



Annual review

Neuroscience and education

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Neuroscience is a relatively new discipline encompassing neurology, psychology and biology. It has made great strides in the last 100 years, during which many aspects of the physiology, biochemistry, pharmacology and structure of the vertebrate brain have been understood. Understanding of some of the basic perceptual, cognitive, attentional, emotional and mnemonic functions is also making progress, particularly since the advent of the cognitive neurosciences, which focus specifically on understanding higher level processes of cognition via imaging technology. Neuroimaging has enabled scientists to study the human brain at work *in vivo*, deepening our understanding of the very complex processes underpinning speech and language, thinking and reasoning, reading and mathematics. It seems timely, therefore, to consider how we might implement our increased understanding of brain development and brain function to explore educational questions.

The study of learning unites education and neuroscience. Neuroscience as broadly defined investigates the processes by which the brain learns and remembers, from the molecular and cellular levels right through to brain systems (e.g., the system of neural areas and pathways underpinning our ability to speak and comprehend language). This focus on learning and memory can be at a variety of levels. Understanding cell signalling and synaptic mechanisms (one brain cell connects to another via a synapse) is important for understanding learning, but so is examination of the functions of specific brain structures such as the hippocampus by natural lesion studies or by invasive methods. Brain cells (or neurons) transmit information via electrical signals, which pass from cell to cell via the synapses, triggering the release of neurotransmitters (chemical messengers). There are around 100 billion neurons in the brain, each with massive connections to other neurons. Understanding the ways in which neurotransmitters work is a major goal of neuroscience. Patterns of neural activity are thought to correspond to particular mental states or mental representations. Learning broadly comprises changes in connectivity, either via changes in potentiation at the synapse or

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via the strengthening or pruning of connections. Successful teaching thus directly affects brain function, by changing connectivity.

Clearly, educators do not study learning at the level of the cell. Successful learning is also dependent on the curriculum and the teacher, the context provided by the classroom and the family, and the context of the school and the wider community. All of these factors of course interact with the characteristics of individual brains. For example, children with high levels of the MAOA gene (monoamine oxidase A) who experience maltreatment and adverse family environments seem to be protected from developing antisocial behaviours (Caspi *et al.*, 2002), possibly via moderating effects on their neural response to stress. Diet also affects the brain. A child whose diet is poor will not be able to respond to excellent teaching in the same way as a child whose brain is well-nourished. It is already possible to study the effects of various medications on cognitive function. Methylphenidate (Ritalin), a medication frequently prescribed for children with ADHD (Attention Deficit Hyperactivity Disorder), has been shown to improve stimulus recognition in medicated children (in terms of attention to auditory and visual stimuli as revealed by neuroimaging; see Seifert *et al.*, 2003). Neuroimaging techniques also offer the potential to study the effects of different diets, food additives and potential toxins on educational performance.

Teaching

It is notable, however, that neuroscience does not as yet study teaching. Successful teaching is the natural counterpart of successful learning, and is described as a 'natural cognition' by Strauss (2003). Forms of teaching are found throughout the animal kingdom, usually related to ways of getting food. However, the performance of *intentional acts* to increase the knowledge of others (teaching with a 'theory of mind') does seem to be unique to humans, and is perhaps essential to what it means to be a human being (Strauss, Ziv, & Stein, 2002). The identification and analysis of successful pedagogy is central to research in education, but is currently a foreign field to cognitive neuroscience. There are occasional studies of the neural changes accompanying certain types of highly focused educational programmes (such as remedial programmes for teaching literacy to dyslexic children, see below), but wider questions involving the invisible mental processes and inferences made by successful teachers have not begun to be asked. Strauss suggests that questions such as whether there are specialized neural circuits for different aspects of teaching may soon be tractable to neuroimaging methods, and this is a thought-provoking idea. Teaching is a very specialized kind of social interaction, and some of its aspects (reading the minds of others, inferring their motivational and emotional states) are after all already investigated in cognitive neuroscience.

Used creatively, therefore, cognitive neuroscience methods have the potential to deliver important information relevant to the design and delivery of educational curricula as well as the quality of teaching itself. Cognitive neuroscience may also offer methods for the early identification of special needs, and enable assessment of the delivery of education for special needs. At the same time, however, it is worth noting that 'neuromyths' abound. Some popular beliefs about what brain science can actually deliver to education are quite unrealistic. Although current brain science technologies offer exciting opportunities to educationists, they complement rather than replace traditional methods of educational enquiry.

A quick primer on brain development

Many critical aspects of brain development are complete prior to birth (see Johnson, 1997, for an overview). The development of the neural tube begins during the first weeks of gestation, and 'proliferative zones' within the tube give birth to the cells that compose the brain. These cells migrate to the different regions where they will be employed in the mature brain prior to birth. By 7 months gestation almost all of the neurons that will comprise the mature brain have been formed. Brain development following birth consists almost exclusively of the growth of axons, synapses and dendrites (fibre connections): this process is called synaptogenesis. For visual and auditory cortex, there is dramatic early synaptogenesis, with maximum density of around 150% of adult levels between 4 and 12 months followed by pruning. Synaptic density in the visual cortex returns to adult levels between 2 and 4 years. For other areas such as prefrontal cortex (thought to underpin planning and reasoning), density increases more slowly and peaks after the first year. Reduction to adult levels of density is not seen until some time between 10 and 20 years. Brain metabolism (glucose uptake, an approximate index of synaptic functioning) is also above adult levels in the early years, with a peak of about 150% somewhere around 4–5 years.

By the age of around 10 years, brain metabolism reduces to adult levels for most cortical regions. 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 (i.e., 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). Similarly, sensitive periods are not all-or-none. If visual input is lacking during early development, for example, the critical period is extended (Fagiolini & Hensch, 2000). Nevertheless, visual functions that develop late (e.g., depth perception) suffer more from early deprivation than functions that are relatively mature at birth (such as colour perception, Maurer, Lewis, & Brent 1989). Thus more complex abilities may have a lower likelihood of recovery than elementary skills. One reason may be that axons have already stabilised on target cells for which they are not normally able to compete, thereby causing irreversible reorganisation.

It is important to realise that there are large individual differences between brains. Even in genetically identical twins, there is striking variation in the size of different brain structures, and in the number of neurons that different brains use to carry out identical functions. This individual variation is coupled with significant localisation of function. A basic map of major brain subdivisions is shown in Figure 1. Although adult brains all show this basic structure, it is thought that early in development a number of possible developmental paths and end states are possible. The fact that development converges on the same basic brain structure across cultures and gene pools is probably to do with the constraints on development present in the environment. Most children are exposed to very similar constraints despite slightly different rearing environments. Large differences in environment, such as being reared in darkness or without contact with other humans, are thankfully absent or rare. When large environmental differences occur, they have notable effects on cognitive function. For example, neuroimaging studies show that blind adults are faster at processing auditory information than sighted

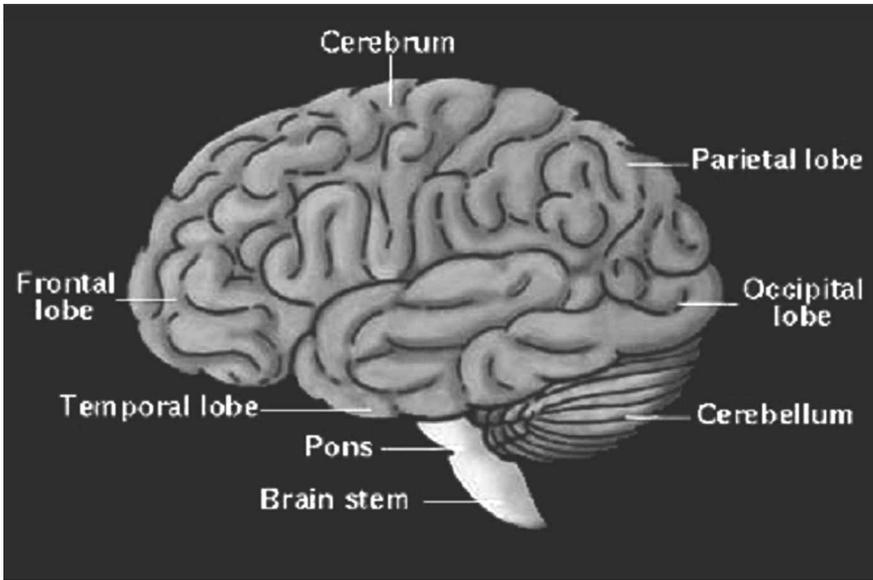


Figure 1. The major subdivisions of the cerebral cortex. The different lobes are specialised for different tasks. The frontal lobe is used for planning and reasoning, and controls our ability to use speech and how we react to situations emotionally. The temporal lobe is mainly concerned with memory, audition, language and object recognition. The parietal lobe controls our sense of touch and is used for spatial processing and perception. The occipital lobe is specialised for vision. Structures such as the hippocampus and the amygdala are internal to the brain, situated beneath the cerebral cortex in the midbrain.

controls, and that congenitally deaf adults are faster at processing visual information in the peripheral field than hearing controls (e.g., Neville & Bavelier, 2000; Neville, Schmidt, & Kutas, 1983; Röder, Rösler, & Neville, 1999).

Nevertheless, neurons themselves are interchangeable in the immature system, and so dramatic differences in environment can lead to different developmental outcomes. For example, the area underpinning spoken language in hearing people (used for auditory analysis) is recruited for sign language in deaf people (visual/spatial analysis) (Neville *et al.*, 1998). Visual brain areas are recruited for Braille reading (tactile analysis) in blind people (see Röder & Neville, 2003). It has even been reported that a blind adult who suffered a stroke specific to the visual areas of her brain consequently lost her proficient Braille reading ability, despite the fact that her somatosensory perception abilities were unaffected (Jackson, 2000). It has also been suggested that all modalities are initially mutually linked, as during early infancy auditory stimulation also evokes large responses in visual areas of the brain, and somatosensory responses are enhanced by white noise (e.g., Neville, 1995). If this is the case, a kind of 'synaesthesia' could enable infants to extract schemas that are independent of particular modalities, schemas such as number, intensity and time (see Röder & Neville, 2003). If this mutual linkage extends into early childhood, it may explain why younger children respond so well to teaching via multi-sensory methods.

Neuroimaging tools for developmental cognitive neuroscience

Neuroimaging studies are based on the assumption that any cognitive task makes specific demands on the brain which will be met by changes in neural activity. These changes in activity affect local blood flow which can be measured either directly (PET) or indirectly (fMRI). Dynamic interactions among mental processes can be measured by ERPs.

PET (positron emission tomography) relies on the injection of radioactive tracers, and is not suitable for use with children. Brain areas with higher levels of blood flow have larger amounts of the tracer, allowing pictures of the distribution of radiation to be created and thereby enabling the localisation of different neural functions. fMRI (functional magnetic resonance imaging) also enables the localisation of brain activity. This technique requires inserting the participant into a large magnet (like a big tube), and works by measuring the magnetic resonance signal generated by the protons of water molecules in neural cells. When blood flow to particular brain areas increases, the distribution of water in the brain tissue also changes. This enables measurement of a BOLD (blood oxygenation level dependent) response which measures changes in the oxygenation state of haemoglobin associated with neural activity. The change in BOLD response is the outcome measure in most fMRI studies. It is very noisy inside the magnet and participants are given headphones to shield their ears and a panic button (the magnet is claustrophobic). Because of these factors, it has been challenging to adapt fMRI for use with children (who also move a lot, impeding scanning accuracy). However, with the advent of specially adapted coils and less claustrophobic head scanners, such studies are growing in number.



Figure 2. A child wearing a specially adapted headcap for measuring ERPs (evoked response potentials). I am grateful to Professor Mark Johnson, Director of the Cognitive and Brain Development Centre, Birkbeck College, London, for this image.

A different and widely used neuroimaging technique that can be applied to children is that of the event related potential (ERP). ERPs enable the timing rather than localisation of neural events to be studied. Sensitive electrodes are placed on the skin of the scalp and then recordings of brain activity are taken. Recording of the spontaneous natural rhythms of the brain is called EEG (electroencephalography). ERP refers to systematic deflections in electrical activity that may occur to precede, accompany or follow experimenter-determined events. ERP rhythms are thus time-locked to specific events designed to study cognitive function. The usual technique is for the child to watch a video while wearing a headcap (like a swimming cap) that holds the electrodes (see Figure 2). For visual ERP studies, the video is delivering the stimuli, for auditory ERP studies, the linguistic stimuli form a background noise and the child sits engrossed in a silent cartoon. The most usual outcome measures are (i) the latency of the potentials, (ii) the amplitude (magnitude) of the various positive and negative changes in neural response, and (iii) the distribution of the activity. The different potentials (characterised in countless ERP studies) are called N100, P200, N400 and so on, denoting Negative peak at 100 ms, Positive peak at 200 ms and so on. The amplitude and duration of single ERP components such as the P200 increase until age 3 to 4 years (in parallel with synaptic density), and then decrease until puberty. ERP latencies decrease within the first years of life (in parallel with myelinisation) and reach adult levels in late childhood. ERP studies have provided extensive evidence on the time course of neural processing and are sensitive to millisecond differences. The sequence of observed potentials and their amplitude and duration are used to understand the underlying cognitive processes.

Selected studies from cognitive neuroscience with interesting implications for education

How valuable is cognitive neuroscience to educational psychologists? Current opinions vary (Bruer, 1997; Byrnes & Fox, 1998; Geary, 1998; Geake & Cooper, 2003; Mayer, 1998; Schunk, 1998; Stanovich, 1998), but in general the consensus is moving away from early views that neuroscience is irrelevant because it only confirms what we already knew. The eventual answer will probably be that it is very valuable indeed. The tools of cognitive neuroscience offer various possibilities to education, including the early diagnosis of special educational needs, the monitoring and comparison of the effects of different kinds of educational input on learning, and an increased understanding of individual differences in learning and the best ways to suit input to learner. I will now describe briefly some recent neuroscience studies in certain areas of cognitive development, and give a flavour of how their methods could contribute to more specifically educational questions.

Language

Despite sharing 98.5% of our genome with chimpanzees, we humans can talk and chimps cannot. Interestingly, genes expressed in the developing brain may hold part of the answer. For example, a gene called FOXP2 differs in mouse and man by 3 amino acid differences, two of which occurred after separation from the common human-chimp ancestor about 200,000 years ago (Marcus & Fisher, 2003). This gene is implicated in a severe developmental disorder of speech and language that affects the

control of face and mouth movements, impeding speech. Neurally, accurate vocal imitation appears to be critical for the development of speech (Fitch, 2000). Hence when linguistic input is degraded or absent for various reasons (e.g., being hearing impaired, being orally impaired), speech and language are affected. Studies of normal adults show that grammatical processing relies more on frontal regions of the left hemisphere, whereas semantic processing and vocabulary learning activate posterior lateral regions of both hemispheres. For reasons that are not yet well understood, the brain systems important for syntactic and grammatical processing are more vulnerable to altered language input than the brain systems responsible for semantic and lexical functions. ERP studies show that when English is acquired late due to auditory deprivation or late immigration to an English-speaking country, syntactic abilities do not develop at the same rate or to the same extent (Neville *et al.*, 1997). Late learners do not rely on left hemisphere systems for grammatical processing, but use both hemispheres (Weber-Fox & Neville, 1996). ERP studies also show that congenitally blind people show bilateral representation of language functions (Röder *et al.*, 2000). Blind people also process speech more efficiently (Hollins, 1989), for example they speed up cassette tapes, finding them too slow, and still comprehend the speech even though the recording quality suffers.

Reading

Neuroimaging studies of both children and adults suggest that the major systems for reading alphabetic scripts are lateralised to the left hemisphere. These studies typically measure brain responses to single word reading using fMRI or ERPs. Reviews of such studies conclude that alphabetic/orthographic processing seems mainly associated with occipital, temporal and parietal areas (e.g., Pugh *et al.*, 2001). The occipital-temporal areas are most active when processing visual features, letter shapes and orthography. The inferior occipital-temporal area shows electrophysiological dissociations between words and nonwords at around 180 ms, suggesting that these representations are not purely visual but are linguistically structured. Activation in temporo-occipital areas increases with reading skill (e.g., Shaywitz *et al.*, 2002), and is decreased in children with developmental dyslexia.

Phonological awareness (the ability to recognize and manipulate component sounds in words) predicts reading acquisition across languages, and phonological processing appears to be focused on the temporo-parietal junction. This may be the main site supporting letter-to-sound recoding and is also implicated in spelling disorders. Dyslexic children, who typically have phonological deficits, show reduced activation in the temporo-parietal junction during tasks such as deciding whether different letters rhyme (e.g., P, T = yes, P, K = no). Targeted reading remediation increases activation in this area (e.g., Simos *et al.*, 2002). Finally, recordings of event-related magnetic fields (MEG) in dyslexic children suggest that there is atypical organisation of the right hemisphere (Heim, Eulitz, & Elbert, 2003). This is consistent with suggestions that compensation strategies adopted by the dyslexic brain require greater right hemisphere involvement in reading.

Although to date neuroimaging studies have largely confirmed what was already known about reading and its development from behavioural studies, neuroscience techniques also offer a way of distinguishing between different cognitive theories (e.g., whether dyslexia has a visual basis or a linguistic basis in children). Neuroimaging techniques also offer a potential means for distinguishing between deviance and delay

when studying developmental disorders. For example, our preliminary studies of basic auditory processing in dyslexic children using ERPs suggest that the phonological system of the dyslexic child is immature rather than deviant (Thomson, Baldeweg, & Goswami, in preparation). Dyslexic children show remarkable similarity in N1 response to younger reading level controls, while showing much larger N1 amplitudes than age-matched controls. Finally, PET studies have shown that the functional organization of the brain differs in literate and illiterate adults (Castro-Caldas *et al.*, 1998). Portuguese women in their sixties who had never learned to read because of lack of access to education were compared with literate Portuguese women from the same villages in word and nonword repetition tasks. It was found that totally different brain areas were activated during nonword repetition for the illiterate versus literate participants. Learning to read and write in childhood thus changes the functional organization of the adult brain.

Mathematics

For mathematics, cognitive neuroscience is beginning to go beyond existing cognitive models. It has been argued that there is more than one neural system for the representation of numbers. A phylogenetically old 'number sense' system, found in animals and infants as well as older participants, seems to underpin knowledge about numbers and their relations (Dehaene, Dehaene-Lambertz, & Cohen, 1998). This system, located bilaterally in the intraparietal areas, is activated when participants perform tasks such as number comparison, whether the comparisons involve Arabic numerals, sets of dots or number words. Because mode of presentation does not affect the location of the parietal ERP components, this system is thought to organize knowledge about number quantities. Developmental ERP studies have shown that young children use exactly the same parietal areas to perform number comparison tasks (Temple & Posner, 1998). A different type of numerical knowledge is thought to be stored verbally, in the language system (Dehaene *et al.*, 1999). This neural system also stores knowledge about poetry and overlearned verbal sequences, such as the months of the year. Mathematically, it underpins counting and rote-acquired knowledge such as the multiplication tables. This linguistic system seems to store 'number facts' rather than compute calculations. Many simple arithmetical problems (e.g., $3 + 4$, 3×4) are so overlearned that they may be stored as declarative knowledge. More complex calculation seems to involve visuospatial regions (Zago *et al.*, 2001), possibly attesting to the importance of visual mental imagery in multi-digit operations (an internalized and sophisticated form of a number line, see Pesenti, Thioux, Seron, & De Volder, 2000). Finally, a distinct parietal-premotor area is activated during finger counting and also calculation.

This last observation may suggest that the neural areas activated during finger-counting (a developmental strategy for the acquisition of calculation skills) eventually come to partially underpin numerical manipulation skills in adults. If this were the case, then perhaps finger counting has important consequences for the developing brain, and should be encouraged in school. In any event, neuroimaging techniques offer ways of exploring such questions. They can also be used to discover the basis of dyscalculia in children. For example, dyslexic children often seem to have associated mathematical difficulties. If dyslexia has a phonological basis, then it seems likely that the mathematical system affected in these children should be the verbal system underpinning counting and calculation. Dyslexic children with mathematical

difficulties may show neural anomalies in the activation of this system, but not in the activation of the parietal and premotor number systems. Children with dyscalculia who do not have reading difficulties may show different patterns of impairment. Knowledge of the neural basis of their difficulties could then inform individual remedial curricula.

Direct effects of experience

Although it is frequently assumed that specific experiences have an effect on children, neuroimaging offers ways of investigating this assumption directly. The obvious prediction is that specific experiences will have specific effects, increasing neural representations in areas directly relevant to the skills involved. One area of specific experience that is frequent in childhood is musical experience. fMRI studies have shown that skilled pianists (adults) have enlarged cortical representations in auditory cortex, specific to piano tones. Enlargement was correlated with the age at which musicians began to practise, but did not differ between musicians with absolute versus relative pitch (Pantev *et al.*, 1998). Similarly, MEG studies show that skilled violinists have enlarged neural representations for their left fingers, those most important for playing the violin (Elbert *et al.*, 1996). Clearly, different sensory systems are affected by musical expertise depending on the nature of the musical instrument concerned. ERP studies have also shown use-dependent functional reorganization in readers of Braille. Skilled Braille readers are more sensitive to tactile information than controls, and this extends across all fingers, not just the index finger (Röder, Rösler, Hennighausen, & Nacker, 1996). The neural representations of muscles engaged in Braille reading are also enlarged. Finally, it is interesting to note that London taxi drivers who possess 'The Knowledge' show enlarged hippocampus formations (Maguire *et al.*, 2000). The hippocampus is a small brain area thought to be involved in spatial representation and navigation. In London taxi drivers, the posterior hippocampi were significantly larger than those of controls who did not drive taxis. Furthermore, hippocampal volume was correlated with the amount of time spent as a taxi driver. Again, localised plasticity is found in the adult brain in response to specific environmental inputs.

Plasticity in children, of course, is likely to be even greater. Our growing understanding of plasticity offers a way of studying the impact of specialized remedial programmes on brain function. For example, on the basis of the cerebellar theory of dyslexia, remedial programmes are available that are designed to improve motor function. It is claimed that these programmes will also improve reading. Whether this is in fact the case can be measured directly via neuroimaging. If the effects of such remedial programmes are specific, then neuroimaging should reveal changes in motor representations but not in phonological and orthographic processing. If the effects generalize to literacy (for example, via improved automaticity), then changes in occipital, temporal and parietal areas should also be observed.

Sleep and cognition

The idea that sleep might serve a cognitive function dates from at least the time of Freud, with his analysis of dreams. Recent neuroimaging studies suggest indeed that Rapid Eye Movement (REM) sleep is not only associated with self-reports of dreaming but is important for learning and memory. Maquet and colleagues (Maquet *et al.*, 2000) used PET to study regional brain activity during REM sleep following training on a serial reaction time task. During task learning, volunteer students were trained to press one of

6 marked keys on a computer in response to associated visual signals on the computer screen. Training lasted for 4 hours, from 4 p.m. until 8 p.m. The participants were then scanned during sleep. Controls were either scanned when awake while receiving the training, or were scanned when asleep following no training. It was found that the brain areas most active in the trained awake group when performing the task were also most active during REM sleep in the trained participants. They were not active during sleep in the untrained participants. Hence certain regions of the brain (in occipital and premotor cortex) were actually *reactivated* during sleep. It seems that REM sleep either allows the consolidation of memories or the forgetting of unnecessary material (or both together). When tested again on the computer task on the following day, significant improvement in performance was found to have occurred. Although the cellular mechanisms underlying this are not understood, it seems likely that memory consolidation relies on augmented synaptic transmission and eventually on increased synaptic density – the same mechanisms that structure the developing brain. Again, this suggests substantial plasticity even in adulthood, supporting educational emphases on life-long learning.

Emotion and cognition

It is increasingly recognized that efficient learning does not take place when the learner is experiencing fear or stress. Stress can both help and harm the body. Stress responses can provide the extra strength and attention needed to cope with a sudden emergency, but inappropriate stress has a significant effect on both physiological and cognitive functioning. The main emotional system within the brain is the limbic system, a set of structures incorporating the amygdala and hippocampus. The ‘emotional brain’ (LeDoux, 1996) has strong connections with frontal cortex (the major site for reasoning and problem solving). When a learner is stressed or fearful, connections with frontal cortex become impaired, with a negative impact on learning. Stress and fear also affect social judgments, and responses to reward and risk. One important function of the emotional brain is assessing the value of information being received. When the amygdala is strongly activated, it interrupts action and thought, and triggers rapid bodily responses critical for survival. It is suggested by LeDoux that classroom fear or stress might reduce children’s ability to pay attention to the learning task because of this automatic interruption mechanism. To date, however, neuroimaging studies of the developmental effects of stress on cognitive function are sparse or non-existent. In the educational arena, studying the role of stress (and emotional affect generally) in classroom learning seems an area ripe for development. Simple ERP measures of attentional processes, such as those used by Seifert *et al.* (2003) to study children with ADHD receiving Ritalin, could easily be adapted for such purposes.

Neuromyths

The engaging term ‘neuromyths’, coined by the OECD report on understanding the brain (OECD, 2002), suggests the ease and rapidity with which scientific findings can be translated into misinformation regarding what neuroscience can offer education. The three myths given most attention in the OECD report are (1) the lay belief in hemispheric differences (‘left brain’ versus ‘right brain’ learning etc.), (2) the notion that the brain is only plastic for certain kinds of information during certain ‘critical

periods', and that therefore education in these areas must occur during the critical periods, and (3) the idea that the most effective educational interventions need to be timed with periods of synaptogenesis.

Regarding neuromyth (1), the left brain/right brain claims probably have their basis in the fact that there is some hemispheric specialization in terms of the localisation of different skills. For example, many aspects of language processing are left-lateralised (although not, as we have seen, in blind people or in those who emigrate in later childhood to a new linguistic community). Some aspects of face recognition, in contrast, are lateralised to the right hemisphere. Nevertheless, there are massive cross-hemisphere connections in the normal brain, and both hemispheres work together in every cognitive task so far explored with neuroimaging, including language and face recognition tasks.

Regarding neuromyth (2), optimal periods for certain types of learning clearly exist in development, but they are sensitive periods rather than critical ones. The term 'critical period' implies that the opportunity to learn is lost forever if the biological window is missed. In fact, there seem to be almost no cognitive capacities that can be 'lost' at an early age. As discussed earlier, some aspects of complex processing suffer more than others from deprivation of early environmental input (e.g., depth perception in vision, grammar learning in language), but nevertheless learning is still possible. It is probably better for the final performance levels achieved to educate children in, for example, other languages during the sensitive period for language acquisition. Nevertheless, the existence of a sensitive period does not mean that adults are unable to acquire competent foreign language skills later in life.

Neuromyth (3) concerning synaptogenesis may have arisen from influential work on learning in rats. This research showed that rodent brains form more connections in enriched and stimulating environments (e.g., Greenough, Black, & Wallace, 1987). As discussed earlier, any kind of specific environmental stimulation causes the brain to form new connections (recall the enlarged cortical representations of professional musicians and the enlarged hippocampi of London taxi drivers). These demonstrations do not mean that greater synaptic density *predicts* a greater capacity to learn, however.

Other neuromyths can also be identified. One is the idea that a person can either have a 'male brain' or a 'female brain'. The terms 'male brain' and 'female brain' were coined to refer to differences in *cognitive* style rather than biological differences (Baron-Cohen, 2003). Baron-Cohen argued that men were better 'systemizers' (good at understanding mechanical systems) and women were better 'empathisers' (good at communication and understanding others). He did not argue that male and female brains were radically different, but used the terms male and female brain as a psychological shorthand for (overlapping) cognitive profiles.

Another neuromyth is the idea that 'implicit' learning could open new avenues educationally. Much human learning is 'implicit', in the sense that learning takes place in the brain despite lack of attention to/conscious awareness of what is being learned (e.g., Berns, Cohen, & Mintun, 1997, but see Johnstone & Shanks, 2001). Almost all studies of implicit learning use *perceptual* tasks as their behavioural measures (e.g., the participant gets better at responding appropriately to 'random' letter strings in a computer task when the 'random' strings are actually generated according to an underlying 'grammar' or rule system which can be learned). There are no studies showing implicit learning of the *cognitive* skills underpinning educational achievement. These skills most likely require effortful learning and direct teaching.

Conclusions

Clearly, the potential for neuroscience to make contributions to educational research is great. Nevertheless, bridges need to be built between neuroscience and basic research in education. Bruer (1997) suggested that cognitive psychologists are admirably placed to erect these bridges, although he also cautioned that while neuroscience has learned a lot about neurons and synapses, it has not learned nearly enough to guide educational practice in any meaningful way. This view is perhaps too pessimistic. Cognitive developmental neuroscience has established a number of neural 'markers' that can be used to assess development, for example of the language system. These markers may be useful for investigating educational questions. Taking ERP signatures of language processing as a case in point, different parameters are robustly associated with semantic processing (e.g., N400), phonetic processing (e.g., mis-match negativity or MMN), and syntactic processing (e.g., P600). These parameters need to be investigated longitudinally in children. Certain patterns may turn out to be indicative of certain developmental disorders. For example, children at risk for dyslexia may show immature or atypical MMNs to phonetic distinctions (Csepe, 2003). Children with SLI (specific language impairment) may have generally immature auditory systems, systems resembling those of children 3–4 years younger than them (Bishop & McArthur, in preparation). Characteristic ERPs may also change in response to targeted educational programmes. For example, the MMN to phonetic distinctions may become sharper (as indexed by faster latencies) in response to literacy tuition in phonics (see Csepe, 2003). If this were to be established across languages, education would have a neural tool for comparing the efficiency of different approaches to the teaching of initial reading. For example, one could measure whether the MMN to phonetic distinctions sharpened in response to literacy tuition based on whole language methods. This is only one example of the creative application of currently available neuroscience techniques to important issues in education. Educational and cognitive psychologists need to take the initiative, and think 'outside the box' about how current neuroscience techniques can help to answer outstanding educational questions.

References

- Baron-Cohen, S. (2003). *The essential difference: Men, women and the extreme male brain*. London: Penguin/Allen Lane.
- Berns, G.S., Cohen, J.D., & Mintun, M.A. (1997). Brain regions responsive to novelty in the absence of awareness. *Science*, 276, 1272–1275.
- Bishop, D.V.M., & McArthur, G. (in preparation). *Using event-related potentials to study auditory processing in children with language and literacy impairments*.
- Bruer, J. T. (1997). Education and the brain : A bridge too far. *Educational Researcher*, 26(8), 4–16.
- Byrnes, J.P., & Fox, N.A. (1998). The education relevance of research in cognitive neuroscience. *Educational Psychology Review*, 10(3), 297–342.
- Caspi, A., McClay, J., Moffitt, T. E., Mill, J., Martin, J., Craig, I. W., Taylor, A., & Poulton, R. (2002). Role of genotype in the cycle of violence in maltreated children. *Science*, 297, 851–854.
- Castro-Caldas, A., Petersson, K.M., Reis, A., Stone-Elander S., & Ingvar, M. (1998). The illiterate brain. Learning to read and write during childhood influences the functional organization of the adult brain. *Brain*, 121, 1053–1063.
- Csepe, V. (2003). Auditory event-related potentials in studying developmental dyslexia. In V. Csepe (Ed.), *Dyslexia : Different brain, different behaviour* (pp. 81–112). New York : Kluwer.

- Dehaene, S., Dehaene-Lambertz, G., & Cohen, L. (1998). Abstract representations of numbers in the animal and human brain. *Trends in Neuroscience*, 21(8), 355–611
- Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsirkin, S. (1999). Sources of mathematical thinking: Behavioural and brain-imaging evidence. *Science*, 284, 970–974.
- Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., & Taub, E. (1996). Increased cortical representation of the fingers of the left hand in string players. *Science*, 270, 305–307.
- Fagiolini, M., & Hensch, R.K. (2000). Inhibitory threshold for critical-period activation in primary visual cortex. *Nature*, 404, 183–186.
- Fitch, W.T. (2000). The evolution of speech: A comparative review. *Trends in Cognitive Sciences*, 4(7), 258–267
- 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), 377–387.
- Greenough, W.T., Black, J.E., & Wallace, C.S. (1987). Experience and brain development. *Child Development*, 58, 539–559.
- Heim, S., Eulitz, C., & Elbert, T. (2003). Altered hemispheric asymmetry of auditory P100m in dyslexia. *European Journal of Neuroscience*, 17, 1715–1722.
- Hollins, M. (1989). *Understanding blindness*. Hillsdale, NJ: Lawrence Erlbaum.
- Jackson, S. (2000). Seeing what you feel. *Trends in Cognitive Sciences*, 4, 257.
- Johnson, M.H. (1997). *Developmental cognitive neuroscience*. Cambridge, MA: Blackwell.
- Johnstone, T., & Shanks, D.R. (2001). Abstractionist and processing accounts of implicit learning. *Cognitive Psychology*, 42, 61–112.
- LeDoux, J. (1996). *The emotional brain*. New York: Simon Schuster.
- Maguire, E.A., Gadian, D.S., Johnsrude, I.S., Good, C.D., Ashburner, J., Frackowiak, R.S., & 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.
- Maquet, P., Laureys, S., Peigneux, P., Fuchs, S., Petiau, C., Phillips, C., Aerts, J., Del Fiore, G., Degueldre, C., Meulemans, T., Luxen, A., Franck, G., Van Der Linden, M., Smith, C., & Cleeremans, A. (2000). Experience-dependent changes in cerebral activation during human REM sleep. *Nature Neuroscience*, 3(8), 831–836.
- Marcus, G.F., & Fisher, S.E. (2003). FOXP2 in focus: What can genes tell us about speech and language? *Trends in Cognitive Sciences*, 7(6), 257–262.
- Maurer, D., Lewis, T.L., & Brent, H. (1989). The effects of deprivation on human visual development: Studies in children treated with cataracts. In F.J. Morrison, C. Lord & D.P. Keating (Eds.), *Applied developmental psychology* (pp. 139–227). San Diego, CA: Academic Press.
- Mayer, R.E. (1998). Does the brain have a place in educational psychology? *Educational Psychology Review*, 10(4), 389–396.
- Neville, H.J. (1995). Developmental specificity in neurocognitive development in humans. In M.S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 219–231). Cambridge, MA: MIT Press.
- Neville, H.J., & Bavelier, D. (2000). Specificity and plasticity in neurocognitive development in humans. In M.S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 83–98). Cambridge, MA: MIT Press.
- Neville, H.J., Schmidt, A., & Kutas, M. (1983). Altered visual-evoked potentials in congenitally deaf adults. *Brain Research*, 266, 127–132.
- Neville, H.J., Coffey, S.A., Lawson, D.S., Fischer, A., Emmorey, K., & Bellugi, U. (1997). Neural systems mediating American Sign Language: Effects of sensory experience and age of acquisition. *Brain & Language*, 57, 285–308.
- Neville, H.J., Bavelier, D., Corina, D., Rauschecker, J., Karni, A., Lalwani, A., Braun, A., Clark, V., Jezzard, P., & Turner, R. (1998). Cerebral organisation for language in deaf and hearing

- subjects: Biological constraints and effects of experience. *Proceedings of the National Academy of Sciences of the United States of America*, 95 (Feb), 922-929.
- OECD (2002). *Understanding the brain: Towards a new learning science*. Available online from oecd.org
- Pantev, C., Oostenveld, R., Engelien, A., Ross, B., Roberts, L.E., & Hike, M. (1998). Increased auditory cortical representation in musicians. *Nature*, 393, 811-814.
- Pesenti, M., Thioux, M., Seron, X., & De Volder, A. (2000). Neuroanatomical substrates of Arabic number processing, numerical comparison, and simple addition: A PET study. *Journal of Cognitive Neuroscience*, 12(3), 461-479.
- Pugh, K.R., Mencl, W.E., Jenner, A.R., Katz, L., Frost, S.J., Lee, J.R., Shaywitz, S.E., & Shaywitz, B.A. (2001). Neurobiological studies of reading and reading disability. *Journal of Communication Disorders*, 34, 479-492.
- Röder, B., & Neville, H. (2003). Developmental functional plasticity. In J. Grafman & I.H. Robertson (Eds.), *Handbook of neuropsychology* (2nd ed., Vol.9, pp 231-270), Oxford: Elsevier Science.
- Röder, G., Rösler, F., & Neville, H.J. (1999). Effects of interstimulus interval on auditory event-related potentials in congenitally blind and normally sighted humans. *Neuroscience Letters*, 264, 53-56.
- Röder, G., Rösler, F., & Neville, H.J. (2000). Event-related potentials during language processing in congenitally blind and sighted people. *Neuropsychologia*, 38, 1482-1502.
- Röder, G., Rösler, F., Hennighausen, E., & Nacker, F. (1996). Event related potentials during auditory and somatosensory discrimination in sighted and blind human subjects. *Cognitive Brain Research*, 4, 77-93.
- Schunk, D.H. (1998). An educational psychologist's perspective on cognitive neuroscience. *Educational Psychology Review*, 10(4), 411-417.
- Seifert, J., Scheuerpflug, P., Zillesen, K.E., Fallgater, A., & Warnke, A. (2003). Electrophysiological investigation of the effectiveness of methylphenidate in children with and without ADHD. *Journal of Neural Transmission*, 110(7) 821-829.
- Shaywitz, B., Shaywitz, S., Pugh, K., Mencl, W., Fulbright, R., Skudlarski, P., Constable, T., Marchione, K., Fletcher, J., Lyon, G., & Gore, J. (2002). Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry*, 101-110.
- Simos, P.G., Fletcher, J.M., Bergman, E., Breier, J.I., Foorman, B.R., Castillo, E.M., Davis, R.N., Fitzgerald, M., & Papanicolaou (2002). Dyslexia-specific brain activation profile becomes normal following successful remedial training. *Neurology*, 58, 1203-1213.
- Stanovich, K.E. (1998). Cognitive neuroscience and educational psychology: What season is it? *Educational Psychology Review*, 10(4), 419-426.
- Strauss, S. (2003). Teaching as a natural cognition and its implications for teacher education. In D. Pillemer & S. White (Eds.), *Developmental psychology and the social changes of our time*. New York: Cambridge University Press.
- Strauss, S., Ziv, M. & Stein, A. (2002). Teaching as a natural cognition and its relations to preschoolers' developing theory of mind. *Cognitive Development*, 17, 1473-1787.
- Temple, E., & Posner, M.I. (1998). Brain mechanisms of quantity are similar in 5-year-old children and adults. *Proceedings of the National Academy of Sciences of the United States of America*, 95 (June), 7836-7841.
- Thomson, J., Baldeweg, T., & Goswami, U. (in preparation). *Auditory event-related potentials during rise time processing in dyslexic and typically-developing children*.
- Weber-Fox, C.M., & Neville, H.J. (1996). Maturational constraints on functional specialisation for language processing: ERP and behavioural evidence in bilingual speakers. *Journal of Cognitive Neuroscience*, 8, 231-256.
- Zago, L, Pesenti, M., Mellet, E., Crivello, F., Mazoyer, B., & Tzourio-Mazoyer, N. (2001). Neural correlates of simple and complex mental calculation. *NeuroImage*, 13, 314-327