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technology, children, schools and families

Educating persons, imaging brains: the potentials of neuroscience for education

John Cromby

Dept. of Human Sciences, Loughborough University

December 2008

Abstract

Although neuroscience has much to offer education, in recent years its potentials have been somewhat obscured by a climate of unrealistic expectations. Now the ‘neuromyths’ that were prevalent have been decisively dismissed by neuroscientists, a more accurate assessment may be possible.

Neuroscience uses a range of research methods including animal and lesion studies, but much contemporary research now uses one or other form of brain imaging. Each of these methods has its own limitations, and the requirements of research design, necessary to produce robust data, impose further restrictions. Moreover, these methodological limitations are bound up with, and sometimes both obscure and magnify, various conceptual limitations. The ‘mereological fallacy’ is an ever-present danger, as are problems of reductionism, reification and unsupported normativity.

Despite these limitations, cognitive neuroscientists have made striking progress with respect to the basic skills underpinning abilities such as reading and number. Social and affective neuroscientists have similarly identified neural systems involved in aspects of emotion and social cognition, and shown their possible relevance to various educational tasks, although their work has yet to be widely taken up.

It seems that progress in applying neuroscience will be slow, and will continue to be bound up with other knowledge and events. It may be associated with the emergence of a new sub-discipline of educational neuroscience, the development of more effectively targeted evaluations and interventions, greater appreciation of the socio-emotional aspects of education, the possible emergence of new neuromyths, and increased use of in-situ neural testing in the classroom.

Keywords: brain, neuroscience, special education, society

1 Introduction

Educators in schools and colleges bear great responsibility and are subject to an enormous weight of expectation, yet must operate in environments where both influence and resources are limited. Consequently, education seems particularly vulnerable to fads and trends (Slavin, 1999), to the promise that 'the next big thing' might resolve its many difficulties. Neuroscience is intrinsically fascinating and obviously relevant to education because its subject matter – the brain – is vital to our ability to learn. At the same time, it would be naive to imagine that neuroscience alone can solve many of the problems encountered by educators.

The 1990's 'decade of the brain' saw massive investment in neuroscience across the English-speaking world. Colourful images generated by brain scanners were taken up eagerly by the media, and studies linking brain areas and systems to capabilities or problems are now rarely out of the news. In a cultural moment where neuroscience, genomics, and pharmacology are jointly enrolled within 'the politics of life itself' (N. Rose, 2001) these developments have justifiably caught the public imagination. They have contributed to a climate where the expectations associated with neuroscience are sometimes unrealistically high, where neuroscience has perhaps been positioned as education's most-recent 'next big thing'.

This report will review current trends in neuroscience as they relate to education. Relevant research methods will be briefly described, some mis-uses of neuroscience will be discussed, and a sketch of current progress in neuroscience relevant to education will be presented. Various limitations upon the application of neuroscience to education will then be described, and some possible future implications of neuroscience for education will be suggested. First, a very brief guide to the structure and function of the brain (drawn primarily from Beaumont, Kenealy, and Rogers, 1996; Damasio, 1999; S. Rose, 1997) will set out something of what is taken to be known and largely uncontroversial, whilst also providing a common language for the discussions that follow.

2 The brain

2.1 Neurons and synapses

Neurons are the active nerve cells of the brain. Each neuron has a cell nucleus, and a large number of branching structures known as dendrites, which are available for potential connections with other neurons. Each neuron also has a long extension called an axon, down which electrical messages flow from the cell nucleus. The end of the axon branches out into connectors called pre-synaptic terminals.

The junction between neurons is called a **synapse**. At a synapse, the pre-synaptic terminals of one neuron are in close contact with the dendrites of another. Although communication within a neuron is electrical, communication across a synapse is chemical. When a neuron 'fires' it discharges an electrical signal down its axon, which releases a **neurotransmitter** into the synapse; this chemical then gets absorbed by the next neuron. Its absorption changes that neuron's chemical properties, influencing the probability that it will also fire.

2.2 Systems

The average adult human brain is thought to contain around 100 billion neurons, most of which are formed before birth. Whilst the number of connections between these neurons varies hugely, they are frequently connected to many thousands of others. The staggering number of connections thus created allows the brain to function as an extraordinarily complex 'system of systems'. These systems are distributed throughout the brain, contain multiple feedback loops, and are organised into **neural networks**.

Consequently, all but the very simplest activities involve activity in more than one area. The great majority of functions are carried out by multiple, more specific, elementary processes. These processes are typically carried out in parallel, rather than sequentially. This means that there are frequently degrees of **redundancy**: not all of the processes the brain conducts may be strictly necessary for a function to be successfully completed.

There is good evidence that some abilities are closely associated with neural activity **localised** to particular areas, which are presumed to be key nodes in the systems of which they are a part. But the brain also exhibits individual variation and marked **plasticity**. Lesions to a specified area do not always have the effect that would be predicted, and brain regions usually specialised for one kind of function can get recruited for others: for example, in the brains of visually-impaired people, areas that usually process vision can be used for reading Braille (Roder and Neville, 2003).

2.3 Gross structure and functions

The outer surface of the adult human brain is called the **cortex.** It has two hemispheres, left and right, joined by a thick bundle of connecting tissues, the **corpus callosum**. The cortex is subdivided into a series of lobes. Although virtually every activity recruits neurons in multiple areas, each lobe is primarily associated with broadly different kinds of function:

Frontal lobes:	planning, reasoning, inhibition of behaviour
Temporal lobes:	hearing, memory, object recognition
Parietal lobes:	integration of information, sensation, spatial processing
Occipital lobes:	visual processing

Because the size of the brain is constrained by the skull some areas of cortex are pushed back upon themselves in folds or **sulci**, giving the cortex a wrinkled appearance. Within the cortex lie a series of deeper, evolutionarily-older structures, including the hippocampus and the amygdala. Below the cortex lies the **cerebellum** or 'little brain', which is implicated in movement, balance and habit. Beneath this, running down into the spinal cord, the **brainstem** regulates sleep, wakefulness, and the basic homeodynamic functions necessary for life.

2.4 Growth and Development

Although the brain already has most of its neurons at birth, many of the synaptic connections between them have yet to be formed. Brain volume quadruples between birth and maturity, and most of this increase is due to the formation of new synapses. Three processes are involved.

Synaptogenesis is the general term for the growth of axons and dendrites and the formation of new synapses. There are genetically pre-programmed periods of intense synaptogenesis in different areas of the brain at different times. Synaptogenesis frequently results in more synaptic connections being formed than will ever be needed. Periods of intense synaptogenesis are therefore followed by periods of **pruning**, when unused connections are eliminated. Once neurons have become organised into relatively stable networks, they frequently get coated in a layer of fatty tissue called myelin. This process, called **myelinisation**, increases the speed of electrical conduction within the neuron.

The brain remains able to form new synapses throughout life. Learning skills, or responding to an injury or stroke, often produces measurable synaptogenesis in relevant brain areas. Nevertheless, large parts of the brain's overall structure are in place at birth or shortly afterwards, and subsequent myelinisation may further restrict the ability of neurons to form new connections. Consequently, there are also limits upon the brain's ability to re-organise itself.

3 Research in neuroscience

Knowledge of the brain and its functions has always been bound up with the technologies used to both investigate and imagine it. In the past, dissection and staining techniques yielded relatively static images of the brain, and its operation was conceptualised using mechanical, telegraphic or hydraulic metaphors (Daugman, 2001). By contrast, contemporary knowledge is frequently bound up with computational metaphors and generated using new imaging methods. However, other research methods remain relevant and continue to contribute important elements of contemporary understanding.

3.1 Lesion studies

Studies of human brain lesions – due to trauma, or following surgery – have long provided an important source of knowledge. Damasio's influential 'somatic marker' hypothesis was prompted by such studies, whilst the unusual case of 'H.M.' continues to inform contemporary memory studies. But human brain lesions are variable and cannot be replicated, so other methods are often needed to interpret their effects.

3.2 Animal experiments

In these experiments, neuroscientists can systematically manipulate brain functions, for example by excising specified areas of tissue. They can also impose extreme, systematic environmental variations, such as complete loss of sight in one eye, or presentation of only one kind of stimulus to a visual field. Using such methods, neuroscientists have been able to establish some very reliable findings.

3.3 Imaging

Many of the most widely taken-up findings in contemporary neuroscience rely upon brain imaging techniques that allow the activity of different brain areas to be reliably measured in real time. They create dynamic representations of neural activation which show how brain activity is associated with the performance of different tasks.

Magnetic resonance imaging is sometimes said to provide the 'gold standard' of brain imaging. Structural magnetic resonance imaging (MRI) scanners can chart the relative size of brain structures, whilst functional magnetic resonance imaging (fMRI) scanners identify differential patterns of brain activity.

Electroencephalography (EEG) uses a net of electrodes attached to the head to measure electrical activity across the scalp; this corresponds to neural activity in the brain. EEG does not produce a pictorial image, but generates graphs with peaks and troughs that represent variation in levels of neural activity. These are described in terms of both their direction and the time-lag between a stimulus and their occurrence. For example, N400 would describe a trough, or negative peak, occurring 400milliseconds after a stimulus.

Functional near-infra-red spectroscopy (fNIRS) is only just beginning to be widely used. It measures the diffusion of near infra-red light projected through the skull; the intensity of the light being diffused is modulated by the level of neural activity, because the light-scattering properties of neurons change when they are active. fNIRS is portable and does not need the person to keep entirely still; some systems can even be used wirelessly, allowing almost free movement.

For various reasons, other imaging technologies are likely to be less useful in relation to education. For example, positron emission tomography (PET) uses radioactive tracers, and so is not suitable for use with children. Magnetoencephalography (MEG) scanners are most effective at detecting activity in bundles of neurons lying in the sulci parallel to the scalp, and seem to be most useful for studying simple sensory and motor processes. They are poor at detecting signals from deeper inside the brain, and less useful for studying complex cognitive activities.

Using these methods, neuroscientists have made striking advances in our knowledge of how the brain works. However, with respect to education their work has also sometimes been misinterpreted, so this survey of their findings will begin by addressing these misunderstandings.

4 Neuromyths

The climate of unrealistic expectations surrounding neuroscience created fertile ground for the establishment and circulation of 'neuromyths'. This term was coined in a 2002 OECD report, and subsequently taken up by neuroscientists concerned about the misuse of their discipline. Neuromyths are culturally-prevalent misunderstandings of neuroscience that have been used to justify educational interventions. Many of these interventions have been developed and marketed by commercial interests. There is little evidence for their efficacy, and their basis in neuroscience is frequently tenuous. Neuromyths include:

- the need for 'balance' between functions localised to left and right cortical hemispheres
- the idea that specific physical exercises can have effects upon particular brain functions
- that there are 'brain buttons', areas of the body where applying physical pressure stimulates brain activity
- that there are global preferences of learning style (typically characterised as visual, auditory or kinetic) rooted in neural differences
- that there are known critical periods for acquiring certain abilities
- that increased synaptogenesis can be fostered by placing children in more complex or 'enriched' environments
- that there are 'male' and 'female' brains
- that educational programmes can use implicit learning to teach advanced cognitive skills without effort or attention

There are serious flaws with each of these claims (Goswami, 2004a). For example, although the brain shows clear evidence of hemispheric specialisation, outside of special education 'balance' need not be a concern. This is because, for the overwhelming majority of people, the corpus callosum provides an abundant flow of bi-directional communication. Similarly, the evidence for critical periods in the acquisition of some abilities mostly comes from animal brains, is mostly confined to sensory and motor areas, and is challenged by evidence of subsequent, ongoing plasticity. For example, even after an experimental manipulation completely deprived one of a kitten's eyes of sight for a year, subsequent use of this eye resulted in significant synaptogenesis (Chow and Stewart, 1972). Likewise, there is no evidence that early environments 'enriched' in specific ways generate noticeable benefits for human brain growth and development. Again, the evidence comes from animals, and actually shows only that impoverished environments (laboratory cages, rather than larger spaces corresponding more closely to natural environments) restrict development (Bruer, 1997).

Although they may take some time yet to fade from the popular imagination, these neuromyths have been decisively dismissed by neuroscientists. In their wake, it is now perhaps easier to realistically assess the contribution that neuroscientists might make to education. Their work is usually divided into the sub-disciplines of cognitive, social and affective neuroscience (although cognitive science - cognitive neuroscience supplemented by computer modelling - is also sometimes distinguished). To date, it is cognitive neuroscience that has attracted most interest in education.

5 Research in cognitive neuroscience

Most of the educationally-relevant research in cognitive neuroscience has been into the developmental sequence of the human brain, and into the acquisition of basic skills such as reading and number. However, there has been some interest in other skills, and in applying cognitive neuroscience to special education.

5.1 Brain development and 'sensitive periods'

As we have seen, the idea of critical periods in human brain development is a neuromyth. Nevertheless, studies of developing humans do show that there are numerous periods of synaptogenesis and pruning in the brain: one in early childhood, another in the early teenage years; and further marked development, particularly in the frontal lobes, in early adulthood (Gogtay et al, 2004).

Because the timing of these processes is relatively invariant, there are identifiable developmental sequences for basic abilities such as visual processing. These sequences mean that more complex, late-acquired abilities – for example, depth perception – may be more sensitive to disruption or environmental deprivation (Goswami, 2004a). However, the evidence suggests that even for these abilities some recovery is possible.

It has therefore been suggested that humans may not have critical periods so much as sensitive periods: times when the developing human brain is 'primed' for certain kinds of experience and especially able to respond to it effectively. However, the practical educational significance of any such sensitive periods remains unknown.

5.2 Reading

An important strand of research in cognitive neuroscience is focused upon reading and reading problems. Imaging studies have shown that, in adults, whilst reading is mostly localised to left-hemisphere systems, there is some variation in patterns of activation as a consequence of different languages. They have also shown that in English-speaking children without reading difficulties there seems to be a developmental sequence of brain activity as reading skills are acquired. In the early stages, reading activates areas of both left and right temporal lobes, but right hemisphere activity gradually declines and significant amounts of activity occur across three main left-hemisphere sites. One of these sites, known as the 'Visual Word Form Area' (VWFA) sits at the junction of the temporal and occipital lobes. In mature readers, it seems to be involved both in visual recognition of words and also in phonology (Paulesu et al, 2001).

However, in children identified as being developmentally dyslexic (failing to learn to read, despite being of average intelligence) this sequence appears not to be followed. In these children significant activation of the right hemisphere continues, and there is also less activation in the VWFA and other left hemisphere sites associated with skilled reading (Shaywitz et al, 2002). These studies have also suggested that after targeted remediation (for example, teaching in phonological skills) this unusual pattern of activity can become more normal (Temple et al, 2003).

5.3 Number

Imaging studies have identified various brain areas, in both hemispheres, that seem to be associated with the successful recognition and manipulation of numbers. One area, the horizontal segment of the bilateral intraparietal sulcus (HIPS) seems to be especially critical for judging quantity, size and differences between numbers (Dehaene, Molko, Cohen and Wilson, 2004). Studies have also shown that there are links between areas of the brain important for visuo-spatial processing and those important for recognising the magnitude of numbers (Hubbard, Piazza, Pinel and Dehaene, 2005).

Some research suggesting the validity of this link has been carried out with girls diagnosed with Turner Syndrome, who typically have both visuo-spatial and number-processing difficulties (Ross, Zinn and McCauley, 2000). This study found unusual patterns of growth or orientation of neurons in the right intraparietal sulcus. Similarly, an imaging study of low-birth weight children who had problems with mathematics found that they had reduced neural density in the left intraparietal sulcus (Isaacs, Edmonds, Lucas and Gadian, 2001).

5.4 Other applications of cognitive neuroscience

Neuroscientists have studied how neural systems enable a range of other abilities relevant to education, perhaps most notably bilingualism, geometry and music. For example, geometry and music are thought to be linked to mathematics, because they involve abilities to identify abstract forms and use visuo-spatial processing. It has been proposed that there is also a link here to 'theory of mind': the ability to fully understand that others are also thinking, feeling beings, failures of which are said to produce autism (Baron-Cohen, Bolton, Wheelwright and Scahill, 1998). There has also been significant work in cognitive neuroscience exploring the ways that sleepiness influences the ability to learn, remember, and perform tasks of various kinds.

5.5 Special education

Cognitive neuroscience has a potentially close link with special education. On the one hand, it may be especially useful in the development and evaluation of targeted interventions and treatment. On the other, the varying difficulties of children in special education may provide natural 'experiments' that help cognitive neuroscientists identify the brain systems associated with particular kinds of ability. Goswami (2004b) proposes that imaging techniques might be used to distinguish between different cognitive theories of dyslexia. There are theories implicating phonological deficit, visual recognition and dysfunctions of movement associated with the cerebellum. Since each theory implies a very different pattern of brain activation, imaging studies of children identified as dyslexic might be able to test their validity. She also proposes that imaging could be used to distinguish between delayed development and deviant development, and so find out whether children who fail to meet developmental milestones are simply developing more slowly, or whether they are developing differently.

6 Research in social and affective neuroscience

Social neuroscience examines how neural systems are involved in socio-cultural processes. Exponents describe it as an attempt to understand the brain systems that enable social behaviour by combining insights and approaches from biological and social research (Cacioppo and Berntson, 1992; Harmon-Jones and Winkielman, 2007). Social neuroscientists do this by examining how the brain mediates social cognition, interpersonal exchanges, group interactions, and relationships (Decety and Keenan, 2006).

One of the most remarked upon recent findings in social neuroscience is the discovery of mirror neurons (Gallese and Goldman, 1998). These are neurons which fire, both when an action is performed and when we see the same action being performed by another. Mirror neurons might be thought of as supplying part of the neural basis for experiences of empathy, since they seem to offer the possibility of quite literally feeling something of what another person feels. They might contribute to the learning of embodied skills by helping us anticipate how the performance of them might feel, and may also be implicated in interpersonal sensitivity and so-called emotional intelligence. It has even been suggested that mirror neurons help to supply the 'theory of mind' posited by Baron

Cohen to be lacking in autism, and some research suggests that there may be deficits in the mirror neuron systems of children diagnosed with autism (Dapretto et al, 2005).

Affective neuroscience investigates the brain systems involved in processing emotion, or affect. Much of the foundational work in this area was conducted using animals (eg Panksepp, 1998) and provided the basis for an understanding of how the mammalian brain enables emotion and feeling. More recent work with humans (Damasio, 1999; Le Doux, 2000) has further developed this understanding, and simultaneously challenged the idea that 'cognitive' processes typically operate without input from emotional systems. Increasingly, affective neuroscience has provided evidence to show that emotion guides and assists thinking and decision-making, rather than simply impeding or biasing them

Currently, the best-known research in affective neuroscience is probably that reported by Damasio (1994, 1999, 2003). Damasio has conducted numerous studies (some experimental, some based upon work brain-injured people) demonstrating how the frontal lobes contain vital nodes of the 'somatic marker' system, which is important in enabling social conventions and ethical rules to be acquired and used. Learning and remembering are central to education, and research in affective neuroscience has uncovered associations between memory and emotion, to which the hippocampus and amygdala are frequently thought to be important. Other aspects of affective neuroscience are sometimes seen as relevant to education because of their possible relevance to affective and mood disorders, and behavioural problems such as those associated with diagnoses of ADHD.

For the most part, however, educators have shown relatively little interest in the findings of social and affective neuroscience, despite the obvious relevance to their practice of social relations, social influence, emotions and feelings. In a rare paper discussing the potentials for education of these sub-disciplines, Imordino-Yang and Damasio (2007) survey evidence linking the frontal lobes to emotionality and to decision-making in social settings. They argue that because emotion guides cognition, it is especially important to the transfer of skills from the classroom. Whilst schools can teach basic skills, the choice of which skills to actually use takes place in wider social settings and is guided by emotional imperatives. They note that emotion also plays a significant role in moral reasoning and social relations, as well as contributing centrally to art, literature, self expression and creativity in general.

As this brief overview suggests, neuroscience does indeed hold much promise for education. However, there are also problems that make the ready application of neuroscience to education more difficult than it might at first seem. Some of these problems will now be described, under three separate headings: conceptual limitations; limitations of particular methods; and general limitations.

7 Conceptual limitations

7.1. The 'mereological fallacy'

Bennett and Hacker (2003) demonstrate that much contemporary neuroscience is characterised by what they call the 'mereological fallacy'. This is their term for a marked tendency in contemporary neuroscience to treat the brain as though it were simply equivalent to the person or the mind. Once this erroneous assumption is made, it can lead to errors of reasoning and interpretation.

Examples of the mereological fallacy appear in one paper which makes the restrictive claim that education "involves the shaping of individual brains via targeted experience in the classroom" (Szucs and Goswami, 2007), and in another which defines the purpose of educational neuroscience as “nurturing the brain” (Ito, 2004). Although not strictly untrue, these claims are highly selective. In taking such a narrow focus they seem to downgrade or exclude many aspects of education that practitioners would see as vital. In offering such a partial view of the goals and the nature of education, they are potentially misleading with respect to the educational potentials of neuroscience.

The mereological fallacy can also mislead neuroscientists themselves with respect to the meaning of their own findings. For example, Bennett and Hacker (2003) describe how it leads neuroscientists to use the metaphor of ‘maps’ in the brain (patterns of brain activation systematically related to features of a stimulus) and then mistakenly claim that the brain ‘reads’ these ‘maps’ just as a person reads an atlas - even though, both logically and practically, this simply cannot be the case. So the mereological fallacy has the potential to foster deep conceptual errors in contemporary neuroscience, errors which may impact upon its educational application.

7.2 Reductionism

Reductionism is the favouring of explanations at the smallest, most basic level. In the present context it involves the assumption that brain processes and features can themselves explain our abilities and experiences. For example, if atypical patterns of brain activation are found amongst individuals who have reading difficulties, a reductionist interpretation might be that these atypical patterns of activity are the cause of their difficulties. An alternative, non-reductionist interpretation is that atypical abilities might well be associated with atypical brain activity, but that this tells us little about the *origins* of the difficulties.

Forms of reductionism are often seen as essential to good science, but the concern here is that reductionism might get over-extended. Stanovich (1998) welcomes the application of neuroscience to education but simultaneously notes that our ability to identify precisely how the brain constrains learning is still quite primitive, even for a skill so extensively studied as reading. He warns that without adequate psychological and behavioural accounts of reading difficulties, applications of neuroscience to this problem will always be inappropriately reductive.

7.3 Reification

Reification is the ‘making real’ of a phenomenon in a certain way. An example in education is the reification of some children’s disruptive and disorganised behaviour as an instance of the psychiatric diagnosis Attention Deficit-Hyperactivity Disorder (ADHD). This is not to deny that some children behave inappropriately and seem to have trouble concentrating, nor to deny that such children can be disruptive and difficult for both parents and teachers. The concern arises when these problems simply get attributed to a disease – ADHD - which, in turn, gets associated with a putative neural flaw (eg Rubia, 2002)

ADHD is a controversial diagnosis, and its validity has been questioned. Timimi (Timimi and Taylor, 2004) observes that the recent ‘epidemic’ of ADHD is difficult to explain if the condition has a neural or genetic basis. He notes that prevalence rates for ADHD vary hugely, and that imaging studies have used unacceptably small samples, failed to control for the effects of medication, and failed to produce consistent evidence of a brain abnormality. He proposes instead that we should look at the ways in which biological and social immaturity become meaningful in a culture where extended family support is frequently absent, schools are pressured and lack moral authority, and parents and families are themselves frequently ‘hyper-active’, over-worked, and unsure of the appropriate ways to discipline their children.

Clearly, the contribution that we imagine neuroscience can make to the resolution of these kinds of problems will differ greatly according to whether or not we conceptualise ADHD as ‘real’ in this way

7.4 Unjustified normativity

In order to be sure that a pattern of brain activation related to a particular ability is dysfunctional, we need to know what functional brain activation looks like. However, the brain's parallel processing and associated redundancy mean there is often more than one way for it to complete an activity. Steven Rose (1997) argues that many brain functions have what he calls a 'norm of reaction', meaning that they exhibit some degree of adaptive flexibility in the face of challenges. So long as challenges remain within typically-occurring limits, the brain can adapt and cope; outside of this range performance tails off sharply. The limits within which performance is largely unaffected provide the norm of reaction.

This concern can be illustrated by considering the relationship between IQ and the brain. Although identical twins reared together have highly-correlated IQ scores, imaging studies show that the relative sizes of different areas of their brains are sometimes significantly different (Steinmetz, Herzog, Schlaug, Huang and LAnke, 1995). At the neural level there is no single route to the same IQ score, and so attempts to find 'optimal' or 'ideal' brain features enabling performance on these tests are likely to fail.

This has two implications. Firstly, that an unusual pattern of neural activity does not necessarily lead to a performance deficit, and so might not be useful diagnostically in the absence of behavioural or performance indicators. Secondly, that some caution is needed when interpreting findings, even when a suitable control group has been used. Research might be applied with more confidence if the relevant norms of reaction were known, but even for widely studied abilities we are still very far from having this kind of population-level data.

These conceptual problems are interlinked and mutually-reinforcing, such that one may frequently lead to, or be associated with, the other. At the same time they feed into, and are sometimes either amplified or concealed by, methodological limitations.

8 Limitations of particular methods

8.1 Animal experiments

Although the core structure of all mammalian brains is quite similar, there are significant inter-species differences with respect to the relative size and development of different areas. Studies that demonstrate sensitive periods for the acquisition of basic abilities in animals find variation even between experimental species. Similarly, the timing and duration of periods of synaptogenesis varies significantly. Most obviously, with respect to education, animals simply do not have many of the complex cognitive abilities with which educators are frequently concerned.

8.2 MRI and fMRI

These scanners have reasonably good spatial resolution and are able to identify areas of activity down to a scale of around 1mm. This is still extremely coarse in relation to the multiple branching dendrites that connect neurons, but it is adequate to resolve patterns of activity to broadly specifiable brain regions.

However, the temporal resolution of MRI scanning is poor. The scanner works by assessing levels of blood oxygen: the more oxygen being taken up by the neurons in an area, the more neural activity is assumed to be taking place. By this means the scanner can only identify activity occurring over fairly lengthy periods of time – as a minimum, around one second. Many brain processes, which typically take only milliseconds to initiate and complete, are therefore missed. Moreover, the temporal sequence of activation *between* different regions is often impossible to discern.

8.3 EEG

Whilst its temporal resolution is excellent the spatial resolution of EEG is very poor, and it can sometimes only locate signals to within one or other of the brain's cortical hemispheres.

8.4 fNIRS

The spatial resolution of fNIRS is significantly less than fMRI, being no more accurate than one square centimetre, although its temporal resolution is better (down to 0.01 seconds). However, fNIRS has two other important limitations. First, it can only image relatively small sections of the brain at a time. Second, it can only image the cortex immediately below the skull, and cannot resolve activity occurring deeper inside the brain.

9 General limitations

Whilst each of the research methods used in neuroscience has its own specific limitations, there are also more general limitations that flow from the need to generate scientifically acceptable, valid and reliable data, under controlled conditions and using recognised procedures. Whilst these conditions and procedures are necessary to obtain robust findings, they inevitably carry their own costs.

9.1 The subtraction method

Results of imaging studies are typically obtained by comparing the average patterns of brain activation between groups performing a target task and groups performing a control task. Comparisons are usually made by subtracting the pattern of activation in the control task from the pattern in the target task. Whatever significant activation remains is then assumed to be associated with features of the target task. But this means that if both tasks activate the same brain region, the results of the comparison will suggest that this region is not significantly activated.

Neuroscientists considering this problem have identified a set of brain areas called the default network, which seem to be activated in *all* imaging studies. The default network is thought to be composed of interacting subsystems located primarily in the temporal and pre-frontal lobes, and to enable activities such as planning for the future, recalling the past, evaluating the actions of others, and assessing the likely outcome of decisions (Buckner, Andrews-Hanna and Schacter, 2008). Whilst these activities are clearly relevant to education, learning, and the transfer and application of knowledge and skills, their investigation using imaging techniques will be difficult.

9.2 Groups and averages

Imaging studies typically compare group averages in the performance of different tasks. As a consequence, when findings are reported individual variations in performance are often rendered mostly invisible. Conversely, patterns of 'average' activation can emerge that were not found in any of the actual individuals studied (Cacioppo et al, 2003). Studies show there are often differences in the patterns of brain activation of individuals performing the same task, as well as marked individual differences between individuals in the relative size of different brain structures. These findings suggest that caution is needed when applying findings from studies of groups to individual cases.

9.3 Practical problems

With the exception of EEG and fNIRS, imaging procedures require participants to keep entirely still, because head movement interferes with data collection. Although some head movement is possible with EEG, these studies typically take place in dimly-lit, soundproofed rooms, and movement is still not entirely free.

MRI and fMRI scanners completely surround participants' heads, occlude their field of vision, and make a loud humming noise during operation. Participants are unable to move, gesture, or interact and communicate naturally with others. Stimuli are presented via headphones or on a small LCD screen, and responses communicated by pressing buttons with fingers.

A constant concern in imaging studies is that random environmental stimuli and participant movements or reactions might interfere with the relatively transient biological signals being measured. Often, this problem is managed by study designs that require participants to undergo many trials of the same repetitive task. This can mean that experiments become quite lengthy, often lasting for two or more hours.

One consequence of all these problems is that social interaction is almost impossible, cannot be conducted spontaneously and by naturalistic means, and is often excluded from consideration. Another is that many abilities and tasks are studied using 'analog' versions of those displayed in everyday life. With respect to education, a particularly important consequence is that the alienating, repetitive, time-consuming nature of many studies is likely to make them especially difficult for children.

10 Current progress assessed

Both the problems and the potentials of neuroscience with respect to education have been extensively discussed in recent years, and scholars have taken up a range of positions.

Some think that the application of neuroscience to education is a fundamentally flawed enterprise because the distance between learner and brain, classroom and neuron, is simply too great. In one much cited commentary, Bruer (1997) describes the link between education and neuroscience as 'a bridge too far'. He observes that there is already a link between education and cognitive psychology, and – in cognitive neuroscience – a link between cognitive psychology and the brain. However, he argues, attempts to forge a direct link between education and neuroscience are forever doomed to failure because cognitive psychology will always be needed to mediate between them.

Bruer's arguments recognise many of the limitations described above, which clearly do create problems for any straightforward application of neuroscience to education. Many of these limitations are also recognised even by those who, compared with Bruer, are relatively optimistic (eg Byrnes and Fox, 1998; Szucs and Goswami, 2007). However, it is less widely accepted that it must always be cognitive psychology that mediates between educational practice and neuroscientific research; some, for example, propose using perspectives from evolutionary psychology and developmental systems theory (Brown and Bjorklund, 1998). It is also fair to say that, in these discussions, the methodological limitations receive far more attention than the kinds of conceptual limitations identified in this report.

Other scholars, whilst acknowledging many of these methodological limitations, argue that progress is already being made in applying neuroscience to education, albeit more slowly than previous unrealistic expectations might have suggested. Since cognitive neuroscience is a hybrid that already includes elements of cognitive psychology, these scholars see the possibility of direct links between education and neuroscience. They argue that advances have been made – for example, in the study of bi-lingualism, language acquisition and conceptual change – that can be applied more or less directly both to the identification of difficulties and the evaluation of treatment programmes (Pettito and Dunbar, in press). They argue that neuroscience can inform education with respect to the early diagnosis of special needs, the evaluation of interventions, and an increased understanding of individual differences in learning (Goswami, 2004a).

Consequently, there have been recent calls for a distinct strand of 'educational neuroscience'. Pettito and Dunbar (in press) describe educational neuroscience as 'an exciting and timely new discipline' whilst Szucs and Goswami (2007) call for an educational neuroscience involving the study of 'mental representations' distributed across multiple brain areas and encoded in neural networks. Educational neuroscience, they propose, will identify biological constraints upon the patterns of neural activation that encode mental representations, and use related neural markers in the early identification of problems. For example, they suggest that the N100 response to auditory stimuli in babies is a reliable marker of auditory processing that might be used to identify potential language difficulties, even "when there are no cognitive or behavioural variables at all". They similarly propose that neuro-imaging might be used "in populations for whom informative behavioural data are difficult to collect", for example children with attention difficulties.

Despite this optimism, controversy may continue. For example, Harre's (2002) rigorous guide to cognitive science explicitly warns against the use of neural markers in the absence of other variables. He notes that three levels of description (persons, organisms and molecules) are always needed to provide meaningful accounts of human activity, since causality operates differently at each level. He argues that because these levels are nested together in a context defined first of all by the embodied social relations of living persons, it is only valid to look for neural correlates (organism or molecule level) if we can first be confident that the ability concerned is actually being enacted (person level). Whilst Harre's arguments are not directed specifically toward either educational neuroscience or this particular example, they are relevant here. Similarly, the view that imaging techniques could easily be used to identify the neural bases of attentional difficulties in children perhaps ignores many of the limitations described above. It is a form of reductionism; it sidesteps the problems with ADHD that Timimi and others have described; and it downplays the practical difficulties of persuading typically restless children, who presumably might not co-operate readily with a classroom test, to nevertheless submit to the typically extensive and sustained constraints of neuro-imaging.

In this regard, it is perhaps notable that despite the many links between neuroscience and special education, the application of neuroscience to intellectual impairment (learning disability) has so far been negligible. The perennial lack of funding for intellectual impairment research is no doubt a contributory factor. However, it is undoubtedly also because of the ethical and practical difficulties of using imaging technologies with intellectually-impaired people, who may neither tolerate, nor understand the need for, the constraints on movement, vision and interaction that are typically required. Children with intellectual impairments are perhaps the archetypal population for whom meaningful cognitive and behavioural data are hard to collect (Hall, 1984). If neuro-imaging is not as readily applicable to this population as Szucs and Goswami propose, then some of their optimism with respect to its potentials is maybe premature.

There is nevertheless widespread recognition that neuroscience has made conspicuous progress in recent years, and that brain imaging technologies which allow real-time, non-invasive imaging have opened up many new avenues of investigation. It is also recognised that cognitive, social and affective neuroscience have uncovered aspects of the ways in which brain systems enable activities – such as reading – that are central to education. These findings may be useful in the design of educational interventions, in the formulation and testing of theories of skill acquisition, learning and teaching, and in the identification and treatment of various kinds of difficulties. Moreover, even amongst those who disagree about the significance of these findings, areas of consensus have begun to emerge. Most scholars do accept that there are clear possibilities for neuroscience to inform educational practice. At the same time, most recognise that many findings are still far too general and provisional to be applied directly in educational settings. Consequently, it is also widely accepted that progress will be slow, and that the potentials of neuroscience for education have for the most part not yet been realised.

Similarly, in the wake of the discussions over neuromyths, there is some recognition that applying neuroscience to education is not straightforward. Amongst other things, this suggests an emergent consensus that many established educational practices will continue to be as vital as they were before. Relatedly, there is growing recognition that evidence from neuroscience will always need to be weighed against evidence derived from other sources for its import to be properly evaluated. Even Byrnes and Fox (1998) who are very enthusiastic about applying neuroscience to education, recommend that neuroscientific evidence should only be considered important by educators when it both gets confirmed by multiple methods (eg both fMRI and EEG), and when it accords with other evidence already gathered using cognitive or behavioural measures.

So it seems that neuroscience will continue to be only one of many influences upon education, and that its impact will remain contingent upon it’s binding with events, practices and knowledge arising elsewhere. With this in mind, some possible future implications of neuroscience for education will now be sketched: first, with regard to developments that seem likely in most probable futures, and second with respect to possible developments that are more contingent and uncertain.

11 Probable futures

11.1 Emergence of a sub-discipline

Publications dealing with the educational implications of neuroscience have steadily increased in recent years: a new journal (Mind, Brain and Education) has been launched, research groups (eg Cambridge University’s Centre for Neuroscience in Education) have been established, and there have already been explicit calls for a new sub-discipline of educational neuroscience. Whilst no consensus has yet emerged, there seems to be a convergence of academic, educational, institutional and commercial interests here which may make some such development all but inevitable *(timescale: less than five years)*

11.2 More effective targeting of evaluation and remediation

Neuroscientists have already made substantial progress in identifying the basic abilities underpinning many skills. This progress seems likely to continue, yielding yet more fine-grained knowledge of the nature of some educational difficulties. This may lead to more precise evaluation of these difficulties, and the application of more targeted programmes of remediation. These developments are likely to be most rapid with respect to reading and language learning, and to involve tailoring existing interventions rather than developing new ones *(timescale: five to ten years)*

11.3 The mutation of cognitive psychology, and its effects

Partly due to its associations with neuroscience, cognitive psychology is already mutating, and this process seems likely to gather pace. There is increasing interest in the approaches known as embodied, enactive, embodied or situated cognition, and a growing recognition that human cognition is never disembodied information processing. As cognitive psychology mutates, its changes will impact back upon education. As a result, it seems likely that findings in social and affective neuroscience, to date largely ignored, will appear more relevant. This, in turn, will lead to renewed educational emphasis on the social and emotional dimensions of teaching and learning *(timescale: five to fifteen years)*

11.4 Emergence of new neuromyths

Debates about the potentials and dangers of applying neuroscience to education seem set to continue. Similarly, there will be ongoing political and institutional pressures to improve educational outcomes, and commercial interests will continue to operate in the education sector. In a climate where the conceptual limitations of neuroscience are infrequently recognised, this creates the potential for new neuromyths *(timescale: five to ten years)*

12 Possible futures

12.1 Proliferation of fNIRS

The portability and flexibility of fNIRS could make it ideal for use in education, making possible in-situ neural testing in the classroom. Because it is limited to imaging small sections of cortex immediately below the skull, it may be most helpful in identifying atypical neural activity associated with quite specific cognitive difficulties. However, its use is contingent on two developments. First, more fine-grained knowledge of the neural bases of those difficulties (as in 11.2 above); second, the technology becoming affordable and widely available *(timescale: ten to fifteen years)*

12.2 Population-level norms of reaction

Many universities and hospitals now have brain scanners, creating the potential to image the brains of very large numbers of people as they conduct the same tasks. In this way, population level norms of reaction for abilities such as reading might be established which would greatly assist interpretation of imaging data. However, this would require substantial funding *(timescale: five to fifty years)*

12.3 The impact of DSM V

At periodic intervals, the diagnostic systems psychiatrists use to classify problems (such as ADHD) are subject to revision. DSM V, the new version of the most influential system, is expected in May 2012, although its content is presently unknown. Depending on how the psychiatric categories most immediately relevant to education (primarily conduct and mood disorders) are modified in DSM V, there will be consequences: for education generally, and particularly for the relationship of neuroscience to education *(timescale: five years and more)*

12.4 Improvements in imaging

Scientists continue to develop imaging technologies, seeking improved power, spatial and temporal resolution, portability and flexibility. Any such developments will impact upon neuroscience as it relates to education, perhaps especially so if they enable more investigation of the default network and greater understanding of temporal sequences of brain activation *(timescale: any)*

12.5 Other technological developments

Developments in neuroscience are already bound up with those elsewhere, so its influence upon education will to some extent depend on advances in other technologies, specifically, genomics, psychopharmacology, and nano-technology. Genomics identifies patterns of genetic transmission and might help illuminate the neural bases of some difficulties, leading to possible new interventions. Developments in psychopharmacology already impact upon education through the occasional use of cognitive enhancers, which seems likely to continue amongst some groups. Other applications depend on developing methods of drug delivery for brain chemicals such as peptides, which are known to be psychoactive but cannot be effectively administered. If this problem could be solved, Panksepp (2004) identified the possibility of 'socio-emotional education' using peptides with vulnerable children. Silva (2006) notes that nano-technology might be used to develop new molecules suitable for such purposes, as well as for purposes such as targeted neural regeneration *(timescale: any)*

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This document has been commissioned as part of the UK Department for Children, Schools and Families' Beyond Current Horizons project, led by Futurelab. The views expressed do not represent the policy of any Government or organisation.