What can neuroscience teach us about teaching?

Professor William T. O'Connor
http://williamoconnor.wordpress.com/

Chair, Head of Teaching and Research in Physiology
Graduate Entry Medical School
University of Limerick
Limerick, Ireland

International Conference on Engaging Pedagogy 2010 (ICEP10) National University of Ireland Maynooth, September 2, 2010

Abstract

The study of perception, learning, memory and recall are converging to unite education with neuroscience - the scientific study of the nervous system- around the emerging field of neuroeducation. In this regard, there has been a plethora of scientific findings of educational relevance (such as plasticity, imitation, attention and the role of factors such as exercise, sleep and stress). Recent brain research shows that different circuits are called upon in the brain for different activities such as math, music and reading. In addition, learning and practicing particular skills can cause corresponding areas in the brain to grow or change by adding a tiny fraction of the brain's neural circuitry and eliminating old ones. Imaging technologies are helping map the circuits and study variability among children with learning difficulties. Moreover, recent research is providing insight into attention systems in the brain and is shedding light on how we plan, initiate, organize, and most importantly, inhibit certain behaviours. This paper contributes to this dialogue by summarising what we already know about the learning process in the brain and suggests how it might inform the teaching/learning process in the classroom.

Keywords Neuroeducation, Neurodevelopment, Neuroplasticity, Teaching, Learning, Dyslexia, ADHD.

1. Introduction

Homo sapiens is the only species that has developed formal ways to enhance learning: teachers, schools and curricula. New insights from many different fields are converging to create a new *science* of learning that may transform educational practice. These fields include developmental psychology which has identified social factors that are essential for learning, machine learning algorithms allowing robots and computers to learn autonomously, neuroscientists who have found brain systems involved in social interactions and mechanisms for synaptic plasticity that contribute to learning and classrooms which are laboratories for discovering effective teaching practice.

Neuroscientists describe the brain as an active ever changing organ that both senses and acts upon the environment. There is no dichotomy between early educational activities and free play. In the first three years of life, free play *is* an educational activity. Driven by their own natural curiosity infants solve problems for the pure joy of learning about the physical and social world. But while the ability to learn is in part genetically programmed in that it provides the basic neuronal wiring pattern – the environment acting *via* the flow of information from the sense organs largely determines what is to be learnt and what talents are to be developed. In addition, brain research demonstrates that the adaptability of the mature brain is greater than a prevailing current view suggests. In fact, brain plasticity remains throughout life. We are all aware that as adults we remember new experiences every day, so at least parts of our brain remain adaptable throughout life. Theories of how memory is laid down and knowledge retrieved for later use is helping to inform students in their learning. As recently as the 1950's, neuroscientists believed that memory is a single albeit highly versatile function. Since then experiments have revealed that there are many types of memory, each underpinned by its own region of the brain.

Curiosity, interest, joy and motivation are the basic ingredients in teaching and learning however neuroeducation and its study of how the brain perceives, learns and remembers has implications for life long learning and will add a new dimension to educational theory and practice.

2. Brain Structure and Function

The study of the brain dates to ancient Egypt with manuscripts dating back to 17,000BC indicating that the Egyptians had some knowledge about symptoms of brain damage. The scientific study of the brain underwent a significant increase in the second half of the twentieth century. It has now become possible to understand, in much detail, the complex processes occurring within a single nerve cell or neuron (Fig. 1). However, how networks of neurons produce intellectual behaviour, cognition, emotion and physiological responses is still poorly understood. The task of neuroscience is to explain behaviour in terms of the activities of the brain. How does the brain marshal its millions of individual neurons to learn and remember and how are these cells influenced by the environment?

The Brain's Vital Statistics

- The average human brain weight about 3lbs (1.2kgs) and is the size of a medium sized cauliflower.
- Twenty per cent of an individual's energy is dedicated to maintaining a brain that is only 2% of the average bodily weight.
- The human brain contains more than 100 billion nerve cells or neurons; each neuron is like an individual creature in its own right, working according to communicating connective impulses employing both electrical charges and chemical messengers.
- There are 100 billion neurons in the average brain - the same number of stars in the known universe, so we each contain a mini-universe of communicating neurons in our heads.
- Neurons are *social* and make an average of 10,000 connections or synapses.
- There are about 100 trillion synapses in the average brain.
- It is an interesting number as there are also about 100 trillion atoms in a single cell, and coincidentally there are about 100 trillion cells in a human body.

Information Processing in the Brain

The brain is full of electrical energy even when asleep. Electrical impulses (action potentials) flow along the nerve axons toward the terminals. These impulses carry coded information the nature of which is still poorly understood. When impulses reach the terminal, chemicals called neurotransmitters are released and they travel across the gap (*synapse)* between two neighbouring neurons to bind to their receptors and new impulses are generated in the neighbouring neuron. In this way information travels from neuron to neuron. The electricity produced by the 100 billion neurons in one person's brain is only enough to power a 20 Watt bulb.

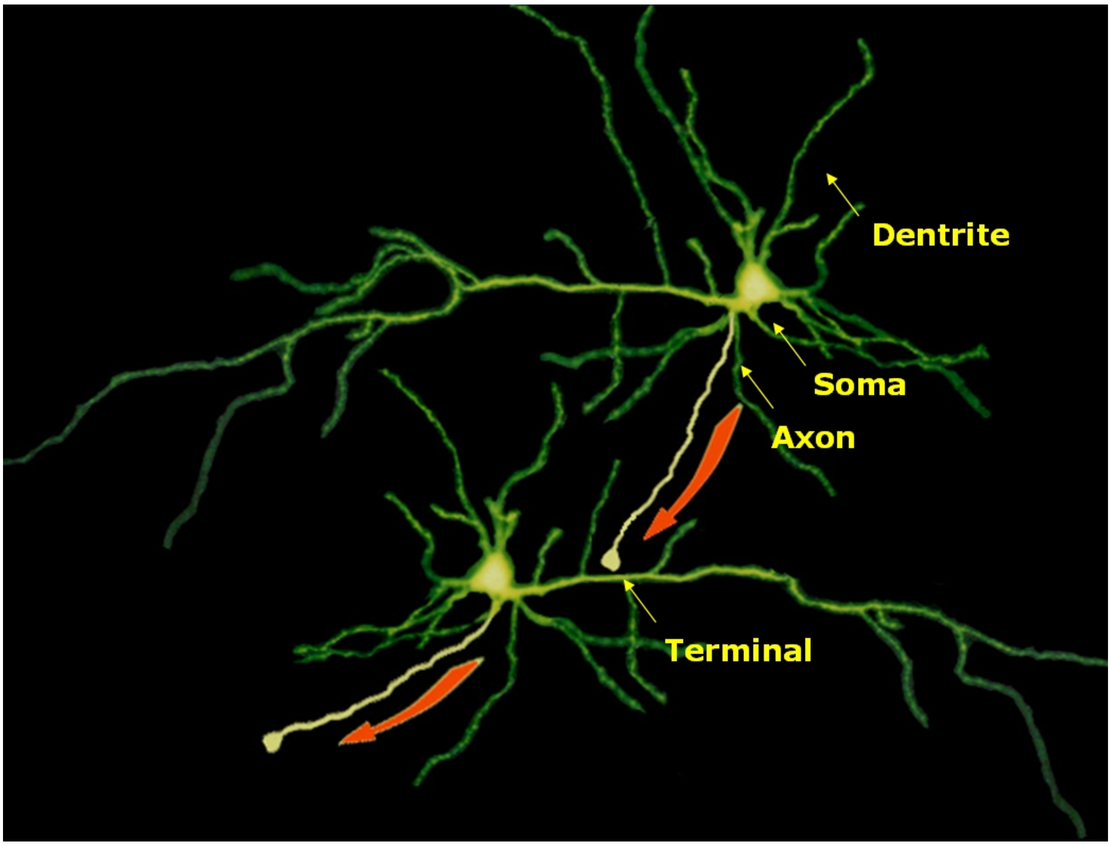

Figure 1. Image showing real neurons from the human brain. They have been filled with a fluorescent dye and viewed through a microscope. The width across an average neuron is the same as the width across the tip of a ball point pen. The anatomy of a neuron includes the cell body (soma), dendrites and axon (yellow arrows). At the end of the axon is the terminal, which makes a connection with another neuron. The area of connection is called the synapse. An electrical impulse travels down the axon toward the terminal (red arrows). *(Adapted from the American Society for Neuroscience).*

Brain Regions

One of the most important discoveries from neuroscience so far is that specific regions of the brain are specialized for carrying out different functions. Certain parts of the brain govern specific functions such as the sensory (*e.g.* visual) and motor cortex, the cerebellum for coordination and hippocampus for memory. Neurons connect one area to another *via* pathways to send and integrate information. Recent brain research shows that different circuits are called upon in the brain for different activities such as math, music and reading (Niogi and McCandliss, 2006) strengthening the concept of multiple intelligences (Gardner, 1983).

Brain Growth and Maturity

Human learning and cultural evolution are supported by a paradoxical biological adaptation: We are born immature. Young infants cannot speak, walk, use tools, or take the perspective of others. Immaturity comes at a tremendous cost, both to the newborn, whose brain consumes 60% of its entire energy budget (Allman, 1999) and to the parents. During the first year of life, the brain of an infant is teeming with structural activity as neurons grow in size and complexity and trillions of new connections are formed between them. The brain continues to grow during childhood and reaches the adult size around puberty. The development of the cerebral cortex has *sensitive periods* during which connections between neurons are more plastic and susceptible to environmental influence: The sensitive periods for sensory processing areas (*i.e.* vision, hearing, touch, taste and smell) occur early in development, higher cortical areas (regulating *e.g.* language) mature later, and the prefrontal cortex continues to develop into early adulthood. Yet immaturity has value. Delaying the maturation and growth of brain circuits allows initial learning to influence the developing neural architecture in ways that support later, more complex learning.

Brain growth takes much longer than presumed. The prefrontal cortex which is activated when a person receives positive reinforcement *(reward)* for certain behaviours and acts to inhibit risky behaviour by working out strategies which delay immediate gratification, does not mature as quickly as thought previously. It is also the last area of the brain to mature (at 20-25 years of age). This *staged maturation* may explain the impulsiveness and risky behaviour which can manifest itself during the late teenage years and suggests immaturity in the prefrontal lobes.

Learning and Memory

Human memory, the ability to recall vivid mental images of past experiences has been studied extensively for more than 100 years. As recently as the 1950's, many scientists believed that memory is a single albeit highly versatile function. Since then experiments have revealed that there are many types of memory, each underpinned by its own region of the brain.

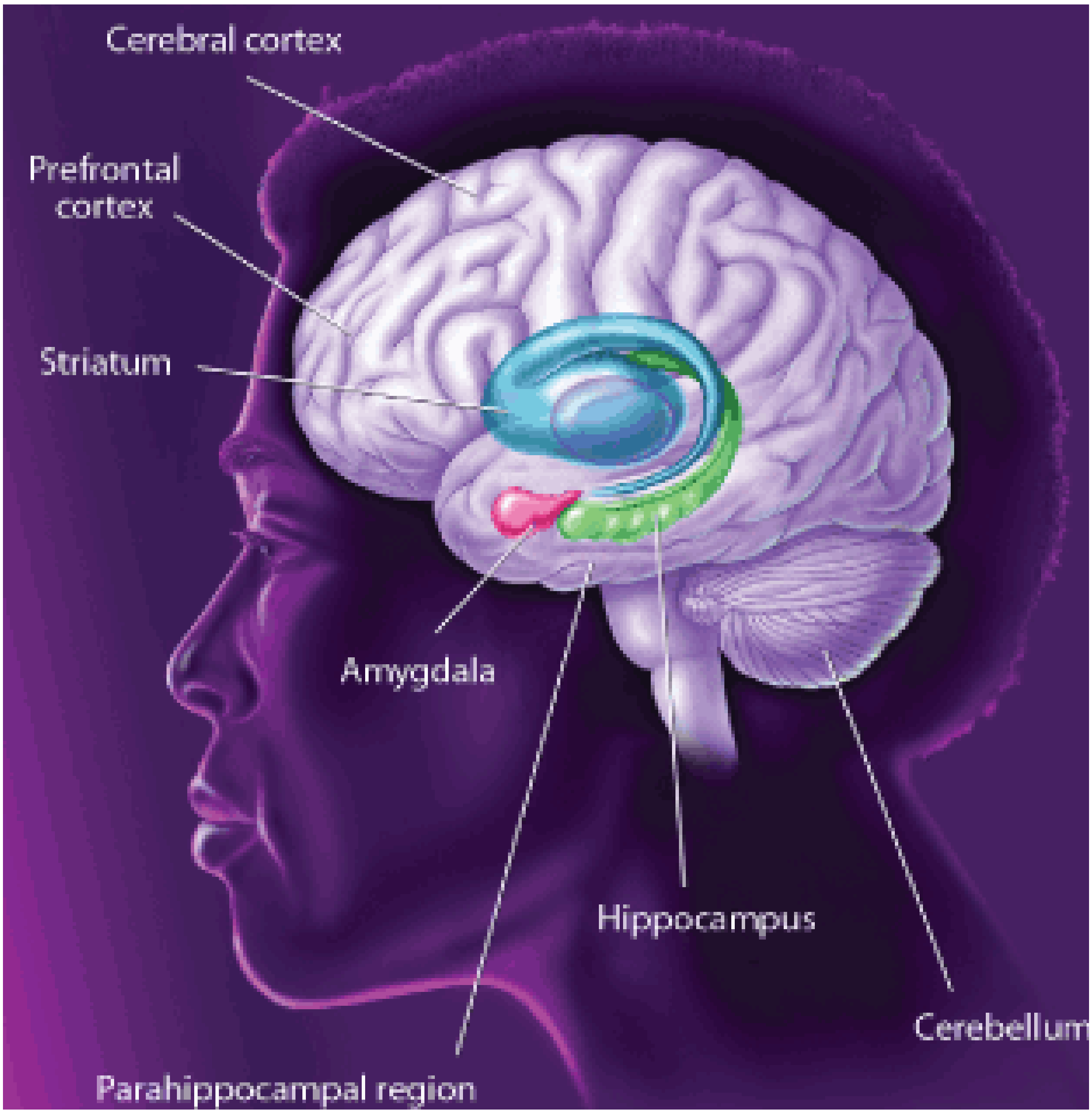

Figure 2. Different brain areas and systems mediate distinct forms of memory. The hippocampus, parahippocampal region, and areas of the cerebral cortex (including prefrontal cortex) compose a system that supports declarative, or cognitive, memory. Different forms of nondeclarative, or behavioural, memory are supported by the amygdala, striatum, and cerebellum. *(Adapted from the American Society for Neuroscience).*

London taxi drivers have a '*sat nav'* inside their heads. These taxi drivers actually grow bigger brains as neurons sprout more connections in the hippocampus - a part of the brain associated with navigation in birds and animals - to help them remember routes (Fig 2). Taxi drivers given brain scans had a larger hippocampus compared with other people and the hippocampus continues to grow larger as the taxi drivers spent more time in the job (Maguire, Gadian, Johnsrude, Good *et al.,* 2000). The hippocampus changes its structure to accommodate their huge amount of navigating experience. The amygdala by contrast stores memory with a high emotional content and there is evidence that the strongest memories are formed when both the hippocampus and amygdala are recruited together (Richter-Levin and Akirav 2000). Other forms of memory such as learning and practicing particular motor skills can cause corresponding areas in the brain to grow or change by adding a tiny fraction of the brain's neural circuitry and eliminating old ones. In this way juggling boosts brain connections. After six weeks of juggling training changes occur in regions of the brain which are involved in reaching and grasping in the periphery of vision (Scholz, Kleim, Behrens and Johansen-Berg 2009).

Sleep can boost learning significantly. The type of learning that appears to be most sensitive to sleep improvement is that which involves learning a procedure. Consolidation of the day's learning occurs the night after the learning occured and interruption of that sleep disrupts the learning cycle (Huber, Felice-Ghilardi, Massimini and Tononi 2004).

Information coming into the brain is immediately split into fragments that are sent to different regions of the cortex for storage. The initial moment of learning is important as the more brain structures recruited and therefore the more connections created the easier it will be to recall that information. Also learning environments and recalling environments should be equivalent – the chances of recall are improved if the environment in which the brain initially learned that information was put. What does it mean to make the encoding and retrieval environments equivalent in the real world of education? It could be as simple as making sure that an oral examination is studied for orally, rather than by reviewing written material. Or perhaps future teachers should be taught about education theory and practise in the classroom where the student learning occurs.

In a more recent study memory and future thought are shown to be highly interrelated such that future thought may be impossible without memories (Scachter, Addis and Buckner 2007). This finding that the ability to remember and creative thought involve the same brain regions demonstrates that good teachers not only impart information but also empower.

Left Brain v Right Brain

Although the brain is symmetrical in structure, with two lobes (hemispheres) emerging from the brain stem and matching motor and sensory areas in each, certain intellectual functions are restricted to one hemisphere (Wager, Luan-Phan, Liberzon and Taylor 2003). A person's dominant hemisphere is usually occupied with language and logical operations, while the other hemisphere controls emotion and artistic and spatial skills. In nearly all right-handed and many left-handed people, the left hemisphere is dominant. The majority of people have a dominant side of the brain and in result, different personalities, preferences and abilities. We choose specific sides of our brain for a variety of daily tasks. This choice is shaped throughout our life by such things as education or experience. For example, most children, before starting education, are proved to be highly creative, which is the domain of the right brain. During the education, we are thought mostly left brain skills such as mathematics or language. Furthermore, it has been argued that by adulthood as little as 2% of the educated population may retain their high levels of creativity. In most people left brain takes control, therefore the lives of the majority of us are ruled by logic and reasoning while the minority of people use imagination and holistic thinking. There are also people who have no brain preference and their hemispheres coordinate together when performing a task. They are said to have optimum mental ability. This coordinating ability may be the key to people's higher intelligence. An important recent finding shows that mood seems also to follow this asymmetry, with positive moods located in the left hemisphere while negative moods located in the right hemisphere (Sutton and Davidson 1997).

Mirror Neurons

The recent discovery of mirror neurons which help us to emotionally *imitate* others by responding sympathetically and empathetically engages parts of the brain that deal with social interaction and empathy (Rizzolatti and Fabbri-Destro 2009). This finding is of particular interest to cognitive neuroscience which addresses the questions of how psychological/cognitive functions are produced by brain circuits. Mirror neurons help connect us emotionally to other people. They help us to respond sympathetically towards others and allow us to anticipative others intentions. For instance when you watch a good movie with good actors then that's why you feel the way you do. In this way social learning is facilitated when people share attention. The best teachers and teaching strategies use shared attention to engage students in their learning. This discovery alone has the potential to revolutionize teacher training and practice including the psychophysical testing of potential teachers.

2. Neuroeducation

Until recently the findings from brain research were of little or no concern to education theory and practice. However during the 1990's it was discovered that the brain is plastic and that every learning experience is accompanied by a change in brain circuits. Each one of us has a constantly changing brain in our constantly changing world. Throughout life the brain is constantly re-wiring itself from the inside out depending on how we choose to use it. Each brain is essentially a work-in-progress and more recent follow up experiments show that exercise can enhance this process while stress seems to work against it (Cotman and Berchtold 2002). Neurons change their connections in response to new experiences. Neuoreducation is built on these findings and from which new theories on teaching and learning are emerging.

Neuroeducation is defined as the study of changes in mental activity during learning. It is an interdisciplinary science that studies the relationship between leaning and brain function during the learning period from birth to old age. Neuroeducation or the neuropsychology of learning is an intersection between the neurosciences and the educational sciences and emerged as a subspecialty in the field of child neuropsychology. Neuroeducation posits that the learning experience lies in brain processes and that cognition improves as the child's brain grows and matures. The goal of neuroeducation is to discover those conditions under which lifelong human learning can be optimized to the highest degree.

3. Putting the Theory into Practice

Shared Attention

Some people think of intelligence as a reflection of individual problem-solving skills. However, a powerful aspect of intelligence is the ability to solve problems collaboratively and humans have special brain and cognitive mechanisms for social interaction (Meltzoff, Kuhl, Movellan and Sejnowski 2009). This makes social interaction a powerful catalyst for learning and in this learning environment discovery learning comes more readily from the intellectual power of the group rather than from studying alone in a garret. Problem based learning (Finucane, Johnson and Prideaux

1998) is a good example of a learning environment that capitalizes on social interaction rather than have the students work alone at desks. A problem case is presented and working in small groups the students set about finding the cause of the problem. They elect a scribe, clarify unknown terms, identify symptoms, brainstorm and rank hypotheses, identify gaps in their knowledge and define learning objectives. The group disperses for self-directed study and after a final report-back information is provided to advance the case into a deeper and broader context. The problem based learning approach also harnesses the students' prior expertise and empowers students to a deeper learning by allowing discovery learning to be incorporated into everyday practice.

Diagnosing and Treating Learning Disorders

Despite being in its infancy neuroeducation research in the field of specific learning disorders such as dyscalculia (math difficulty), dyslexia, dysgraphia, specific language development disability and attention deficit hyperactivity disorder (ADHD) is already revealing new insights into brain function and new treatment approaches. Neuoroeducation expounds that learning disorders can be best understood and treated as disorders in certain brain circuits. Advocates of neuroeducation emphasise the importance of early detection of learning disorders followed by intensive one-on-one remediation focused on re-wiring specific nerve circuits within regions in the brain.

Dyslexia

Reading is essential in modern societies, but it is estimated that dyslexia, a reading and writing disability, affects 5% of the population mostly boys aged between 7 and 9 years. Dyslexia often arises from impaired phonological awareness, the auditory analysis of spoken language that relates the sounds of language to print (Shaywitz 2003). Behavioural remediation, especially at a young age, is effective for many, but not all, children. Imaging studies have revealed differences in brain activity and circuits that are characteristic of dyslexia whereby specific patterns of unusual brain activation in dyslexia relate to the specific reading or language processes (Gabrieli 2009). Neuroimaging in children with dyslexia has revealed reduced activation of the left temporo-parietal cortex for phonological processing of print, altered brain circuits, and re-wiring associated with effective intervention. The findings demonstrate how neuroscience may interact with education to help children with dyslexia. Particularly promising is the possibility that early identification of risk for dyslexia, through combined behavioural and neuroscience measures, may allow for preventive treatment such that many children with dyslexia who would otherwise fail to read would, instead, succeed at reading.

Attention Deficit Disorder

There are two types of attention in two separate regions of the brain. The prefrontal cortex is in charge of wilful concentration; if you are studying for a test or writing a novel, the impetus and the orders come from there. But if there is a sudden, riveting event—the attack of a tiger or the scream of a child—it is the parietal cortex that is activated. Scientists have learned that the two brain regions sustain concentration when the neurons emit pulses of electricity at specific rates—faster frequencies for the automatic processing of the parietal cortex, slower frequencies for the deliberate, intentional work of the prefrontal. ADHD affects between 3% and 5% of school children and although more prevalent in boys, girls are more seriously affected. Theoretically, a spectrum of different drugs that modulate neural frequencies or target specific areas of the brain could fine-tune attention to suit the task at hand. There may be different forms of ADHD and by tailoring drugs for these two different frequencies, it may be possible to enhance attention for specific forms of the disorder. As for moderate use in normal people - when the new products arrive, there may be different '*flavours*' for the surgeon, the fighter pilot, and the aspiring Ph.D. Alternatively, studies of Tibetan Buddhist monks have shown a correlation between transcendental mental states and a type of electrical energy emitted by the brain - gamma waves (Lutz, Greischar, Rawling, Ricard and Davidson 2004). According to recent findings on seasoned meditators, regular meditation can dramatically increase gamma brain wave patters in the frontal and parietal lobes. This finding may radically alter our understanding of attention disorders and provide new opportunities to learn how brains pay attention in real world settings and acquire healthy habits to enhance learning.

4. Conclusions and Future Work

The origin of human intelligence is still a deep mystery. However, collaborative research between neuroscience and education is a promising field. There is an expanding landscape of discoveries and tools that are contributing to understanding the ways in which children and adults learn. At the same time the education profession is eager to embrace neural and cognitive science and to actively inform the future agenda of brain research. In this regard, the study of child development, the plasticity of the human brain, and computational approaches to learning are laying the foundation for a new science of learning that provides insights into the origins of human intelligence.

There is an urgent need to close the gap between laboratory neuroscience research and teachers' practice in their classroom. Neuroeducation advocates the shaping of learning to fit brain development and sets to challenge many basic educational assumptions. We know that early learning sculpts the brain in important ways. This has lead to an industry of selling products that promise to increase the baby's IQ and learning abilities. But there is no scientific evidence that any product on the market does that. This situation has lead to much confusion among parents and much frustration among teachers and developmental scientists.

It is only when teachers become aware of the brain processes involved in the learning experience that pre-school, older children and adults will receive the teaching instruction congruent with their brain development. Thus, in unexpected ways, neuroscience and educational theory and practice are beginning to join hands and reinforce each other to develop strategies and tools with the potential to ultimately improve education.

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