

Neuroscience and Education: Issues and Opportunities

A Commentary by the Teaching and Learning Research Programme



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Improving education is a national priority for the UK. In this Commentary, we explore the scope for our emerging knowledge of the working of the brain to contribute to better educational outcomes, especially for children.

This publication unites two of the Economic and Social Research Council's principal concerns. One is for education. The Teaching and Learning Research Programme is the ESRC's largest research initiative. It is dedicated to performing excellent research that leads to better education for people at all stages of life. From its inception, it has promoted discussion of the link between education and neuroscience.

In addition, the ESRC is one of the UK's main supporters of psychology research. Our programmes reflect an awareness that our knowledge of the brain is growing in power, and will be relevant to areas of social science such as economic and political behaviour as well as to education.

In this publication, the latest in a series of TLRP Commentaries, researchers supported by the TLRP point to a range of issues at the junction between neuroscience and education. As they say, the brain is the principal organ involved in learning. It is natural that our increased knowledge of its working can inform educational practice. But as they also make clear, attempts to introduce neuroscience approaches into the classroom have to date been of mixed quality. Often they have relied too little upon research evidence and too much on impressive-sounding but scientifically questionable formulae.

The authors leave us in no doubt that these are early days in this story. Because of the rapid progress now being observed throughout neuroscience, some approaches that are now in use may soon be seen to be invalid. Others that are now used will become better-corroborated. And unexpected approaches may emerge from research now under way.

The ESRC is delighted to be involved in this exciting new field of science. We are keen that it should not be regarded as a one-way process in which neuroscience sheds light on how people learn. Instead, we want a two-way cooperation in which our knowledge of learning and of the brain feed one another. The result will be new knowledge about neuroscience and about education, and improved learning outcomes.

We would welcome your response to this Commentary via our web site: www.esrcsocietytoday.ac.uk

Professor Ian Diamond FBA AcSS
Chief Executive
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Introduction	4
Background	5
About the Brain	6
Brain Development	8
Early Years	8
Adolescence	8
Adulthood	9
Brain Care	10
Omega 3	10
Caffeine	10
Sleep	11
Water	11
Neuroscience and Developmental Disorders	12
Dyslexia	12
Dyscalculia	13
ADHD	14
Strategies for Teaching and Learning	15
Commercial 'brain-based' Programmes	15
Brain Scan to Lesson plan: the Role of Cognition	17
Issues on the Horizon	19
Smart Pills	19
Neurofeedback	20
Biology is not Destiny	21
The Future: Can Education, Neuroscience and Psychology Work Together?	22
The Need for Cautious Optimism	



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Introduction

In a recent survey of teachers, almost 90 per cent thought that a knowledge of the brain was important, or very important, in the design of educational programmes¹. Indeed, for at least two decades, educational programmes claiming to be 'brain-based' have been flourishing in the UK. Unfortunately, these programmes have usually been produced without the involvement of neuroscientific expertise, are rarely evaluated in their effectiveness and are often unscientific in their approach. Perhaps this is unsurprising since, although the central role of the brain in learning may appear self-evident, formal dialogue between neuroscience and education is a relatively new phenomenon.

This commentary builds on the work of the recent TLRP-ESRC seminar series on Neuroscience and Education, which brought together national and international educational and scientific experts to discuss how these two areas might work together in the future, particularly in regard to collaborative research. By the time of its conclusion in June 2006, over 400 teachers, educational researchers, psychologists and neuroscientists had attended one or more of the events in this series. Each event involved formal discussions about the theoretical and methodological issues arising within this emergent and interdisciplinary field of enquiry, and the opportunities that may lie ahead. These discussions helped inform the production of this document, and their summaries can be found on the series web site (www.bris.ac.uk/education/research/sites/brain).

This TLRP commentary reports upon only a selection of areas where neuroscientific issues are impacting upon education. But it provides an impression of the breadth of issues involved and ample evidence that this influence is increasing. In the future, education may have much to gain from greater cognisance of the workings of the brain and improved dialogue with those working in the neuroscience and psychological communities. Such dialogue will help:

- Produce a common language and understanding about learning. This will inform attitudes, educational approaches and the quality of discussion around an increasing range of educational issues such as those associated with ADHD and dyslexia
- Prompt further, more educationally-focused, scientific inquiry
- Develop multidisciplinary projects and forums that can identify tractable and useful research questions, develop collaborative research to address them, scrutinise neuro-myths and evaluate programmes of 'brain-based' learning
- Provide greater preparedness for imminent social, cultural and scientific change.

In every phase of education, from early years to later life, there are educational issues whose understanding requires concepts about brain function. The debate about how

this knowledge should be included in educational thinking has only just begun.



Background

The current resurgence of educational interest in the brain reflects an increasing belief amongst some scientists, as well as educators, that education can benefit from neuroscientific insights into how we develop and learn. In the past decade, several attempts have been made to assess the opportunities offered by this new perspective, and a fresh interdisciplinary dialogue appears to be emerging^{2,3,4,5}. Most notably, in 2000, Professor Uta Frith and her colleague Dr Sarah-Jayne Blakemore completed a commission by the Teaching and Learning Research Programme (TLRP) to review neuroscientific findings that might be of relevance to educators⁶. This review attacked a number of 'neuromyths', including those concerning critical periods for educational development, and highlighted new areas of potential interest to educators such as the role of innate mathematical abilities, visual imagery, implicit processes, and sleep in learning. Rather than point out areas where neuroscience could be immediately applied in the classroom, the review sought to highlight neuroscientific research questions that might interest educators, an important initial step towards defining an interdisciplinary area of collaborative research.

In 1999, as the Blakemore and Frith report was being commissioned in the UK, the supranational project on 'Learning Sciences and Brain Research' was being launched by the Centre for Educational Research and Innovation (CERI) at the Organisation for Economic Cooperation and Development (OECD). The first phase of the project (1999-2002) brought together international researchers to review the potential implications of recent research findings in brain research for policy-makers, with a second phase (2002-2006) channelling its activities into three significant areas, Literacy, Numeracy and Lifelong Learning. This OECD project revealed the high level of international interest in developing a dialogue between neuroscience and education, as well as highlighting the diversity of approaches across the world⁷. In April 2005, the TLRP began its second initiative in this area, by commissioning the seminar series 'Collaborative Frameworks in Neuroscience and Education', upon which this commentary is based.

This commentary draws upon those areas explored in the recent TLRP seminar series that appear most significant in terms of their existing or future impact upon education. It highlights the need for improved collaboration between neuroscience, psychology and education, and how this may help us engage with the issues and opportunities that lie ahead.



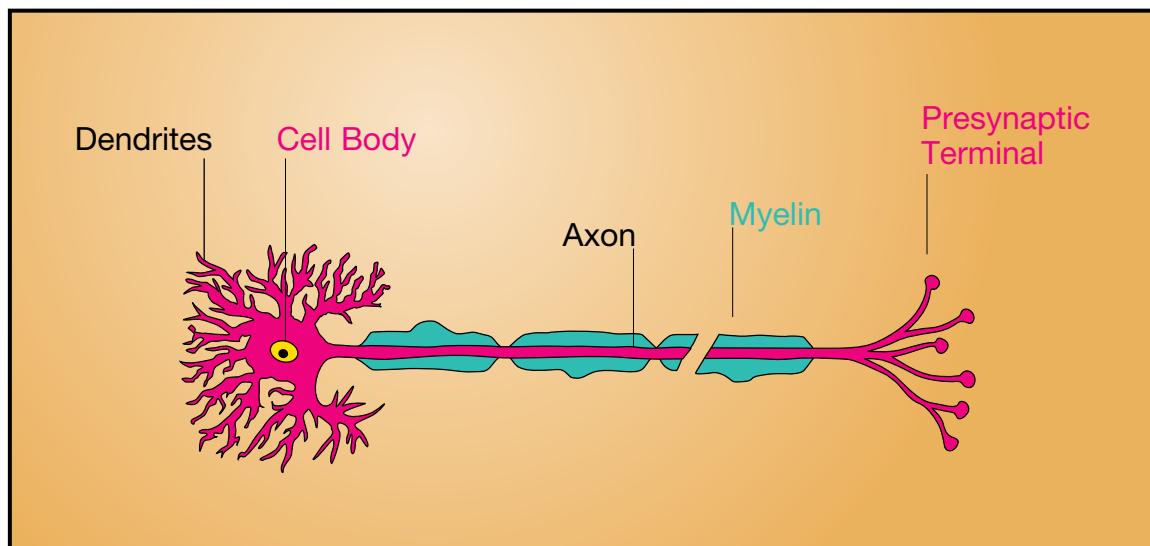
Andrew Pollard
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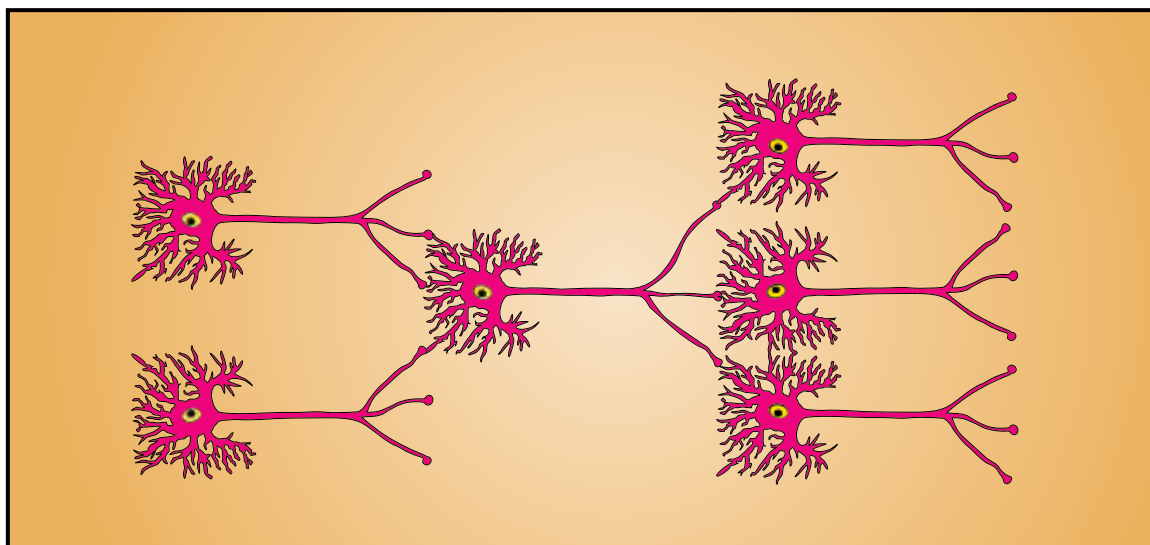
About the Brain

Understanding the educational significance of neuroscientific findings does not require a high level of specialist knowledge. However, acquiring a few anatomical terms and phrases can be useful and some of those you will encounter in this document are explained here.

The adult brain contains about 100 billion brain cells – or *neurons*. Each neuron consists of a *cell body*, to which are connected *dendrites* and an *axon*.



The *terminals* at the end of the axon make contact with the dendrites of other neurons and allow connections, or *synapses*, to form between neurons. In this way, complex neural networks can be created.





Within such networks, signals can flow down the axons of one neuron and cross the synapse to other neurons, allowing neurons to communicate with each other. The signal passing down the axon is electric, and its progress is hastened by insulation around the axon known as *myelin*. However, the process that allows the signal to pass through from the synaptic terminals to the dendrites of the next neuron is chemical. This process involves transmission across the synaptic gap of special substances known as *neurotransmitters*.

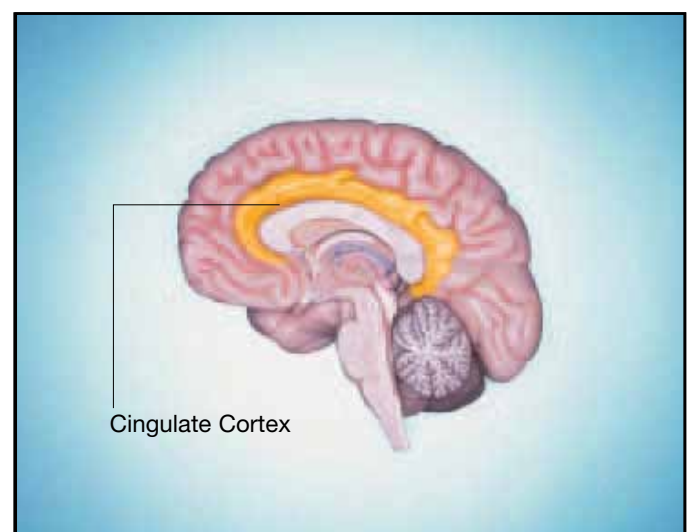
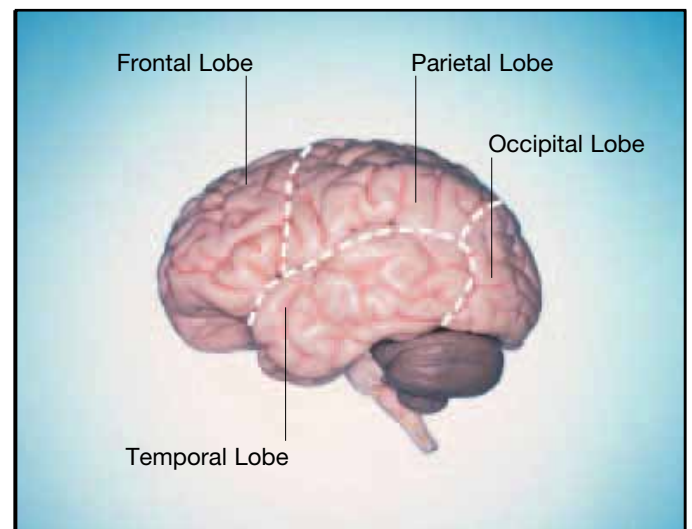
The brain is often described in terms of two hemispheres, left and right, joined together by a mass of fibres known as the *corpus callosum*. These can further be divided into four lobes: the *frontal*, *parietal*, *occipital* and *temporal*. Each lobe has been associated with a different set of cognitive functions. The frontal lobe may, perhaps, be of particular interest to educators due to its involvement with many different aspects of reasoning as well as movement. The temporal lobe is associated with some aspects of memory, as well as auditory skills. The parietal lobes are heavily involved in integrating information from different sources and have also been associated with some types of mathematical skill. The occipital lobes are critical regions for visual processing.

However, as we shall see, it is not advisable to consider any one part of the brain as being solely involved with any one task. Any everyday task recruits a large and broadly distributed set of neural networks that communicate with each other in a complex fashion.

The *cortex* of the brain refers to the wrinkled surface of these lobes. This surface is more wrinkled in humans than any other species, a characteristic thought to reflect our greater reliance upon higher level thought processes. The evolutionary pressure to maximise cortical area has resulted in some of our cortex existing well below the outer surface. One notable example of this is the *cingulate cortex*. The *anterior* (or forward) part of the cingulate cortex becomes active when we engage with a wide variety of tasks, and appears to have a significant role in the allocation of attention.

Beyond identifying an area of the brain by its lobe, scientists find it useful to name each valley or ridge on the lobe's wrinkled surface. A valley is referred to by the latin name of *sulcus* (plural *sulci*) and a ridge is called a *gyrus* (plural *gyri*).

The brain, however, is not composed entirely of cortex and there are many other types of structure that are critical for learning. These include structures deeper within the brain such as the *hippocampus* – a part of the brain critical to consolidating new memories, and the *amygdalae*, which play an important role in our emotional responses.





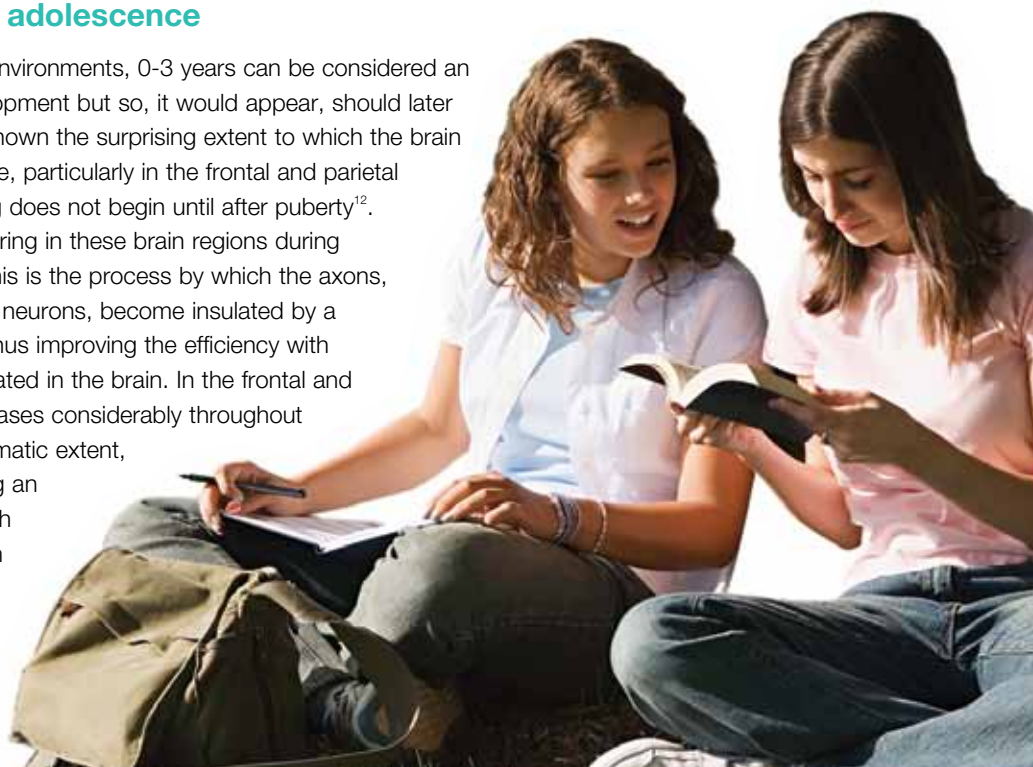
Brain Development

Early years: when should education begin?

Contrary to much popular belief, there is no convincing neuroscientific case for starting formal education as early as possible. Three arguments for this approach have been used, but each involves the erroneous interpretation, or over-interpretation, of the evidence. Firstly, it is true that synaptogenesis (the making of synapses, or connections between neurons) occurs at a greater rate amongst children than in adults, as does synaptic pruning (in which infrequently used connections are eliminated). It is fair to consider that such overt changes in brain connectivity help make childhood a good time to learn. Much of what we know about synaptogenesis and pruning is derived from research with other primates. In monkeys, these processes occur early, suggesting that the first three years of their life may be especially significant in terms of learning⁸. However, we now know that structural changes, including synaptogenesis and pruning, continue well into puberty and throughout most of adolescence in some areas of the human brain that are very significant for education (see below). A second argument, often linked to the first, has been constructed from the concept of the critical period – a window in time when a child can learn a particular skill or ability. For example, it is known that adults have more difficulty in discriminating sounds that they didn't hear before the first six months of life⁹. However, scientists now believe that critical periods should be referred to as sensitive periods. They are not fixed and rigid. They exist more as subtle differences in the brain's ability to be shaped by the environment. Furthermore, they chiefly involve visual, movement and memory functions that are learned naturally in a normal environment. Research on sensitive periods is fascinating but it cannot yet contribute to meaningful discussions regarding the formal curriculum. The third argument points to research into the effects of enriched environments on learning and the development of synapses¹⁰. However, this research involved rats living in environments that were no more enriched than their natural habitat. These rats were compared with caged rats existing with no stimulus in their cages at all. Thus, the results say more about the effects of deprived environments than enriched ones, resonating with studies of neglected children showing delays and deficits in cognitive development. Overall, there is some evidence to suggest that impoverished environments inhibit neural development, but no evidence that enriched environments enhance it¹¹.

Brain development in adolescence

Whatever the role of enriched environments, 0-3 years can be considered an important period of brain development but so, it would appear, should later childhood. Neuroscience has shown the surprising extent to which the brain is still developing in adolescence, particularly in the frontal and parietal cortices where synaptic pruning does not begin until after puberty¹². A second type of change occurring in these brain regions during puberty involves myelination. This is the process by which the axons, carrying messages from and to neurons, become insulated by a fatty substance called myelin, thus improving the efficiency with which information is communicated in the brain. In the frontal and parietal lobes, myelination increases considerably throughout adolescence and, to a less dramatic extent, throughout adulthood, favouring an increase in the speed with which neural communication occurs in these areas¹³.





Taking these considerations together, one might expect the teenage brain to be less ready than an adult brain to carry out a range of different processes. These include directing attention, planning future tasks, inhibiting inappropriate behaviour, multitasking, and a variety of socially-orientated tasks. Indeed, psychological testing has even shown a 'pubertal dip' in some areas of performance, such as matching pictures of facial expressions to descriptors. In this task, 11-12 year olds performed worse than younger children¹⁴. A plateau has also been shown for the prospective memory ability required to remember appointments¹⁵, as well as discontinuities in abilities underlying social communication such as taking on the viewpoint of another person, or so-called 'perspective-taking'^{16,17}.



As in the earliest years of life, a second wave of reorganisation of the brain is taking place during the teenage years. Research on adolescent brain development suggests that secondary and tertiary education are probably vital. The brain is still developing during the period: it is thus presumably adaptable, and needs to be moulded and shaped.



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Just as linguistically sensitive periods have been linked to synaptic pruning in very young children, continuing synaptic pruning in adolescence suggests the possibility of sensitive periods here too. For example, research has shown that teenagers activate different areas of the brain from adults when learning algebraic equations, and this difference has been associated with a more robust process of long-term storage than that used by adults^{18,19}.

However, an important point here is that, while young children's development in areas such as language is advantaged by biological start-up mechanisms specific to these language skills, no such start-up mechanisms for adolescents are likely to exist that are specific to the KS3 curriculum. Thus, formal education, as well as social experience, may have a particularly important role in moulding the teenage brain.

Brain Development in Adulthood

Although the changes are less radical than during childhood, the brain continues to change and develop through adulthood. With increasing age, of course, the brain does become less malleable, and we begin to lose neurons at an increasing rate, although the educational effects of this loss are still not well understood. However, there is also evidence that neurogenesis (the birth of new neurons) continues in at least one part of the brain in adulthood. This is in the hippocampus, an area with an important role in learning and memory. The brain's continuing plasticity suggests that it is well designed for lifelong learning and adaptation to new situations and experiences, and such adaptation can even bring about significant changes in its structure (see page 21 for an example of this).



Brain Care

Omega-3

The existing research suggests that good regular dietary habits are probably the most important nutritional issue influencing educational performance and achievement²⁰. By contrast with the proven importance of having breakfast, evidence for the effectiveness of food supplements such as Omega-3 (in fish oils) is more controversial. There have been several studies exploring the effects of fatty-acid supplements on children with ADHD, but findings here have been contradictory and no clear consensus has emerged²¹. Further research may help explain why such supplements appear to work in some contexts for some individuals with ADHD²² and not in others²³. There has been a flourishing of products on supermarket shelves that provide supplementary Omega-3 despite the fact that, to date, there have been no published scientific studies that demonstrate Omega-3 supplements enhance school performance or cognitive ability amongst the general population of children. However, evidence for a link between ingesting Omega-3 and positive effects upon brain function does appear to be growing, with intake being correlated with reduced risks of dementia in later life²⁴ and consumption of fish during pregnancy being correlated with infant IQ²⁵.

Caffeine

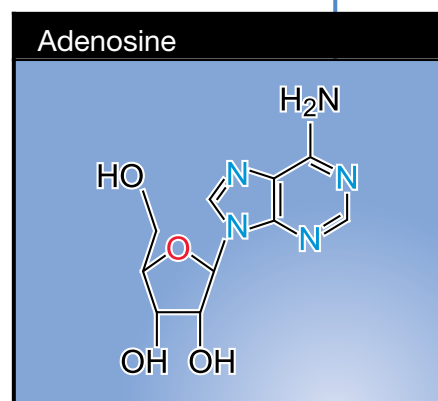
Caffeine is the only psychoactive drug legally available to children and their consumption of it is very widespread. A small 500 ml bottle of cola, such as those dispensed by a vending machine, has the same amount of caffeine as a cup of coffee. It is hardly surprising, therefore, that children commonly experience caffeine withdrawal^{26,27}. Researchers recently studied children aged 9-10 who habitually consumed the equivalent of no more than two cans a day of cola and showed these children demonstrated decreased alertness relative to low users. Their alertness only rose to baseline levels when they had received some caffeine and then, of course, only temporarily. Echoing the results of adult studies²⁸, it would appear that the cola 'caffeine fix' provides only a momentary return to the state of alertness offered by a caffeine-free lifestyle.

How does caffeine affect the learner?

The effects of caffeine (found in tea, coffee, cola, etc.) on our physiology and behaviour occur primarily because caffeine blocks the action of adenosine at adenosine receptors. Adenosine is produced naturally by the body. For example, adenosine levels increase during wakefulness and decrease during sleep. Adenosine receptors are found on the surface of cells, including neurons, throughout the body and brain. With regular consumption of caffeine, counter-regulatory changes occur in the adenosine system, which result in adverse effects when caffeine is withdrawn. Even overnight abstinence from caffeine can cause fatigue and slowed thinking and, although taking some more caffeine rapidly reverses these effects, it does not appear to increase functioning to above normal levels. It seems there is little net benefit for mood and cognitive function from regular caffeine consumption. Intermittent intake, as often occurs in children, increases the risk of experiencing the fatigue and headache of caffeine withdrawal.



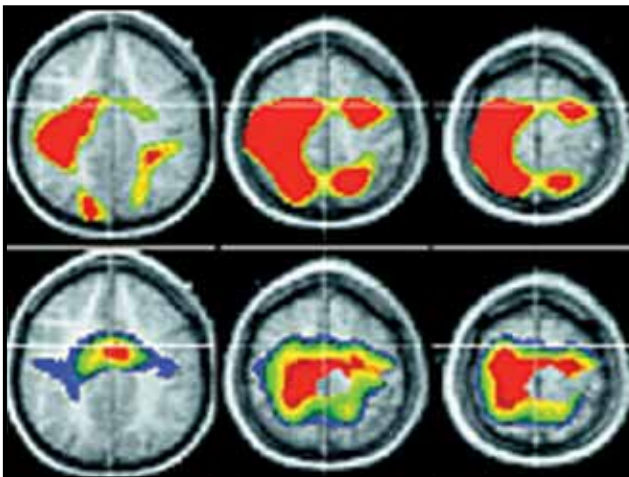
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Sleep

There is more bad news for the student ingesting caffeine to sustain late night revision: sleep is an important part of learning. Neuroscience is beginning to reveal the processes by which sleep helps us 'lay down' and consolidate our memories so that they remain more robust when we wish to access them later. The sleeping brain has even been shown to reproduce the neural activities that characterise whatever we experienced in our preceding hours of wakefulness²⁹. The neurotransmitter ACh (acetylcholine) has been identified as a 'switch' that changes our state of wakefulness and how we process information. High levels of ACh help maintain a wakeful state that supports the encoding of information, while low levels of ACh during sleep minimise the encoding of new memories but maximise consolidation of what has already been experienced³⁰. As well as helping us remember what we learn when awake, sleep also helps us prepare to learn more and use what we know to generate insights³¹. Regular and sufficient sleep is essential for the brain to learn efficiently.



Sleep is not just about resting but also about consolidating what we have learnt during the day. The sleeping brain (3 bottom images) appears to reproduce the neural activities resembling those recorded during preceding hours of wakefulness (3 top images)³².

Water

In a popular book on educational kinaesthetics (Brain Gym), Cohen and Goldsmith³³ ask teachers to encourage their children to sing (with the tune of "Frere Jacques"):

"Let's drink water, I love water.
It gives me En-er-gy"

The drinking of water has sometimes been promoted as a way to improve learning, usually on the basis that even small amounts of dehydration can reduce cognitive ability. There are very few studies investigating the effects of dehydration on children, but these few, together with adult studies³⁴, confirm the deleterious effect of even mild dehydration on our ability to think. However, a recent adult study has shown that drinking water when not thirsty can also diminish cognitive ability³⁵. In fact, we know that our brains possess a sophisticated system by which we become thirsty when our bodies (including our brains) need water. So encouraging children to drink water when they are thirsty may be a more sensible approach than constantly monitoring the amount of water they consume. Exercise and unusually hot weather are the exception to this rule, when there is evidence that children's own monitoring systems are less reliable and they should be encouraged to drink in order to avoid dehydration^{36,37}.



Neuroscience and Developmental Disorders

Dyslexia

Reading in adults is known to involve a network of language areas in the left hemisphere³⁸, including the posterior superior¹ temporal cortex. This area appears to be vitally involved in our ability to separate words into sound-based components. Such phonological skills are a good indicator of later reading ability and a recent study of young readers has shown that the amount of activity in this brain area correlates with these early phonological skills³⁹.

Children with developmental dyslexia display reduced activation in this and other typical left hemisphere sites for reading, and also show atypical engagement of right hemisphere sites^{40,41,42}. Some educational interventions that improve language outcomes have also been shown to help remediate these differences in neural activity^{43,44,45}. This research demonstrates the potential effectiveness of brain imaging in investigating both learning difficulties and the educational interventions intended to ameliorate them. It also demonstrates the plasticity of the brain and the need to avoid considering differences in brain activity between different groups of children (and indeed adults) as evidence for permanent, biologically determined differences in ability. Education can critically influence how the brain operates.

As our understanding improves and techniques are further developed, it may be possible to identify children at risk from dyslexia well before they begin school, allowing the earliest possible intervention. One promising technique is electroencephalography (EEG), which involves placing a net of electrodes on the scalp to detect and record the minute patterns of electrical activity produced by the brain. Because it is very non-invasive and child-friendly, it has already proved immensely useful in identifying the earliest stirrings of linguistic awareness (see box).

What does Electroencephalography (EEG) tell us about dyslexia?

EEG has revealed infant processing of the stress patterns of natural language via a measure called mis-match negativity – this is an electrical signal from the brain prompted by hearing a difference in sound. Studies of this signal have suggested that children can begin to distinguish different stress patterns as early as five months, and that the stress patterns of the language around them quickly attain a special status in their memory⁴⁶. Another EEG signal that is usually detectable by 19 months is the N400, an indicator of semantic integration or word meaning. The absence of this signal by 19 months can help predict whether expressive language difficulties will be present⁴⁷. Similar neural markers may be found for developmental dyslexia. One promising candidate is duration detection and another is insensitivity to the auditory parameters that yield the ‘stress beats’ or syllable rhythms of natural speech. In our research⁴⁸, we found significant differences in detection of the onset of the amplitude envelope (a cue to syllable stress) between dyslexic and normally-reading children, and between young early readers and normal developers. Dyslexic children were relatively insensitive, and young early readers were particularly sensitive. If such measures prove robust at the individual level, then EEG would offer a number of potential neural markers of risk for later language and reading impairments.



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¹Posterior meaning to the rear, superior meaning towards the top

Dyscalculia

What is Dyscalculia?

The DfES currently characterises developmental dyscalculia as a number-specific cognitive deficit – a difficulty in understanding simple number concepts, a lack an intuitive grasp of numbers and problems learning number facts and procedures. Even when a correct answer arises or a correct method is used, it may happen mechanically and without confidence. This difficulty is identifiable using tests that focus on the building blocks of number understanding, such as measuring the time taken to count objects and to order numbers by magnitude. These tests rely little on the child’s education, unlike standardised arithmetic tests. Developmental dyscalculia is not a consequence of other cognitive disabilities, and can appear in the most intelligent and well-educated of individuals – like dyslexia. It persists – probably in most cases – into adulthood. It seems to be congenital and there is evidence that abnormalities in the parietal lobe are involved.

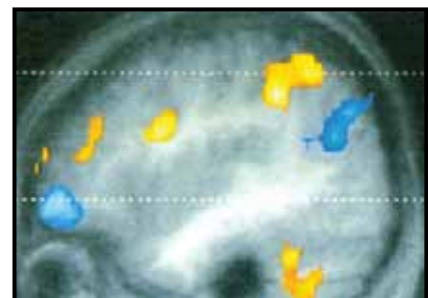


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Insights into the causes of dyscalculia, which is thought to affect about 4-6 per cent of children in the UK⁴⁹, are beginning to emerge from the neuroscience of mathematical processing. In a neuroimaging study involving normal participants, activity was observed in areas of the brain involved in word association and language activity, the left frontal and angular gyri, when participants calculated answers exactly⁵⁰. If the type of exact calculation we learn in school recruits areas of the brain associated with language, this suggests that the acquisition of formal mathematics relies on our ability to learn rules and procedures. However, when the same participants attempted to estimate answers, the role of a more ancient and innate ability to approximate was seen to be linked to bilateral activity in the intraparietal sulci.

Even at six months, it seems, most of us can approximately differentiate between large numbers of items for ratios of between 1:2 and 2:3⁵² and it seems that we share this approximate number sense with other animals⁵³. Such innate mathematical ability may have a critical role in ‘bootstrapping’ our capacity to formally grasp exact differences and procedures^{54,55}. Dyscalculia has been linked to a deficit in these ‘premathematical’ abilities.

A study⁵⁶ of low birth-weight adolescents with numerical difficulties revealed less gray matter in an area of the intraparietal sulcus. Further research is needed to confirm the direction of cause and effect in such studies, but insights from brain imaging research are already inspiring interventions based on new notions of how we develop our mathematical ability, and some of these are showing promise (for example, see Liane Kaufmann’s research on page 22).



Side view of left hemisphere activities when participants were asked to carry out exact calculations (in blue) and approximations (in yellow)⁵¹.



ADHD

Approximately 3-6 per cent⁵⁷ of the school-age population is thought to suffer from Attention Deficit Hyperactivity Disorder (ADHD). The behaviour of these children may be characterised as inattentive, overactive and impulsive. They present a particular challenge to the teacher, and to themselves. The overt activity of children with ADHD can often distract teachers from empathising with these pupils, who are often made frustrated and distressed by their own behaviour.

The neuroscience of ADHD is still not clear but, from the many studies conducted, some agreement is emerging that sufferers exhibit neural differences in areas such as the anterior cingulate and prefrontal cortex. Although our understanding of ADHD at a brain level is still the subject of debate, its treatment has increasingly involved the psychoactive drug methylphenidate, most commonly sold as Ritalin. In 1991, only 2000 prescriptions for this drug were given out in the UK. By 2005, this figure had risen to 359,000, and it is currently growing by 18 per cent per year⁵⁸. There are now concerns about the long-term effects of drugs such as methylphenidate on the developing brain⁵⁹ although the use of medication seems likely to endure as an important part of the solution for many families.

However, the prevalence of drugs in the treatment of ADHD does not mean that this disorder is wholly a medical problem beyond the influence of the school environment. On the contrary, there is growing evidence that teachers following informed strategies can play an important role in improving the well-being and academic performance of students suffering from ADHD^{60,61,62}. Recent successful interventions include the application of cognitive and instructional approaches to managing children's behaviour, the inclusion of parents and teachers in such interventions and the training of students themselves in self-management. Such research emphasises the importance of teachers' understanding of the disorder, its medication and management.

Why "ADHD"?

The idea of ADHD – Attention Deficit/Hyperactivity Disorder – identifies an important way in which children differ. Some are much more impulsive, restless and disorganised than others; and the strongest influences on this variation are genes that affect brain chemistry and neuropsychological functioning. It is really helpful to use the idea in education because:

- It emphasises that it is not a moral failing; the children cannot just choose not to have ADHD
- There are some ways of teaching that suit such children better than the ordinary style of curriculum and classroom management – and these deserve to be in a school's repertory
- At the extreme of variation, some children will receive a medical diagnosis and perhaps medication. Then it is important for there to be good communication between the prescriber and the school



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Strategies for Teaching and Learning

Commercial 'Brain-based' Programmes

Since the 1990's, an increasing number of educational programmes have claimed to have a 'brain basis'. There are few examples of such programmes having been evaluated, and they often appear to have developed without neuroscientific scrutiny.

Some of the ideas promoted by these programmes have become part of the educational culture in many schools. In the survey mentioned at the beginning of this commentary, about 30 per cent of teachers attending an INSET day had already heard of the commercial programme known as 'Brain Gym'⁶³. This programme promotes the idea that neural mechanisms can be influenced by specific physical exercises. The pseudo-scientific terms that are used to explain how this works, let alone the concepts they express, are unrecognisable within the domain of neuroscience. For example, there is a claim that, if children provide pressure on their 'brain buttons', they can help re-establish the brain organisation required for reading and writing⁶⁴. 'Brain buttons' are described as indentations between the 1st and 2nd ribs directly under the collar bone to the right and left of the breastbone. Other exercises include the Cross-crawl, promoted on the basis of activating left/right, top/bottom and back/front areas of the brain simultaneously, and varieties of 'Hook-up' for calming and stress-relieving effects.

Approaches to learning that come under the broad heading of 'Accelerated Learning' are a more eclectic mixture of ideas from popularly-reported neuroscience and psychology, synthesised with practice derived from classroom experience. In books that promote accelerated learning, concepts from psychology and neuroscience are often introduced as a means to promote and explain learning processes. However, these too often do not survive scientific scrutiny. For example, as in Brain Gym, there is a still an emphasis on the desirability of balance between the left and right part of the brain. In Smith⁶⁵, we are reminded 'Remember that the synergy generated in creating new pathways between left and right results in all-round improvement'. In fact, except in the rare case of brains which have been lesioned, pathways exist permanently between the left and right hemispheres, most notably via the corpus callosum. At present, there is no scientific evidence to suggest we can voluntarily create new ones.

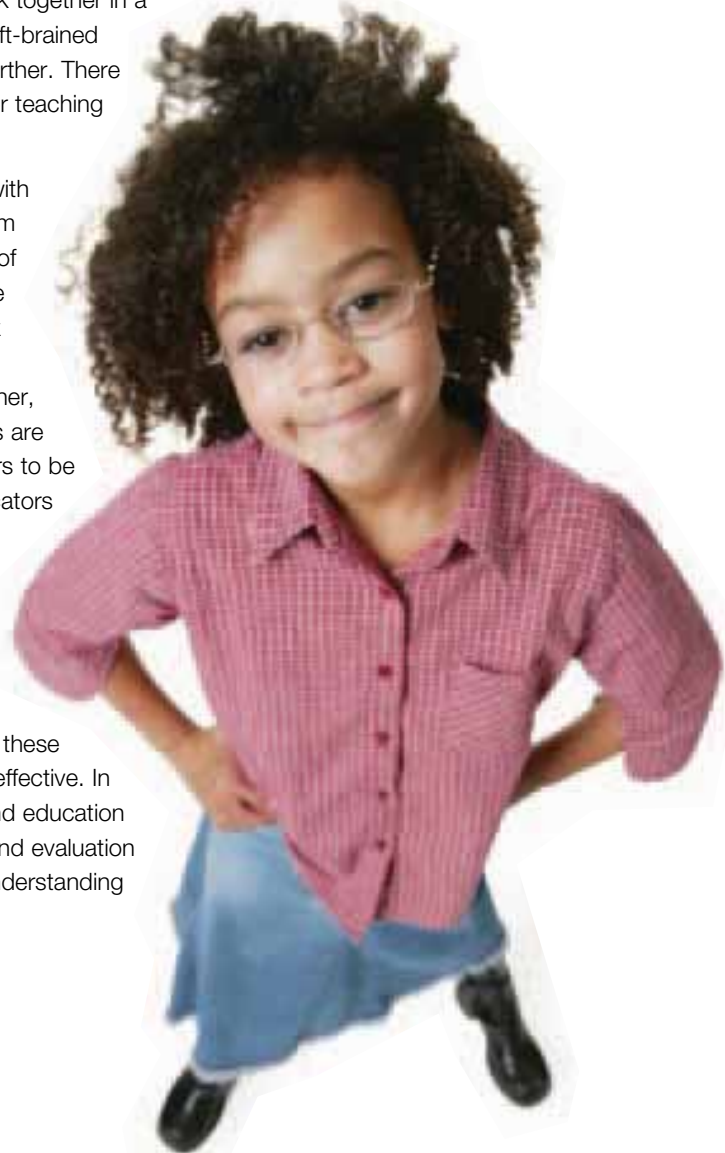




Accelerated learning also embraces other popular brain concepts such as Learning Style Preferences. Here, psychological evidence supports the possibility that individual preferences exist regarding how we like to learn. In education, learners may be allocated to one of three types of learning style (Visual, Auditory or Kinesthetic – VAK). Some believe that presenting material in a way that suits an individual's preferred learning style can improve their learning. (Note that it could also be argued that the reverse might also be helpful, as a remedial intervention to improve processing associated with the other learning styles.) However, there is a considerable scarcity of quality research to support the value of identifying learning styles⁶⁶. A recent psychological investigation of the VAK principle tested recall of information presented in the three different styles⁶⁷. This study showed no benefit from having material presented in one's preferred learning style, concluding that attempts to focus on learning styles were 'wasted effort'. Of course, this does not detract from the general value for all learners when teachers present learning materials using a full range of forms and different media. Such an approach can engage the learner and support their learning processes in many different ways, but the existing research does not support labelling children in terms of a particular learning style.

Variations on the basic concept of learning preferences and styles can include sorting pupils into other types of category. For example, some texts encourage teachers to determine whether a child is left or right brained⁶⁸. It is true that some tasks can be associated with extra activity that is predominantly in one hemisphere or the other. For example, language is considered to be left lateralised. However, no part of the brain is ever normally inactive in the sense that no blood flow is occurring. Furthermore, performance in most everyday tasks, including learning tasks, requires both hemispheres to work together in a sophisticated parallel fashion. The division of people into left-brained and right-brained takes the misunderstanding one stage further. There is no reliable evidence that such categorisation is helpful for teaching and learning.

Many ideas about the brain in education may be at odds with present scientific understanding, but perhaps not all of them should be dismissed entirely. For example, short sessions of Brain Gym exercise have been shown to improve response times⁶⁹, and such strategies, if they are effective, may work because exercise can improve alertness. If they do help learning, the basis for this effect should be researched further, to support improved understanding and practice. Teachers are not always satisfied with knowing that an approach appears to be working. They would also like to know why and how. Educators also care about the validity of scientific claims used to promote an idea⁷⁰ while a greater understanding of underlying processes also contributes to more effective evaluation. One thing is clear. Education has already invested an immense amount of time and money in 'brain-based' ideas that were never based on any recognisable scientific understanding of the brain. Many of these ideas remain untested and others are being revealed as ineffective. In the future, an improved dialogue between neuroscience and education will be critical in supporting the development, application and evaluation of educational programmes based on a sound scientific understanding of the brain.





Brain scan to lesson plan – the role of cognition

Many different experimental techniques are used in brain research. But the outcomes of high resolution imaging such as functional Magnetic Resonance Imaging (fMRI) have probably attracted the greatest popular interest. However, such techniques only provide us with an image of the biological changes occurring in the brain, such as blood flow. They do not allow us to ‘see’ thinking or learning directly. To understand what such an image has to do with learning, we need a psychological model to help us relate it to our mental processes – i.e. a cognitive model. When cognitive models and our knowledge of biological processes inform each other, we can feel more confident about both. Cognitive neuroscience is very much concerned with exploring this relationship between the biology of the brain and the cognition of the mind. In this way, cognitive neuroscience is also drawing new attention to a variety of existing psychological concepts relevant to education, and in a very visual manner.

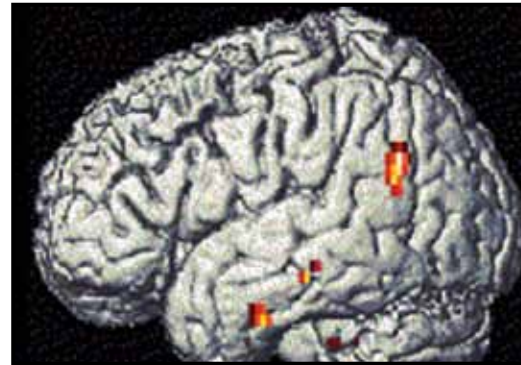
Examples of Environmental factorsected	Examples of Intra-individual factors	Factor aff
Oxygen Nutrition Toxins	Synaptogenesis Synaptic pruning Neuronal connections	BRAIN
Teaching Cultural institutions Social factors	Learning Memory Emotion	MIND
Temporary restrictions e.g. teaching tools	Performance Errors Improvement	BEHAVIOUR

A model of Brain->Mind->behaviour from cognitive neuroscience. Scientifically observable facts reside at the brain and behaviour levels, but cognitive theories are required to link these together⁷¹.

Working memory is one example of how neuroscience is helping to ‘concretise’ psychological concepts. Working memory refers to our capacity to temporarily hold a limited set of information in our attention when we are processing it. This limitation is the reason why we prefer to write down a telephone number a few digits at a time rather than be told the whole number and then start writing. The average upper limit of this type of memory is about seven chunks of information, but there are individual differences in this limit that are linked to differences in educational achievement⁷². However, understanding pupils’ dependency upon working memory becomes more ‘real’ when brain activities associated with mathematical training are visible. In one recent study, adults learning long multiplication demonstrated a shift, with practice, in the areas of the brain they were using to complete their calculations⁷³. At first, considerable demand upon working memory was demonstrated by activity in the left inferior frontal gyrus, as students explicitly and formally followed the processes they were learning. After practice, this activity reduced and was replaced by greater activity in the left angular gyrus, as processes became more automatic. The images generated by this study provide a helpful and very visual illustration of how the types of mental resource required to solve a problem change with practice. They resonate well with classroom observations of the difficulties faced by many learners when engaging with new problems. In such situations, it can be particularly helpful for pupils to show their working since, apart from many other advantages, external representations can help offload some of these heavy initial demands upon working memory.



Hot spots show where brain activity decreased after participants undertook mathematical training – reflecting a decreased demand on working memory



A different analysis of the same participants, this time with hot spots showing areas where brain activity increased after mathematical training – reflecting an increase in automatic processing⁷⁴

Many other psychological insights being explored by neuroimaging have broad implications for teaching and learning strategies. For example, it has been known for some time that visualisation is a useful strategy for learning. As well as being able to produce strong physiological responses, we now know that visualising an object recruits most of the brain areas activated by actually seeing it⁷⁵. This ability of mental imagery to engage so much of the brain circuitry involved with a real perceptual experience emphasises its potential power and usefulness as a learning tool.

The construction of meaning has also been identified as a key to understanding and remembering information. When we learn new information, the links that form between this new information and our existing knowledge serve to make it meaningful. An area of the left hemisphere, the left inferior prefrontal cortex, has been identified as a vital structure in this construction of meaning. When learning something new, additional activity in this area occurs when we try to decide upon its meaning in relation to what we know already. The new information becomes more memorable once we have completed this process of ‘meaning making.’ How much more memorable the information becomes is linked to the amount of increased neural activity in the left inferior prefrontal cortex⁷⁶.

A better understanding of the earliest processes involved in learning a new subject may also help orientate new approaches to mainstream teaching. Again, psychological data suggests that we have an automatic and early preference to represent the magnitude of a number as if on a line travelling from left to right⁷⁷. Neuroimaging studies have linked this ability to activity in the intraparietal sulcus⁷⁸ and Goswami⁷⁹ suggests that such evidence supports spatially-based approaches to teaching about ordinality (i.e. the order and sequence of numbers) and place value. These approaches include using empty number lines to improve efficiency, for example when adding and subtracting numbers of more than one digit⁸⁰.



Issues on the Horizon

Smart Pills

Although the use of methylphenidate (e.g. Ritalin) has accelerated in recent years, it is still generally confined to a particular group of students and requires a prescription. There is now a new wave of drugs being developed that may find a broader market amongst learners. A recent report commissioned by the Office of Science and Innovation foresees that cognitive enhancers (or 'cogs', 'smart pills') will start appearing in the UK labour force around 2011 and, by 2017, may become "an acceptable part of the knowledge professional's tool kit"⁸¹. The first generation of these drugs was developed to help relieve memory loss amongst sufferers of Alzheimer's disease, and their prescribed use is currently very restricted. One drug, donepezil, operates by inhibiting the chemical cholinesterase in the brain. This chemical is part of the brain's housekeeping system, and mops up some of the neurotransmitter acetylcholine which, as discussed on page 13, is produced by circuits responsible for working memory and attention, which in turn influence the encoding of long-term memory. By inhibiting the clean-up operation, these circuits are allowed to produce more acetylcholine, allowing the brain to work at higher levels of efficiency. Donepezil has been found to significantly improve the memory of healthy adults, including young adults⁸². Some well-respected scientists are now suggesting that all of us might benefit from such drugs in the future. The neuroscientist Michael Gazzaniga wrote recently "The government should keep out of it, letting our own ethical and moral sense guide us through the new enhancement landscape"⁸³.

Despite reports in the popular press, smart pills are not about to be stacked next to vitamins on supermarket shelves, but they can already be purchased over the internet. Attitudes to them are likely to be different from those associated with the casual use of drugs for leisure. Pressures to use them will be economic and professional. Undergraduates' well-known tendency to experiment, combined with strong professional motivations, may produce particularly high rates of use in some areas of higher education, where their use may be inspired more by office culture than club culture.

Discussion during the recent TLRP seminar series included a focus on the ethical implications of cognitive enhancers for education. Various questions emerged about their use. Is the value of a qualification reduced by having used drugs to achieve it and, if so, will measures be required to monitor and regulate drug use? Will these drugs worsen the division between the rich and poor in terms of access to education?





Neurofeedback

Neurofeedback refers to the monitoring of one's own brain activity with a view to influencing it. Recent work investigating electroencephalographic (EEG) neurofeedback has found it helpful in improving the performance ability of music students. Conservatoire students received training using neurofeedback and improvements in their musical performance were highly correlated with their ability to progressively influence neural signals associated with attention and relaxation⁸⁴. Similar results have been found for dancers⁸⁵. This is an interesting and unusual example of a technique being borrowed from neuroscience to provide direct improvements for learners. Despite its apparent success, these interventions are not built around any particular cognitive model and the processes involved are not completely understood. However, the helpfulness of EEG feedback in raising levels of attention indicates its potential benefit in a broad variety of educational areas⁸⁶.



Does neurofeedback work?

The results of our research with RCM students showed that one particular neurofeedback protocol had quite a beneficial effect on the quality of students' performances, in some cases improving performance marks by as much as one degree class. Furthermore, the students who showed the greatest improvement were those who had learned the neurofeedback protocol most successfully. The challenge for the Royal College of Music – and indeed other Higher Education music institutions – is to determine the best means for integrating such successful learning interventions into our curricula.



Dr Aaron Williamon
Royal College of Music

Biology is not Destiny

The existence of differences in brain structure or function between different groups of learners may inspire insights and contribute to more effective learning programmes and interventions. However, it can also lead to unhelpful notions of permanent deficits and of ceilings to performance that are biologically determined.

This was illustrated recently in the public debate inspired by ‘The Dyslexia Myth’ on Channel 4 (2005), which demonstrated how easily biological knowledge becomes incorrectly and unhelpfully associated with deterministic ideas. Commentators noted how the original TV documentary promoted “all-or-none theorising amongst the public” and how these misconceptions highlighted the need to “combine formal and pedagogic approaches, preferably incorporating modern views on brain function”⁸⁷. The call to include modern neuroscience arises because current developmental cognitive neuroscience avoids predictive mechanisms of biological cause and effect⁸⁸. Current resonances between neuroscience and education encourage models of learning that emphasise the complexity of interaction between biological and educational environments, and the enduring possibility of mitigation (see box).

“

Cause is not an easy word. Its popular use would be laughable if it was not so dangerous, informing, as it does, government policy on matters that affect us all. There is no single cause of anything and nothing is determined.

”



Professor John Morton
Institute of Cognitive Neuroscience
University College London

Biology provides no simple limit to our learning, not least because our learning can influence our biology. For example, although the number of neurons we possess does not change greatly throughout the lifecourse, it has been known for some time that experience can change the number of connections between them, our synaptic density. More recently, there have been several pieces of research demonstrating how even the structure of the brain, including the adult brain, can be changed by educational experience. In a recent study of juggling, the brain areas activated at the beginning of a three-month training period increased in size by the end of it. After three months of rest, these areas had shrunk back and were closer to their original size⁸⁹. This graphic example of ‘if you don’t use it, you lose it’ demonstrates the potential importance of education in mediating brain development throughout our lives. Further evidence of the effects of education on brain structure comes from research into Alzheimer’s disease, which is associated with the death of brain cells due to the development of deposits called plaques within the brain and the formation of tangles of fibrils within individual brain cells. Despite the biological basis of the disease, it is becoming increasingly clear that the risks of developing Alzheimer’s in later life are reduced not only by previous educational attainment⁹⁰, but also by the level of challenge encountered in one’s working life⁹¹. Even after the onset of Alzheimer’s, there is evidence that the progress of some symptoms can be diminished by training⁹².



The Future: Can Education, Neuroscience and Psychology Work Together?

Our burgeoning knowledge of the brain is producing expectations of new educational insights, and many such insights are already beginning to surface. At the same time, neuroscientists are becoming increasingly interested in how the brain functions in complex environments more closely resembling those found in classrooms. Education thus appears set to become an interesting area of challenge for cognitive neuroscience, as it attempts to explore new contexts. Some neuroscientists have even suggested that education might be considered as “a process of optimal adaptation such that learning is guided to ensure proper brain development and functionality”⁹³. This sense of increasing mutual interest underlies calls for a two-way dialogue between neuroscience and education that could helpfully inform both areas⁹⁴. On a broader canvass, the synergy of psychology and education has a very long history – though one which has not been so much in evidence in recent decades.

Of course, brain scans cannot give rise directly to lesson plans. There is a need for bridging studies that interpret scientific results in terms of possible interventions, and evaluation of these interventions in suitable learning contexts. One example of such research comes from Innsbruck, where brain imaging and educational interventions have both been used to understand the basis of dyscalculia and methods to remediate it^{95,96}. Experimental imaging results suggested the need for basic numerical and conceptual knowledge at an early stage of mathematics education. A classroom intervention also demonstrated that children with dyscalculia can show considerable improvements in a broad range of calculation abilities when these areas of learning, often neglected in school mathematics, are specifically focused upon. Another challenge for professionals dealing with dyscalculia concerns the fact that calculation abilities often appear to be related to non-numerical skills such as visual-spatial cognition, language, working memory etc. Thus, only a very small proportion of children with calculation difficulties exhibit a ‘pure’ dyscalculia, with most having difficulties in non-numerical domains as well. In order to track down the neurocognitive overlaps of the symptoms of dyscalculia and spatial deficiencies, an ongoing fMRI project involving Liane Kaufmann is using fMRI to delineate these two areas in children with and without dyscalculia (see box). A deeper understanding of the interplay between numerical and spatial cognition appears likely to influence teaching methods and mathematics curricula in the future.

“

Neuroscientists are putting increasing efforts into developing imaging paradigms with process-orientated tasks that are also ecologically valid and educationally relevant...but there’s still a long way to go. Nevertheless, I’m convinced a better understanding of the neural underpinnings of behaviour and learning will not only enhance our knowledge of how the brain-behaviour relationship develops, but will also help tailor pedagogical curricula towards pupils’ individual neurocognitive resources.

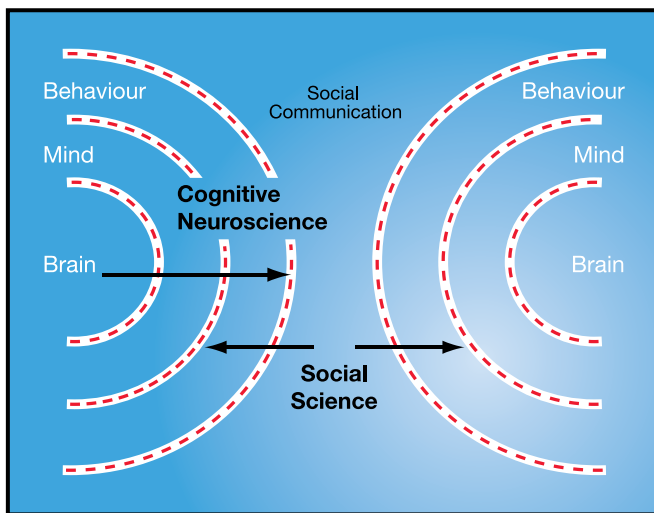
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Dr Liane Kaufmann
Innsbruck University Children’s Hospital



There is also a growing need for collaborations between neuroscience, psychology and education that embrace insights and understanding from each perspective, and that involve educators and scientists working together at each stage. Such collaborations are not straightforward, since the philosophies of education and natural science are very different – with various forms of psychology, in a sense, bridging the two. Educational research, with its roots in social science, places strong emphasis upon the importance of social context and the interpretation of meaning. Natural science, on the other hand, is more concerned with controlled experimental testing of hypotheses and the development of generalisable cause-effect mechanisms. This suggests that collaborative research projects may need to extend the cognitive neuroscience model of brain->mind->behaviour illustrated on page 17, to incorporate processes of social construction pertinent to learning. Although challenging, such interdisciplinary projects may be the most effective way to co-construct and communicate concepts involving neuroscience, psychology and education that are both scientifically sound and educationally relevant.



To interrelate the most valuable insights from cognitive neuroscience and the social science perspectives of education and psychology (represented by arrows), the brain->mind->behaviour model may need to be extended. Even the example of two individuals interacting, as represented here, is suggestive of the complexity that can arise when behaviour becomes socially mediated. Such complexity remains chiefly the realm of social scientists, who often interpret the meaning of such communication in order to understand the underlying behaviour. Cognitive neuroscience has established its importance in understanding behaviour at an individual level but is only just beginning to contemplate the types of complex social domains studied by researchers in social psychology and education.

A recent example of this type of collaboration arose in the teaching of drama. Here, an educational question about the fostering of creativity resulted in an fMRI study in which trainee teachers participated⁹⁷. The study revealed that brain activities associated with creative effort increased when the initial stimuli for a creative story decreased in their relatedness to each other. For example, producing a story that includes the words ‘dolphin, jewel, print’ produced more activity in areas associated with creative effort than ‘artist, brushes, paint’. The stories produced using unrelated words were also judged as more creative by an independent panel, but the fMRI results suggest this is linked to increased ‘creative’ brain activity rather than arising simply from the story including three unrelated words. These results, combining insights at an educational and brain level, support the value of such strategies in fostering creativity in the classroom and have prompted further insights into their application. Teacher trainers are now using the results of this study, together with other insights from neuroscience and psychology, in a project to help enhance trainees’ understanding about fostering creativity in their pupils⁹⁸. The project aims to co-construct, with the trainee teachers, an understanding that is scientifically valid and suitable for non-specialist communication. Such interdisciplinary research may be an efficient way to approach the challenging interface between neuroscience, psychology and education, both in terms of revealing new insights and through the development of a common language by which to express them.



The Need for Cautious Optimism

We are still at an early stage in our understanding of the brain. Most of what we know arises from scientific experimentation, in environments that differ greatly from everyday learning contexts. Another limitation in applying such studies is their focus upon individual cognitive factors rather than the complex abilities required in everyday or academic settings. And, even in respect of these basic cognitive factors, many recent findings have served to emphasise how much more there is to know.

The techniques being used to explore the brain are developing rapidly, but many important limitations still exist here too. EEG can provide accurate timing information but provides little impression of where in the brain a particular activity is occurring. In contrast, fMRI provides some accurate idea of the location of brain activity, but is less effective when it comes to identifying when it occurs, especially on a cognitive time scale of milliseconds. Also, techniques such as fMRI are often not considered suitable for routine studies using children, so most fMRI investigations only involve adult participants. The neuroimaging literature tells us more about the adult brain than about that of a developing child.

Given these and other limitations, considerable caution needs to be applied when attempting to transfer concepts between neuroscience and education. Such attempts need to be well-informed by expertise from within both fields. On the other hand, to ignore the relevance of present neuroscientific understanding to education flies in the face of a common-sense connection. There is a belief, shared by an increasing number of researchers in both fields, that neuroscience has a fundamental and increasing relevance to education that, together with related psychological perspectives, needs to be cautiously explored. More pressingly, popular ideas about the brain have flourished without check and are impacting upon teaching and learning already. Such ideas deserve improved scientific and educational evaluation. New developments on the horizon, including the enhancement of brain function, further emphasise the need for educational perspectives that include a greater understanding of developments within neuroscience. In the future, neuroscience promises to positively influence the policy, practice and experience of education in a number of important areas, but the full and successful realisation of that promise will require careful educational and scientific scrutiny at all stages.





References

1. Pickering, S. J. and Howard-Jones, P.A. (2007) Educators' views of the role of Neuroscience in Education: A study of UK and International perspectives, *Mind, Brain and Education*, 1(3)
2. Byrnes, J.P. and Fox, N.A. (1998) The educational relevance of research in cognitive neuroscience, *Educational Psychology Review*, 10(3), 297-342
3. Geake, J.G. and Cooper, P.W. (2003) Implications of cognitive neuroscience for education. *Westminster Studies in Education*, 26(10), 7-20
4. Goswami, U., Thomson, J., Richardson, U., Stainthorpe, R., Hughes, D., Rosen, S. and Scott, S.K. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis, *Proceedings of the National Academy of Sciences*, 99 (16), 10911-10916
5. Goswami, U. (2006) Neuroscience and Education: From Research to Practice? *Nature Reviews Neuroscience* 7(5), 406-413
6. Blakemore, S.J. and Frith, U. (2000) *Report on the implications of recent developments in neuroscience for research on teaching and learning*, a consultation paper commissioned by the Teaching and Learning Research Programme, ESRC
7. OECD (2002) *Understanding the brain: Towards a new learning science*, Paris: OECD Publications
8. Rakic, P. (1995). Corticogenesis in human and non-human primates. In M.S. Gazzaniga (Ed.) *The Cognitive Neurosciences* (pp 127-145). Cambridge, MA: MIT Press
9. Kuhl, P.K., Williams, K.A., Lacerda, F., Stevens, K.N. and Lindblom, B. (1992) Linguistic experience alters phonetic perception in infants by 6 months of age, *Science*, 255 (5044), 606-608
10. Diamond, M.C., Greer, E.G., York, A., Lewis, D., Barton, T. and Lin, J. (1987) Rat cortical morphology following crowded-enriched living conditions, *Experimental Neurology*, 96 (2), 241-247
11. Blakemore, S.J., and Frith, U. (2005) *The Learning Brain: lessons for education*. Oxford: Blackwell Publishing
12. Huttenlocher, P.R. (1979) Synaptic density in human frontal cortex – developmental changes and effects of aging, *Brain Research*, 163, 195-205
13. Sowell, E.R., Peterson, B.S., Thompson, P.M., Welcome, S.E., Henkenius, A.L. and Toga, A.W. (2003) Mapping cortical change across the human life span, *Nature Neuroscience*, 6 (3), 309-315
14. McGivern, R.F., Andersen, J., Byrd, D., Mutter, K.L. and Reilly, J. (2002). Cognitive efficiency on a match to sample task decreases at the onset of puberty in children. *Brain and Cognition*, 50, 73-89
15. Mackinlay, R., Charman, T. and Kamiloff-Smith, A. (2003). Remembering to remember: A developmental study of prospective memory in a multitasking paradigm, Poster presented at the Society for Research in Child Development, Biennial Meeting, Tampa, Florida, 24-27 April.
16. Blakemore S.J. and Choudhury, S. (2006) Development of the adolescent brain: implications for executive function and social cognition, *J Child Psychol Psychiatry*, 47(3-4), 296-312
17. Choudhury, S., Blakemore, S. J. and Charman, T. (2006) Social cognitive development during adolescence, *Social Cognitive and Affective Neuroscience*, 1, 165-174
18. Luna, B. (2004) Algebra and the adolescent brain, *Trends in Cognitive Sciences*, 8, 437-439
19. Qin, Y., Carter, C.S., Silk, E.M., Stenger, V.A., Fissell, K., Goode, A. and Andersen, J.R. (2004) The change of the brain activation patterns as children learn algebra equation solving, *Proceedings of the National Academy of Sciences*, 101, 5686-5691
20. Bellisle, F. (2004) Effects of diet on behaviour and cognition in children, *British Journal of Nutrition*, 92: S227-S232 Suppl. 2
21. Richardson, A. J. (2006) Omega-3 fatty acids in ADHD and related neurodevelopmental disorders, *International Review of Psychiatry*, 18(2), 155-172
22. Richardson A.J. and Puri B.K. (2002) A randomized double-blind, placebo-controlled study of the effects of supplementation with highly unsaturated fatty acids on ADHD-related symptoms in children with specific learning difficulties, *Prog Neuropsychopharm Biol Psychiat*, 26(2) 233-239
23. Voigt, R. G., Llorente, A.M., Jensen, C.L., Fraley, J.K., Berretta, M.C. and Heird, W.C. (2001) A randomized, double-blind, placebo-controlled trial of docosahexaenoic acid supplementation in children with attention-deficit/hyperactivity disorder, *The Journal of Pediatrics*, 139, 189-96
24. Morris, M.C., Evans, D.A., Bienias, J.L., Tangney, C.C., Bennett, D.A., Wilson, R.S., Aggarwal, N. and Schneider J (2003) Consumption of fish and n-3 fatty acids and risk of incident Alzheimer disease, *Archives of Neurology*, 60 (7), 940-946
25. Oken, E., Wright, R.O., Kleinman, K.P., Bellinger, D., Amarasiwardena, C.J., Hu, H., Rich-Edwards, and J.W. Gillman, M.W. (2005) Maternal fish consumption, hair mercury, and infant cognition in a US cohort, *Environmental Health Perspectives*, 113 (10), 1376-1380
26. James, J.E. (1997) *Understanding Caffeine: A biobehavioural analysis*, Thousand Oaks, CA: Sage
27. Heatherley, S.V., Hancock, K.M.F. and Rogers, P.J. (2006) Psychostimulant and other effects of caffeine in 9- to 11-year-old children, *Journal of Child Psychology and Psychiatry*, 47:2 (2006), 135-142
28. Rogers, P.J. and Démoncourt, C. (1998) Regular caffeine consumption: A balance of adverse and beneficial effects for mood and psychomotor performance, *Pharmacology Biochemistry and Behaviour*, 59, 1039-1045
29. Maquet, P., Laureys, S., Peigneux, P., Fuchs, S., Petiau, C., Phillips, C., Aerts, J., Del Firoe, G., Degueldre, C., Meulmans, T., Luxen, A., Franck, G., Van Der Linden, Smith, C. and Cleermans, A. (2000) Experience dependent changes in cerebral activation during human REM sleep, *Nature Neuroscience*, 3(8), 831-6
30. Rasch, B.H., Born, J. and Gais, S. (2006) Combined blockade of cholinergic receptors shifts the brain from stimulus encoding to memory consolidation, *Journal of Cognitive Neuroscience*, 18(5), 793-802
31. Wagner, U., Gais, S., Haider, H., Verleger, R. and Born, J. (2004) Sleep inspires insight, *Nature*, 427 (6792): 352-5
32. Maquet, P., Laureys, S., Peigneux, P., Fuchs, S., Petiau, C., Phillips, C., Aerts, J., Del Firoe, G., Degueldre, C., Meulmans, T., Luxen, A., Franck, G., Van Der Linden, Smith, C. and Cleermans, A. (2000) Experience dependent changes in cerebral activation during human REM sleep, *Nature Neuroscience*, 3(8), 831-6. Adapted by permission from Macmillan Publishers Ltd: *Nature Neuroscience*, 3(8) (2000)



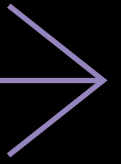
References (continued)

33. Cohen, I. and Goldsmith, M. (2000) *Hands On: how to use Brain Gym ® in the Classroom*, Sea Point, South Africa: Hands On Books
34. Cian, C., Koulmann, N., Barraud, P.A., Raphel, C., Jimenez, C., and Melin, B. (2000) Influence of variations in body hydration on cognitive function: effect of hyperhydration, heat stress, and exercise-induced dehydration, *Journal of Psychophysiology*, 14, 29-36
35. Rogers, P.J., Kainth, A. and Smit, H.J. (2001) A drink of water can improve or impair mental performance depending on small differences in thirst, *Appetite*, 36, 57-58
36. Bar-David, Y., Urkin, J. and Kozminsky, E. (2005) The effect of voluntary dehydration on cognitive functions of elementary school children, *Acta Paediatrica*, 94, 1667-1673
37. Bar-Or, O., Dotan, R., Inbar, O., Rotshstein, A. and Zonder, H. (1980) Voluntary hypohydration in 10 to 12 year old boys, *Journal of Applied Physiology*, 48, 104-8
38. Fiez, J.A. and Petersen, S.E. (1998) Neuroimaging studies of word reading. *Proceedings of the National Academy of Sciences*, 95, 914-921
39. Turkeltaub, P.E., Gareau, L., Flowers, D.L., Zeffiro, T.A., Eden, G.F. (2003) Development of neural mechanisms for reading, *Nature Neuroscience*, 6(6), 767-773
40. Temple, E. Poldrack, R.A., Salidis, J., Deutsch, G.K., Tallal, P., Merzenich, M.M. and Gabrieli, J.D.E. (2001) Disrupted neural responses to phonological and orthographic processing in dyslexic children: an fMRI study, *Neuroreport*, 12, 299-308
41. Shaywitz, B.A., Shaywitz, S.E., Pugh, K.R., Mencl, W.E., Fullbright, R.K., Skudlarski, P., Constable, R.T., Marchione, K.E., Fletcher, J.M., Lyon, G.R. and Gore, J.C. (2002) Disruption of posterior brain systems for reading in children with developmental dyslexia, *Biological Psychiatry*, 52 (2), 101-110
42. Shaywitz, S.E., Shaywitz, B.A., Fulbright, R.K., Skudlarski, P., Mencl, W.E., Constable, R.T., Pugh, K.R., Holahan, J.M., Marchione, K.E., Fletcher, J.M., Lyon, G.R. and Gore, J.C. (2003) Neural systems for compensation and persistence: young adult outcome of childhood reading disability, *Biological Psychiatry*, 54 (1) 25-33
43. Shaywitz, B.A., Shaywitz, S.E., Blachman, B.A., Pugh, K.R., Fullbright, R.K., Skudlarski, P., Mencl, W.E., Constable, R.T., Holahan, J.M., Marchione, K.E., Fletcher, J.M., Lyon, G.R. and Gore, J.C. (2004) Development of left occipitotemporal systems for skilled reading in children after a phonologically- based intervention, *Biological Psychiatry*, 55(9), 926-933
44. Temple, E. et al. (2003) Neural deficits in children with dyslexia ameliorated by behavioral remediation: Evidence from functional fMRI, *Proceedings of the National Academy of Sciences*, 100, 2860-2865
45. Simos, P.G., Fletcher, J.M., Bergman, E., Breier, J.I., Fooman, B.R., Castillo, E.M., Davis, R.N., Fitzgerald, M. and Papanicolaou, A.C.(2002) Dyslexia-specific brain activation profile becomes normal following successful remedial training, *Neurology*, 58(8), 1203-1213
46. Weber, A., Hahne, A., Friedrich, M. and Friederici, A.D. (2004). Discrimination of word stress in early infant perception: *Electrophysiological evidence, Cognitive Brain Research*, 18, 149-161
47. Friedrich, M. and Friederici, A.D. (2006). Early N400 development and later acquisition, *Psychophysiology*, 43, 1-12
48. Goswami, U., Thomson, J., Richardson, U., Stainthorp, R., Hughes, D., Rosen, S. and Scott, S.K. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis, *Proceedings of the National Academy of Sciences*, 99 (16), 10911-10916
49. Lewis, C., Hitch, G. and Walker, P. (1994). The prevalence of specific arithmetic difficulties and specific reading difficulties in 9- and 10-year-old boys and girls, *Journal of Child Psychology and Psychiatry*, 35, 283-292
50. Dehaene, S., Spelke, E., Pined, P., Stanescu, R. and Tsivkin, S. (1999) Sources of mathematical thinking: behavioral and brain-imaging evidence, *Science*, 284, 970-974
51. Dehaene, S., Spelke, E., Pined, P., Stanescu, R. and Tsivkin, S. (1999) Sources of mathematical thinking: behavioral and brain-imaging evidence, *Science*, 284, 970-974
52. Starkey, P. And Cooper, R.G. (1980) Perception of numbers by human infants, *Science*, 210, 1033-1035
53. Boysen, S.T. and Capaldi, E.J. (1993) *The development of numerical competence: Animal and Human Models*, Erlbaum
54. Johnson, M.H. (2004). *Developmental Cognitive Neuroscience: An Introduction*, 2nd Edition, Oxford: Blackwell
55. Carey, S. (2004) Bootstrapping and the origins of concepts, *Daedalus*, 59-68
56. Isaacs, E.B., Edmonds C.J., Lucas A. and D.G. Gadian (2001) Calculation difficulties in children of very low birthweight – A neural correlate, *Brain*, 124, 1701-1707
57. Robison, L.M., Sclar, D.A., Skaer, T.L. and Galin, R.S. (1999) National trends in the prevalence of attention-deficit/hyperactivity disorder and the prescribing of methylphenidate among school-age children: 1990-1995, *Clinical Paediatrics*, 38, 209-217
58. Information Centre for Health and Social Care (2005) *Prescribing monitoring report for Quarter 2: 2004-2005, UK: IC Prescription subscribing unit*
59. Anderson, S.L. (2005) Stimulants and the developing brain, *Trends in Pharmacological Sciences*, 26 (5), 237-243
60. Gureasko-Moore, S., DuPaul, G.J. and White, G. (2006) The effects of self-management in general education classrooms on the organizational skills of adolescents with ADHD, *Behavior Modification*, 30:2, 159-183
61. Corkum, P.V., McKinnon, M.M., Mullane, J.C. (2005) The effect of involving classroom teachers in a parent training program for families of children with ADHD, *Child and Family Behavior Therapy*, 27:4, 29-49
62. Miranda, A., Presentacion, M.J. and Soriano, M. (2002) Effectiveness of a school-based multicomponent program for the treatment of children with ADHD, *Journal of Learning Disabilities*, 35(6), 546-562
63. Pickering, S. J. and Howard-Jones, P.A. (2007) Educators' views of the role of Neuroscience, in Education: A study of UK and International perspectives, *Mind, Brain and Education*, 1(3)
64. Cohen, I. and Goldsmith, M. (2000) *Hands On: how to use Brain Gym ® in the Classroom*, Sea Point, South Africa: Hands On Books



References (continued)

65. Smith, A. (1996) *Accelerated Learning in the Classroom*, Bodmin: Network Educational Press Ltd
66. Coffield, F., Moseley, D., Hall, E., & Ecclestone, K. (2004) *Learning styles and pedagogy in post-16 learning: A systematic and critical review*, (Report No. 041543). London: Learning and Skills Research Centre
67. Kratzig, G.P. and Arbutnot, K.D. (2006) Perceptual learning style and learning proficiency: A test of the hypothesis, *Journal of Educational Psychology*, 98(1), p238-246
68. Hoffman, E. (2002) *Introducing Children to their Amazing Brains*, Middlewich: LTL Books Ltd
69. Sift, J.M. and Khalsa, G.C.K. (1991) Effect of educational kinesiology upon simple response-times and choice response-times, *Perceptual and Motor Skills*, 73 (3), 1011-1015
70. Pickering, S. J. and Howard-Jones, P.A. (2007) Educators' views of the role of Neuroscience, in *Education: A study of UK and International perspectives*, *Mind, Brain and Education*, 1(3)
71. Morton, J. and Frith, U. (1995). Causal Modelling: A Structural Approach to Developmental Psychopathology, in Cicchetti, D. and Choen, D.J. (eds.) *Manual of Developmental Psychopathology: Volume 1*, New York: Wiley
72. Pickering, S.J. (2006) (Ed.) *Working Memory and Education*. Academic Press
73. Delazer, M., Domahs, F., Bartha, L., Brenneis, C., Lochy, A., Trieb, T. and Benke, T. (2003) Learning complex arithmetic – an fMRI study, *Cognitive Brain Research*, 18, 76-88
74. Reprinted from *Cognitive Brain Research*, 18, Delazer, M., Domahs, F., Bartha, L., Brenneis, C., Lochy, A., Trieb, T. and Benke, T. Learning complex arithmetic – an fMRI study, 76-88, (2003), with permission from Elsevier
75. Kosslyn, S.M. (2005) Mental images and the brain, *Cognitive Neuropsychology*, 22 (3-4), 333-347
76. Fletcher, P.C., Stephenson, C.M.E., Carpenter, T.A., Donovan, T. and Bullmore E.T. (2003) Regional brain activations predicting subsequent memory success: An event-related fMRI study of the influence of encoding tasks, *Cortex*, 39 (4-5), 1009-1026
77. Berch, D.B., Foley, E.J., Hill, R.J. and Ryan, P.M. (1999) Extracting parity and magnitude from Arabic numerals: Developmental changes in number processing and mental representation, *Journal of Experimental Child Psychology*, 74 (4), 286-308
78. Dehaene, S., Piazza, M., Pinel, P. and Cohen, L. (2003) Three parietal circuits for number processing, *Cognitive Neuropsychology*, 20 (3-6), 487-506
79. Goswami, U. (2006) Neuroscience and Education: From Research to Practice? *Nature Reviews Neuroscience* 7(5), 406-413
80. Bramald, R. (2000) Introducing the empty number line: the Dutch approach to teaching number skills. *Education* 3-13, 28, 5-12
81. Jones, R., Morris, K. and Nutt, D. (2005) *Drugs Futures 2025? Foresight: Brain Science, Addiction and Drugs State of Science Review*, at www.foresight.gov.uk and in Nutt, D., Robbins, T., Stimson, D., Ince, M. and Jackson, A. (2006) *Drugs and the Future*, Academic Press
82. Gron, G., Kirstein, M., Thielscher, A., Riepe, M.W. and Spitzer, M. (2005) Cholinergic enhancement of episodic memory in healthy young adults, *Psychopharmacology*, 182 (1), 170-179
83. Gazzaniga, M.S. (2005) Smarter on Drugs, *Scientific American: Mind*, 16(3), 32-37
84. Gruzelier, J. H. and Egner, T. (2004). Physiological self-regulation: Biofeedback and neurofeedback. In A. Williamon (Ed.), *Musical Excellence* (pp. 197-219). Oxford: Oxford University Press
85. Raymond, J., Sajid, I., Parkinson, L. and Gruzelier, J.H. (2005) The beneficial effects of alpha/theta and heart rate variability training on dance performance, *Applied psychophysiology and biofeedback*, 30, 65-73
86. Egner, T. and Gruzelier, J.H. (2001) Learned self-regulation of EEG frequency components affects attention and event-related brain potentials in humans, *Neuroreport*, 12 (18), 411-415
87. Nicolson, R. (2005) Dyslexia: Beyond the myth, *The Psychologist*, 18(11), 658-659
88. Morton, J. (2004) *Understanding Developmental Disorders: A Causal Modelling Approach*, Oxford: Blackwell
89. Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U. and May, A. (2004) *Nature*, 427, 311-31
90. Elkins, J.S., Longstreth, W.T., Manolio, T.A., Newman, A.B., Bhatelia, R.A. and Johnston, S.C. (2006) Education and the cognitive decline associated with MRI-defined brain infarct, *Neurology* 67, 435-440
91. Wilson, R.S. (2005) Mental challenge in the workplace and risk of dementia in old age: is there a connection? *Occupational and Environmental Medicine*, 62, 72-73
92. Loewenstein D.A., Acevedo, A., Czaja, S.J. and Duara, R. (2004) Cognitive rehabilitation of mildly impaired Alzheimer disease Patients on cholinesterase inhibitors, *American Journal of Geriatric Psychiatry*, 12 (4), 395-402
93. Koizumi, H. (2004) The concept of "developing the brain": a new natural science for learning and education, *Brain and Development* 26, 434-441
94. Geake, J.G. (2004). *Cognitive neuroscience and education: two-way traffic or one-way street?* *Westminster Studies in Education*, 27(1), 87- 98
95. Kaufmann, L., Handl, P. and Thony, B. (2003) Evaluation of a numeracy intervention program focusing on basic numerical knowledge and conceptual knowledge: a pilot study, *Journal of Learning Disabilities*, 36 (6), 564-573
96. Delazer, M., Ischebeck, A., Domahs, F., Zamarian, L., Koppelstaetter, F., Siedentopf, C.M., Kaufmann, L., Benke, T. and Felber, S. (2005) Learning by strategies and learning by drill – evidence from an fMRI study, *Neuroimage* 25 (3), 838-849
97. Howard-Jones, P.A., Blakemore, S.J., Samuel, E., Summers, I.R. and Claxton, G. (2005) Semantic divergence and creative story generation: an fMRI investigation, *Cognitive Brain Research*, 25, 240-250
98. Howard-Jones, P.A., Winfield, M. and Crimmins, G. (2007) Co-constructing an understanding of creativity in drama education that draws on neuropsychological concepts, *Proceedings of the British Educational Research Association Annual Conference 2007*, Institute of Education, London



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