A Neurocognitive Model for Students and Educators

Michael Atherton (athe0007@umn.edu)
Department of Educational Psychology, 178 Pillsbury Drive SE
Minneapolis, MN 55455 USA

Abstract

Computer metaphors for cognitive processes have become dated and new models are required to help college students and classroom teachers interpret research in the neurosciences as it begins to impact the fields of education and psychology A model of cognition using a metaphor of neural activation is presented and supported by finding in the neurosciences.

Introduction

In 1986, Rumelhart and McClelland published Parallel Distributed Processing and revolutionized our conception of memory and thought processes. Their introduction of neural networks as a model of memory served as a starting point for the growth of neurologically based computational models. Today, cognitive and computational neuroscience research is continuing to enhance our understanding of cognition. However, while the neurosciences influence how researchers comprehend thought processes, there has been little change in the models we teach students in introductory psychology and education classes. What is needed are models that provide students with a framework for understanding the neural bases of cognition and are at the same time simple to communicate and comprehend.

The Need for a New Model

The information processing model of cognition has provided us with many useful characterizations of mental functions: sensory registers, short-term memory, working memory, and long-term memory. Its ultimate failure has been its inability to integrate these characterizations with research findings in attention, imagery, and reasoning to form a comprehensive model of cognition. This failure is caused in part because theoretical descriptions of behavior are weakly constrained and allow multiple valid interpretations of the same phenomenon. This variability in description has fractionalized cognitive research into narrow domains focused on particular aspects of mental activity. Thus, students study cognitive topics such as perception, memory, and learning that have little relation to each other, leaving them without an associative framework.

Another problem with the information processing model is that its conceptualizations of thought processes often clash with research findings in contemporary neuroscience. It is now clear that memories are not compartmentalized into boxes or transferred from location to location as they are in a computer. Such characterizations can lead students to inferences that are not always valid, and in education such inferences can lead to instructional methods that are not always effective. In the past ten years technological and methodological advances in the neurosciences have produced a wealth of research results that have greatly increased our understanding of the biological underpinnings of cognition. This research has already impacted traditional cognitive theories (Miyake & Shah, 1999), but what is needed are not models that have been updated to account for the new data. What is needed are models that are built from the neuron upwards, rather than from behavior downwards. Such models stand a better chance of providing an internally consistent integrative framework for understanding cognitive research.

This revolution in orientation from top-down to bottom-up analyses represent a fundamental shift in the science of cognition and as Kuhn (1962, p. 109) has pointed out, "...when paradigms change, there are usually significant shifts in the criteria determining the legitimacy both of problems and of proposed solutions." Thus, we see major issues in popular culture such as the division between mind and body become irrelevant as old axioms are rejected and new ones formed (Crick, 1994). This paradigm shift is well underway in the field of psychology (Gazzaniga, 1998) and cognitive science, but has been hampered in education by the dubious application of the neurobiological research; to wit, "brain-based learning" has become the phrenology of the new century (Bruer, 1999a). The fact that such questionable conceptualizations of cognitive neuroscience are being actively marketed to educational practitioners begs for models that are well grounded by research in the neurosciences. The purpose of this paper is to present one such model in the hope that it will inspire discussion within the educational community. I will begin by presenting the model as it might be presented to students and the following section will review the scientific justification for the model.

The Model

The cognitive model presented below is a synthesis of the current research in the neurosciences. It is proposed as a descriptive theory in which the complexity of some neurological processes has been simplified for pedagogical advantage. For the most part I have tried to avoid issues that are the subject of on going debate, however I do make theoretical assumptions at some points to create an internally consistent model. Readers should keep in mind that what follows is a hypothetical description and that some, or many, aspects of the model have yet to be verified empirically.

Structure

Neurons The fundamental processing element in the brain is the neuron. A neuron is a cell that consists of dendrites, a body, and an axon. Signals are transmitted between neurons by chemicals called neurotransmitters at junctions between dendrites and axons called synapses. When neurotransmitters pass across a synapse from the axon of one cell to the dendrite of another they cause chemical changes in the dendrite and the body of the neuron and have an effect on the physical structure of the synapse. When a sufficient number of signals infringe on a neuron, they cause that neuron to release neurotransmitters at the synapses of its axons. When a neuron is in such a state, is receiving signals and releasing neurotransmitters, it is said to be *active*. The signals that a neuron sends can have either an excitatory and inhibitory effect. Excitatory effects cause other neurons to increase their activity; inhibitory effects prevent neurons from becoming active, i.e., from sending signals to other neurons.

Networks Neurons are highly interconnected; a single neuron can have thousands of synapses connecting to thousands of other neurons. Neurons that activate in common are linked together by synapses into networks. Networks of neurons can be local to a particular location in the brain, or they can be global and distributed across different regions of the brain. Local networks can be confined to an area a thousandth of an inch, whereas global networks can extend over distances of several inches and be comprised of multiple local networks. Networks can also be classified as task networks or control networks. A task network performs a specialized function such as the processing of the orientation of a line, of a color, or a phoneme. Task networks are also involved in more complex processing, such as the graphical representation of a word, or a human face. A control network, on the other hand, regulates the processing of a task network via connections that inhibit or activate neurons. This activation or inhibition by control networks functions to maintain, select, monitor, sequence, or integrate activity within task networks.

Control networks can be either local or global. Local control networks regulate task networks and are not necessarily physically distinct from them, but instead maybe spatially intertwined. Global control networks serve to regulate the activation between multiple task networks. Within the brain local control and task networks are generally located in regions known as the occipital, parietal and temporal lobes. Global control networks are generally located in the frontal lobes (Figure 1). General cognitive functions, such as auditory or visual processing that are executed by task networks are localized to particular areas in the brain such as the temporal and occipital lobes. While task and control networks maybe localized to different regions this does not mean that they are disconnected, rather as a general rule all classes of networks are highly interconnected.

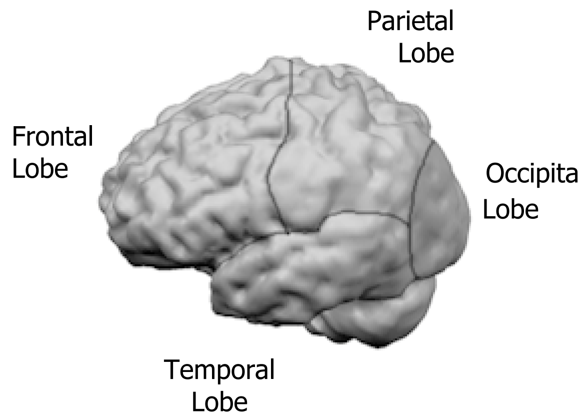

Figure 1: Global control networks are located in the frontal lobes; local task networks are located in the occipital lobes, parietal, temporal lobes.

Processes

With the neural and network structure outlined above traditional cognitive processes can be redefined in relation to their neurological processes. It is assumed that since thought processes are a function of brain activity, all of the concepts in traditional cognitive psychology can be redefined within such a framework. This paper covers fundamental topics such as learning, basic forms of memory, and attention.

Learning Learning is the process of making enduring changes in the relationships between neurons through the modification or creation of synapses. Learning is the intrinsic result of sensation, perception, thought, physical action, or the result of intention. Since thought or perception requires the activation of neurons, activation induces a change in the physical state of the synapses involved. When these changes are retained over time they form memories; when ephemeral they, along with the biochemical and electrical processes that cause them, form thoughts. Not all neurons exhibit the same properties; neurons and synapses differ in the rate at which changes are retained. Thus, long term physical changes in neurons located in areas that process sensory stimuli would occur slowly, whereas changes in neurons storing life experiences would occur more rapidly.

Memory A memory is a stored pattern of synaptic connections within local networks or across an interconnected network of neurons. A single neuron might contribute to several memories by releasing varying amounts of neurotransmitters depending on how it is activated, but the activation of a memory requires interactions between neurons. That is to say, no one specific memory is stored in a single neuron, rather a memory is distributed across a network of neurons as a pattern of synaptic relations. Additionally, several memories may be stored in the same network by different patterns of synaptic connections.

Traditional cognitive models have identified different functional categorizations of memory. Traditionally, the major categorizations have been short-term, working, and long-term memory. Within the current model each of these can be defined by neurological processes. Short-term memory represents the dynamic patterns of activation in networks across the brain. These patterns of activation arise from transitory chemical and electrical properties of neurons lasting a few seconds. Working memory represents a combination of short-term memory processes along with other chemical and transient physical synaptic changes lasting several minutes. Long-term memory represents physical synaptic changes lasting from minutes to days, weeks, or years, thus long-term memory is viewed as scaled physical changes in synapses on a continuum across time, rather than as discrete storage locations. Physical changes in synapses may revert to a previous state in some types of neurons if not reactivated.

Memory Capacity Traditional short-term or working memory has been shown to have a limit on the number of items that can be held in consciousness simultaneously. In the current model memory capacity is regulated by both the physiological and structural aspects of neural networks. Physiologically neural activity is limited by the production and transmission of neurotransmitters and rate at which cells can produce signals. While neurophysiology places a limit on what can be held in neural networks at any single point in time, working memory capacity can be increased by adapting the underlying network structure for particular types of memories. Thus, experts in specialized areas such as chess have better working memory for meaningful configurations of pieces than do novices because they have tailored synaptic patterns to particular stimuli.

Forgetting In short-term memory forgetting occurs as cells stop sending signals and the concentration of neurotransmitters decays and returns to baseline. This process normally occurs within seconds unless activation is renewed. In long-term memory forgetting may occur when physical synaptic changes decay or as activation overlays new synaptic patterns over existing ones causing interference.

Attention Attention is the modulation of activation in a network by a control network. Modulation takes the form of either a rise or a reduction of activation. This modulation can occur across widely separated regions in the brain or locally within a specific part of the brain. Attention can be focused in different regions when a global control network or a combination of global control networks modulates activation within local task networks. Attention is a process which occurs when specific stimuli or tasks require specialized processing. Attentional processing may be required to keep particular memories active (maintenance), discriminate between similar stimuli (selection), when anticipating environmental stimuli (monitoring), when planning a particular action (sequencing), or when it is necessary to coordinate multiple responses (integration). Attentional modulation may be initiated from the bottom-up by neural signals originating in task networks that then activate global control networks, or from the top-down when global control networks execute a motivational goal.

Attention can also be focused in specific areas in the brain by local control networks without modulation by global control networks. This can occur within task networks when a local control network modulates activation. Many of the same functions executed by global control networks (maintenance, selection, monitoring, and sequencing) can be also be performed by local control networks. The process of transferring control from a global control network to a local one is called automation. Automation occurs by adjusting synaptic connections within a task network so modulation of activation is stimulated and responded to by activity within the task network. This adjustment of synaptic connections in task networks occurs through attentional modulation or by sensory activation. This is generally a slow process and may require both focused attention and repeated practice.

Retrieval from Memory Memory retrieval in traditional psychology is divided into two general classes: recall and recognition. Recall involves the explicit retrieval of information from memory. Recognition, on the other hand, only requires knowing if something has been previously encountered. In the current model retrieval is defined as the reactivation of a previously active network. Recall differs from recognition in that recall requires full activation of a local network by a global control network in a top-down process, whereas recognition involves signaling a control network that some activation occurs in some local network and can occur as either a bottom-up or a top-down process.

An Activation Metaphor

Being able to imagine how thought processes occur in the brain can help teachers plan lessons and can also help undergraduate students tie together disparate concepts in psychology. The current model lends itself to a activation metaphor so that students can picture thought processes as dynamic intensifying and receding patterns of activation, much as neural activation is depicted by differences in blood oxygenation levels in the brain by functional magnetic resonance imaging (fMRI; see Figure 2).

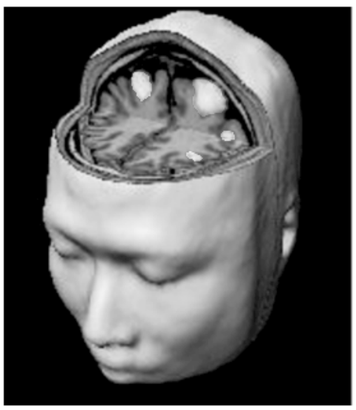

Figure 2: The brighter areas identify implied patterns of neural activation as detected by fMRI.

The processes of reading provides a good example of how levels of activation can be used to represent thought processes. When a word is first presented the visual areas in the rear of the brain become active. Activation is next seen in the word form area on the lower left side of the brain (Cohen, et al., 2000). At about this time there is an interaction between control networks in the left frontal areas and task networks in the lateral and posterior regions. There appears to be separate control networks for different aspects of reading such as grammar and those relating to semantics and these different networks appear to control specific task networks (Bokde, Tagamets, Friedman, & Horwitz, 2001; Poldrack, et al., 1999). Reading progresses as an interplay of activation between the control and task networks performing the functions of phonics, grammar, and semantics. Levels of activation in these areas can increase or decrease depending on the complexity of the task, when syntactic errors are encountered, or when semantic anomalies occur. Comprehension of longer passages of text appears to activate control and task networks on the right side of the brain (Robertson, et. al, 2000; St George, Kutas, Martinez, & Sereno, 1999).

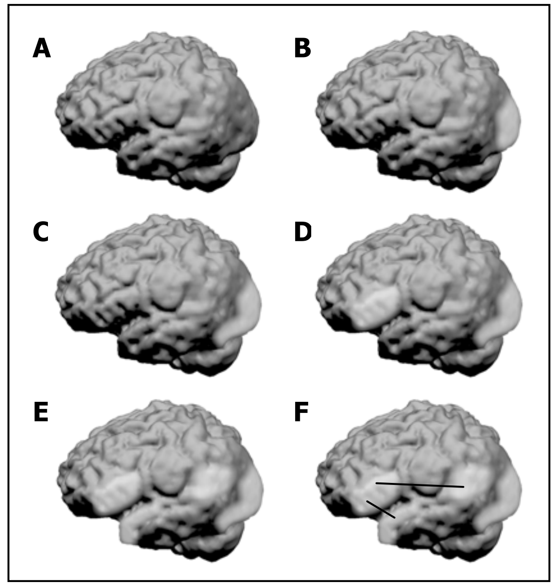

Figure 3: Idealized activation patterns during reading. (A) Displays the brain at rest. (B) Activation of visual areas. (C) Activation of the word form area. (D) Initial activation of frontal control networks. (E) Additional activation of phonological and semantic areas. (F) Interplay between control and task networks. The upper line indicates areas associated with phonological processing; the lower line with semantic processing.

While patterns of activation can provide an understanding of interacting networks, attention, short-term and working memory it should be kept in mind that long-term memory is the result by physical changes and is not necessarily reflected directly in the activation patterns, i.e., long-term memory is resultant effect of the activations.

Supporting Evidence

While some aspects of the model have not yet been verified empirically, most of the concepts are accepted by at least a portion of the neuroscientific community. In this section I will outline some of the research supporting the model.

The view that the changes in synaptic junctions are at least one of the major components of learning has been accepted for some time (Collingridge & Bliss, 1995; Larkman & Jack, 1995) and current research has been supportive of this hypothesis (Kennedy, 2000; Matus, 2000), however the exact mechanisms underling learning (Barinaga,1999) and forgetting (Berman & Dudai, 2001) remain the object of ongoing research. The assumption that learning occurs through the formation of new synapses (Klintsova & Greenough,1999) is more debatable and has been questioned by Goldman-Rakic a leading researcher (as cited in Education Commission of the States, 1996, p. 11). A far more controversial conjecture has been the formation of memories via the creation of new neurons. Recent publications have indicated that, contrary to previous doctrine, new neurons are created after birth (Gould, Tanapat, Rydel & Hastings, 2000; Shankle, Rafii, Landing, & Fallon, 1999) and may also be involved in the formation of memories (Shors, et al., 2001), but these conclusions have been challenged (Kornack & Rakic, 2001).

The interpretation of short term memory as dynamic biochemical and electrophysiological processes is hypothetical, but research has shown that transmission between nerve cells is separable into different chronological processes (Greengard, 2001). The concept of working memory extending over longer periods of time was introduced by Ericsson and Kintsch (1995) and is support by neuroscience research showing dendritic changes occurring on a continuum ranging from seconds to days (Antonova, et al., 2001; Wong & Wong, 2001)

The existence of large scale modularity in the brain has been recognized since the 1800s when it was discovered by Broca and Wernicke (Gazzaniga, Ivry & Mangun, 1998). The high degree of specificity in local networks has been a more recent finding. Spatially limited networks, characterized by the current model as task networks, have been found to subserve functions such as: the detection and orientation of lines (Hubel & Wiesel,1968), the motion of patterns (Movshon, Adelson, Gizzi, & Newsome, 1985), the recognition of objects (Tanaka, 1997), and the recognition of faces (O'Craven & Kanwisher, 2000). The existence of global networks is widely accepted in the neuroscience and cognitive communities (Stuss & Alexander, 2000; Varela, Lachaux, Rodriguez, & Martinerie, 2001); as is the recognition of networks that modulate attention, although agreement on the specific mechanisms of modulation may differ (Driver & Frith, 2000; Posner & Rothbart, 1998; Rogers, Andrews, Grasby, Brooks & Robbins, 2000). The concept of integrative networks can be thought of as a reformulation of accepted views of the functioning of working memory in the frontal lobes (Duncan & Owen, 2000; Levy & Goldman-Rakic, 2000), but once again, the opinions on the exact organization and mechanisms differs.

Conclusions

Given the advances in the neurosciences it is now both necessary and advantageous to formulate cognitive models based on neurological processes rather than on metaphors derived from other disciplines. Inevitably, we will see many new comprehensive models linking cognition to its neurological foundations. This paper represents an initial attempt to formulate such a model in the hope that it can be used as a pedagogical tool for students and teachers.

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