Neuroscience and Education

A review of the contribution of brain science to teaching and learning

John Hall

February 2005

SCRE Research Report No 121

ISBN 1 86003 090 4

First published February 2005

Contents

Executive Summary

1. Introduction and context

- This review of brain-based learning and what is currently known of its implications for learning was undertaken during 2004 by the SCRE Centre of the University of Glasgow. It was commissioned by the Scottish Executive Education Department. The aim is to review recent research on brain function and development and the possible impact on young people's learning. The main findings are summarised below.
- The 1990s were the 'decade of the brain' in the USA, and this led to increased interest in the implications of recent neuroscientific research for education.
- Important reviews of this area have been conducted for the ESRC Teaching and Learning Research Programme and for the OECD, as well as others written by individuals and teams for journals.
- We must be careful to distinguish between neuroscience, psychology, and education and be cautious about how we translate findings from one area into another.

2. Inside the brain

- The human brain contains 100 billion active neurons which are connected via synapses.
- The number of neurons in the brain remains more or less constant throughout life. The growth of the brain between childhood and adulthood is almost entirely due to the formation of new connections between neurons (synaptogenesis).
- The processes of synaptogenesis, pruning and plasticity are all important to the development of the brain.
- The brain is divided into two hemispheres, each of which has four lobes which are associated with cognitive functions.
- The brain has an evolved modular structure in which elementary functions are widely distributed; it is a parallel processor, with high connectivity, and high redundancy, and operates in a probabilistic manner.

3. What do we know about the brain?

- Brain research has used a variety of research methods, including invasive techniques, animal studies, and a range of imaging techniques. Each method has its strengths and weaknesses, and produces results which need to be interpreted with care.
- Studies with rats have shown that 'enriched' environments increase synaptic density.
- Studies of cats and monkeys have suggested that some functions may be subject to 'critical periods' for their development.

- Imaging studies of the developing human brain have shown that growth and development continues until early adulthood.
- Imaging studies of adults have shown continuing plasticity in the adult human brain.
- There are a number of 'neuromyths' which need to be debunked. These include ideas about 'right and left brains', 'critical periods' in the early years, and 'enriched environments' for young children.

4. Towards a consensus?

- Early disagreements between 'enthusiasts' and 'sceptics' appear to be giving way to a new consensus with a number of ideas now generally accepted.
- These ideas include the continued plasticity of the human brain, and the possibility of sensitive periods affecting the ease of certain types of learning.
- These sensitive periods extend at least into the teenage years, and possibly further.
- Neuroscience can also offer specific insights into some aspects of skills development, and is beginning to suggest new avenues of exploration in the investigation of some skills deficits.
- Neuroscience is confirming earlier psychological theories about the importance of emotional engagement in learning.

1: Introduction

1.1 Aims and methods

This is a review of brain-based learning and what is currently known of its implications for learning. It was written by the SCRE Centre of the University of Glasgow at the request of the Scottish Executive Education Department (SEED), who asked that we produce a:

> Review of recent research on brain function and development, and the impact of those on young people's learning, including possible implications for the design of learning experiences, programmes and classroom practice in pre-school, primary and secondary settings.
>
> (SEED Research specification)

In subsequent discussions with SEED it was specified that the review should concentrate on 'literature published in the last five years unless it is cited frequently in the recent literature and should not be ignored'. As we shall see, some very influential pieces of brain research pre-date the 'last five years' and have been the subject of much recent discussion. They are either included here directly, or recent interpretations of them are discussed.

Searching for relevant literature posed some particular problems in that the neuroscientific literature was an unfamiliar area to us, and the two sets of literature (neuroscientific and educational) showed very little overlap in the terms used as keywords in the literature databases. Only the very broadest categorisations could be used. For example, in one educational database nothing more subtle than the keyword 'brain' could be used without losing almost all references. Educational databases do not contain a rich set of neuroscientific descriptors, and neuroscientific databases do not contain a rich set of educational descriptors. As a result only very broad and undiscriminating searches were possible, and the results of these were then scrutinised for possible relevant publications. Fortunately this process quickly identified a few key publications which discussed the relationship between neuroscience and education, and the citations from these were then used to identify further relevant literature. This 'snowball technique' quickly resulted in the identification of a sizeable body of literature. Searching for further examples stopped at the point of 'saturation': when each new set of citations in a publication began to repeat key citations which had already been identified. In this way we believe that we have identified a core set of publications which encompass significant neuroscientific studies, important reviews of the field, and the major debates which have occurred.

The main databases which were searched were: the British Education Index (BEI), ERIC, PsychInfo, and EducationLine.

1.2 Background

The 1990s were declared the 'Decade of the Brain' in the USA (Bush, 1990), and this resulted in a large programme of research into the functioning and development of the human brain (LC/NIMH, 2000). Much of the initial focus was on mental health, degenerative disorders, or possibilities of understanding how drugs affect the brain, but interest extended to the implications of brain research for education. International interest in this topic also grew throughout the decade (OECD, 2002).

Out of all of this activity grew a great deal of public interest, partly as a result of a flurry of publications aimed at a general readership (eg Greenfield, 1999; Pinker, 2000), or at teachers (Bruer, 1999b; Jensen, 1998), or at both parents and teachers (Diamond & Hopson, 1998). This activity was especially pronounced in the United States, where official endorsements of 'brain based learning' appeared (eg ECS, 1998) alongside collections of resources for teachers (Krasner, 2002a; b), but has even made itself known in Scotland in articles in the popular educational press (eg Saunders, 2003). As we shall see in this review, some of what has been written has been extremely enthusiastic about the possibilities for education opened up by advances in the neurosciences. There has also, however, been an almost inevitable backlash from sceptics who claim that the enthusiasts have over-simplified neuroscientific research and over-interpreted its findings (Bruer, 1997; Davis, 2000).

Alongside this public interest there was also a growth in academic interest in the ways in which advances in neuroscience could be applied to education. The ESRC, as part of their *Teaching and Learning Research Programme (TLRP)*, commissioned a review of 'The Implications of Recent Developments in Neuroscience for Research on Teaching and Learning' (Blakemore & Frith, 2000), while the OECD held a number of international symposia on 'brain mechanisms and learning' (OECD, 2001a; b; c) which brought together many eminent neuroscientists and cognitive psychologists and resulted in a major publication (OECD, 2002). Growing academic interest has also been marked by such events as the publication of a special issue of the journal *Developmental Science* devoted to 'The Developing Human Brain' (Posner *et al*, 2001) and of a number of review articles surveying the field (Byrnes & Fox, 1998; Geake & Cooper, 2003; Goswami, 2004). The Byrnes and Fox article in turn attracted a number of responses from neuroscientists and psychologists (Berninger & Corina, 1998; Brown & Bjorklund, 1998; Geary, 1998; Mayer, 1998; O'Boyle & Gill, 1998; Schunk, 1998; Stanovich, 1998; Wittrock, 1998) most of whom were broadly supportive of its arguments in favour of 'the benefits of incorporating findings from cognitive neuroscience into the field of educational psychology' (Byrnes & Fox, 1998). Reviews and articles such as these have provided the starting point for much of what follows.

1.3 Neuroscience, psychology, and education

In 1997 John Bruer published an influential statement of the sceptic's view of the relationship between neuroscience and education in which he distinguished between 'neuroscience', 'cognitive science', and 'education'. He argued that it was possible to bridge the gap between neuroscience and cognitive science, and also to bridge the gap between cognitive science and education, but that the overall gap between neuroscience and education was too wide to bridge in one span as it was ‘a bridge too far’ (Bruer, 1997). It is possible to make even finer distinctions than Bruer, and amongst references to ‘brain science’ as a general and fairly neutral term, there are also more technical terms such as ‘neurobiology’, ‘neurophysiology’, ‘cognitive neuroscience’, ‘cognitive psychology’, ‘educational psychology’ and variations on these. The important point to make is that there are at least three distinctive types of study involved. The boundaries between them can become fuzzy, and there is growing interest in the links between them, but a crude characterisation of them would be to say that:

- At the first level, scientists are concerned with the inner workings of the brain. This is the level of ‘neuroscience’ where various aspects of biology, physiology, and chemistry are concerned with the structure, organisation and development of the brain as a physical organism;
- At the second level, the brain is thought of as a ‘black box’, studied experimentally from outside. This is the level of ‘psychology’, particularly in its experimental and cognitive forms, and is interested in the behavioural impact of various types of input applied in specified contexts;
- At the third level we are dealing with the practical application of knowledge about human behaviour to promote effective teaching and learning. This is the realm of ‘education’ which is as much a social endeavour as a scientific one.

Of course, neuroscience has implications for psychology, just as psychology has for education: ‘cognitive neuroscience’ is attempting to link the first and second levels, and it is easy to see that disciplines like social psychology or educational psychology are as close to the third level as the second, but these distinctions are a useful reminder that it is a very long journey from a discovery about the physiology or organisation of the brain to a practical application in a classroom.

Even the most supportive reviewers of the possible contributions of neuroscience enter a note of caution:

> Despite the remarkable progress, brain research has not yet found an application in theory or practice of education.
>
> (Blakemore & Frith, 2000)

and:

> The identification and analysis of successful pedagogy is central to research in education, but is currently a foreign field to cognitive neuroscience.
>
> (Goswami, 2004)

The OECD report on the outcomes of their symposia elaborates on some of the practical and methodological difficulties in making this connection:

> Current research methods in cognitive neuroscience necessarily limit the types of questions that are addressed. For example, questions such as “How do individuals learn to recognise written words?” are more tractable than “How do individuals compare the themes of different stories?”. This is because the first question leads to studies where the stimuli and

> responses can be easily controlled and contrasted with another task. As such, it becomes understandable in reference to known cognitive models. The second question involves too many factors that cannot be successfully separated during experimental testing. For this reason, the type of educational tasks favoured by society will remain more complex than the ones that might suit cognitive neuroscience.
>
> (OECD, 2002)

Having noted these cautions, we will now look at what we know of the brain, how we know it, and what some important neuroscientific studies have to suggest about the brain and learning.

1.4 Summary

- The 1990s were the ‘decade of the brain’ in the USA, and this led to increased interest in the implications of recent neuroscientific research for education.
- Important reviews of this area have been conducted for the ESRC Teaching and Learning Research Programme, and for the OECD, as well as others written by individuals and teams for journals.
- We must be careful to distinguish between neuroscience, psychology, and education, and be cautious about how we translate findings from one area into another.

2: Inside the brain

2.1 Neurons and synapses

The average adult human brain weighs around one and a quarter kilograms and contains somewhere in the region of 100 billion active nerve cells, known as neurons, which are responsible for all our mental activity (Greenfield, 1999). The neurons form the 'grey matter' of the brain. Alongside them there are also many billions (possibly 1000 billion) 'glial cells' which form a supporting structure, but do not contribute directly to mental activity. Each neuron consists of a cell nucleus, a 'tail' known as an axon which functions as the route for the transmission of electrical messages from the neuron, and a large number of smaller branching structures, known as dendrites, which act as receptors for messages from other neurons. Messages between neurons do not seem to operate in a binary fashion – ie it is not the case that a neuron is switched 'on' or 'off' like part of a computer circuit – but rather the level of activation of neurons appears to be continuously variable (OECD, 2002). The connection between neurons – the point at which a dendrite receives a message from an axon – is known as a synapse. In this way any one neuron may be connected to many thousands of other neurons. While the total number of neurons in the human brain remains relatively constant from birth, the number of synaptic connections between neurons undergoes significant changes, and much of neuroscience has been concerned with studying these changes.

It is now believed that almost all the neurons which will eventually comprise the mature human brain are formed while in the womb and are present from birth (although it has recently been reported that some parts of the brain have been found to generate new neurons (OECD, 2002: 67)). What changes most dramatically is the growth of axons, and dendrites, and the number of synapses connecting neurons. This process is known as synaptogenesis and seems to occur in different parts of the brain at different times. Somewhat counter-intuitively, it also results in the developing brain having far more synapses than will be present in the adult brain: one part of brain development consists not of growth, but of 'pruning' of the number of synaptic connections between neurons, a process which appears to be a variety of 'fine tuning' of the brain in response to environmental stimuli, and results in the reduction of the number of synapses to adult levels. As development continues a process known as 'myelinisation' takes place. This involves an increase in the coating of the axon of each neuron which serves to improve its insulation and therefore make the established connections more efficient. The ability of the brain to change as a result of learning, or in response to environmental changes, is known as 'plasticity' and is particularly apparent in, but not confined to, infants in the early years of development (OECD, 2002). Brief outlines of brain development are given in Greenfield (1999), Blakemore and Frith (2000), Goswami (2004), and elsewhere.

> The general pattern of brain development is clear. There are bursts of synaptogenesis, peaks of density, and then synapse rearrangement and stabilisation with myelinisation, occurring at different times and rates for different brain regions (ie different sensitive periods for the development of different types of knowledge). Brain volume quadruples between birth and adulthood, because of the proliferation of connections, not because of the production of new neurons. Nevertheless, the brain is highly plastic, and significant new connections frequently form in adulthood in response to new learning or to environmental insults (such as a stroke).
>
> (Goswami, 2004)

2.2 Larger structures in the brain

The brain is not a homogeneous mass of cells. There are identifiable structures within it and, at a gross level, parts of the brain are associated with particular types of mental activity. Possibly the most well known fact of brain geography is that it is split into two hemispheres, the left and right, which are connected by a mass of nerve fibres called the corpus callosum, which carries messages between the two hemispheres. The brain is also divided into those parts which deal with the unconscious regulation of the bodily functions (eg breathing or digestion), basic drives and emotions, and those parts where thinking occurs. The part of the brain responsible for conscious thought is the neocortex, which is at the outer surface of the brain (OECD, 2002).

Each hemisphere is divided into 'lobes' which have been identified with particular tasks: the frontal lobe with planning and action; the temporal lobe (situated at the lower side of each hemisphere) with hearing, memory and object recognition; the parietal lobe (upper middle) with sensation and spatial processing; and the occipital lobe (rear) with vision (OECD, 2002). Parts of the brain in these areas may also be identified as the 'motor cortex', 'sensory cortex' and 'visual cortex' (eg in Blakemore & Frith, 2000). Lying within the brain are the hippocampus, which appears to be concerned with the formation of memories, including spatial memory and navigation, and the amygdala which is connected with our emotional responses. At the bottom rear of the brain is the cerebellum which is responsible for co-ordinating movement; and connecting the brain to the spinal cord is the brain stem which acts as the main messaging system between the brain and the rest of the body. The OECD report warns us, however, that:

> These are gross characterisations, of course, as each lobe is further subdivided into interlocking networks of neurons specialised for very specific information processing. Any complex skill, like addition, or word recognition, depends on the co-ordinated action of several of these specialised neural networks localised in different parts of the brain.
>
> (OECD, 2002)

2.3 Localisation of functions

Byrnes and Fox (1998) outline the history of a long-standing argument between proponents of the view that specific cognitive functions are localised in particular areas of the brain (the ‘localists’), and those who believed that ‘all regions [of the brain] have an equal ability to perform different tasks’ (the ‘globalists’). The arguments in favour of the localists derived from studies of brain injuries or lesions in particular areas of the brain which result in loss of specific functions, while the globalists drew on data which showed that injuries in different parts of the brain can result in the same deficit, and animal studies which showed that large parts of rat brains could be removed without any apparent deficit (Byrnes & Fox, 1998). As might be expected, the current view is more complex, and to some extent accommodates both views. It is now thought that almost any cognitive function is composed of the combined action of a number of smaller ‘elementary’ functions, at least some of which are localised. Therefore, at least some parts of the brain have specialist functions. However, more complex functions are made up of a number of these elementary functions distributed across multiple areas of the brain. ‘Complex’ in this context is a relative term, and even basic tasks which may seem ‘elementary’ in an educational context (eg number recognition) may be neuroscientifically ‘complex’. The current view is that the brain works via a number of ‘distributed functions and subsystems’ (Byrnes & Fox, 1998).

There are several other features of the way that the brain functions which lessens the force of the strict localist argument, while not denying the possibility of specific elementary functions being associated with identifiable brain areas. These are the notions of ‘parallelity’, ‘connectivity’, ‘redundancy’ and ‘probabilistic action’ (Byrnes & Fox, 1998). In brief, ‘parallelity’ asserts that the elementary functions which make up a complex function are performed simultaneously in different areas of the brain and not one after another in serial fashion; ‘connectivity’ notes that the very high number of connections between neurons implies a high degree of interaction between subsystems; ‘redundancy’ holds that ‘the brain often performs more tasks than it has to do’ so that it can perform complex functions even with the failure of some elementary functions; and ‘probabilistic action’ means that certainty does not need to be achieved for a function to be performed. Byrnes and Fox give this example:

> To illustrate with a simplified example, let’s say that a function such as recognizing the “b” sound is carried out by four clusters of neurons (N1, N2, N3, and N4), and that if any three of these neural clusters are active, then the “b” sound is recognized.
>
> (Byrnes & Fox, 1998)

All of these factors together explain why specific brain lesions or other abnormalities do not always produce the deficits in performance which one would expect to see if complex functions were highly localised. Elsewhere, Brandt has described this organisation of the brain as ‘the evolved modular brain’ (Brandt, 1999). The problem for neuroscientists then becomes one of understanding how all the elementary functions interact and work together. Geake and Cooper describe it thus:

> … data from the past decade have been particularly informative about functional modularity – that different discrete areas of the brain, especially within the cortex, are critically involved in mediating various

> cognitive behaviours … For example, PET scans have revealed different cortical language-related areas in the dominant cerebral hemisphere for reading, speaking, writing and comprehending words … As these tasks are often performed simultaneously, the less understood issue of synchronisation, the so-called 'binding problem', is predicted as being the focus of cognitive neuroscientific research for the current decade.
>
> (Geake & Cooper, 2003)

One other factor to consider is that the functions performed by particular areas of the brain are not necessarily pre-determined from birth, but can alter as the result of environmental differences. Goswami (2004) describes how a part of the brain which is normally associated with auditory analysis (hearing), is used for visual/spatial analysis by people who are born deaf and use sign language. Similarly, in blind people who read braille, it has been found that an area of the brain which is normally associated with vision becomes used for tactile analysis. Clearly these are extreme environmental differences, but they do suggest that at least some areas of the brain can develop to perform different functions depending on the environmental stimuli to which they are exposed (Goswami, 2004). It is also increasingly clear that the synaptic connections within the brain can change and re-form throughout life as a result of learning, or in response to injury, so that 'the brain retains its plasticity over the life-span' (OECD, 2002).

2.4 Summary

- The human brain contains 100 billion active neurons which are connected via synapses.
- The number of neurons in the brain remains more or less constant throughout life. The growth of the brain between childhood and adulthood is almost entirely due to the formation of new connections between neurons (synaptogenesis).
- The processes of synaptogenesis, pruning and plasticity are all important to the development of the brain.
- The brain is divided into two hemispheres, each of which has four lobes which are associated with cognitive functions.
- The brain has an evolved modular structure in which elementary functions are widely distributed; it is a parallel processor, with high connectivity and high redundancy, and operates in a probabilistic manner.

3: What do we know about the brain?

In this section we will look briefly at some of the methods which have been used to study the brain, and at some of the key neuroscientific studies which have been used as the basis for a neuroscientific view of education. In a later section we shall see how some of these results have been over-interpreted and have given rise to a number of popular misconceptions, before attempting a synthesis of what is currently accepted as reasonably well-established knowledge regarding neuroscience and its implications for education.

3.1 Methods of studying the brain

There are a number of ways in which scientists have studied the brain. As we shall see, each of these has its uses, and its limitations, although modern techniques are becoming much more sophisticated and offer hope for much increased knowledge in the future.

3.1.1 Invasive techniques

One of the first, and most direct, ways of studying the brain is through autopsy and brain surgery. Clearly, while this offers direct access to the object of study, it is of limited use in forming conclusions about the general, healthy, human population. It has, in the case of autopsy, allowed scientists to do such things as measure synaptic densities with some accuracy and, in the case of surgery, to study the effects of surgical interventions, brain damage, or brain lesions due to injury or disease on behaviour (OECD, 2002).

Neuroscientists who have studied the effects of brain lesions on cognitive functioning have linked damage to specific areas of the brain with specific cognitive functions. Byrnes and Fox (1998) have noted some problems with this approach: because brain lesions typically affect multiple small regions of the brain, it is not always possible to be certain about which is the key area – even if a link between damage and loss of function is established, this does not mean that that area controls the function (it may perform a crucial but ancillary function). Furthermore, damage to an area of the brain often causes loss of performance rather than complete elimination of an ability or function (which suggests that there is not an exact correspondence between brain area and function). Finally, considerable individual differences in localisation of function have been discovered (in other words, all our brains are not organised in the same way) (Byrnes & Fox, 1998). For all of these reasons some caution has to be exercised when drawing out the implications of this type of study.

3.1.2 Animal studies

There are a number of ways in which animals have been used in neuroscientific studies. Some of these have involved surgery to examine the effects of damage on function; others include studying the effects of drugs or hormones, or inducing temporary disability through lowering the temperature of parts of the brain; and then there is the use of ‘single unit recording’ which involves inserting an electrode into the animal's brain to record localised electrical activity (Byrnes & Fox, 1998). Finally there are behavioural studies of animals such as those which involved rearing rats in environments with varying degrees of 'enrichment' (Byrnes & Fox, 1998; Greenough *et al*, 1987). Animal studies such as these may, or may not, involve post-mortem study of the effects of the intervention on brain structure and development.

Once again, Byrnes and Fox have summarised the limitations of animal studies: the obvious point is that animals are not humans – they are less flexible in their behaviour and do not possess human higher-order skills. It is also known that the locations of certain processes in animal brains are different from those in human brains (eg rats and humans appear to use different parts of the brain for working memory), and that the brain matures differently in different species (analyses of synaptic densities in infants and adults of different species shows different patterns of development) (Byrnes & Fox, 1998). All of which means that we have to be very careful when extrapolating from animal studies to possible implications for human learning.

3.1.3 Imaging and measuring techniques

There are several imaging techniques which are commonly used to study the brain and its activity. These are extensively described within the literature (Blakemore & Frith, 2000; Goswami, 2004; OECD, 2002; Posner *et al*, 2001). They rely on the assumption that any task will make specific demands on the brain and that this will be reflected in changes in brain activity. Some measure electrical activity within the brain, while others measure the flow of blood within the brain (on the assumption that increased activity demands increased blood flow). Some techniques have very good temporal resolution (they can measure changes which take place within milliseconds), while others have good spatial resolution (they can locate activity to within millimetres); but few techniques can achieve both, although there are improved methods and technology becoming available. It is also sometimes possible to combine techniques.

Electroencephalography (EEG) works by attaching a set of electrodes to the outside of the scalp and measuring the minute electrical activity of the brain. These electrodes can be fitted into a headcap to allow for some mobility. A closely related technique is that of measuring evoked response potentials (ERPs), which are changes in electrical activity in response to some stimulus. Magnetoencephalography (MEG) relies on measuring the magnetic fields associated with electrical activity. All of these techniques have good temporal resolution, but relatively poor spatial resolution.

Magnetic resonance imaging (MRI) can be used to study the structure of the brain because different structures within it have different magnetic properties depending on their composition. Closely related to it is functional magnetic resonance imaging (fMRI), which is used to study brain activity, and works because the magnetic properties of blood change according to the amount of oxygen it contains, and this in turn changes with the level of activity. These techniques can achieve high spatial resolution. The levels of temporal resolution are improving all the time, but do not yet match those of EEG. Disadvantages of MRI and fMRI are that they require the subject to lie still within a confined scanning chamber, which can be difficult for subjects prone to claustrophobia, and that they also demand a powerful magnetic field and can be extremely noisy. Subjects need to wear earplugs to protect their hearing. It therefore requires pliant and willing subjects (ie it is unlikely to be useful with children).

Positron emission tomography (PET) relies on a radioactive isotope being injected into the bloodstream. Radiation detectors positioned around the head can then detect the flow of blood within the brain. The use of ionising radiation clearly limits the subjects with which PET scans can be used (it is not suitable for use with children, or with women of child-bearing age). The temporal resolution of PET scans is relatively low, and the scan itself can take a long time to do (up to 2 hours).

Other techniques which are occasionally encountered include transcranial magnetic stimulation (TMS) in which magnetism is used to create a temporary disruption, or inhibition, of a localised area of the brain, so that researchers can then study whether this is related to a particular function. Further work is needed to determine whether this technique is free of adverse effects (Posner *et al*, 2001). Optical topography (OT) uses near-infra-red spectroscopy (NIRS) to study blood flow, but requires further development. These techniques are less common than EEG, fMRI, PET scans, and their variants.

With all of these techniques there are limitations concerning the spatial or temporal resolution which they can achieve, practical difficulties in conducting the scan, and questions about the suitability of different techniques for different types of subject. There are also other limitations which are not so readily apparent. For example, there is a 'lack of anatomical standardization' which hinders comparisons between subjects, 'heterogeneity in different subjects' responses' (ie individual differences), problems with the signal-to-noise ratio of the technique, and problems with the statistical power of the (statistical) tests used to identify differences (Posner *et al*, 2001). All of which leads to a cautious approach to the use of findings from these imaging techniques:

> For all these reasons, negative findings should be interpreted with caution, positive findings should be interpreted in the form of testable hypotheses, and imaging studies should be used in a manner that complements other research strategies.
>
> (Posner ***et al***, 2001)

3.2 Key neuroscience studies

Over the years there have a number of key neuroscientific studies which have come to be seen as having important implications for education. Some are based on animal studies, while others use information from imaging studies of human subjects.

3.2.1 Rats and 'enriched environments'

This is a classic set of studies on the effects of the environment on brain development. It is discussed by Blakemore and Frith (Blakemore & Frith, 2000) and is based on experiments conducted by a number of researchers (Diamond *et al*, 1987; Green *et al*, 1983; Greenough *et al*, 1987). In the original experiment rats were brought up in either an 'enriched' or a 'deprived' environment. The 'deprived' environment was a normal laboratory cage for a single rat, while the 'enriched' environment included various toys such as wheels and ladders, and also had other rats for company. It was found that the rats brought up in the 'enriched' environment had:

> … up to 25% more synapses per neuron in brain areas involved in sensory perception than 'deprived' rats, raised alone in a lab cage with no 'playmates' or toys. Furthermore, the rats raised in complex environments perform learning tasks better than deprived rats.
>
> (Blakemore & Frith, 2000)

Later studies with rats showed that adult rats could also form new synapses in response to an 'enrichment' of their environment through the addition of toys and new experiences, which suggests that experience can also shape the adult rat brain (Green *et al*, 1983).

3.2.2 Cats, monkeys, and 'critical periods'

Animal studies have been a rich source of data for what we know about brain development and the results of deprivation. Changes in the numbers of synapses per neuron were first shown in the visual system of cats in 1975 (Cragg, 1975a; b). It was found that as cats grew from infancy the number of synapses in the visual system first increased rapidly and then slowly fell back to adult levels. Similar investigations of rhesus monkeys have shown that the density of synapses in the brain reaches its maximum at around 3–4 months old, and then falls back, reaching adult levels when the monkey is around three years old. This corresponds to the age of sexual maturity in rhesus monkeys (Goldman-Rakic, 1987; Rakic, 1995).

These processes of synaptogenesis and pruning have been connected back to earlier experiments on visual deprivation in cats in which one eye of new born kittens was fixed shut for three months (Wiesel & Hubel, 1965). After this time the researchers studied the connections between the two eyes ('open' and 'shut') and the brain and found that there was 'a severe deterioration of neuronal connections in the visual areas of the brain' because of lack of stimulation of the closed eye. The brain had, in effect, wired itself to receive information only from the open eye and remained blind in the other eye (Blakemore & Frith, 2000). When adult cats were subjected to a similar period of visual deprivation in one eye, there was no deterioration in neuronal connections. The conclusion was that, at a certain period of development, the brain requires sensory input if it is to 'wire itself' to deal with that sensory input. This is a 'critical period' of brain development. If this critical period is missed the brain will not be able to cope with the sensory input.

However, subsequent research has shown that some recovery of function is possible, depending on the extent of the deprivation, and whether suitable recovery training is offered (Chow & Stewart, 1972), so that the effects of deprivation are less irreversible than previously thought. These findings are further discussed by Blakemore and Frith, and Bruer (Blakemore & Frith, 2000; Bruer, 1997).

3.2.3 The growth of the teenage brain

For some years now a group of researchers in the USA have been using MRI scans to study the brain development of a number of normal, healthy young people and teenagers (Giedd *et al*, 1999; Gogtay *et al*, 2004; NIMH, 2001; NIMH, 2004; Thompson *et al*, 2000). At the time of the latest report from this study, the oldest subjects were 21 years old. The researchers have combined the results from all the scans from all of the subjects to produce a computerised 'time-lapse' picture of how the brain develops between the ages of 5 and 20. Because of individual differences in brains, this has entailed the use of complicated models of the brain structure which allows the researchers to map anatomical landmarks in the scans of different brains on to one another, to combine them, and to interpret the scans using statistical models of grey matter density in the brain. The resulting time-lapse animations are therefore *interpretations* of what is happening.

What the researchers have found is that the initial, and well-known, phase of synaptogenesis followed by pruning, which occurs in early childhood (see, for example, Chugani *et al*, 1987), was followed by a second wave of synaptogenesis and pruning in the early teenage years, and then further development of the brain with the frontal lobes (associated with reasoning and problem solving), not fully maturing until early adulthood. They interpret their findings as implying that 'phylogenetically older brain areas mature earlier than newer ones' (ie those areas of the brain which belong to the earliest stages of human evolution are the first to mature, with later evolutionary developments maturing later); and 'higher-order association cortices mature only after lower-order somatosensory and visual cortices, the functions of which they integrate, are developed' (Gogtay *et al*, 2004). The brain therefore seems to develop in stages from those areas governing lower-order functions to those governing higher-order functions:

> The new study found that the first areas to mature (eg, extreme front and back of the brain) are those with the most basic functions, such as processing the senses and movement. Areas involved in spatial orientation and language (parietal lobes) follow. Areas with more advanced functions – integrating information from the senses, reasoning and other "executive" functions (prefrontal cortex) – mature last.
>
> (NIMH, 2004)

The normal development of the growing human brain therefore appears to go on for much longer than had previously been thought.

3.2.4 Taxi drivers, musicians, and 'plasticity'

There have been a number of studies which have demonstrated the fact that the adult human brain retains a degree of 'plasticity' - ie that its structure and organisation can physically change as a result of new demands placed upon it, and that these changes can occur in adulthood and are not confined to a period of childhood development. One of these studies was a comparison of structural MRI scans of the brains of London taxi drivers with a group of control subjects who did not drive taxis (Maguire *et al*, 2000). It was found that 'posterior hippocampi of taxi drivers were significantly larger relative to those of control subjects' and that the hippocampal volume correlated with the amount of time spent as a taxi driver. It was concluded that:

> These data are in accordance with the idea that the posterior hippocampus stores a spatial representation of the environment and can expand regionally to accommodate elaboration of this representation in people with a high dependence on navigational skills.
>
> (Maguire ***et al***, 2000)

Clearly, the taxi drivers had elaborated their 'spatial representation of the environment' as adults. The significant point is the demonstration of continued plasticity in the adult brain.

Other studies of adult learning have included work with musicians which discovered that part of the auditory cortex of skilled musicians was up to 25% larger than in non-musician control subjects, and that the extent of the comparative enlargement was correlated with the age at which the musicians began to practice (Pantev *et al*, 1998). Taxi drivers and skilled musicians have developed a high degree of specialised knowledge over a long period of time. However, studies have also shown that the brain can adapt itself remarkably quickly to new demands being placed on it, and that the physical evidence for this plasticity shows up very quickly. One study took a group of non-musicians and asked them to practice a set of five-finger exercises for the piano for two hours a day for five days. At the end of the five days the part of their brain responsible for finger movement was found to be enlarged and more active compared to a group of control subjects who had not performed the exercises (Pascual-Leone *et al*, 1995).

Studies such as these, and those discussed in previous sub-sections, have suggested a great deal about how the brain works, and its capabilities. However, to some commentators they have suggested more than can reasonably be justified by the evidence.

3.3 Neuromyths

The term 'neuromyth' was first used in the report of the OECD symposia on brain research (OECD, 2002), and has also been used by Goswami (Goswami, 2004), while others have identified the problem without using the term (eg Jensen, 2000). It refers to popular assumptions about the implications of brain research which have somehow become established as common belief, but which are not justified by the research. Several such ‘neuromyths’ are quite widespread and are commonly encountered.

3.3.1 Brain laterality

One of the oldest and most well-established of the neuromyths concerns brain laterality, or the idea that the two halves of the brain work in fundamentally different ways. The ‘left brain’ is usually characterised as the logical half of the brain, concerned with reasoning, problem-solving, and language, while the ‘right brain’ is characterised as the intuitive and creative side, concerned more with images than words. Popular accounts based on this notion have been around for many years (Edwards, 1982; Williams, 1986). They still appear within the literature (Sabatella, 1999).

Unfortunately this is a gross over-simplification which is not supported by the brain research literature (Bruer, 1999a; OECD, 2002). It was based largely on studies of ‘split brain’ patients who had the corpus callosum (which connects the two hemispheres) severed as a treatment for epilepsy. This is a highly abnormal circumstance which results in disruption of communication between the two halves of the brain. In the normal, healthy adult human brain such gross characterisations of ‘laterality’ do not hold. For a start, functions ascribed to the two halves of the brain are at too high and generalised a level. Almost all functions of any complexity are found to consist of a series of elementary functions which are distributed throughout the brain. Even so simple a task as the identification of arabic numerals (‘1’, ‘2’, etc) activates parts of the brain in both hemispheres, and the same goes for decoding written words, recognising speech sounds and understanding spatial relationships (OECD, 2002). Most tasks require multiple areas of the brain to work together. As the OECD report explains ‘The brain is a highly integrated system; one part rarely works in isolation’ and ‘most tasks require both hemispheres to work in parallel’ (OECD, 2002).

3.3.2 ‘Critical’ periods

The idea that there are ‘critical’ periods for brain development derives from the studies of visual deprivation in kittens cited earlier (Cragg, 1975a, b) and from the related studies of brain development in rhesus monkeys (Goldman-Rakic, 1987; Rakic, 1995). It is closely related to our understanding of the processes of synaptogenesis and pruning in the developing brain. In its extreme form this neuromyth becomes the ‘myth of the first three years’ (Bruer, 1999b) which states that the brain is uniquely prepared for learning during the period of maximum synaptogenesis (which proponents usually take to be the first three years of life) and that, if advantage is not taken of this period of rapid growth, then the opportunity for maximum brain development will be lost. This is sometimes stated as a ‘use it or lose it’ argument.

There are several problems with this idea. They are discussed by Bruer (Bruer, 1997; 1998a; 1999a) and in the OECD report (OECD, 2002), and are summarised here.

Firstly, the animal studies relate only to the development of sensory systems, and even here, it has been shown that recovery is possible (Chow & Stewart, 1972). It may be that the idea of 'critical periods' applies only to some forms of learning ('… we have evidence for the existence of critical periods only for component functions within sensory and motor systems and in humans for components of language' (Bruer, 1997)). Secondly, the argument from the studies of rhesus monkeys assumes that the course of synaptogenesis is the same for humans as it is for the monkeys (and some of the studies cited earlier, in Section 3.2.3, cast some doubt on this). Thirdly, the assumption is that the period of maximum synaptogenesis corresponds with the period of maximum learning, and that more synapses mean more brainpower – an idea which has simply not been demonstrated. (Indeed, experience and a moment's reflection reveal that we all can continue to improve some skills and capacities long after the process of synaptic pruning has reduced synaptic density to adult levels.)

The neuroscientists have now shied away from the term 'critical periods' although they have identified certain types of learning which are subject to 'sensitive periods' – ie times when the brain appears to be particularly primed for certain types of input, and ready to adapt itself to meet such demand, but which are not a case of 'all or nothing' (OECD, 2002). There is evidence, for example, that in humans some aspects of language development are subject to 'sensitive periods'. The sensitive period for acquiring mastery of phonology and syntax appears to extend to the early teenage years. However, acquisition of vocabulary (lexicon) and understanding of meaning (semantics) are not so affected. This does not mean that humans cannot master the phonology and syntax of a language after their early teenage years (many do) but it is suggested that perhaps different brain mechanisms are used and that, for example, pronunciation is likely to mark out a later learner as 'non-native'.

Neuroscientists have come to draw a distinction between 'experience expectant' learning and 'experience dependent' learning (Greenough *et al*, 1987). 'Experience expectant' learning has been conditioned by our evolutionary development and is where the brain expects certain kinds of input (eg visual, tactile or auditory stimulus) to which it will adapt itself. It is a response to our environment which allows the brain to fine-tune itself, and it may be subject to 'sensitive periods' when the brain is particularly ready to respond to these stimuli, which are ever-present in the environment. 'Experience dependent' learning does not have these constraints. It is the type of learning which will only occur if the need arises for it, and tends to be of the sort which features in culturally transmitted knowledge systems. The development of speech is 'experience expectant' in that we all have an evolutionary imperative to learn to communicate by speech, and tend to do so at a particular stage of childhood; but learning to read is culturally determined, 'experience dependent', learning, which will not happen by itself, demands training, and results from cultural and social necessity.

3.3.3 Enriched environments

This neuromyth is based on an extrapolation from studies of rats brought up in either 'enriched' or 'deprived' environments (eg Diamond *et al*, 1987), and described in an earlier section. The rats brought up in the 'enriched' environment were found to have greater synaptic density in their brains. Commentators have extrapolated from this that young children should be brought up in an 'enriched' environment in order to enhance their learning potential. (See, for example, Whitebread, 2002.) Apart from the obviously dubious procedure of deriving conclusions about humans from studies of rats, there are also other problems with this:

> The neuromyth logic is that the more synapses available, the higher the potential nerve activity and communication, thus making better learning possible. An associated belief is that early educational intervention using 'enriched environments' can save synapses from pruning, or can create new synapses, thereby leading to greater intelligence or greater learning capacity. Feeding this is the additional problem of quoting the facts of a pertinent study and then assigning meaning that goes well beyond the evidence presented in the original research paper.
>
> (OECD, 2002)

As the OECD report goes on to make clear, there is no evidence in humans linking synaptic densities and improved learning; and there is no evidence relating synaptic densities in early life with those in later life. The reasoning has also been criticised on the grounds that the so-called 'enriched' environment for the rats was, in fact, much closer to a normal rat environment, so that what the study showed was the detrimental effects of an artificially 'deprived' environment. There is some human evidence to support this second conclusion. This derives from studies of Romanian orphans who were brought up in severely impoverished environments (O'Connor *et al*, 1999). These children suffered ill effects from this deprivation, although rehabilitation was still found to be possible in many cases.

The original rat studies also went on to show that the effects of environment (whether 'enriched' or 'deprived') were evident in rats of all ages, and not just young rats (Green *et al*, 1983; Greenough *et al*, 1987). They were providing, in fact, evidence for the continued plasticity of the brain. A final problem is that, as John Bruer has put it, ' "enriched", when applied to early education for humans, is very much in the eye of the beholder, often reflecting the beholder's cultural and class values' (Bruer, 1997), and this preference is definitely not supported by neuroscience.

3.3.4 Myths to come?

Brain laterality, 'critical' periods and 'enriched' environments may be the most prevalent current neuromyths, but Goswami for one, believes that others are also in circulation. In particular, ideas about the 'gendered brain' and 'implicit learning' are appearing (Goswami, 2004). The notion that there are identifiable differences between males and females in brain structure and organisation is occasionally encountered (Hansen & Monk, 2002; O'Boyle & Gill, 1998) and may have some basis in fact (Blakemore & Frith, 2000). The OECD report classes it as ‘intelligent speculation’, and does not dismiss it out of hand, although it notes that any implications for education are, at present, ‘equivocal’ (OECD, 2002). However, it is known that there are considerable differences between individual brains, and it is not at all clear whether the ‘between group’ statistical differences outweigh the ‘within group’ differences (or conversely whether individual differences are so great that they swamp any identifiable differences between sexes). Nor is it entirely easy to separate the biological from the cultural bases of any gender differences (OECD, 2002).

‘Implicit’ learning occurs when the brain absorbs information which is not consciously being attended to (Blakemore & Frith, 2000; OECD, 2002). It is certainly an important factor to bear in mind when trying to avoid distractions from learning. However, experiments which have investigated implicit learning have tended to concentrate on perceptual learning tasks rather than cognitive tasks, and there is some doubt as to whether implicit learning is applicable to cognitive tasks (Goswami, 2004). A typical perceptual task to investigate implicit learning involves showing subjects allegedly random sequences of stimuli which in fact adhere to complex rules of sequencing. Subjects’ responses on a prediction test show that they have ‘learnt’ the sequence even though they remain unaware of the sequencing principle (Blakemore & Firth, 2000).

Neither of these ideas has yet gone much beyond the stage of investigation and speculation in neuroscience research, and they have not yet given rise to full-blown neuromyths.

3.4 Summary

- Brain research has used a variety of research methods, including invasive techniques, animal studies, and a range of imaging techniques. Each method has its strengths and weaknesses, and produces results which need to be interpreted with care.
- Studies with rats have shown that ‘enriched’ environments increase synaptic density.
- Studies of cats and monkeys have suggested that some functions may be subject to ‘critical periods’ for their development.
- Imaging studies of the developing human brain have shown that growth and development continues until early adulthood.
- Imaging studies of adults have shown continuing plasticity in the adult human brain.
- There are a number of ‘neuromyths’ which need to be debunked. These include ideas about ‘right and left brains’, ‘critical periods’ in the early years, and ‘enriched environments’ for young children.

4: Towards a consensus?

4.1 The debate

The debate about the relationship which should exist between neuroscience and education was mentioned briefly in the introduction to this review. It continues to be extensively discussed. (See, for example, Berninger & Corina, 1998; Brown & Bjorklund, 1998; Byrnes & Fox, 1998; Geake & Cooper, 2003; Geary, 1998; Goswami, 2004; Mayer, 1998; O'Boyle & Gill, 1998; Schunk, 1998; Stanovich, 1998; Wittrock, 1998.) There continue to be enthusiastic proponents of the insights which neuroscience can offer to education (Clark, 2001; Diamond & Hopson, 1998; Greenleaf, 1999; Sabatella, 1999), and others who are deeply sceptical, believing that these claims are the result of over-simplification, over-generalisation, and unjustified extrapolation. The key figure among the 'sceptics' has been John Bruer, whose arguments carry some force in that they are clearly based on wide knowledge and understanding of the neuroscientific literature (Bruer, 1997; 1998a; b 1998; 1999a 1999 b; 2002.) He is not, however, alone (see, for example, Davis, 2000; Jensen, 2000; Wolfe & Brandt, 1998). It seems clear that the sceptics are right to criticise some of the wilder claims that have been made for the place of neuroscience in education. Some educationalists have been keen to appropriate neuroscientific research to promote their own views, whether these be of early childhood education (Whitebread, 2002), the education of gifted children (Sabatella, 1999), the teaching of adolescents (Greenleaf, 1999), or the teaching of those with additional support needs (Pope & Whitely, 2003). Some of these are on firmer ground than others, and some owe at least as much to the psychological literature as to the neuroscientific literature. It is noticeable that there is less traffic in the other direction, so that 'it is rare to find an article written by a neuroscientist in the educational literature' (Bruer, 1998b).

It is also fair to say that the main reviews of the area which have appeared in recent years, and which have attempted an objective evaluation of the educational import of the neuroscientific literature, have tended to give some support to the sceptical argument (Blakemore & Frith, 2000; Byrnes & Fox, 1998; Goswami, 2004; OECD, 2002). They have not, however, entirely dismissed the case made by the 'enthusiasts'. What has faded slightly is the belief that some grand scheme of 'brain based education' can be made instantly available to transform learning and teaching. In its place is a more cautious and incremental approach which acknowledges that our current state of knowledge is incomplete and may be, in some aspects, inaccurate. It is also being increasingly acknowledged that any account of how education works which makes any claim to being complete, coherent, and scientific, will need to be entirely congruent with what we know about how the brain works. Attempts are being made to link neuroscientific research, cognitive psychology, and education by a more careful and realistic drawing out of the implications of neuroscientific research, but also by using the insights of education and psychology to guide neuroscience towards new areas of research. A cautious, new, synthesis is beginning to emerge and something approaching a consensus can be discerned in the more recent literature.

4.2 Where are we now?

The OECD report makes a plea that we should distinguish between:

> *a*) what is well-established (plasticity), *b*) what is probably so (sensitive periods), *c*) what is intelligent speculation (the implications of gender) and what is a popular misconception or oversimplification (the role of the “left and right hemispheres”).
>
> (OECD, 2002)

As this indicates, there are varying degrees of certainty attached to different neuroscientific ideas. Other commentators have also come up with their lists of findings which they judge to be more, or less, well established. In 1998, Wolfe and Brandt suggested four key findings which they believed were ‘well established’. These were: that ‘the brain changes physiologically as a result of experience’ (ie plasticity); that ‘IQ is not fixed at birth’; that ‘some abilities are acquired more easily during certain sensitive periods’; and that ‘learning is strongly affected by emotion’ (Wolfe & Brandt, 1998). Hansen and Monk (2002) suggested that:

- There appears to be maturation and changes occurring in the brain up to a much later age than expected.
- There is some evidence of periods of rapid growth, which may suggest brain maturation is a key factor in determining the timing and course of cognitive development and when pupils may then be ready for the next 'stage'.
- The adult/child processing of stimuli may be different and equally children who are pre-operational may be processing information differently to those at an operational level.
- There is some evidence for at least a second wave of over production of synaptic connections that can be influenced by experience and hence, reflexively, influence cognitive development itself.
- There are suggestions of gender differences.
- Increased myelineation is being linked with improved cognitive processing.

(Hansen & Monk, 2002)

Both Wolfe and Brandt and Hansen and Monk mix psychological concepts in with the neurological findings in their lists (eg ‘IQ’, and ‘operational’ and ‘pre-operational’ levels). Nevertheless, we can see that there is general consensus beginning to emerge about those areas where neuroscience seems to be on relatively firm ground. We can now pull together all that we have covered in earlier sections of this report.

4.2.1 *Synaptogenesis, pruning, and sensitive periods*

The neuroscientific evidence in these areas has been presented in Section 3. It is now accepted that the processes of synaptogenesis and pruning are central to the development of the brain, and it seems increasingly likely that they are not confined to the early years of childhood in humans. The brain shows continuing signs of growth and development into the early adult years, and continued signs of plasticity in response to new environmental demands throughout adult life. The evidence on sensitive periods is more mixed: they do appear to exist for certain types of learning, but they are not confined to the early years of childhood, and they are not as dramatically critical as some proponents originally believed. The idea that it is a case of ‘use it or lose it’ appears to be an exaggeration of the truth, although for some skills and abilities it may be that there are periods of development when they are much more easily acquired.

The educational implications of this are significant. First, the implications of continued plasticity are reassuring for all proponents of lifelong learning – it is, put simply, never too late to learn. Brain research in the area of ageing tends to concentrate on the study of pathologies and diseases and their effects, but what it tells us about normal healthy brains is optimistic in that it suggests that old dogs can indeed learn new tricks (OECD, 2002).

Sensitive periods are much more complex in their implications. Skills and abilities which are naturally evolved in humans appear to be more prone to sensitive periods of development than culturally transmitted knowledge. (The first is ‘experience expectant’, while the second is ‘experience dependent’.)

There are no grounds for believing in the supreme importance of the first three years, nor in the efficacy of any form of infant ‘hot housing’. Any normally stimulating human environment will be (in neuroscientific terms) sufficient for normal human infant development. What is important at this stage is that any sensory or motor impairment should be identified as soon as possible in order that remediation can begin. This is because the main sensitive periods in early childhood appear to concern sensory and motor development and those skills and abilities which humans are conditioned to develop by their evolution (including spoken language). The sooner remediation of any deficit begins, the greater chance there is of overcoming the deficit. There is less certainty about any later sensitive periods, although it does appear that some skills, such as learning a musical instrument, or learning a second language, will benefit from learning which takes place before the age of around 12 or 13. Some recent research may suggest that there is a possibility of another sensitive period for reasoning and problem solving abilities in the teenage years, but this is at present still speculative.

4.2.2 *Skill development, deficits, and hints for the future*

It seems clear that if any ‘grand theory’ of learning is to emerge it will do so from a combination of neuroscience, psychology, and education, and not from neuroscience alone (OECD, 2002). At present we are only on the first stages of a journey towards such a theory. In the introduction it was pointed out that we are still a long way from any direct, practical application of neuroscience to education. However, there are some particular areas of learning where neuroscientific findings are beginning to shed some helpful light.

One of these is in the area of language development and second language learning. The neuroscientific research is strongly suggestive of there being a sensitive period for the acquisition of phonology and grammar which extends until around the age of 12 or 13 (OECD, 2002; Posner *et al*, 2001). Second language learning after these ages is perfectly possible but, it is suggested, the learner is very likely to retain features of pronunciation which mark him or her out as a 'non-native' speaker, and will find it relatively difficult to completely master the finer and more subtle points of native syntax. The learning of vocabulary and meaning are not so affected. Even in second language learning, however, there has been some interesting work with Japanese learners of English which suggests that proper training can overcome difficulties. A problem for Japanese learners of English is that the Japanese sound system makes no distinction between /r/ and /l/ sounds, so that a mature native Japanese speaker can literally not hear the difference and therefore cannot produce the appropriate sound (consider the difficulties which speakers of RP English have with the Scottish /x/ sound represented by 'ch' in 'loch'). It has been found that with specialised training using exaggerated initial distinctions, it is possible for native Japanese to learn to distinguish and pronounce these sounds (OECD, 2002; Posner *et al*, 2001). It may therefore be that, for later learners of a second or other language, different approaches to teaching are required in some cases where meaningful distinctions exist in one language but not another.

The relationship between form and meaning, and the ways in which the brain integrates these, may also have implications in other areas of language learning. We know that the brain tends to work in ways which are 'parallel', 'distributed' and highly interconnected (Byrnes & Fox, 1998), and this may suggest that, for example, the argument in the initial teaching of reading about whether to use a phonics approach or a whole word approach is actually a false dichotomy: for normally developing children the isolated treatment of either 'parts' or 'wholes' may be less effective than treating them together. Fred Genessee has developed this argument in his review of the implications of brain research for second language learning, but it is equally applicable in areas of mother tongue development (Genessee, 2000). Noting that 'the flow of neural activity is not unidirectional, from simple to complex; it also goes from complex to simple', he goes on to suggest that this implies that:

> … effective teaching should include a focus on both parts and wholes. Instructional approaches that advocate teaching parts and not wholes or wholes and not parts are misguided, because the brain naturally links local neural activity to circuits that are related to different experiential domains. For example, in initial reading instruction, teaching phonics independently of the meaning of the words and their meaningful use is likely to be less effective than teaching both in parallel. Relating the mechanics of spelling to students' meaningful use of written language to express themselves during diary writing, for example, provides important

> motivational incentives for learning to read and write. Second, and related to the preceding point, teaching (and learning) can proceed from the bottom up (simple to complex) and from the top down (complex to simple). Arguments for teaching simple skills in isolation assume that learners can only initially handle simple information and that the use of simple skills in more complex ways should proceed slowly and progressively. Brain research indicates that higher order brain centers that process complex, abstract information can activate and interact with lower order centers, as well as vice versa.
>
> (Genessee, 2000)

Clearly this is an extrapolation from the neuroscience research, and we have seen that there are dangers in that, but it is consistent with what is currently known.

Other areas in which neuroscience may begin to offer insights to education include ways of dealing with specific deficits. For example, Pope and Whitely (2003) have recently described an experimental approach to the treatment of dyslexia which uses exercise-based interventions aimed at improving motor skills. This relies on brain research which has suggested that dyslexia may be connected with an 'underlying anatomical syndrome that originates in the cerebellar or vestibular areas of the brain', which are normally associated with co-ordination of muscular activity (Pope & Whitely, 2003). This is, as yet, experimental and must be regarded as 'not proven' but it illustrates how brain research may serve to guide new avenues of exploration. It is also hoped that further neuroscience studies will 'offer a way of distinguishing between different cognitive theories (eg, whether dyslexia has a visual basis or a linguistic basis in children)' (Goswami, 2004).

Neuroscience is also providing some basic insight into children's problems with number. It is now accepted that the brain works with what has become known as the 'triple code model for three basic number manipulations' (OECD, 2002). In other words different areas of the brain are involved in recognising a visual digit (eg '3'), hearing or reading a number word ('three'), or understanding a number as a quantity. Number difficulties may either be the result of problems in associating one of the representations ('3' or 'three') with the quantity, or may be caused by some disruption of the mechanism which deals with quantity itself. Once again, research in these areas is at an early stage. However, it is suggested that, where there are problems with linking number representation and quantity, spatial or concrete metaphors (such as number lines or an abacus) may help to alleviate or overcome the problem (OECD, 2002).

One final area in which neuroscience may contribute to education in the future is in the understanding of the link between emotion and learning. At present 'information in this domain is sparse and incomplete. Lack of measurement and theoretical foundation limits progress of the study of emotional regulation in educational practice' (OECD, 2002). Although psychologists have known for some time that excess stress and fear can inhibit cognitive performance, the links between the 'emotional brain' (the amygdala and hippocampus) and the reasoning part of the brain (particularly the frontal cortex) are only just beginning to be understood. It is known that the amygdala and the hippocampus are linked to the frontal cortex, and that ‘when these connections are impaired either due to stress or fear, social judgement suffers, as well as cognitive performance, because the emotional aspects of learning, including responses to reward and risk, are compromised’ (OECD, 2002). This has clear implications for classroom (and school) ethos. Some recent work has suggested that ‘emotional arousal’, whether pleasant or unpleasant, improves recall (McGaugh, 2004). The amygdala has been associated with the acquisition and retention of memories of emotional experiences. Human imaging studies and animal studies agree in suggesting that:

> activation of the amygdala influences the consolidation of long-term memory; the degree of activation of the amygdala by emotional arousal during encoding of emotionally arousing material (either pleasant or unpleasant) correlates highly with subsequent recall. The activation of neuromodulatory systems affecting the BLA [basolateral complex of the amygdala] and its projections to other brain regions involved in processing different kinds of information plays a key role in enabling emotionally significant experiences to be well remembered.
>
> (McGaugh, 2004)

In other words learners are likely to remember things better when they are emotionally involved in their learning. Boring classrooms are likely to be inefficient classrooms.

4.3 Conclusion

Neuroscience is a fascinating area, and educationalists are becoming increasingly aware of the advances it is making, and are looking for the insights it can offer to improve their practice. At present, however, it cannot offer a ‘grand theory’ of learning with direct impact on school-based education, and premature attempts to derive such a theory may prove to be misguided. What it can offer is additional data, from a different viewpoint, which can be integrated with the knowledge of psychologists and educationalists as they all strive towards a better understanding of human learning. It also has very specific insights to offer in detailed aspects of learning and learning deficits. As the body of neuroscientific knowledge grows, we can confidently expect that it will have an increasing amount to tell us.

4.4 Summary

- Early disagreements between ‘enthusiasts’ and ‘sceptics’ appear to be giving way to a new consensus with a number of ideas now generally accepted.
- These ideas include the continued plasticity of the human brain, and the possibility of sensitive periods affecting the ease of certain types of learning.
- These sensitive periods extend at least into the teenage years, and possibly further.

- Neuroscience can also offer specific insights into some aspects of skills development, and is beginning to suggest new avenues of exploration in the investigation of some skills deficits.
- Neuroscience is confirming earlier psychological theories about the importance of emotional engagement in learning.

5: Bibliography

Berninger, V.W. & Corina, D. (1998) 'Making Cognitive Neuroscience Educationally Relevant: Creating Bidirectional Collaborations Between Educational Psychology and Cognitive Neuroscience.' *Educational Psychology Review*. 10(3): 343-354.

Blakemore, S.-J. & Frith, U. (2000) 'The Implications of Recent Developments in Neuroscience for Research on Teaching and Learning'. London: Institute of Cognitive Neuroscience.

Brandt, R. (1999) 'Educators Need to Know About the Human Brain.' *Phi Delta Kappan*. 81(3): 235ff.

Brown, R.D. & Bjorklund, D.F. (1998) 'The Biologizing of Cognition, Development, and Education: Approach with Cautious Enthusiasm.' *Educational Psychology Review*. 10(3): 355-373.

Bruer, J.T. (1997) 'Education and the Brain: A Bridge Too Far.' *Educational Researcher*. 26(8): 4-16.

Bruer, J.T. (1998a) 'Brain Science Brain Fiction.' *Educational Leadership*. 56(3): 14-18.

Bruer, J.T. (1998b) 'Let's Put Brain Science on the Back Burner.' *National Association of Secondary School Principals. NASSP Bulletin*. 82(598): 9-19.

Bruer, J.T. (1999a) 'In Search of ... Brain-Based Education.' *Phi Delta Kappan*. 80(9): 648-654.

Bruer, J.T. (1999b) *The Myth of the First Three Years: A New Understanding of Early Brain Development and Lifelong Learning*. New York: Free Press.

Bruer, J.T. (2002) 'Avoiding the pediatrician's error: how neuroscientists can help educators (and themselves).' *Nature Neuroscience*. 5: 1031-1033.

Bush, G. (1990) *Presidential Proclamation 6158*. Retrieved, 22 January 2004, from <http://lcweb.loc.gov/loc/brain/proclaim.html>.

Byrnes, J.P. & Fox, N.A. (1998) 'The Educational Relevance of Research in Cognitive Neuroscience.' *Educational Psychology Review*. 10(3): 297-342.

Chow, K.L. & Stewart, D.L. (1972) 'Reverse of structural and functional effects of long-term visual deprivation in cats.' *Experimental Neurology*. 34: 409-433.

Chugani, H.T., Phelps, M.E. & Mazziota, J.C. (1987) 'Positron Emission Tomography Study of Human Brain Function Development.' *Annals of Neurology*. 22: 487-497.

Clark, B. (2001) 'Some Principles of Brain research for Challenging Gifted Learners.' *Gifted Education International*. 16(1): 4-10.

Cragg, B.G. (1975a) 'The development of synapses in kitten visual cortex during visual deprivation.' *Experimental Neurology*. 46: 445-451.

Cragg, B.G. (1975b) 'The development of synapses in the visual system of the cat.' *Journal of Comparative Neurology*. 160: 147-166.

Davis, S.M. (2000) 'Look Before You Leap: Concerns About "Brain-Based" Products and Approaches.' *Childhood Education*. Winter 2000/01: 100-101.

Diamond, M. & Hopson, J. (1998) *Magic Trees of the Mind: How To Nurture Your Child's Intelligence, Creativity, and Healthy Emotions from Birth through Adolescence*. New York: Dutton.

Diamond, M.C., Greer, E.R., York, A., Lewis, D., Barton, T. & Lin, J. (1987) 'Rat cortical morphology following crowded-enriched living conditions.' *Experimental Neurology*. 96(2): 241-247.

ECS (1998) *Brain Research and Education: Neuroscience Research Has Impact for Education Policy*. Policy Brief. Denver, CO.: Education Commission of the States.

Edwards, B. (1982) *Drawing on the Right Side of the Brain*. Glasgow: Fontana/Collins.

Geake, J. & Cooper, P. (2003) 'Cognitive Neuroscience: implications for education?' *Westminster Studies in Education*. 26(1): 7-20.

Geary, D.C. (1998) 'What is the Function of Mind and Brain?' *Educational Psychology Review*. 10(4): 377-388.

Genessee, F. (2000) *Brain Research: Implications for Second Language Learning*. ERIC Digest ED447727. Washington, DC: ERIC Clearinghouse on Languages and Linguistics.

Giedd, J.N., Blumenthal, J., Jeffries, N.O., Castellanos, F.X., Liu, H., Zijdenbos, A., Paus, T., Evans, A.C. & Rapoport, J.L. (1999) 'Brain development during childhood and adolescence: a longitudinal MRI study.' *Nature Neuroscience*. 2: 861-863.

Gogtay, N., Giedd, J.N., Lusk, L., Hayashi, K.M., Greenstein, D., Vaituzis, A.C., Nugent III, T.F., Herman, D.H., Clasen, L.S., Toga, A., W, Rapoport, J.L. & Thompson, P.M. (2004) 'Dynamic mapping of human cortical development during childhood through early adulthood.' *Proceedings of the National Academy of Sciences of the United States of America*. 101(21): 8174-8179.

Goldman-Rakic, P.S. (1987) 'Development of cortical circuitry and cognitive function.' *Child Development*. 58: 601-622.

Goswami, U. (2004) 'Neuroscience and education.' *British Journal of Educational Psychology*. 74: 1-14.

Green, E.J., Greenough, W.T. & Schlumpf, B.E. (1983) 'Effects of complex or isolated environments on cortical dendrites of middle-aged rats.' *Brain Research*. 264(2): 233-240.

Greenfield, S., Ed. (1999) *Brain Power: Working out the human mind*. Shaftesbury, Dorset: Element.

Greenleaf, R.K. (1999) 'It's Never Too Late! What Neuroscience Has To Offer High Schools.' *National Association of Secondary School Principals. NASSP Bulletin*. 83(608): 81-89.

Greenough, W.T., Black, J.E. & Wallace, C.S. (1987) 'Experience and brain development.' *Child Development*. 58: 539-559.

Hansen, L. & Monk, M. (2002) 'Brain development, structuring of learning and science education: where are we now? A review of some recent research.' *International Journal of Science Education*. 24(4): 343-356.

Jensen, E. (1998) *Teaching with the Brain in Mind*. Alexandria, VA: ASCD.

Jensen, E. (2000) 'Brain-Based Learning: A Reality Check.' *Educational Leadership*. April 2000: 76-80.

Krasner, S. (2002a) 'Brain-Based Learning and Research: January 1994-June 2002': Connecticut State Department of Education.

Krasner, S. (2002b) 'World Wide Web Resources on Brain-Based Learning and Research.' Connecticut State Department of Education.

LC/NIMH (2000) *Project on the Decade of the Brain*. Retrieved, 22 January 2004, from <http://www.lcweb.loc.gov/loc/brain/>.

Maguire, E.A., Gadian, D.G., Johnsrude, I.S., Good, C.D., Ashburner, J., Frackowiak, R., S J & Frith, C.D. (2000) 'Navigation-related structural change in the hippocampi of taxi drivers.' *Proceedings of the National Academy of Sciences of the United States of America*. 97(8): 4398-4403.

Mayer, R.E. (1998) 'Does the Brain Have a Place in Educational Psychology?' *Educational Psychology Review*. 10(4): 389-396.

McGaugh, J.L. (2004) 'The amygdala modulates the consolidation of memories of emotionally arousing experiences.' *Annual Review of Neuroscience*. 27: 1-28.

NIMH (2001) *Teenage Brain: a work in progress*. Retrieved, 17 June 2004, from <http://www.nimh.nih.gov/publicat/teenbrain.cfm>.

NIMH (2004) *Imaging Study Shows Brain Maturing*. Retrieved, 17 June 2004, from <http://www.nimh.nih.gov/press/prbrainmaturing.cfm>.

O'Boyle, M.W. & Gill, H.S. (1998) 'On the Relevance of Research Findings in Cognitive Neuroscience to Educational Practice.' *Educational Psychology Review*. 10(4): 397-410.

O'Connor, T.G., Bredenkamp, D. & Rutter, M. (1999) 'Attachment disturbances and disorders in children exposed to early severe deprivation.' *Infant Mental Health Journal*. 20(10): 10-29.

OECD (2001a) *Brain Mechanisms and Early Learning. Preliminary Synthesis of the First High Level Forum on Learning Sciences and Brain Research: Potential Implications for Education Policies and Practices*. Retrieved, 26 September 2003, from <http://www.oecd.org/dataoecd/40/18/15300896.pdf>.

OECD (2001b) *Brain Mechanisms and Learning in Ageing. Preliminary Synthesis of the Third High Level Forum on Learning Sciences and Brain Research: Potential Implications for Education Policies and Practices*. Retrieved, 26 September 2003, from <http://www.oecd.org/dataoecd/40/39/15302896.pdf>.

OECD (2001c) *Brain Mechanisms and Youth Learning. Preliminary Synthesis of the Second High Level Forum on Learning Sciences and Brain Research: Potential Implications for Education Policies and Practices*. Retrieved, 26 September 2003, from <http://www.oecd.org/dataoecd/40/40/15302628.pdf>.

OECD (2002) *Understanding the Brain: Towards a New Learning Science*. Paris: OECD.

Pantev, C., Oostenvel, R., Engelien, A., Ross, B., Roberts, L.E. & Hoke, M. (1998) 'Increased auditory cortical representation in musicians.' *Nature*. 392: 811-814.

Pascual-Leone, A., Nguyet, D., Cohen, L.G., Brasil-Neto, J.P., Cammarota, A. & Hallet, M. (1995) 'Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of fine motor skills.' *Journal of Neurophysiology*. 74(3): 1037-1045.

Pinker, S. (2000) *The Language Instinct: How the Mind Creates Language*. San Francisco, CA: Harper Perenniel.

Pope, D.J. & Whitely, H.E. (2003) 'Developmental dyslexia, cerbellar/vestibular brain function and possible links to exercise-based interventions: a review.' *European Journal of Special Needs Education*. 18(1): 109-123.

Posner, M., Rothbart, M., Farah, M. & Bruer, J.T., Eds. (2001) *The Developing Human Brain*. Developmental Science 4(3). Oxford: Blackwell.

Rakic, P. (1995) 'Corticogenesis in human and nonhuman primates.' In: Gazzaniga, M.S. (Ed.) *The Cognitive Neurosciences.* Cambridge, MA.: MIT Press**:** 127-145.

Sabatella, M.L.P. (1999) 'Intelligence and Giftedness: changes in the structure of the brain.' *Gifted Education International*. 13: 226-237.

Saunders, J. (2003) 'Take your kids to the brain gym.' *Times Educational Supplement Scotland*, 14 February 2003.

Schunk, D.H. (1998) 'An Educational Psychologist's Perspective on Cognitive Neuroscience.' *Educational Psychology Review*. 10(4): 411-418.

Stanovich, K.E. (1998) 'Cognitive Neuroscience and Educational Psychology: What Season Is It?' *Educational Psychology Review*. 10(4): 419-426.

Thompson, P.M., Giedd, J.N., Woods, R.P., MacDonald, D., Evans, A.C. & Toga, A., W (2000) 'Growth patterns in the developing brain detected by using continuum mechanical tensor maps.' *Nature*. 204: 190-193.

Whitebread, D. (2002) *The implications for Early Years education of current research in cognitive neuroscience*. Paper presented at British Educational Research Association Annual Conference, University of Exeter. Also available from <http://www.leeds.ac.uk/educol/documents/00002545.doc>.

Wiesel, T.N. & Hubel, D.H. (1965) 'Extent of recovery from the effects of visual deprivation in kittens.' *Journal of Neurophysiology*. 28: 1060-1072.

Williams, L.V. (1986) *Teaching for the Two-Sided Mind: a guide to right brain/left brain education.* New York: Simon and Schuster.

Wittrock, M.C. (1998) 'Comment on "The Educational Relevance of Research in Cognitive Neuroscience".' *Educational Psychology Review*. 10(4): 427-430.

Wolfe, P. & Brandt, R. (1998) 'What do we know from Brain research?' *Educational Leadership*. 56(3): 8-13.