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The Implications of Neurological Models of Memory for Learning and Teaching

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Introduction

The ability to hold and collate information is critical to fundamental brain activities such as abstract thought, language, planning and, above all, to learning. The slow process of unraveling neurological links between brain areas involved in cognition has delayed an understanding of how learning actually takes place which goes beyond the working models of memory we use to optimize teaching. However, the advent of sophisticated techniques to image live nerves has led to ground-breaking revelations in the understanding of neurological processing of information to the point where the molecular detail of brain function can now inform educational practice. The latest neurological research provides real insight into the process of learning and could provide the means for significant enhancement of teaching and learning.

Memory Models

In the absence of detailed physiological information, models of information processing were generated by psychologists to, amongst other things, allow an evaluation of the efficacy of teaching methods. The first recognized modern theory of memory borrowed Hebb's (1949) separation of primary and secondary memory visualizing information as a linear "memory stream" to long-term storage, where 'rehearsal' is the process that leads to information retention (Figure 1, Atkinson and Shriffin, 1968). Unprocessed information was seen to last ~30 seconds, but once it enters into long-term store it becomes fairly permanent.

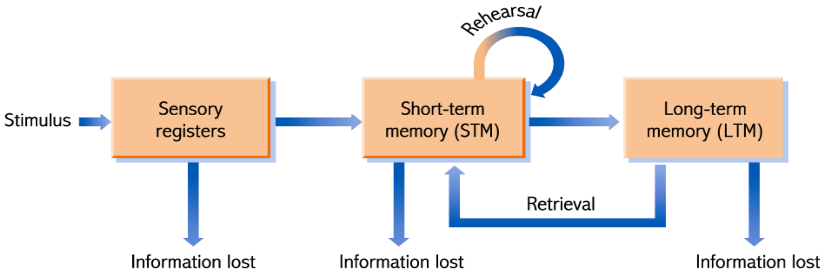

Figure 1: Multi-Store Model Of Memory Function. Information in Short Term Memory is lost in 15-30 seconds unless transferred to Long Term Memory by rehearsal. (Atkinson and Shiffrin, 1968).

It soon became evident that learning was not a linear process when executive influences on learning such as attention and motivation were identified (Gagne, 1965), and abstract and semantic analysis of information came to be distinguished. Moreover, processing and revision of knowledge were shown to be continuous and an integral part of the process of information assimilation that enables retention (Craig and Lockhart, 1972). Evidence from medical patients such as 'HM', for example, who, after surgical resection of the right medial temporal lobe for epilepsy, could not create **new** long-term memories but could **recall** normally, demonstrated that encoding and retrieval of long-term information are distinct systems.

Further exploration also demonstrated other forms/processes of 'memory' such as 'declarative', 'episodic' and 'procedural' memory in which events are analyzed according to intrinsic, experiential or technical associations (Tulving, 1972). These could not be accommodated in early models of information processing until Baddeley and Hitch (1974) proposed a three-component working memory (Figure 2) comprising a control system of limited attention capacity (termed 'the central executive') assisted by two subsidiary storage systems, the 'phonological loop' for sound and language and the 'visuospatial sketchpad', which cooperate in cognitive skills such as language comprehension and deductive reasoning.

This working memory model has since flourished, supported by anatomical studies and imaging of cerebral blood flow which clearly shows simultaneous activation in right-hemisphere prefrontal, occipital, parietal and premotor cortices accompanying the use of spatial working memory. The simplicity of the model has enabled the continued development of modeling of learning and memory functions by approximating these complex cortical interactions.

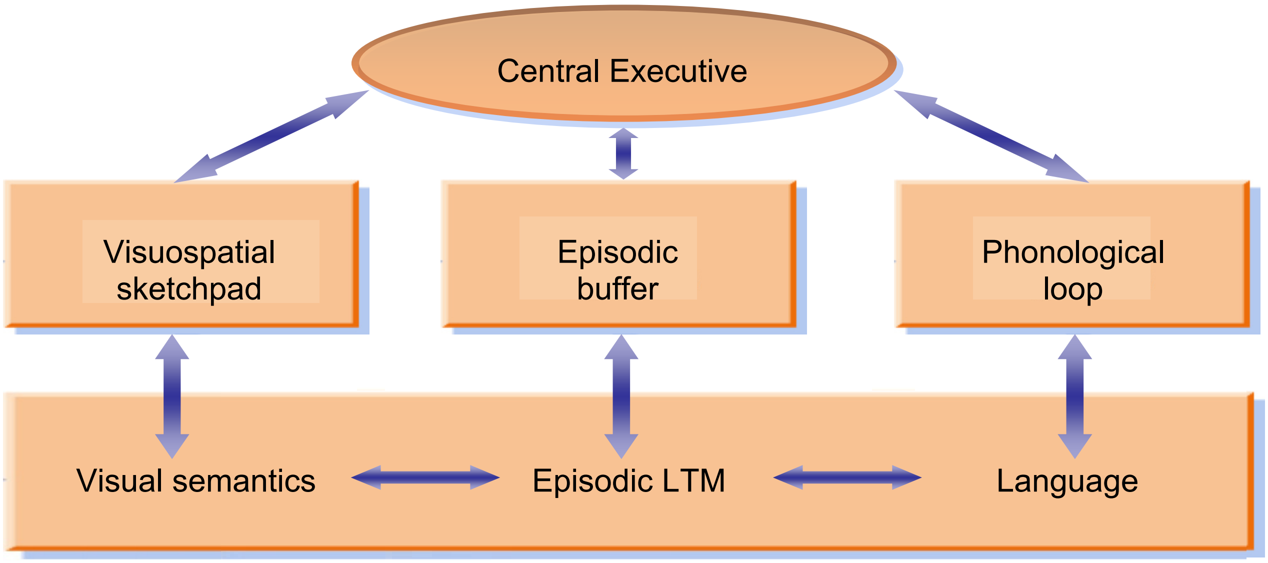

Figure 2: Multicomponent Model of Working Memory. The central executive controls attention while the episodic buffer integrates information from the phonological loop and visuospatial sketch pad (Baddeley and Hitch, 1974).

Neurological Research
The working brain – a short detour

Brain neurons are different from motor and sensory nerves, as they have greater density, more branches or dendrites and vast numbers of synapses when compared with other neurons. Adaptive pressures in 4 billion years of human history; climate change, upright bipedal movement, tool usage, forsaking forest for open grassland, communal living, socialization and urbanization have all contributed to the generation of a convoluted brain structure that coordinates multiple inputs from diverse sensory and interpretive sites, thus making it spectacularly good at inferring patterns from information and 'learning'. In this way, the adaptive success of man is related to the evolution of distinct neurological areas which process sound, visual and other sensory information separately in a large cortical network in a domed skull. The expansion in brain mass and the folds and convolutions of the cortex, generating space for neural connections - operating in much the same way as the intestinal villi and microvilli do to increase adsorptive surface - has been the escape route from the primordial jungle.

The superior processing capability of a human brain is related to the vast number of connections, forming an immense neural network between brain cells. The number of connections is truly astronomical, with over a billion-million nerves in the average human brain where one trillion neural links, called synapses, may fit into a thimble. Each nerve is connected to thousands of other neurones by synapses on an array of dendritic spines (Figure 3A). It is the intricacy of these connections between areas of different specialty that adds another dimension to the processing capacity of brain. The simultaneous contact with different areas of grey matter enables sensory stimuli to be received and referenced with prior information, processed with other collaborative details, stored with any manner of different sources, and retrieved instantaneous or at leisure with all sorts of perceptive associations that emerge as thoughts, ideas, conjectures, analyses and conclusions. Moreover, recent research has shown that individual nerves and the formation of the neural network is shaped by personal experience, growing and adapting to repetition and the strength of stimuli.

Brain, behavior and learning

The advent of non-invasive imaging techniques such as PET and functional magnetic resonance imaging (fMRI), which can follow single nerve impulses in live tissue, confirmed the duration of short-term memory and the position of areas of brain involved (Jonides *et al.*, 1993). Whereas spatial and visual information are represented in brain in parametric fashion, primary visual cortex organization relating directly to the retina, input to memory and learning are assembled in a complex network of interconnected cortical and subcortical areas (see Figure 3B; Squire, 2004). Perceptions such as object identity, face recognition, intuition, are not organized in precise physical locations in the brain but are built up by neural relay. Nerves involved in word recognition or auditory processing vary in different individuals as they are built into the neural net through individual experience (Newberg and Alavi, 2003). This data supplies great credence to the long-held adage of learning theory that students learn in individual ways. According to Kolb's Experiential Learning Theory (Kolb, 1984), there are two ways of 'grasping' experience (Concrete Experience and Abstract Conceptualization) and two ways in which we transform experience, (Reflective Observation and Active Experimentation) – and all four functions are engaged in learning. The observed tendency of individuals to favour particular ways of grasping and transforming make sense in light of individual brain development and variation in the neural net connections.

It is frequently stated in physiology textbooks that brain growth stops at birth and brain cell death occurs progressively thoughout life. Research has shown that neurons are not fixed but continue to grow in density, gray matter and neural connections. Less-used neurons are eliminated but the remaining neurons become thicker, have greater myelin sheathing, thus becoming more efficient and able to operate more rapidly (Giedd *et al.*, 1999). The somatosensory cortex, for example, is increased in newly blind people who master Braille, and violin players who practice regularly, increase the parietal lobe of the brain which is associated with sensation in the fingers of the left hand (Sowell *et al.*, 2003). Gray matter thickens by the branching of neurons and formation of synaptic connections and is accompanied by condensing of the brain's white matter as the fatty myelin sheaths that insulate the axons carrying information increase, making signal transmission faster and more efficient.

The plasticity of the brain allows reshaping and reorganization, generating a lifelong increase in the supporting cells and in the connections responsible for communication between the neurons (Geidd *et al.*, 2004) that are fundamental to learning and memory. Additionally, large numbers of new neurons are generated throughout adulthood in what is known as the hippocampal dentate gyrus (DG) (Eriksson *et al.,* 1998). The DG is located inside the medial temporal lobe, beneath the cortical surface (Figure 3B), where new nerves are functionally integrated into pre-existing neuronal circuits and conduct learning and memory functions (Zhao, Deng and Gage, 2008). The survival of new neurons is dependent on high-frequency stimulation with long-term potentiation (LTP) being especially influential in the survival of newly formed neurons. This is of enormous importance for how individuals learn and, perhaps for approaches to teaching.

A critical level of stimulation is reached in a neural grid that allows the continuation of a single nerve impulse, normally lasting a few milliseconds, for minutes to months via a mechanism that requires prolonged gene expression and protein synthesis (Kelleher *et al.*, 2004). Enhanced nerve stimulation is governed by associativity and cooperativity (Cooke and Bliss, 2006), in which phosphokinase A activation and calcium influx induce synapse tranactivators (Kovaks *et al.*, 2007) which additive potentiate all the nerves in the net. The extended electrical pulse, reverberating through the neural net between areas of specialist information in an ongoing interpretive process, is called long-term potentiation (LTP; Bliss and Lomo, 1973) and so closely equates with our concept of cognition that it is thought to be cellular basis of learning. The associative nature of LTP induction certainly accounts for the benefit of associated facts in learning theory. Chunking of information (Miller, 1956), a strategy for making more efficient use of memory by recoding information, and Patterning (Rickard, Varfaellie and Grafman, 2006), linking similar information to aid memorization, are both means relying on the connections of a neural net between areas of brain processing capacity, setting off LTP. Multiple association of ideas is an old strategy that triggers a threshold in a brain neural net to download a much greater assemblage of facts than the initial stimulus.

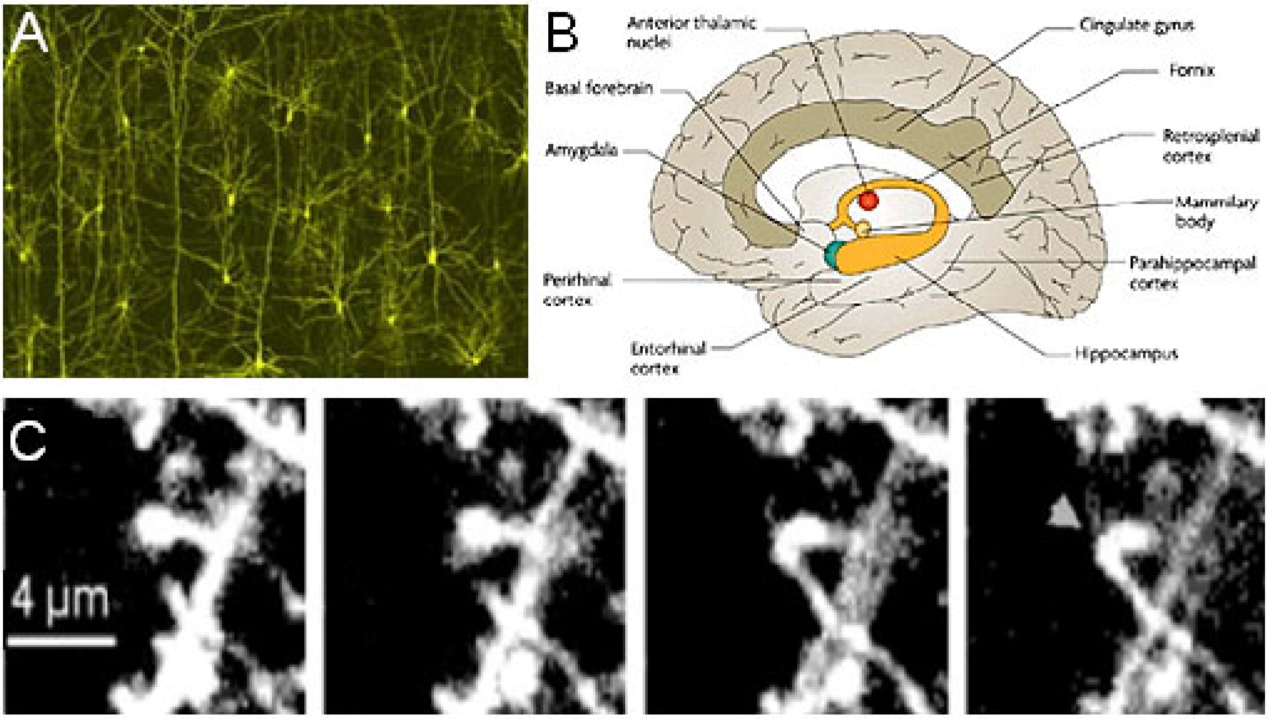

Figure 3: (above) Cellular Mechanisms Of Learning And Memory. A: Electrical signal reverberating in a circuit connecting thousands of neurones reinforces structure and forms new synapses. B: Sensory input from brain cortex is linked with processing areas including hippocampus, parahippocampal and perirhinal cortices and amyglia in midbrain to create thinking and learning. C: contact between an emerging filopodium on a dendritic segment and an axon in LTP makes a new connection (Lendvai et al., 2000).

Most novel brain synapses occur on small dendritic appendages called spines, preceded in development by spiny, actin-rich protrusions called filopodia. In the cerebral cortex dendritic filopodia, sprouting in response to LTP, are highly motile and appear to actively search for contact with axons, leading to synapse formation (Figure 3C; Ziv and Smith, 1996). The latest live imaging techniques, such as two proton microscopy which delivers high resolution images of the calcium ions that trigger synaptic biochemical events (Lee *et al.*, 2009), have shown that spines and filopodia alter within minutes, within the time frame to provide a practical explanation of the dynamics of learning. Additionally, measurements of synapse turnover suggest that sensory experience drives the formation and elimination of synapses and that these changes might underlie adaptive remodelling of neural circuits (Trachtenberg *et al.,* 2002). The correlation between LTP induced intraspine calcium and reorganization of postsynaptic densities on the neurone surface making spine remodeling an attractive structural mechanism underlying learning and memory (Kasai *et al.*, 2003). The capacity to form new connections, to expand and incorporate additional information in a vital, plastic neural net, is what allows us all, teachers and students alike, to become life-long learners (Candy, 1991).

The Biological Principles Of Teaching To Enhance Learning

The fact that brain neurons are pliable has tremendous import for teaching and learning. The lesson from the neurological arrangement of brain, that information needs to be linked to an existing framework in order to be preserved, rather than rely on repetition or processing to advance material to a more durable store beyond short-term memory (McKeachie, 1987), has great significance for teaching. The more ways that classroom material is introduced and reviewed, the more sensory inputs and ideas are associated, the more synaptic interneural connections will be created. The pathways will become stronger, building axons and the insulating covering to make faster and more efficient connection that survive longer with association and use. The association of multiple facets of data in a series of neural connections such that a single sensory trigger can unravel the entire network of associated facts makes biological sense of the long held belief that engaging students via multimedia teaching leads to better retention. Multiple teaching strategies including oral communication, writing, metaphor, reiteration, interactive activities, humour, music that independently benefits learning enhances information retention through the pedagogic principle of extra information processing (Gopnick *et al.*, 1999) and the physiological engendering of neural structures (such as spines and filapodia).

One's socio-cultural environment also affects learning (Vygotsky, 1978), our natural instinct being to make sense of new situations or knowledge with reference to past experience - relating to the personalized neural net in each individual. Learning, according to Vygotsky, involves the transformation of external experience into internal processes through person perspective and cultural interpretation. Knowledge is constructed according to a student's perspective and personal beliefs and educators must promote lifelong learning values in their students by indicating social and cultural values in their teaching (Taylor, Marienau and Fiddler, 2000).

Short-term and working memories keep data for some 20 minutes, a time-frame in accordance with filopodia stimulation. The challenge facing teachers is to move that information into developing neural connections within that time frame by helping students to recognize patterns, make links and stratifying facts to simplify addition to the physical form of individual neuron networks. Long-term potentiation (effectiveness) of a neural net is dependent on a critical level of associations so that features that reinforce material such as sign-posting slides, talk outlines, learning objectives, reiteration, section summaries, links and conclusions are all liable to build to LTP and create permanent learning. The biological modification of brain over millennia of adaptive evolution to change, stress and danger, means that learning is best achieved through interactive methods such as hands on activities and group work (Kolb, 1984) that bring together several strands of sensory perception for cooperative neuronal activation. With repeated use, activated protein chemical transmitters strengthen and reinforce permanent neuronal circuits making informational links more accessible and faster. This has an effect such that engaging in the process of learning actually increases one's capacity to learn.

It is clear that many of principles of teaching are derived from the older learning theories, developed from psychological investigation in the later half of the last century. For example, the benefits observably derived from variation in media for presentation of information and simply connecting new information to what students know, can now be seen to have an underlying biological basis. If teachers set out to reinforce and extend the informational neural connections of students they can, using biological principles, literally change their students' brains.

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Biographical Note

Tim Scott-Taylor is a Senior Lecturer in Biomedical Sciences at the School of Human Sciences. I have a research programme in allergy and in the immunotherapeutic uses of dendritic cells. I am interested in the better delivery of practical biology and am currently developing a Weblearn site for the e-learning of scientific reporting and laboratory science.