable spatial and temporal networks toward a more stable network composed of areas that communicate with each other in more efficient (i.e., faster and dependent on fewer brain areas for input and processing) and predictable ways.

Another tenet of this network model is critical. The brain is highly integrative, increasingly so with development. With the development of neural processes that support one set of skills, changes in the brain's organization within and across neural regions invariably will impact the manner in which the brain subsequently acquires and organizes other skills.

Figure 1 illustrates a neural development progression in organization in which initially an extended set of neural processes are engaged during learning (Fig. 1a). These processes are distributed across the brain and involve multiple areas potentially differing in relative size and distance from one another. Distance can be defined from the neural processes first receiving input as well as the distance between each of the subsequent members of this network. In addition, there are temporal differences in the order of activation – the sequence in which these different areas contribute during the processing of new information and how this processing is related in time to other engaged brain areas. With further experience and processing (Fig. 1b), the network becomes more refined, engaging fewer areas. In addition, the temporal order of the neural areas engaged also decreases as does the overall time for the processing to be completed. However, there remains some instability in the network, with other areas becoming engaged from time to time. Such variations are inherent to this process and provide the network with the flexibility to react to and incorporate other inputs that could in turn enhance network functioning (i.e., speed and efficiency). The end result of this process (Fig. 1c) is a smaller set of stable brain areas that are activated in a spatially and temporally reliable sequence. Fig. 2 captures the inability of the network to change its temporal and spatial relationships across time following, for example, a mTBI. In this case, (1) there is limited or no reduction in the number of areas activated, while at the same time (2) there is continued change from one moment to the next in the specific areas engaged (3) as well as the number of areas engaged, and (4) the failure to develop stable temporal and sequential relationships between the activated areas as one progresses from time 1 (Fig. 2a) to time 2 (Fig. 2b) to time 3 (Fig. 2c.)

New learning, the maintenance of current skill levels and the ability to respond to novel events in the environment all depend on optimal cognitive systems that are supported by an intact and dynamic neural support systems. When brain damage occurs, the individual's ability to respond optimally is compromised.

For learning new skills and acquiring information, this theory leads to a number of specific predictions. These include:

1. At the beginning of the learning process, a spatially distributed set of brain regions/ areas are engaged and the order in which these brain areas are engaged will be unstable.
2. As learning progresses, the spatial distribution and the number of neural areas engaged in the learning process will decline.
3. With the reduction in spatial distribution and the number of neural areas, processing speed will increase and response times decrease.
4. Such changes will utilize some neural areas originally engaged while abandoning others, even while connecting yet other areas to the network.
5. As learning progresses, the order in which the brain areas engaged in processing information will become more stable.
6. With the mastery of information or the development of more advanced cognitive abilities, a reduced set of brain areas are engaged. The order in which these areas engage during processing will become increasingly stable.
7. As a result of the stability of brain areas engaged and the order in which they are activated, the speed of processing will increase.
8. However, even with the acquisition and stabilization of the neural network supporting a cognitive function, the system will still exhibit periods of instability as the neural network continues in its attempt to develop more efficient means to process information, thereby reducing processing load, increasing processing speed, and conserving energy. These variations also provide the system with the flexibility to react to and incorporate other inputs that could in turn further enhance network functioning.

In the case of brain injury, the theory makes the following predictions:

1. Following injury, the neural network will become spatially and temporally unstable.
2. The ability of neural networks to function will be impaired at a cost to the overall neural systems, reducing levels of neural functioning as reflected in speed and accuracy of performance, as well as the ability to integrate information across neural networks.
3. The level of neural disruption (brain injury) will be inversely related to cognitive processing speed. The more severe the damage to the brain, the more slowly the individual will respond and the more errors will accrue.
4. Recovery from injury will require new local and distal networks to develop that will invariably engage at least partially different neural systems in different temporal and spatial relationships than the damaged or partially disrupted neural systems.

5. **5.** Remnants of the damaged processing system could interfere with the establishment of a new neural network and impeded recovery.

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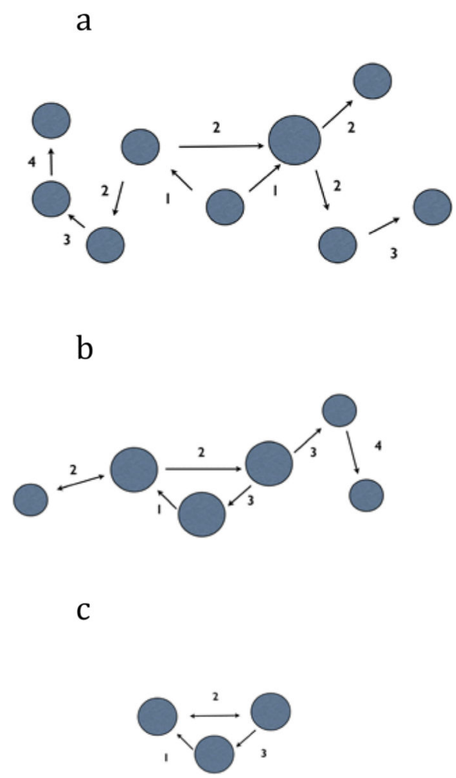

Figure 1.

Schematic of a neural progression in organization from initial exposure to material to mastery. during learning. Initially an extended set of neural processes are engaged during the early stages of the learning process (Fig. 1a). As learning occurs and mastery of material progresses, the neural substrate supporting this particular learning event becomes more efficient, engaging fewer brain areas, each of which contributes to the processing of information. During the second stage of this process (Fig. 1b), the neural network further constricts, improving processing accuracy and speed by engaging fewer brain areas and utilizing fewer but more reliable pathways of communication between areas. In stage 3 (Fig, 1c), the engaged areas are further reduced and the temporal and spatial links between areas becomes very stable, resulting in increased accuracy and decreased processing time.

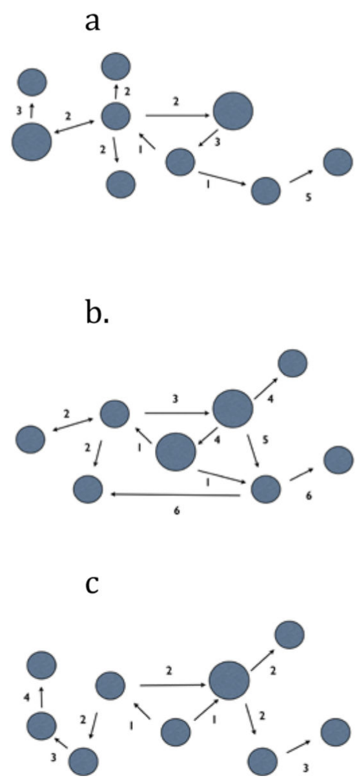

Figure 2.

Schematic of neural disorganization following mTBI that interferes with the maintenance as well as recovery of former skills and with the acquisition of new information. Following a mTBI, the operational network is compromised. Instead of the smaller ensemble of routinized pathways connecting a limited set of neural processes, the individual now has access to a less efficient network that resembles in part the early network illustrated in Fig. 1a. When an individual attempts to process familiar information, perform a prior existing skill or learn a new task, the brain experiences difficulty in utilizing those neural network structures that were disrupted by the injury. Instead, as indicated in Fig. 2b, the brain is unable to re-establish the network in the absence of former connections. Instead, it must now engage other areas using different pathways in an attempt to approximate its earlier level of functioning. This process requires additional time to establish such connections, thereby slowing processing time and efficiency. Further attempts by the neural system to reestablish maximize neural efficiency are impeded because the network remains unstable (Fig. 2c) with different areas becoming engaged from one moment to the next. In addition, interference from remnants of the original network could impede the establishment of an independent network.