NEUROCOGNITIVE THEORY AND CONSTRUCTIVISM IN SCIENCE EDUCATION: A REVIEW OF NEUROBIOLOGICAL, COGNITIVE AND CULTURAL PERSPECTIVES

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A review of current thought in science education, especially constructivist perspectives, emphasizing cognitive and neuroscientific theory and research is presented with particular attention to teaching and learning science. A brief historical perspective on antecedent theories that emerged during the latter half of the twentieth century is presented as a context for integrating a neurocognitive model of information processing with modern perspectives on how students think and learn scientific ideas and ways of knowing through inquiry. A neurocognitive model is presented, rationalized in terms of current evidence and finally applied to explain, and hopefully enhance, how science can be taught more effectively using current inquiry approaches. Recommendations are made for curriculum design, improving inquiry practices, enhancing scientific thinking, and future research.

Introduction

The future holds high promise for modern multidisciplinary approaches to theory building in education. We have borrowed heavily in the past from philosophy, psychology, and the learned reflection of practitioners to build our current scholarly base for informed educational practice. The expanding frontiers of cognitive and neural sciences offer a new opportunity to create a more comprehensive theory of human learning. This paper presents a synthesis between two emerging fields: neurocognitive learning theory and constructivist philosophy of science teaching and learning. The latter has already become a major guiding model for instructional design in many disciplines, especially science teaching and learning. My goal is to explore the interface between these two modern perspectives, propose a neurocognitive model of constructivist cognition, present some integrative evidence from cognitive and neuroscientific research to support the neurocognitive model and its educational implications; and finally, in a summary perspective, integrate the model and related published research to theoretically explain some of the modern constructivist approaches to science teaching and learning. Hopefully, this may help to promote further inquiry in the field.

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An Overview of Neurocognitive Learning Theory

Neurocognitive learning theory is a synthesis of three traditionally separate strands of inquiry: 1. Neurophysiology with an emphasis on the biological bases of brain and neural activity, 2. Cognitive science with a focus on information processing and internal representations of experience, and 3. Learning theory that explains how we cumulatively interact with, and adapt to, our environments. To the extent that each of these strands of scholarship provides mutually reinforcing explanations of human learning, our ability to understand and predict learning is enhanced. However, this composite perspective is no stronger than the weakest components in the triad, and it becomes abundantly clear as we pursue this synthesis how much progress on the one hand we have made on each of these fronts in the last several decades while on the other hand how many unsolved mysteries still beckon us, especially in the realm of the neurobiological bases of human cognition and its applications to science teaching and learning. While it is increasingly clear that much of the more fundamental aspects of human cognition and self identity can be based on principles of science, we also need to recognize that human cultural history is also a remarkable construction that should not be limited by materialistic explanations. While we earnestly strive to understand the neural basis of cognition, we need to also acknowledge evidence from the humanities, including art and other imaginative aesthetic endeavors, that bear witness to the creative capacity of humans to utilize our biological heritage to construct and define our identities (e.g., Eccles, 1989; Granit, 1977). Thus, while I firmly believe that explanations of human experience can be rooted in scientific theory, I am also convinced that the remarkably generative and creative cognitive capacities, engendered through our biological and cultural evolution, have granted us a uniquely self-defining role. Whatever the ultimate materialistic explanation for human cognition, we also can take strength in the knowledge that our cultural and personal heritage is grounded in the capacity to construct a definition of who we are. Among all of the other forms of life, we share a remarkable evolutionary/cultural gift - the capacity to decide how we shall define our history, our destinies, and ourselves. In the twenty-first century, the roles of science and technology will undoubtedly expand as important contributors to our ability to innovate and metacognitively reflect on maintaining a sustainable environment. Therefore, the enhancement of science teaching and learning will continue to be a major challenge that hopefully will be promoted by more interdisciplinary theory building of the kind proposed here.

Thus, the aim is to explore our unique person-defining attributes, not by reducing them to a set of materialistic axioms, but rather to explore more deeply how wisdom from several different sources of scholarship can enlighten how we construct meaning from experience, and how in the future we may better maximize our capacities to fulfill our biological and cultural heritages as increasingly wise and intelligent human beings. There is a dynamic and complementary relationship among our biological heritage, socially constructed culture and individually constructed personalities. Our biological heritage (physical form and neurobiology) began historically well before the emergence of social groups, including our capacity to create social cultures and to explore and construct personal identities. However, these latter processes, though rooted in biological heritage, are not fully defined by it; and all three mutually influence one another giving rise at any moment in time to emergent cognitive states that define our conscious being. It is important to keep in mind the interdependence of these three state-defining attributes of humanity. If we focus only on one or a few, we lose sight of the remarkable generative capacity of human thought and
creativity. Our goal here is to examine some of the intricate interrelationships among these variables, especially as they pertain to modern conceptions of epistemology (how we construct knowledge) and how we learn, with a focus on science education. Current advances by cognitive scientists and science educators are beginning to make insightful applications of neurobiology to learning (e.g., Anderson, 1991, 1992, 1997, 2009; Bransford, Brown & Cocking, 2000; Kwon & Lawson, 1999, 2000; Lawson, 2003, 2006). However, both the basic science and the emerging applications in education are in relatively early stages of development.

**Four Benchmarks of Modern Learning Theory Culminating in Constructivist Views of Science Teaching and Learning**

I choose four benchmarks (described below) of learning theory that have marked science educational thought during the latter half of the twentieth century. These will serve as a structural framework for my remarks on neurocognitive bases of constructivism in education. They fall on a continuum from logical empiricism (a prominent guiding rationale for educational efforts following World War II) to constructivist-based learning strategies that have emerged most vigorously within the twentieth century.

**Benchmark 1: Empiricism and Behaviorist Perspectives**

Behaviorism, promoted particularly by B. F. Skinner of Harvard University, assumed that information about inner states of the mind were unnecessary to explain and predict behavior. This largely associationist theory, based on external application of reinforcing stimuli, recommended creating appropriate environmental contexts that elicited responses to be reinforced, thus building up a repertoire of behavior. No attempt was made to rationalize the cognitive processes or inner states mediating learning. Theory was grounded in chaining of responses shaped by external environmental reinforcing contingencies. Behavior was assumed to be occasioned by the environment. Internal representations, if at all, were ignored. Interestingly, early neurocognitive theorists, especially those of the Pavlovian era also held similar views.

For example, Sechenov (1863), while not denying consciousness, concluded in his book on *Reflexes of the Brain*,

Since the succession of two acts is usually regarded as an indication of their causal relationship (post hoc ergo propter hoc), thought is generally accepted as the cause of action. When the external influence, i.e., the sensory stimulus, remains unnoticed, which occurs very often, thought is even accepted as the initial cause of actions. Add to this the strongly subjective nature of thought, and you will realize how firmly man must believe in the voice of self-consciousness when it tells him how such things occur. But actually this is the greatest of falsehoods; the initial cause of any action always lies in the external sensory stimulation, because without this thought is inconceivable. (p. 88)

As we shall see shortly, below, modern neurocognitive views have departed significantly from this model toward more holistic information processing paradigms that recognize the central role of internal organizing states in cognition. However, modern applications of behavioral analysis also continue to provide new insights into how we learn through complex processes of conditioning (e.g., Greer & Singer-Dudek, 2008; Singer-Dudek &
Greer, 2005). Current neuropsychological research also clarifies a distinction between learning based on conditioning through reinforcement, in contrast to higher learning strategies based on logic, higher cognitive processes, critical thinking, and communication (e.g., Petri & Mishkin, 1994). From a neurocognitive perspective, behaviorist conditioning mediates learning, initially at least, through the more ancient part of our brain (the paleocortex that underlies the cortical hemispheres). Though in humans, it is unlikely that this conditioning always occurs without some interpretative activity, that involves cerebral centers. Critical thinking and constructivist approaches to learning maximize the intellectual functions of the neocortex - the biologically most recent cerebral elaboration of the brain. Extreme behaviorism of the mid-twentieth century fundamentally denied the significance of scientifically exploring higher brain functions and inner cognitive states, thus delimiting the scope of their inquiry.

**Figure 1.** Suchman’s inquiry cycle. Sensory intake (1) is mediated by cognitive and motivational processes in relation to memory (2) in an attempt by the student to categorize the sensory intake based on prior experiences. If there is a match detected by the mediation center (3) appropriate action is directed (4), which affects the environment (5) and gives rise to further sensory reception. If there is a mismatch at step (2) the mediation center directs actions to manipulate the environment as a source of additional information until an appropriate congruence is found with prior experiences. Based on Suchman (1966).

**Benchmark 2: Early Inquiry Perspectives**

A major shift toward cognitive explanations in the late twentieth century emerged with the heuristic or inquiry-based movement. Suchman (1966), for example, conceptualized inquiry learning as a dynamic process with five components known as “The cycle of inquiry”
The important advance in his model was a clear designation for the role of cognition in dynamic interaction with the environment. There are five components: 1. A memory module that is parsimoniously categorized into three parts, a) encounters with the environment (E), b) systems of explanation for encounters (S), and c) generalized rules and meanings based on experience (G); 2. Intake module representing sensory reception; 3. Action module representing motor and output functions of cognition; 4. Motivation and affective state module providing emotional modulation of experience; and 5. A mediation module that coordinates interactions among the foregoing modules.

This was an important step forward toward constructivism since it recognized the active role of the learner in organizing information in memory, using stored information to direct exploration of the environment, and the executive role of mediation in coordinating the work of the other components in creating an explanation for, and active response to, the environment. The central role of mediation is critical to the model. It assumes there is a brain function that serves an executive role in integrating sensation, affective states and motivation with memory retrieval and action. As we shall see, subsequently, this is highly consonant with modern neurocognitive theory.

**Benchmark 3: Constructivist Theories**

Constructivism, a theory of knowledge (e.g., Bentley, 2007; Bodner, 1986; Fosnot, 2005; Tobin, 1993; von Glasersfeld, 1993), is closely related to the critical inquiry movement of the mid-twentieth century. Some principles are summarized briefly:

1. Knowledge is actively created through interaction with sensory experience and is in part unique to the cultural and educational history of the individual. Active construction of knowledge takes place by relating new information to pre-existing information in memory. Thus, how we interpret new experiences is in large measure determined by what we already know. Two processes of constructing new knowledge have been proposed by Piaget, i.e., assimilation and accommodation (e.g., Fosnot, 2005) and incorporated into constructivist models. Assimilation is a process of merging new knowledge within networks of compatible knowledge in memory. This may be envisioned as a process of extending existing knowledge networks to include the new knowledge. Accommodation is a process of markedly reorganizing existing knowledge when it no longer is sufficiently congruent with new experiences to permit assimilation. For example, when a child finds that naive notions about the movement of the planets no longer allows her/him to explain the changing seasons, there may need to be a dramatic reorganization of the prior knowledge to better accommodate the new evidence of seasonal change that the student has encountered. The reorganization of existing explanations may be substantial and require construction of a fundamentally new set of propositions. This process of assimilation, characterized by periods of relatively steady-state knowledge structures, interspersed with periods of dramatic change and reorganization during accommodation of new experiences, is closely parallel to the ideas of major paradigm shifts that have occurred historically in science as proposed by Kuhn (1970). That is, scientific theories hold sway as long as they adequately account for evidence. When sufficiently compelling other evidence is gathered that cannot be merged into existing theory, these theories may need to be dramatically reformulated or abolished and new ones of wider encompassing quality constructed. However, we must remember that the historical way scientific knowledge has advanced may not represent the most effective way to sequence science learning, because the learner brings much different prior conceptions to bear compared to the prevailing beliefs in a particular historical epoch.
2. Knowledge construction is mediated through social dialogue whereby linguistic communities, often with a common cultural heritage, share information thus arriving at a consensus explanation of experiences and sensory phenomena. Thus, in contrast to the logical positivists who sometimes assert that reality is given to us preformed in our external environment and we discover this reality through research and exploration, the constructivists presume that we create knowledge through dialogue and consensus-making. This aspect is also consistent with Vygotsky’s (1962) views of cognitive development and the role of language in mediating transitions from earlier developmental stages to later ones. His concept of the zone of proximal development, briefly stated, is a developmental transitional stage where there is a potential to move into a higher cognitive state. This is mediated through language. That is, the teacher or other facilitator is essential to enhance passage through a zone of proximal development by engaging the learner in challenging discourse.

3. While logical propositions can be evaluated as true or false, the merits of constructed knowledge are judged by how well it promotes adaptation and survival in a given environment. That is, constructed knowledge is deemed meritorious if it enhances human adaptation and our perceived satisfaction in coping with the natural and social environment. While there is no truth value to knowledge in an absolute sense, constructivism is not inconsistent with scientific inquiry. Hypotheses are interpreted as constructed explanations that are tested for their ability to predict events in the environment. Thus, good hypotheses are those that allow the scientist to predict satisfactorily, i.e. a state of better adaptation. Poor hypotheses do not predict as well. The set of hypotheses and theoretical explanations accepted by the majority of scientists at any point in time is “public knowledge.” Its stability endures as long as the community of scientists agrees that these currently accepted explanations serve adequately to understand and predict natural phenomena.

4. We are not merely shaped by our environment, but we are active participants in defining who we are through building explanations of ourselves, our communities and the natural environment surrounding us. This last premise is the most appealing and powerful from the perspective of modern educational philosophy, for it affirms the capacity of learners to take hold of their own learning, to become self-directive and increasingly mature in their educational development, and to pro-actively develop learning strategies rather than being passive recipients of information. This self-directive aspect is closely akin to the cognitive psychological idea of “self-regulation;” the capacity to monitor and evaluate our behavior to become better adapted as critical thinkers and problem solvers in a particular environment.

Margenau (1959) proposed one of the earliest, modern philosophical models of constructivism (Figure 2). Theoretical explanations of sensory experience are depicted as networks of constructs (the C field) consisting of logically interrelated networks of ideas forming a mental model of sensory experience. These constructions are produced through perception of externally driven sensory experiences (P field). The P plane is the interface between our ordered mental models of the world and raw sensory experiences. Through rules of correspondence, we transform percepts from sensory data (P1) into constructs in the C field. Likewise, by deduction, we generate predictions (P2) that can be tested to determine the predictive validity of our constructed model. Thus, a circuit of verification is created that is reminiscent of the inquiry cycle proposed by Suchman (1966). Perception is not a simple impress of external reality on memory, rather our prior constructed knowledge influences
the perceptual interpretations we create. Hence, the P plane is a dynamic interface, where prior conceptions are used to shape incoming sensory experience.

**Figure 2.** Margenau’s model of constructed reality. Interpretations of nature are made through percepts (P1) of sensory data within the perceptual field (P field) and interpreted in relation to existing logical networks of conceptual knowledge (C field) through rules of correspondence (R) that we use to actively interact with the environment, eventually resulting in actions on the environment to test our interpretations (P2). This may lead to a new intake of information, evaluating the consequences of our actions; thus completing what is known as the “cycle of verification” – basically, a process of interpreting the environment relative to our conceptual frameworks, generating hypotheses, based on our theoretical network of knowledge, and testing them against evidence from the environment. Based on Margenau (1959).

This is consistent with current cognitive theory, i.e., that percepts are constructed by dynamic interaction between existing knowledge and sensory input. Experiments with tachistoscopic images presented in rapid succession demonstrate this effect. If a picture of a person with an outstretched hand is followed rapidly by a view of a carpenter’s tool, the viewer is likely to state that the individual is a construction worker. If, however, the same picture of the person is followed by a briefly presented picture of a pistol, the viewer frequently will respond that the person is a robber (e.g., Neisser, 1967). This top-down perceptual processing of using prior knowledge to shape our percepts, based on sensory data of varying clarity and complexity, has also been verified by neuroscientific evidence and imaging of the brain (e.g., Eger, Henson, Driver & Dolan, 2007; McKay, 1978). As described more fully below, the quality of the sensory input, in terms of the saliency, composition, and discrimination value, known as bottom-up processes, is also a critical factor. Thus, percepts are synthesized by molding incoming information to make sense in relation to what is already known, perhaps as a result of evolutionary adaptations to search for patterns in sensory experiences (Coward, 1990). Many additional examples of more
complex interpretative behavior also support the dynamic nature of percept construction guided by prior knowledge.

*Benchmark 4. Modern Learning Cycle Approaches*

More recently, the so-called learning cycle, largely derived from Piagetian structural constructivist perspectives, has gained prominence as a way of enhancing student learning of scientific knowledge and some scientific ways of thinking, involving evidence in making judgments of scientific claims and explanations (e.g., Lawson, Abraham & Renner, 1989; Marek & Methven, 1991; Marek, Laubach & Pedersen, 2003; Renner & Marek, 1990; Treagust, 2007). Fundamentally, there are three phases in the model, i.e., 1. engagement and exploration, 2. explanation (concept invention), and 3. application, including in some cases an evaluation step focusing on a critical analysis of the application as well as prior intervening steps. During exploration, the students examine scientific phenomena relevant to the science conception to be constructed, this is followed by discussion where the scientific concept is invented, usually mediated by teacher guidance, leading to an application phase where the students apply their knowledge to some aspect of laboratory investigation of the phenomenon. This latter phase may lead naturally to additional “exploration” thus reinitiating a new cycle of learning. During the course of the exploration and conceptual invention phases, the students’ prior conceptions or scientifically inaccurate conceptions (“misconceptions”) are likely mobilized thus providing an opportunity to refine their conceptualization of the scientific phenomenon, or to revise any misconceptions through a variety of cognitive processes including conceptual change (e.g., Hewson & Hewson, 1983; Posner, Strike, Hewson & Gertzog, 1982; Treagust, Duit & Fraser, 1996; West & Pines, 1985). The initial engagement phase introducing exploration may include some contextual problem or situational example that relates to students’ lives and/or interests to enhance motivation. Recently, this fundamental model has been augmented to include a hypothetico-deductive reasoning step, where the conceptual invention phase may involve creating a hypothesis that is tested in the subsequent application phase (e.g., Lavoie, 1999; Lawson, 2000). This newer perspective has also been situated within a more general model of theory based, hypothetico-deductive science (e.g., Duschl, 1990; Lawson, 2009; Lewis, 1988), but more about this later in the final summary perspective. In general, the learning cycle is compatible with the models of Margenau (1959) and Suchman (1966), and further analyses from a neurocognitive perspective are presented below. For example, the initial phase of the learning cycle involving an exploration of a scientific phenomenon is consistent with the P plane phase (P1) of Margenau’s model where direct sensory experience is used to access information perceptually about the natural environment. The second phase of inventing a conception or explanation parallels the C field of his model where cognitive interpretive actions based on the perceptual input lead to a construction of a conceptual understanding using networked logical knowledge to generate new explanations. The final phases of application and evaluation relate to the arrow projecting back to the P plane (P2) and P field where evidence is gathered to test the constructions and/or hypotheses developed in the second phase, thus comporting well with the hypothetico-deductive models. Interestingly, both the learning cycle and its interpretation relative to the Margenau model are consistent with Suchman’s view of inquiry; namely, intake of information about the environment, that is interpreted through cognitive mediating functions drawing on memory, and finally resulting in actions (such as hypothesis testing) that affect the environment and lead to a new “intake of information.” The role of motivation is significant in his model, and is
partially addressed in the learning cycle model by the engagement phase. The role of emotions and motivation in science learning will be addressed when analyses based on the neurocognitive model are presented in the summary perspective following the next section. Inquiry learning and related approaches to science teaching such as the learning cycle and project method (cited more fully in the final summary section) are increasingly supported by basic psychological studies (e.g., Dean & Kuhn, 2007; Kuhn, 2007; Kuhn & Pease, 2008) and science education research (e.g., Anderson, 2009; Krajick & Blumenfeld, 2006; Lavoie, 1999; Lawson, Abraham & Renner, 1989).

**Figure 3.** A neurocognitive, constructivist-based model of information processing. Perceptions (P) of sensory input are shaped by our prior experiences, mobilized by the executive function module(s) (M) localized in the brain’s frontal lobes. Information flows in parallel pathways, not simply serially, and the brain can process the multiple inputs almost simultaneously in various brain processing centers (e.g., Aystö, 1988), including working memory (a dynamic temporary storage center) localized in the frontal lobe, where incoming information is shaped and reworked (KR) in relation to prior stored information in long term memory. Decision making and templates for response patterns are weighed by the affective or emotional valence (AF) of the information in relation to prior experiences as mediated by neuronal projections from the limbic system to the frontal lobe, among other locations. These affective states also influence how the incoming sensory data are perceived and integrated with prior knowledge. When an appropriate response template (RT) is selected, the response pattern is actualized by motor pathways producing an effect on the environment that is perceived through feedback (F) as sensory input, thus completing what is known as an “action-reaction loop.” The double-headed arrows within the diagram also indicate multiple neuronal linkages among brain modules that mutually interact by action-reaction loops of signals and responses. Based on Anderson (1999)
A Model of Constructivist-based Cognition Grounded in Neuroscience

A model of constructivist-based cognition (Figure 3) combines elements from cognitive science, philosophy and neuropsychology (Anderson, 1991, 1999, 2009). Sensory input, via the five senses, is processed in parallel streams, not merely serially as older views presumed. Indeed, the cyclical models of thought that reduce cognition to a circular series of actions (though consistent with neurobiological feedback loops), belies the complexity of the multiple pathways of information processing that may occur in the central nervous system. An executive function module of the brain coordinates incoming sensory information in relation to prior experiences stored in long-term memory. This coordination shapes perception. The perceptual units and patterns we construct depend on the interaction of prior knowledge with sensation to produce perception. However, in addition to this “top-down” processing mediated by executive functions, there are also “Bottom-up effects,” namely, the attributes of the sensory data that make them salient or easily discriminated. These initial perceptual constructions are held temporarily in working memory and selected parts pass into long term memory. The double-headed arrows connecting the executive functions with working memory signify the dynamic interaction between the two components, represented by internal “action-reaction responsive loops.” That is, the nervous system organizes itself partially by internal information loops, namely, signal sending from one region and feedback responses from the region of the brain that received the signal. Information reconstructed from prior memory (KR) is stored in working memory and serves as a temporary buffer during information processing. Affective/emotional responses (AF) aroused by the information processed by the executive module affect or “color” our perception; and, moreover, through positive or negative valence, based on prior experiences, influence thinking and decision making (e.g., Damasio, 1998; Heilman, 1994; LaBerge, 1995; Meeks & Jeste, 2009).

Long term memory is compartmentalized into a variety of forms, here exemplified by procedural and declarative kinds of knowledge. In simple terms, procedural knowledge concerns “how” (ways of dealing with information) and declarative knowledge concerns “what” (information about facts and principles, etc.). There are separate regions of the frontal lobe that mediate these two functions. Working memory is temporary and limited, providing flexible processing of information in the moment-to-moment dynamics of perception and reasoning. Based on incoming information and mobilized prior knowledge, response patterns are selected. When a response pattern template (RT) is selected, motor functions of the body based on ensembles of neurons that drive patterned motor responses, act through effector organs to yield observable responses. These produce changes in the environment and also are perceived by the actor through sensory feedback and proprioception (internal sensation of action and location as in the muscular system).

This is a further example of an “action-reaction loop” involving motor output and feedback information of the effects of our actions on the environment through feedback information arriving by way of sensory receptors. Although the input and output flow may seem to imply that a simple serial loop is activated, modern neurocognitive science has clearly established that internal processing is complex and parallel, flowing through and among numerous neuronal networks and information processing modules in the brain in closely coordinated nearly simultaneous patterns – the brain though modularized to some
degree (each part serving a particular role) is also highly interconnected and functions holistically as a network.

Figure 4. A model of the dynamic processes of knowledge construction during learning and knowledge reconstruction during recall (see text for details). Incoming information is perceived relative to the contextual characteristics of a learning environment and constructed in relation to prior knowledge networks, where it is integrated and stored in memory as enlarged segments of the networks that form schemas or internalized representations of experience. Upon recall, the context of the recall situation influences how information is reconstructed from stored knowledge, and thus recall is not simply a direct, read-out process. From Anderson and Demetrius (1993).

Knowledge Construction and Reconstruction During Recall
An important concept in this model is the idea of knowledge reconstruction during mobilization from memory. Constructivist theorists have traditionally emphasized the active role of the learner in creating new knowledge. Retrieval of information from memory, however, is often treated as a simple read-out process where stored information is instantiated in working memory for processing. Current neurocognitive theory as presented in the next section clearly points to a dynamic reassembly of information during knowledge recall. This is conceptualized in a model (Figure 4) showing the dynamic role of knowledge construction in both information storage and retrieval (Anderson, 2009; Anderson & Demetrius, 1993).

Context, or the situational sensory information that occasions information processing, has an important role and is thought to be mediated by executive function modules in the brain. Sensory information (information source) is constructed as knowledge in relation to the context (concurrent circumstances and co-occurring events) and is stored as networks of ideas (schemas or other internal representations) in long-term memory. Recall of information, instantiated in working memory (e.g., Baddeley, 1992), is mobilized from long-term memory and organized again by the executive function module of the brain in relation to a given context occasioning the recall. Thus, context becomes a significant factor...
in determining what, and how, information will be instantiated in working memory and subsequently what form it will take as a response pattern expressed in recall. Consequently, context in science learning becomes a major factor, and current practices of using “situated learning” or “context-dependent learning,” (e.g., Bransford, et al., 2000; Dede, 2009; Sadler, 2009) where student-relevant problems or situations are used to introduce the domain-specific science content or problem task, is well supported by the neurocognitive model.

**Neurobiological Correlates of the Cognitive Constructivist Models of Learning**

Beginning at the most general level, to what extent does modern knowledge of neuroanatomy and physiology support cognitive-constructivists models of learning as shown in Figures 3 and 4? Our ability to apply modern neurobiology to broad scale issues in science education is somewhat limited due to the relative early stage of development of the field. Much of the research involves correlating data from neuroimagery or other neurobiological monitoring methods with observations of behavior, typically in a laboratory setting. With this fundamental information in hand, future more experimental-based studies in neurocognition and in science education theory derived from it are likely to emerge. Modern neuroimaging of brain functions has been particularly effective in identifying regions that correlate with cognitive tasks, but we are far from discovering detailed explanations of how complex thought and action take place. Indeed, if we ask four cardinal questions about brain function “where, what, how, and why” certain activities take place; we largely can address “where and what,” but we are not so clearly informed about the details of “how” major networks are functioning (but see Shepherd, 1998) or what the evolutionary and adaptive origins (“why”) are for the functions. Hence, given the above mentioned ambiguities, we are limited in our capacity to make broad and incisive prescriptions for reforming science education. However, information from neurocognitive science can provide a richer set of explanations for current best practices in science education and also provide new insights on how to maximize our emerging modern methods of teaching and learning of science (more about this in the final section of the paper). In the following section, some current information on brain function that supports the model (Figure 3) will be presented.

**Neuroscientific Sources of Evidence Supporting the Neurocognitive Model**

Current evidence indicates that sensory input is largely a parallel process. Nerve fibers from the five sensory organs enter the brain stem in parallel and as afferent fibers passing through the thalamus where some integrative activities occur, then radiate out to the cerebral cortex toward the major sensory processing centers of the brain (Figure 5). These centers include the occipital lobe for vision, the somatosensory cortex for body surface sensations and internal proprioceptions, and the temporal lobe and associated areas for auditory input (Ojemann, 1991; Penfield & Roberts, 1959) and representation of some conceptual information (anterior pole of the temporal lobe). Although these centers are somewhat modular, there are convergent zones where sensory information is integrated (e.g., Stein & Meredith, 1993). Thus, we are able to discriminate sensory input, but also at a fundamental level comprehend how these separate sensory signals are interrelated, thus generating a coherent map of relations among the five senses. These fundamental mechanisms, at both the non-conscious and conscious level, are inherently important in scientific activities and support the hands-on, minds-on approach to modern science education. The integration of
sensory input also promotes more integrated representations in memory of our experiences and provides network maps of information that are richer, more stable, and likely more accessible than would be the case if there was less integration of multiple sensory representations (e.g., Anderson, 2009).

Figure 5. A schematic diagram of the left-side of the brain showing major functional regions. Working memory located in the frontal lobe, including localized regions for representation of spatial percepts and words, is closely associated with the executive module (partially located in the cingulate gyrus) that regulates how information is organized and interrelated in working memory and also dynamically in relation to stored information in long-term memory. An executive attention network modulates what incoming information is particularly attended to (dashed opaque arrow), including visual information (received by and stored in the occipital lobe), and words (W) and other verbal information (including conceptual information “What”) stored in the temporal lobe (posterior portion, IT). Deeper regions in the occipital lobe mediate visual representations of motion, color, location, form, etc. Visual, verbal and spatial information (latter mediated by the parietal lobe, “Where”) is integrated partially at the posterior portion of the temporal lobe at a nexus with the occipital lobe, posterior to the region marked (IT). The corpus callosum is one of several massive fiber tracts, in this case linking functional centers of the left and right hemispheres. Based on Anderson (1999).

Executive functions are a major component of the model, and current evidence shows that the frontal cortex (Figure 5) in coordination with the parietal lobe is a major center for mediating metacognitive processes of planning, strategizing, and predicting events (e.g.,
Stuss & Benson, 1986) and also is the site of working memory where long term memory information is temporarily assembled to mediate immediate tasks (e.g., Klingberg, 2006). To what extent is there modern neurobiological evidence for an executive function and short term working memory center in human brains? Recent research using non invasive imagery techniques such as positron emission tomography (PET) and magnetic resonance imagery (MRI) have demonstrated enhanced activity in the frontal lobe region when subjects are actively involved in controlling attention in a cognitive task (e.g., Posner & Raichle, 1994; Unterrainer & Owen, 2006). The kinds of mental models or representational networks mobilized in working memory are also critically important in attentional mechanisms (e.g., Moore, Porter & Weissman, 2009). In addition to the bottom-up processes mentioned in the preceding section, the information from memory mobilized in the frontal cortices affects what we attend to and how we perceive the sensory input. For example, fiber tracts from the frontal lobe project toward the occipital lobe and signals sent there can broaden or narrow the registration of incoming visual information within the deeper layers of the occipital lobe. Hence, it is of vast importance during science teaching to be aware of what kinds of mental models students are mobilizing when engaged in an inquiry task, because these representational networks may substantially influence what the students attend to and what they perceive – a possible limiting factor in creative an effective inquiry learning.

Neuroanatomically, the frontal lobe is spatially and functionally closely related to the motor cortex, and posteriorly to the parietal cortex where spatial relational thought is partially localized. Moreover, emerging neuroscientific evidence indicates that mathematical skills are linked to activity of the parietal cortex and, therefore, may have strong neurocognitive affinities to spatial thinking processes (e.g., Loetscher, Bockisch & Brugger, 2008). This is consistent with the advice of Polya (1973) in his book on “How to Solve It,” that it is helpful to “make a drawing” as a way to represent the initial conditions of a posed mathematical problem. The close affinity of mathematical thinking with spatial representational activity also suggests that the mutually beneficial effects of interdisciplinary curricula merging science and mathematics may go beyond basically using mathematics in a meaningful and applied way in science (as valuable as this may be) and may include a reciprocal strengthening of the two disciplines through the strong spatial interpretive skills often required in mastering scientific inquiry in a quantitative context. Indeed, laboratory learning that is “hands-on,” and also encourages students to use psychomotor skills in representing scientific and quantitative information as diagrams, graphics, or other visuo-spatial representations, may enhance both the learning of science and mathematics (e.g., Longo, Anderson & Wicht, 2002). Hence, there is further evidence (more than can be adequately addressed here) that the complex set of linkages among executive functions, working memory, and motor response patterns (the latter mediated by the motor cortex), shown in the constructivist model of cognition (Figure 3), is fundamentally supported. Thus, the well established aphorism that “thought and action are closely linked” is probably neurobiologically sound, and likely is a two-way interaction.

The close spatial and functional linkage of the frontal lobes with the motor cortex also suggests the possible importance of motor functions in the development of higher order thought operations mediated by the frontal lobe, both in biological heritage through evolution and through individual ontogeny (maturation). This is a research topic in constructivist learning that deserves much closer scrutiny. That is, to what extent does the use of appropriate coordinated motor activity of adequate diversity during early education facilitate higher order cognitive maturation that may be built upon the prior motor
templates? Questions of this kind are particularly relevant to recent ideas of teaching by “doing and thinking” or as it is also known “hands-on, minds-on learning.” In general, multimodal learning, especially of complex higher order cognitive information, involving vision, hearing, somatosensory input, and psychomotor behavior, is likely to promote encoding across neural networks in memory. Modern science education practices of “hands-on” inquiry based learning, exemplify teaching and learning strategies that are consistent with emerging neurocognitive theory, and if appropriately organized and designed to build in a logically consecutive way, based on the students’ prior learning, can enhance the stability and applicability of science knowledge. Consequently, such active learning strategies should promote a more efficient capacity to mobilize science information within and among brain functional modules during recall than would be possible if only one sensory mode is used. The highly distributed information among knowledge networks can provide multiple, and cross-referenced, pathways for mobilization and reconstruction during recall. Likewise, such recall is likely to be more creative than information acquired in a more unidimensional way.

Table 1

* A Proposed Model of Fundamental Units of Operations and Derived Cognitive Functions Mediated by Frontal Lobes *

<table>
<thead>
<tr>
<th>Operations (Rows)</th>
<th>Cognitive functions (Columns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower order</td>
</tr>
<tr>
<td>Signification/Categorization</td>
<td>Content clustering</td>
</tr>
<tr>
<td>Equivalence judgments</td>
<td>Judging identities</td>
</tr>
<tr>
<td>Ordinal relations</td>
<td>Serial ordering</td>
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<tr>
<td>Proportional relations</td>
<td>Proportional part judgments</td>
</tr>
<tr>
<td></td>
<td>Higher order</td>
</tr>
<tr>
<td></td>
<td>Concept formation</td>
</tr>
<tr>
<td></td>
<td>Perceptual target and goal evaluation</td>
</tr>
<tr>
<td></td>
<td>Constructing themes and plans</td>
</tr>
<tr>
<td></td>
<td>Social and task procedural judgments</td>
</tr>
</tbody>
</table>

Note. The Operations are presumed to be more primitive activities, a product of our biological heritage, and that the Cognitive Functions are derived activities of the brain that are constructed using the Operations as fundamental templates or building units. They emerge during ontogeny (maturation) as a dynamic product of the interaction of the individual with the physical, social and cultural environment. That is, the cognitive functions are highly plastic and their characteristics are determined as much by cultural influences as by biological origins. The higher order functions are derived from lower order ones by refinement and by their aggregation into new superordinate complexes. These form pattern templates in memory to guide future higher cognitive thought such as critical thinking and creative constructions. In general, the more complex functions are those listed lower down in the columns and further to the right. The dashed arrows signify possible developmental stages between lower and higher order cognitive functions, but the emergence of higher complex functions probably involves coordination of two or more functions listed in the table. These may reside in different modules or local networks (Shepherd, 1998) in the CNS and are coordinated by the executive networks of the frontal cortex.
A Model of Some Fundamental Frontal Lobe Functions Pertinent to Science Learning

Given the significant executive functions of the frontal lobe in coordination with other brain centers, and the need to restrict the focus of this review, some additional detailed information is presented on frontal lobe activity. There is some controversy regarding the biological origins, physiological bases, and most fundamental characterization of these functions (e.g., Grafman, 1994). A seminal question needs to be addressed: are categories such as “supervisory,” or “executive” the most fundamental functional units? That is, to what extent are these operations culturally and developmentally derived rather than being neurocognitively basic? Constructivist philosophy also provides additional insight on this issue. Since cognitive representations are contextually bound and embedded in prior experiences, our cultural and social heritages are also intimately involved in such higher brain functions. Therefore, to avoid cultural biases in describing these functions, it is important to begin with the most reductionistic categories of function that may serve as the foundations for the full play of cultural effects in forming frontal lobe neurocognitive activities during human development. Thus, we need to begin with the biologically most basic building blocks in describing the hierarchical functioning of the brain, to allow ample opportunity for cultural effects during maturation. If we begin with highly derived categories such as “supervisory function” or “executive control,” these labels already imply a certain cultural imagery. I propose the following model for building a theory of frontal lobe function that is consistent with neurobiology and consonant with constructivist theories of cultural influence and plasticity in human development (Table 1). These processes are also likely to be fundamental to higher order thinking in science and mathematics. Hence, some additional information is presented later on how the model pertains to age-relevant curriculum development.

This model assumes that the most fundamental operations of the frontal cortex are fourfold (rows, Table 1) and include those that are least culturally biased (left-hand column, Table 1). That is, the fundamental operations are neurobiologically grounded and provide the biological foundations for subsequent development of cognitive operations that are built upon them. The four basic operations (Table 1, rows) are: 1. Signification/categorization (fundamental sign learning and grouping of experiences into categories); 2. Equivalence operations (judging the equality of two or more entities perceived or recalled); 3. Ordinal relations (ordering entities in space or time); and 4. Proportional relations (making ratio judgment estimates about temporal, spatial, and eventually symbolic representations). Given fundamental physiological requisites for brain information processing, I propose that these four operations are likely to be genetically determined at the most basic level. Analyses of visual information processing indicate that the visual cortex is genetically predisposed to form very basic categorization functions. Perceived objects are signified by color, movement, orientation and form as a normal developmental process for visually competent individuals following birth. This fundamental process of neuronal signification is inherent in the genetically determined wiring of the visual cortex and is sufficiently plastic to allow variations depending on the history of visual experiences during maturation. Competent development of visual categorizing capacity depends on sensory input through visual stimulation. In the absence of visual stimulation, full visual competency may be impaired, sometimes permanently. There is good evidence that other portions of sensory cortex also acquire fundamental categorization capacity forming templates or schemas that parse sensory input into predictable patterns. A variety of fundamental comparator functions are genetically wired in the brain that appear to have equivalence monitoring functions. These
include modules that detect equivalence or lack of it for incoming sensory data from bilateral receptors, e.g., the two ears. Likewise, comparators provide equivalence judgments between “intended motor behaviors” leading to changes in position of the limbs and the feedback signals from proprioceptors in the muscles and joints that provide information on “actual” position of the limbs in space. Such fundamental comparator functions for equivalence of signals can be the genetic foundations of higher cognitive equivalence judgments using symbolic representations (language, etc.). Timing and coordination of basic brain neural activity seems to require some form of temporal monitoring. The time-order of arrival of incoming sensory information needs to be coordinated for perceptual integrity. This suggests the presence of a basic capacity for monitoring ordinal relations among neural signals. That is, perception of time and the sequential coordination of sensory input and motor output patterns suggests that the brain has some fundamental mechanisms for monitoring temporal ordering of events. Finally, nerve signals are based on frequency of discharges of the nerve fiber membrane. A frequency-based signaling system would likely have some very basic genetic mechanisms for judging proportional relations among frequency codes (Cook, 1986); for example, the capacity to detect that the frequency of one arriving signal is twice that of another, thus allowing balanced and proportionate responding to the signal sequences. These comparator functions may be widely distributed in the brain within microscale processing circuits.

Based on individual cognitive development patterns and socio-cultural experiences, these fundamental genetically based operations can be aggregated through learning into “Products” or functions (Table 1, columns) of lower- to higher-order cognitive rank. Lower order functions that are fairly closely related to the four operations are, respectively: 1. Clustering information as in primitive grouping of percepts to make a more manageable load in memory; 2. Establishing identities, as for example to judge whether or not the retinal image of an approaching individual matches our internal memory pattern of a friend; 3. Serial ordering, as in arranging objects by size, and 4. Proportional part reasoning, as for example in deciding that one friend appears to be two-thirds the height of another, or is about as half as friendly as the other (the latter being a more abstract example). These in turn can be aggregated across rows and down the columns to yield higher order functions such as: 1. Concept formation; 2. Target and goal evaluations; 3. Making themes and plans; and 4. Rendering social and procedural judgments of a balanced and proportioned kind. The latter set of four is increasingly more culturally dependent and molded during development to take a form that is most adaptive and functional for successful survival in a given natural and social environment.

By clearly segregating basic (i.e., genetically determined operations) from the cognitive functions derived from them (as shown by the dashed arrows from left- to right-hand columns, Table 1), learning and cultural influences can be formally included in a model of frontal lobe functional development. That is, each social learning environment produces different expressions of the cognitive functions built upon the basic genetic operations. Through maturation and enculturation, the individual constructs adaptively appropriate cognitive functions emerging from the genetically based operations. This emergence can account for differences in cognitive schemas across cultures including: 1. differences in conceptual structures among cultures, 2. varying ways that individuals across cultures order their lives, set goals and judge accomplishment of targeted goals, 3. create themes to represent themselves individually and collectively in social systems and systematize life activities in plans and procedures, and 4. develop balanced and proportioned
patterns of judgment in dealing with phenomena in the natural environment and social situations. Each level, encompasses the preceding levels in an interactive hierarchical arrangement. The fourth level includes some of the most complex and intellectually advanced forms of human behavior within a particular cultural context. Science as a socially mediated inquiry enterprise, likewise, shares these cultural imprints peculiar to its domain-specific activities.

**Application of the Frontal Lobe Functions Model to Science Learning**

What are some implications for science learning? This model implies that during early education, we need to give close attention to how we arrange learning environments to promote effective individualized cognitive development of the most basic four operations. If these four operations are among the most fundamental ones supporting higher products of thinking, then during schooling, our curricula should support student construction of a variety of ways of improving these functions as they become developmentally appropriate. There is increasing neuroscientific evidence that the frontal cortex undergoes continued maturation into late adolescence, including increased nerve myelination (e.g., Fuster, 2002). There are also differentiated rates of progression in the development of higher order modes of information processing including those cited in Table 1, and in higher thinking skills such as controlling variables and hypothetico-deductive reasoning (e.g., Davies & Rose 1999; Kwon & Lawson, 1999, 2000). Additional attention is also warranted in understanding gender differences in male and female students’ information processing. Neuroscientific evidence indicates differences in the rate and kind of frontal lobe nerve maturation between the sexes, including more rapid rate of spatial thinking in male students, but evidence of finer motor skills in females (Perrin, Leonard, Perron, Pike, Piotit, Richer, Veillette, Pausova & Pau, 2009); with thicker nerve fibers (caliber) in males and more myelination (nerve coating) in females. Thus, there may be beneficial gains by mixed gender classes, including due attention to grouping male and female students during social constructivist learning discussion sessions in science, to make maximum benefit of the gender differences in maturational rate and ways of thinking. Although, there are these rather specific gender differences, overall both male and female students exhibit varying degrees of frontal lobe development well into late adolescence, and teachers are advised to engage in communications with students to determine their individual differences in higher order thinking skill development, as well as using essay evidence and laboratory inquiry reports to assess their state of development and individual needs. This should include a more careful analysis of the individual differences in frontal lobe functional development to compose groupings of students with varying developmental abilities to maximize peer group learning, especially to enhance higher order thinking and improve knowledge networking (e.g., Anderson & Contino, 2009). These issues are addressed more fully in the final section of this paper.

Moreover, we need to carefully consider how to embed this learning in a culturally appropriate context to help the learner build higher order thinking skills that are mutually supportive and consistent with the broader cultural (especially increasingly multicultural) and social contexts where the learner will be an active participant. Likewise, in science education, we need to recognize that communities of scientists represent cultures with their particular world views and procedural ways of dealing with sensory experience (e.g., Cobern, 1991). Thus, in addition to our broader cultural environment, science education involves enculturation in particular patterns of higher cognitive functions including...
specialized kinds of categorical and conceptual development, formalized procedures for setting goals and judging adequacy of goal achievement, constructing themes to explain and guide behavior, and using proportional reasoning in formulating plans and judging relations among natural events and our relations with peers in group processes in science. If the matrix of functions in Table 1 is a good approximation to the complex ways higher cognitive functions emerge from basic neurological operations during development, it may be very important to begin activities in science education sufficiently early in schooling to provide maximum growth in the particular thought patterns that characterize scientific communities. That is, entrée into the particular ways of thinking of scientists can be enriched, and the students given early advantage in developing appropriate frontal lobe functions to support these activities, by beginning science education activities at an appropriate level of difficulty early in schooling. Domain specific ways of thinking and reasoning may be embedded within the particular ways individuals learn to use frontal lobe functions within the cultural settings specific to communities of individuals within particular content domains (e.g., natural sciences, arts, music, humanities, etc.). Therefore, we should be giving careful attention to the social and physical characteristics of learning environments to maximize frontal lobe developmental patterns appropriate to the varied social and professional cultural environments where students will eventually need to function as adults.

Long-term Memory and Working Memory in Neurocognitive Perspectives

Finally, given the importance of prior learning in constructivist theories, some elucidation of how long-term memory is established and mobilized in working memory is addressed as further background for the final section where the neurocognitive model is applied to analyze and explain “inquiry learning.” Long-term memory (diagrammed in Figures 4 and 5) is shown as distributed throughout a neural network in the cortex. There is well-established histological evidence that the cortex is a complex network of interlinked neurons. Some nerve extensions interact with nearby neurons forming a local circuit, while others extend long distances to other lobes of the cortex, including for example those in the corpus callosum (Figure 5) that link right and left hemispheres, thus increasing the complexity of circuitry and permitting coordination of many different parts of the brain. More importantly, some of the nerve extensions not only project away from local domains, but also are reflexively linked back to the local output neurons, thus allowing monitoring of both incoming information and feedback signals emerging from a particular locale internally and from the external environment. This merging of incoming and outgoing information allows the brain to be self-monitoring and flexibly relate incoming, new information with existing information. Neuronal networks, favoring both convergence and divergence of information flow, are much more consistent with modern views of constructive learning as opposed to associative learning theories or simple reflex models. As early as 1949 Hebb proposed that learning is a process of modifying the connection strengths among neurons within cortical network assemblies. These networks (local or more extended) act as an assembly to encode experiences. The synaptic connective strength among neurons is the effective parameter producing these stable, event-related micro networks representing experiences. His work has been seminal in modern neurocognitive thought.

Knowledge networks and science learning. Indeed, if the central nervous system is organized as networks, what evidence is there that “ideational networks” in memory are
related to higher forms of learning including knowledge construction of large organizing ideas in a discipline (principles and generalizations), critical thinking and inquiry based learning, and general performance in academic work? A substantial amount of cognitive scientific and conceptual learning theory supports the hypothesis that richness of ideational networks should be correlated with improved classroom performance (Anderson, 1992, 1997, 2009; Lavoie, 1995; West & Pines, 1985). There is some emerging science education evidence to support this hypothesis. Audio recordings of interviews and written narrative can be systematically analyzed for networking of ideas expressed as recursive logical thoughts using a process called “flow mapping” (Anderson 2009; Anderson & Demetrius, 1993; Tsai & Huang, 2002). The information flow and cross referencing of ideation in the student’s narrative is displayed as a network diagram. A network score is obtained by counting the number of cross-linking ideas. Does the network score predict academic performance? To what extent is it correlated with learning about theories, principles and generalizations in a field? Does it predict success in critical thinking and inquiry lessons? Based on a study of urban middle school students, we found the network score for high academic ability students (mean = 7.7 ± s.e. = 0.9) was nearly twofold greater than that of low academic ability students (mean = 4.3 ± s.e. = 0.7) (t = 3.8, p< 0.01). Furthermore, a positive statistically significant relationship was found when network scores of additional students were correlated with performance in critical thinking and inquiry-based laboratory lessons in biology (r = 0.35, p< 0.01) and in the accuracy of their written explanations of biological theory (r = 0.7, p<0.01). Moreover, students with higher network scores learn and apply more principles and generalizations over the course of a unit of study than students who have lower network scores (Bischoff & Anderson, 1998) and exhibit greater understanding of some principles of scientific epistemology (e.g., Tsai, 1998).

Knowledge networks and frontal lobe activity. To what extent is knowledge networking capacity related to frontal lobe activity as implied by executive functions (Figure 5)? During the course of our work on knowledge networks (e.g., Anderson, 2009; Anderson, Mangels & Fuhrman, 2006) we examined to what extent network capacity is related to established neuropsychological tests of frontal lobe organizing activity, i.e., the Wisconsin Card Sorting Test (WCST). We found a statistically significant correlation between science students’ flow map network scores and their WCST scores for conceptual level of responses (r = 0.48, df = 30, p < 0.01) and also the accuracy of sorting the cards into conceptual categories (r = 0.47, df = 30, p < 0.01). Both of these WCST measures are considered evidence of frontal lobe executive operations. To further determine if the flow map scores were related simply to a generalized function of frontal lobe working memory capacity, or as we hypothesized more specifically related to executive functions; the correlation of the students’ flow map scores with short-term memory capacity was examined by administering a letter number sequence memory span test (LNS). The correlation was negligible (r = 0.04, df = 30, p = 0.83), indicating that the flow map networking scores are likely associated with frontal lobe executive activity and not merely a function of working memory capacity. Networks of information are a central component of constructivist theories in explaining knowledge assimilation and accommodation. There is growing neurocognitive and educational research evidence to support the premise that ideational networks enhance knowledge construction and that they are consistent with fundamental organizational features of cortical neuronal circuits (e.g., Anderson, 1997, 2009; Dhindsa & Emran, 2006; Dhindsa & Makrimi-Kasim, 2007; Tsai, 1998).
Evidence for active information processing during recall. Returning to the general model of constructivism (Figs. 3 and 4), to what extent is there evidence that recall of knowledge from memory is an active process of reconstruction as opposed to a simple read-out mechanism? Modern positron emission tomography (PET) analyses of brain activity during active memory recall of experienced events show that the sensory part of the brain initially involved in encoding the experience is activated when the person mobilizes memories of the events. Thus, when a person is actively recalling visual information from memory, regions of the occipital cortex are activated. Likewise, recall of auditory experiences is accompanied by activity in the temporal lobe, if relevant, etc. Thus, memory is distributed throughout the cortex in event-linked portions of the brain where the sensory information is neuronally encoded, initially. How then is it assembled into coherent recall? This problem of binding, or the coordination of various activated sensory regions during memory, is not fully understood. Damasio (1990) for example proposes that there are “convergent zones” in the cortex that coordinate the assemblage of representations. Working memory, now identified at least in part in the frontal cortex, also most assuredly must be involved and probably is supported by activity of executive function centers. In any event, it is clear from inner experience that the distributed memory components are assembled into, what appears to be, a coherent reactivation of prior events. Likewise, during imaginary play, or a re-creation of combinations of events forming novel, imaginary, or creative thought based on experience, we confront again the remarkable capacity of the human brain to reconstruct traces of prior memory in unique ways. From a psychological perspective, creative and imaginary thought based on prior experiences is probably one of the best sources of evidence that memory can be a reconstructive process. We are not limited to a simple redaction of the immediate experiences encoded in memory during recall. This principle is central to constructivist learning theory and brings together neurocognitive science and psychology as sources of supportive evidence. To actively merge new information with existing information during learning and to flexibly monitor thought and action requires such plasticity in recall from memory.

Creativity and science learning in a neurocognitive perspective. There is increasing evidence in science education research, that creativity may be closely linked with plasticity in mobilizing diverse motor and cognitive representations of experience in memory, including a capacity to switch flexibly among a variety of sensory and motor representations of experience when analyzing information (e.g., Brandoni & Anderson, in press). Some current data using neuroimaging methods indicate that creative thoughts and the generation of original ideas are associated with synchronization of activity in frontal brain regions accompanied by a diffuse and widespread pattern of synchronization over parietal cortical regions (e.g., Fink, et al., 2009). Such synchronized widespread activity may potentiate efficient transitions across different representational modalities and mediate plasticity in mobilizing rich and varied forms of cognitive representations during a creative task. In this neurocognitive perspective on creativity, the data of Brandoni and Anderson merged with that of Fink, et al. suggest that creativity may involve mobilization and seamless transitioning among major representational and action centers of the brain. Thus, for example, the several frames of mind proposed by Gardner (1985) as instances of multiple intelligences, may become seamlessly integrated in the highest forms of creative thinking, especially those that promote major innovations in science. Hence, students should be encouraged to mobilize and integrate various forms of cognitive representations (e.g.,
Visual, psychomotor, semantic, logical, and quantitative, and perhaps even musical, etc.) during inquiry learning experiences to promote more creative scientific thinking.

Summary Perspective: Application of the Neurocognitive Model to Analyze Inquiry-based Science Learning

Action-reaction Loops in Brain Functioning
One of the fundamental principles of brain function portrayed in the neurocognitive model (Figure 3) is that the brain actively constructs representations of experience at various levels through integrated “action-reaction loop” mechanisms. These include all of the many ways that the brain engages in internal activation and self regulation (indicated by double-headed arrows between modules in the model) in addition to sensory feedback mechanisms linking our external actions to sensory feedback (shown by a recursive arrow linking output to sensory input). Thus, the brain continuously engages in constructive activity, either internally initiating interactions among functional modules to self regulate and initiate new internal states, or by mobilizing internal representations to actively perceive and incorporate incoming sensory experiences into existing systems of logic and knowledge networks.

The inquiry cycle of Suchman (1966), verification cycle of Margenau (1959), and the modern science inquiry learning cycle are all examples of a generalized or derived “action-reaction” loop built upon the more fine-scale, neuronal action-reaction loops mediating nervous system function. That is, “the intake of sensory information” that initiates each of these cycles occurs by active scanning of the environment through dynamic attentional and perceptual processes of the central nervous system (an action) resulting in the construction of interpretations or explanations structured by mobilization of knowledge networks in working memory (reaction). These constructed interpretations may result in further dynamic sensory information processing through redirected attention or manipulative responses (actions) leading to further information intake and processing (reaction), etc. This more generalized action-reaction loop of information processing is diagrammed in Figure 3 by the output arrow (right-hand side of the model) recursively linking back to the sensory input (left-hand side of the model) leading to internal information processing modules (working memory, long-term memory, etc.). Additional detailed applications of this generalized model are presented below.

Brain Functional Modules and Their Integrated Activity During Science Learning
While the entire brain acts as a coordinated information processing unit, variations in activity occur within and among functional modules. The frontal lobe complex, through executive and working memory functions, subserves much of the dynamic activities of mobilizing prior conceptions from long term memory during knowledge construction and reconstruction. This includes declarative as well as procedural knowledge (mobilized in different brain regions), embracing respectively what we know and can declare, and what we know how to do, e.g., in gaining and evaluating information. The conceptual field (C field) of Margenau (1959) and the mediation mechanism proposed by Suchman (1966), that organizes information from memory in relation to incoming sensory experiences, represent executive controls and working memory functions situated in the frontal lobes. The subcerebral limbic system, mediating motivation and arousal, is closely linked by extensive nerve fibers to the frontal lobe and thus provides emotional tone for executive functions (Damasio, 1998). During the inquiry learning cycle, the engagement phase includes
experiences that are intended to orient the student to the inquiry task and encourage motivation, a process at least partially attributable to interactions between frontal lobe and limbic systems. Because the limbic system is sub-cerebral and more likely to establish conditioned reaction patterns (Crosson, 1992; Petri & Mishkin, 1994) affecting mood and memory, it is important to maintain a positive and supportive tone during phases of the inquiry cycle. More particularly students should be challenged, but it is important to carefully regulate excessive demands. These may lead to negative affect that could excessively generalize to inquiry learning in general (e.g., Anderson, 1992, 1997).

The role of attention and perception during inquiry learning. The way incoming sensory information is selectively attended to and interpreted depends to a great extent on the prior representations that are mobilized, including cultural perspectives and the learned organizing perspectives gained from personal experience and formal instruction. These organizing perspectives have profound affects on what we attend to and how we actively construct perceptions of sensory input (e.g., Eger, et al., 2007; Laberge, 1995). As an example, assume that a student is challenged with an inquiry situation where a burning candle is presented within an apparatus and is asked to explain what is happening (for examples see: Birk & Lawson, 1999; Tai, 2009). We will purposefully leave the details vague to simulate the student’s initial ambiguous state. If the student recalls that burning is a chemical reaction, she/he (S/he) may attend to the flame and reason about the likely reactants and products, perhaps ignoring the larger apparatus containing the candle. Or, if the student mobilizes a conceptual model that the system is being driven by the heat of the candle, S/he may mobilize the gas law (PV = nRT) to provide an interpretive framework to guide analyses. In this case, attention may be directed to the totality of the apparatus to reason where and how the heat is making an effect, especially on pressure or volume. Finally alternatively, if S/he recognizes heat production, but assumes the situation involves convection processes, then attention may be directed to the flow of gases including the flow of any soot particles in smoke within the apparatus. Further cognitive processing, that involves perception and knowledge integration, will be largely affected by the structure of the knowledge networks in memory (e.g., Anderson, 2009; Linsker, 1990). For example, if the student attends to the candle and interprets it as a problem in combustion, then S/he may mobilize information from memory related to combustion. If the knowledge network is limited to a few conceptions such as combustion involves taking up oxygen and releasing carbon dioxide while heat is emitted, this may seriously limit the problem solving accuracy; particularly, if the problem requires recognizing that the candle contains wax, a hydrocarbon, and burning hydrocarbons produce water vapor as well as carbon dioxide as products.

We know that there are frontal lobe fiber projections to the sensory regions of the brain (sight, sound, touch, etc.) and these projections can affect the information flow and analysis within deeper layers of the sensory cortex, either delimiting the attentional field or making it more expansive. Moreover, the information mobilized as networked knowledge is critical in determining what conceptual information is activated in the anterior pole of the temporal lobe and incorporated into working memory. We have evidence that the richer and more extensive the knowledge network, the more adept students are at integrating activated conceptual knowledge into verbal expressions (e.g., Anderson, 2009) a function that is mediated by a region of the brain where the posterior part of the temporal lobe joins the parietal lobe (usually on the brain’s left side). This is also at a nexus with the visual cortex.
(occipital lobe) and represents a structural and functional region mediating linkage of spatial, visual, and verbal information processing (Figure 5). Consequently, there is a rich potential for students to integrate multimodal representations when proper opportunity and encouragement is provided. Hence, during information gathering, it is wise for the teacher as mediator to encourage students to think broadly and mobilize a range of explanatory conceptions early on in the process to determine which ones may be most productive for the initial given conditions of the problem. Clearly, the kind of knowledge networks mobilized also influence the kind of information that is brought to bear in reasoning about a given problem as well as the suite of reasoning skills that are used to address a problem.

**Knowledge networking and frontal lobe executive functions.** The amount of information, and the extent of its networking, can also influence the effectiveness of frontal lobe executive functions in solving inquiry tasks (e.g., Anderson, 2009; Anderson, Randle & Covotsos, 2001; Rolls, 1998). This mediating function as Suchman (1966) described it, encompasses a broad range of frontal lobe functions and, depending on the age level of the student, may involve a range of information processing strategies such as those in Table 1, as well as formal logical reasoning algorithms. The complexity of the task should be adjusted to challenge the students within their developmental level of ability, and as recommended earlier, to use social constructivist (group discussion) strategies to encourage as much diversity in information processing as possible. Current neurobiological and cognitive evidence for individual differences in frontal lobe maturation, extending into adolescence, should be kept in mind to adjust the demands of the learning situation to challenge students, but not to exceed their developmental level. There is good evidence that appropriate teacher mediation can enhance students’ progress in making transitions from less formal into more formal ways of thinking (e.g., Lawson & Wollman, 1976; Withers, 1981). However, the teaching strategies must be deliberate; for example, by carefully analyzing the students’ current level of thinking and conceptualization and appropriately using challenging and encouraging questions and suggestions to motivate the student to use more formal ways of thought. However, in this process, we need to remember that working memory is limited in capacity, and tasks with extensive demands for higher order thinking and use of extensive abstract knowledge may exceed the students’ capacity, leading to cognitive strain. Appropriate teacher guidance in mobilizing relevant knowledge networks and scaffolding of relevant logical ways of thinking can reduce some of the excessive demands on working memory capacity within the frontal lobe.

**Scientific reasoning and frontal lobe activity.** In the learning cycle approach, the application and evaluation phases may involve predictions that can be tested. In its most sophisticated form, this may involve theory-based, hypothetico-deductive reasoning, where the students extend existing knowledge networks to make predictions to be tested (Lavoie, 1999). Lawson (2006) has cogently argued that the brain is fundamentally organized to function in a hypothetico-deductive way and has nicely demonstrated how formal logical reasoning can be explained by some current neurobiological evidence (e.g., Grossberg, 1982). However, these higher order functions may also be a more generalized and highly integrated expression of some of the more fundamental processes of the brain “action-reaction loops,” including basic pattern matching (e.g., Coward, 1990) and feedback control algorithms that also sustain self regulation in the brain. Nonetheless, the inclusion of hypothetico-deductive reasoning during inquiry learning, especially during application and evaluation phases,
should be a significant goal of inquiry learning. Lawson (2006) has recommended some strategic questions that teachers can use to stimulate students’ development of “if-then” type reasoning that is characteristic of hypothetico-deductive thinking. For example: “What did you observe? What questions are raised? What are some possible answers/explanations? How could these possibilities (alternative hypotheses) be tested? What does each hypothesis and planned test lead you to expect to find? What are your results? How do your results compare with your predictions? What conclusions if any can be drawn?”. Students should be encouraged to develop these more formal ways of information processing as mental models that can be mobilized during scientific experimentation and reasoning (e.g., Duschl, 1990). This process is nicely exemplified in the Margenau model as the “Circuit of verification.” Eventually, as assumed in the learning cycle model, stating hypotheses and evaluating them should involve active construction of procedural knowledge networks that can be mobilized within the appropriate declarative knowledge frameworks to solve new scientific problems, thus completing the inquiry loop – leading to new explorations of the environment. In all of these information processing steps, it is important to recognize the role of feedback; that is helping students to reflect on their internal representations and ways of thinking (metacognition, a frontal lobe function) as well as to use multiple sensory inputs to more clearly refine their problem solving.

Inquiry learning cycle phases and frontal lobe cognitive functions. To be most productive in developing inquiry cycle learning and hypothesis testing, teachers are encouraged to think carefully about the developmental level of the students relative to the dimensions in Table 1. For example, if a student is having difficulty expressing a coherent statement of what s/he has observed, then s/he may need assistance in improving capacities for the operations in rows 1 and 2 of the table. For example, by discussing the student’s understanding of what s/he is observing and asking what information they have observed in terms of the particular aspects, and what ways can they group that information into categories, the teacher may get evidence if the student has conceptual formation capacity. If the student cannot explain grouping or clustering of basic observational data, this is where the teacher needs to begin by providing guidance in categorizing and grouping. Then, by building up on this basic categorization, conceptual information can be developed. That is, by asking the students to think about what is the more general category that this clustered group represents in terms of what they have previously read or learned, etc., the students can be encouraged by a series of successive approximations to move from basic categorizing to larger clustering, to finally making abstract designations of what the clustered data represent. It is very important to realize that some students may still be at a stage where they cannot rationally identify basic units of information and assemble them into categories; so that is where assistance should be directed first. Data gathering also may involve making identities, that is judging what aspects of observables are similar or different. This fundamental skill needs to be considered, as a starting point. If the student is capable of making judgments of identities, then it is possible to encourage further development toward making judgments about perceptual targets, that is what has been observed and what is the purpose in observing – or more specifically what is the purpose in observing toward perceiving scientifically relevant information? In other words, encourage the students to state why they are observing phenomena and what information they hope to extract from their observations? Eventually, the student should be able to state a goal for the observation, such as a goal of making an explanation of what was observed, and at a more advanced level stating an hypothesis based
on what was explained. The final two rows in Table 1 are most pertinent to the stages of testing hypotheses and making judgments about the accuracy of hypothesis. For example, to plan a way of testing an hypothesis, students need basically to be able to serially order the objectives or tasks that they want to do in relation to their prior stated explanations, goals and hypotheses. If a student lacks skill in logically ordering fundamental steps in doing a task, this is where the teacher must begin first; namely, to encourage individuals and groups of students to begin stating what are the things that they want to do and in what order. Based on this fundamental skill, they can be invited to think how their ordered tasks can be developed into a plan or how they can state a theme for what they are trying to do. Finally, many significant scientific analyses require the ability to do proportional reasoning (row 4, Table 1), another verified function of the frontal lobe. At the most fundamental level, students need to be able to make judgments of relationships among observables, such as relative size, relative mass, relative numerical values and in such a way to state what proportion or percent of similarity exists. Likewise, this includes assessing how things vary with one another or correlate with one another. If some observables (e.g., variables) change, then how much and in what direction does one or more other related observables change? Is there a positive or negative correlation of relations? To what degree do two or more observables (variables) correlate with one another? Finally, this may lead to making judgments about larger scale issues, such as how much time relatively should be appointed for one part of an experiment versus another, and what relative emphasis should be given to different kinds of results from an experiment, how should the roles and time commitment of different members of a group be apportioned to complete an experiment, etc.? In general, many of these cognitive functions are involved more broadly in science inquiry, including project-based learning, where students are encouraged to develop more long-term projects using scientific thinking (e.g., Krajick & Blumenfeld, 2006; Krajick & Mamlok-Naaman, in press; Rivet & Krajick, 2004). Likewise, during these thinking tasks, this provides an excellent opportunity to encourage students to mobilize knowledge networks and to more consistently think in logically linked ideas, rather than uttering short explanations or a stream of less connected discourse. By particularly asking students to think about how their current thoughts are related to earlier thoughts using dialogue and “multilogue” (group discussions), teachers may enhance the logical networking capacity of students leading to improved scientific thinking (e.g., Anderson, 2009).

A word about creativity, multi-modal representations and inquiry learning. Given the evidence that divergent/creative science thinking may involve flexible and relatively seamless transitions among varied sensory and motor representations of immediately perceived and also of recalled experience (e.g., Brandoi & Anderson, in press; Fink, et al., 2009), students should be provided with challenging learning environments that encourage the use of divergent modes of thinking and expressing information, including so-called “hands-on, minds-on” problem tasks that provide ample opportunity for students to use multi-modal explorative and explanatory ways of thinking. As best we can determine currently, students should be encouraged to make dynamic and transitive interpretations of phenomena using multiple modalities in as simultaneous a manner as possible. That is, in addition to serially ordered use of varied modalities to represent phenomena and recalled experience, students should be encouraged to explain the interrelatedness of their various representations and how one form of representation can be transformed into another. Presently, there appears to be only limited research on multi-modal integration of
interpretations in science learning, and more research is warranted in this potentially seminal field. It is increasingly clear that the brain, though modularized to serve certain functions, operates in a holistic way when processing complex information, especially in highly creative expressions. The more students are encouraged to mobilize and integrate information processing across a wide range of sensory and motor representations, the more likely they may construct enhanced knowledge networks, that are more stable, readily accessed during recall through multiple routes of accessing information nodes, and more likely to yield creative insights.

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