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TARGET ARTICLE WITH COMMENTARIES

The learning brain: Lessons for education: a précis

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For commentaries on this article see Ansari (2005), Goswami (2005) and Howard-Jones (2005).

Why write this book? And why now?

This book highlights the importance of anchoring education in an evidence base derived from neuroscience. For far too long has the brain been neglected in discussions on education and often information about neuroscientific research is not easy to access. Our aim was to provide a source book that conveys the excitement of neuroscience research that is relevant to learning and education. This research has largely, but not exclusively, been carried out using neuroimaging methods in the past decade or so, ranging from investigations of brain structure and function in dyslexia and dyscalculia to investigations of the changes in the hippocampus of London taxi drivers. To speak to teachers who might not have scientific backgrounds, we have tried to use non-technical language as far as possible and have provided an appendix illustrating the main methods and techniques currently used and a glossary, defining terms from Acetylcholine, Action Potentials and ADHD to White Matter, Word Form Area and Working Memory.

We start with the idea that the brain has evolved to educate and to be educated, often instinctively and effortlessly. We believe that understanding the brain mechanisms that underlie learning and teaching could transform educational strategies and enable us to design educational programmes that optimize learning for people of all ages and of all needs. For this reason the first two-thirds of the book follows a developmental framework. The rest of the book focuses on learning in the brain at all ages.

There is a vast amount brain research of direct relevance to education practice and policy. And yet neuroscience has had little impact on education. This might in part be due to a lack of interaction between educators and brain scientists. This in turn might be because of difficulties of translating the neuroscience knowledge of how learning takes place in the brain into information of value to teachers. It is here where we try to fill a gap. Interdisciplinary dialogue needs a mediator to prevent one or other discipline dominating, and, notwithstanding John Bruer's remarks that it is cognitive psychology that 'bridges the gap' between neuroscience and education (Bruer, 1997), we feel that now is the time to explore the implications of brain science itself for education.

Nature and nurture

Individual brains, like individual bodies, are different from each other but there is almost nothing that you cannot improve or change. When we look at the world around us there are many examples of how culture has enhanced or improved on nature. A few examples that come to mind are glasses that improve eyesight, nutrition for growth, and orthodontists for crooked teeth. The brain is just the same. Educators are, in a sense, like gardeners. Of course, gardeners cannot grow roses without the right soil and roots in the first place, but a good gardener can do wonders with what is already there. Just like gardening, there are many different ideas of what constitutes the most admirable and there are distinct cultural differences and fashions over time. Nevertheless, individual gardens involve making the best of what is there and it is possible to make astonishing new and influential designs. This analogy can illustrate what we mean by shaping the brain through teaching and learning.

The aim of our book is to demonstrate how research on the brain and learning could influence the way we

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think about teaching. On the other hand, much of the research is not yet ready for implications to be drawn, and where we believe this is the case, we say so. Here, we highlight some of the more provocative themes in our book.

Plasticity in the brain

Until relatively recently, it was widely believed that the adult brain was incapable of change. There used to be a strong assumption that after the first few years of life the brain is equipped with all the cells it will ever have, and that adulthood represents a downward spiral of loss of brain cells and deterioration in learning, memory and performance generally. But research is beginning to show that this view of the brain is too pessimistic: the adult brain is flexible, it can grow new cells and make new connections, at least in some regions, such as the hippocampus. Although laying down new information becomes less efficient with age, we believe it is important to make people aware that there is no age limit for learning.

The brain's *plasticity* – its capacity to adapt continually to changing circumstances – depends critically on how much it is used. Research on plasticity suggests that the brain is well set up for life-long learning and adaptation to the environment, and that educational rehabilitation in adulthood is possible and well worth investment. On the other hand, the research also suggests that there is no biological necessity to rush and start formal teaching earlier and earlier. Rather, late starts might be reconsidered as perfectly in time with natural brain and cognitive development.

Is 3 years too late? The early years education debate

From early in postnatal development, the brain begins to form new synapses, so that the synaptic density (the number of synapses per unit volume of brain tissue) increases enormously. This process, called synaptogenesis, lasts for some time: for different lengths of time depending on the species of animal. It is followed by a period of synaptic pruning in which frequently used connections are strengthened and infrequently used connections are eliminated. So, as soon as a baby is born, its synapses start growing and changing. Which connections survive and grow, and which fade away and die, is determined partly by the genes the baby inherits from its parents and partly by the baby's early experiences. Should babies therefore be exposed to as many learning experiences as possible during their early years?

Not necessarily. The assumption is that the time course of synaptogenesis and pruning is the same for humans as monkeys, where it takes place during the first three years (Rakic, 1995). However, given that the development of monkeys is much quicker than that of humans and their span of childhood much shorter, the period of rapid growth in brain development in humans is likely to be considerably longer than in monkeys. At 3 years monkeys are sexually mature, so this age might well be equivalent to about 12 or 13 years in human beings.

Critical vs. sensitive periods in brain development

Researchers have known for the past 30 years that an animal requires certain kinds of environmental stimulation at specific times – a critical period – during its development for the brain's sensory and motor systems to develop normally (Wiesel & Hubel, 1965). Research on critical periods and the irreversible consequences of early sensory deprivation is often cited as evidence for the importance of early childhood experiences. The research findings have been used to suggest that certain learning experiences must occur by a certain age or the brain will never develop properly and it will be impossible for the child ever to acquire those skills or abilities.

However, subsequent research has suggested that some recovery of function is possible depending on the specific period of deprivation and the circumstances following deprivation (Chow & Stewart, 1972). Most neuroscientists now believe that critical periods are not rigid and inflexible. Rather, most interpret them as 'sensitive' periods comprising subtle changes in the brain's ability to be shaped and changed by experiences that occur over a lifetime. For some functions to develop normally, the animal must receive appropriate sensory input from the environment at a particular stage during development. However, appropriate input need not be in any way especially sophisticated. Instead, it tends to be basic and general, and is readily available in normal environments. The presence of patterned and coloured visual stimuli, sounds and objects to touch and manipulate, for example, is ample stimulation for the developing sensory cortices of the human brain. What is particularly important in the case of human infants is interaction with other human beings, including language and communication.

Currently, the one main implication of the research findings on sensitive periods is that it is important that we identify and, if possible, treat children's sensory problems, such as visual and hearing difficulties, so that even belatedly they can regain normal function. The findings suggest that early sensory deprivation can have lasting consequences, possibly very subtle ones, undetectable in everyday life. They also suggest that even after sensory deprivation, recovery and learning can still occur. Such late learning may be different from the type of learning that occurs naturally during sensitive periods.

Brain development and an enriched environment

A fundamental characteristic of brain development is that environmental experiences are as important as genetic programmes. Research on rats has revealed how the environment affects the brain's synapses during development (Greenough, Black & Wallace, 1987). This research is often cited as evidence for the importance of enriched early childhood environments.

Early studies showed that laboratory rats raised in an enriched environment, with wheels to spin, ladders to climb on, and other rats to play with, had up to 25% more synapses per neuron in brain areas involved in sensory perception than 'deprived' rats, raised alone in a lab cage with no playmates or toys (Grossman, Churchill, Bates, Kleim & Greenough, 2002). Furthermore, the rats raised in complex environments performed learning tasks better and were quicker to navigate around mazes than were deprived rats. Enriched early environments, then, seem to create cleverer rats. In addition to neural consequences, experience also affects other aspects of brain cellular structure. The amount of physical activity and exercise a baby rat has determines the long-term state of the blood supply to its brain.

Do these results mean that a baby's environment should be specially manipulated to make it richer than it is normally? There is no suggestion from the experiments on rats that 'the richer the environment the better'. In these experiments, the enriched environment in the laboratory was actually more like the normal environment of a rat in the wild. So, rather than showing that extra stimulation leads to an increase in synaptic connections, it might be more accurate to say that a 'normal' environment leads to more synaptic connections than does a deprived environment. It is unlikely that children brought up in any 'normal' child-oriented environment could be deprived of the sensory input that is necessary for brain development. The research does, however, indicate that there is a threshold of environmental richness below which a deprived environment is likely to harm a baby's brain (cf. Rutter & O'Connor, 2004).

Greenough's ground-breaking studies showed that the environment does not just affect the developing rat's brain. Experience can also shape the *adult* rat brain. In subsequent studies, Greenough and his colleagues showed that the brains of adult rats also form new synapses in response to new experiences and toys. Overall, the research does not support the argument for a selective educational focus specifically on children's earliest years.

The adolescent brain

Adolescence is a time characterized by change – hormonally, physically and mentally. It was not until the late 1960s and 1970s that research on post-mortem human brains revealed that some brain areas, in particular the frontal cortex, continue to develop well beyond childhood. There are two main changes in the brain before and after puberty. First, although overall volume of brain tissue remains stable, there is an increase in myelin in the frontal cortex after puberty compared with before (Yakovlev & Lecours, 1967). As neurons develop, they build up a layer of myelin on their axon. Myelin acts as an insulator and increases the speed of transmission of electrical impulses from neuron to neuron. Whereas sensory and motor brain regions become fully myelinated in the first few years of life, the frontal cortex continues to be myelinated well into adolescence. This is remarkable because it means that the transmission speed of neurons in the frontal cortex may get faster after puberty.

Further studies revealed a decrease in the density of synapses in the frontal cortex after puberty (Huttenlocher, 1979). Unlike sensory brain regions, where synaptic pruning is over much earlier, in the frontal cortex, there seems to be a second wave of synaptogenesis at the onset of puberty, after which synaptic pruning occurs. This results in a gradual decrease in synaptic density in the frontal lobes throughout adolescence.

Given the continued developmental changes in the frontal cortex during adolescence, it might be expected that cognitive abilities that rely on this region should also change during this time period. There is some evidence that performance on executive function tasks improves linearly with age (Anderson, Anderson, Northam, Jacobs & Catroppa, 2001). One study, on the other hand, found evidence for a dip in performance on a match-to-sample task at puberty. These results were interpreted as reflecting the proliferation of synapses that occurs at the onset of puberty (McGivern, Andersen, Byrd, Mutter & Reilly, 2002). It is possible that the excess of synapses at puberty, which have not yet been incorporated into specialized, functional systems, results in poor cognitive performance for a while. Only later, after puberty, are the excess synapses pruned into specialized, efficient networks.

The idea that children who have reached sexual maturity should still go to school and be educated is relatively new. And yet the research on brain development during adolescence shows that secondary and tertiary education are vital. The brain is still developing during this period, the brain is adaptable, and needs to be moulded and shaped. Perhaps the aims of education for adolescents should change to include strengthening of internal control, for example, self-paced learning, critical evaluation of transmitted knowledge and meta-study skills.

Developmental disorders

A minority of children with developmental disorders are severely affected and need a very different approach to teaching. This approach has to do with coping with and overcoming problems. The idea is that compensation may be possible, even if a cure is not possible as yet. Many hold that only education can make a substantial difference to the quality of life of affected individuals. Education does not cure the conditions, but it can certainly improve them.

One of the most remarkable findings about developmental disorders, such as dyslexia and autism, is their specificity: a child can be highly intelligent and excel in many different ways, and have just one 'gap' in an otherwise normally functioning mind. One controversial idea is that the brain of the newborn infant comes equipped with various start-up mechanisms. These enable fast-track learning in particularly important domains. In a developmental disorder such as autism or dyslexia, one or more of these modules may be faulty.

What start-up mechanisms are we talking about? We presume that there is such a mechanism for learning language, for learning numbers, and for learning music, because all these abilities develop quickly and can exist in relative isolation from other types of learning. This isolation means that they act like modules in a complex machine. A module can break. It is possible to be highly intelligent and creative and yet have absolutely no ear for music. On the other hand, a single module can survive while many others are damaged. It is possible to be very slow at learning anything except music. Such isolated talent exists. But since we are talking about development, where one thing hinges on another, even a minor malfunction in a single module is likely to have huge consequences. The broken module may prevent others from developing in the manner of a domino topple.

For the idea of start-up mechanisms to work, it is necessary to assume that there are neural structures that are geared towards processing a particular kind of stimulus and to facilitate a particular kind of learning. We also assume that there is, in addition, an all-purpose 'mind-machine' that is not specifically geared to particular stimuli, but can cope with almost anything. This is like a general learning system that simply responds to associations of experience. Again speculatively, we suggest that this general mechanism might take over if a module is faulty. It would make any learning different from normal fast learning, but still feasible. These ideas are controversial and alternatives are being actively researched as well.

In our book, we describe research on developmental disorders in which neuroscience has already made substantial contributions, ready to reap benefits in the classroom. This is true in particular in the case of dyslexia and dyscalculia, disorders that are now recognized as having a genetic origin and a basis in the brain. We review recent research highlighting a small region in the left hemisphere of the brain, which is refashioned into a visual word form area by becoming literate (Paulesu, Demonet, Fazio, McCrory, Chanoine, Brunswick, Cappa, Cossu, Habib, Frith & Frith, 2001). In the case of number, we now know that two processes, quantity estimation and exact calculation, are dealt with differently in the brain (Dehaene, Molko, Cohen & Wilson, 2004). It is possible to have problems with one without the other being affected. We also review research suggesting that autism is associated with problems in a circumscribed brain network that underlies our ability to 'mentalize', that is our ability to understand other people's minds (Frith & Frith, 2003).

Life-long learning

Teaching and learning apply to all ages. Brain research has time and time again demonstrated the flexibility of the adult brain and has shown that there is no age limit for learning. The adult brain can change, in size and activity, and these changes generally occur as a result of usage. In other words, the brain continually adapts to its environment. Much research has been performed on plasticity in the hippocampus, a structure deep inside the brain that is essential for remembering where things are ('spatial memory'). Brain imaging studies have shown that the human hippocampus changes in size as a result of navigation experience in London taxi drivers (Maguire, Gadian, Johnsrude, Good, Ashburner, Frackowiak & Frith, 2000). Part of the hippocampus is larger in taxi drivers than non-taxi drivers and its size is related to the time the person has been driving taxis. This demonstrates that parts of the brain can grow depending on how much they are used. However, a different part of the hippocampus was found to be smaller in taxi drivers. So, there might be costs when one part of the brain develops and grows through experience.

Numerous studies have shown that in just five days the sensory and motor areas of the adult brain can adapt according to how they are used. The brain is capable of 'relocation of function' – brain cells change the specific job they perform depending on their usage. For example, when blind people read Braille, the part of their brains that would normally process vision now processes touch (Sadato, Pascual-Leone, Grafman, Ibanez, Deiber, Dold & Hallett, 1996). This useful strategy makes use of cortex that would otherwise be redundant. This abundance of evidence that the brain remains very plastic and flexible in adulthood has implications for life-long learning.

What in the brain changes as a result of teaching?

This question is only beginning to be asked and is tricky to answer as many different factors can affect changes that are not to do with teaching but simply occur over time. A recent experiment answered this question for the case of learning to read musical notation (Stewart, Henson, Kampe, Walsh, Turner & Frith, 2003). Musical novices embarked on a three-month piano course, which established an automatic response so that merely looking at a sheet of music – without being told to read it – compelled the pupil to do so. Furthermore, a small part of the motor cortex sprang into action in readiness to play the melody. In addition, the intraparietal sulcus became active during playing after training, while it was not active in untrained people. This experiment gives an inkling of the transformations in the brain that happen as the result of all sorts of skills that are being taught and are part of our everyday culture, such as learning to read, learning to do maths, or learning to read maps.

Methods of learning

Visual imagery

Brain science is providing evidence for methods of learning that go way beyond simple rote learning. Visual imagery involves 'seeing with the mind's eye'. How many pictures are hanging up in your living room? To answer this question most people close their eyes and visualize the room inside their heads, scan this mental image, and count the pictures. Visual imagery, or visualization, is powerful – most people can actually control their mind's eye and use it to have a look around the corners of their living room to count the pictures in their head. Patients with damage to the occipital lobes of the brain, where the visual cortex lies, often have visual memory problems and do not benefit from visual imagery when trying to memorize words. This suggests that the visual brain regions are necessary for forming visual images. Brain imaging studies have revealed that at least two-thirds of the same brain areas are activated when you imagine an object compared with when you actually see the same object (Ganis, Thompson & Kosslyn, 2004). So, mental images of objects and events can engage much of the same processing that occurs during the corresponding perceptual experience.

Imitation

One of the vehicles of teaching and learning is imitation. However, we learn merely by observation, even without performing the action ourselves. How is this possible? An important new insight of brain science is that simply observing someone performing an action activates the same brain areas that are activated by producing movements oneself (Rizzolatti, Fadiga, Gallese & Fogassi, 1996). When you see someone reaching for a cup of coffee, your brain does not just process the visual percept of hand plus cup – it also reproduces the action. A recent brain imaging study showed that activity in the brain's motor regions is further increased if the observer watches someone else's actions with the intention of imitating them later (Grezes, Costes & Decety, 1999). Your brain mimics other people's actions even if you don't.

Simulating observed actions in the brain might make performing that action easier if and when you come to perform the action yourself. Some aspects of teaching and learning depend upon this effect. Imagine trying to learn to dance without being able to observe someone dancing first. Learning from observation is usually easier than learning from verbal descriptions, however precise and detailed the descriptions may be. This might be because, by observing an action, your brain has already prepared to copy it. We are predisposed to imitate those around us. This echoes the belief of many educators that we should not just impart *what* to know, but also demonstrate *how* to know. The teacher's values, beliefs and attitude to learning could be as important in the learning process as the material being taught.

Regions of the brain necessary for motor learning are activated just by thinking about movement (Gerardin, Sirigu, Lehericy, Poline, Gaymard, Marsault, Agid & Le Bihan, 2000). Mental exercise can be exploited in training of physical skills such as sport, dancing, acting, and possibly even painting and drawing.

Exercising the brain

Emerging new research in animals suggests that physical exercise may boost brain function and increase learning. Mice who had access to a running wheel over a period of six weeks became better at learning than sedentary mice who had no wheel (van Praag, Christie, Sejnowski & Gage, 1999). The number of brain cells in the hippocampus (one of the brain regions responsible for learning and memory) of the mice who had wheels was almost double the number in the inactive mice. Furthermore, the brain cells of the mice that ran were better able to sustain long-term potentiation (LTP), the proposed basis of laying down long-lasting memories in the brain, than the sedentary mice. The increased number of cells in the hippocampus and the enhanced LTP can explain how exercise improves learning. What is most fascinating about these findings is that they undermine the notion that the adult brain cannot grow new cells – all the mice in this study were adults. This overthrows the dogma that we are born with all the brain cells we will ever have and no more can ever grow. Use it or lose it. This slogan applies to the body and physical exercise, but it also applies to the brain and mental exercise. New learning is possible and changes not only the function but also the structure of brain regions.

Learning while you sleep

Many studies have shown the detrimental effect of sleep deprivation on learning. Recently, research has shown that the brain regions involved in learning the day before are *reactivated* during sleep. In one study, volunteers were trained on a complex sequence task during the day. As they learned, a brain scanner recorded their brain activity. That night, while asleep, the volunteers had their brains scanned again. The same brain areas that were activated during the training became activated again during REM sleep. The brain activity recorded during REM sleep presumably reflected reinforcement of the learning that took place during the day. Moreover, participants' performance on the task had improved the following day, after sleep. The brain reactivations observed were indeed beneficial to memory and learning (Maquet, Laureys, Peigneux, Fuchs, Petiau, Phillips, Aerts, Del Fiore, Degueldre, Meulemans, Luxen, Franck, Van Der Linden, Smith & Cleeremans, 2000). In fact, just having a nap after learning a task seems to improve performance on the task (Mednick, Nakayama & Stickgold, 2003). The brain reactivations during sleep may reflect the reinforcement of connections between neurons that are important for the task. In this way, they allow the new skill to be incorporated into long-term memory. This research clearly has implications for managing the time between teaching and learning phases.

We have deliberately picked out some of the more controversial ideas in our book so as to spark off discussion. The book was written in a spirit of adventure with the expectation of controversy, given that many results that we report are quite new and in need of replication. For this and other reasons, many would counsel that it is still premature to speculate about the impact of brain research on teaching. We have not taken this view because we do not think that it is too early to think about the applications of many achievements of brain science. Society's enduring interest in education after all bears witness to the basic human desire to improve our brains and minds.

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