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Neuroscience in Education

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Summary

Educational programmes claiming to be 'brain based' are burgeoning in the UK, yet the science base for such programmes is largely absent. Nevertheless, neuroscience has the potential to make important contributions to education. These potential contributions are of at least three kinds: novel understanding about the biological and environmental processes determining learning; the identification of early neural markers for educational risk; and neural methods for evaluating different teaching approaches, remediation packages or educational debates. A deeper understanding of brain development and brain function is likely to yield significant information for educators. Nevertheless, stringent research designs and the recognition that correlation does not entail causation are required for neuroscience to contribute effectively to education. Furthermore, neuroscientists and educators must engage with each other at every stage of the research process. Currently, the rather different philosophies underpinning education and the natural sciences are impeding this engagement. Greater interaction between these disciplines could lead to significant progress in evidence-based neuroeducation.

1. Educational promise of neuroscience

The brain is the major organ of learning, and neuroscience is the study of the brain. It is therefore clear that neuroscience will be important for education. Indeed, most teachers think that knowledge of the brain is important for designing educational programmes (Pickering and Howard-Jones, 2007). However, education as a discipline has been slow to engage with neuroscience. This is creating a knowledge gap which is being exploited by commercial packages claiming to be 'based on neuroscience'. Typically, the scientific support for these packages is tenuous at best (Howard-Jones, 2007). Nevertheless, neuroscience holds out great promise for education. Three areas are likely to be of particular future importance, namely:

1. An understanding of the neural basis of the mental representations important for effective education (e.g. for literacy and numeracy);
2. The discovery of neural markers for educational risk, which can be measured at any age using passive processing paradigms (i.e. without attention);
3. The evaluation of debates in education that have been difficult to resolve on the basis of behavioural data.

This review ends with examples for each area.

2. Why neuroscience should matter for education

Neuroscientists investigate the *processes* by which the brain learns and remembers, from molecular and cellular processes right through to how brain systems function. As other reviews in this Foresight project cover the nature and development of these aspects of learning, the focus here is on the implications of brain processes for education.

The brain uses electrochemical activity to represent knowledge, with patterns of neural activity corresponding to particular mental states or mental 'representations'. These patterns of activity depend on the connections between neurons, as neurons need to be 'wired' to each other to 'fire' together. In general, it is thought that mental representations comprise synchronised neuronal activity within cell assemblies (networks of neurons) distributed across many brain areas. Every lesson that a child participates in at school where something is learned will change the connectivity of their brain. So too will every other learning experience that the child has, including social and emotional experiences. Biological constraints, such as inter-regional interactions (e.g. which neural areas are connected via feedback processes and top-down interactions) will also affect the development of the neural structures shaped by learning.

All these biological factors will affect the brain's response to environmental experiences such as targeted education. The most critical biological processes are captured theoretically by neuroconstructivism (Mareschal et al., 2007). The learning environment will also affect these biological processes, as for example social aspects of the environment can affect biological functions such as gene expression (Gottleib, 2007). Essentially, brain development and cognitive learning reflect the progressive specialisation of neural structures within developmental trajectories constrained by biology and environment.

The potential of neuroscience for education arises from the fact that we now have techniques for investigating these processes of specialisation directly.

An important corollary of a neuroscience perspective is that altered constraints on brain development will alter the developmental trajectory of the child's learning. These altered constraints can be both biological and environmental, and neuroscience can study the effects of both. If, for instance, particular neural processes are atypical, this will affect sensory processing and cognitive development. An example is the atypical auditory processing found in developmental dyslexia (e.g. Goswami et al., 2002). Children with developmental dyslexia appear to have brains that are inefficient at processing auditory cues to linguistic rhythm and stress, particularly those cues associated with syllable onsets (such as rise time). This could have a biological cause. Neurons in the brain oscillate at different rhythms, and the theta rhythm appears to phase-lock to the syllabic rate of speech (Luo and Poeppel, 2007) such that the intrinsic rhythmic activity of neurons aligns itself with the onsets of spoken syllables. This neuronal mechanism for speech discrimination may be impaired in dyslexia, and neuroscience can study this hypothesis.

Similarly, if certain affective experiences are atypical, this will influence emotional development and the development of social cognition. For example, children who are insecurely attached to their primary caretakers show low levels of certain neurochemicals such as serotonin, which could mean that the expression of these neurotransmitters is affected by social environmental factors (Gottleib, 2007). Again, this effect on the brain will shape developmental trajectories, and can be measured.

To describe cognitive development adequately, all of these interactions need to be understood, and correlation needs to be distinguished from cause. Cognitive neuroscience offers the required theoretical frameworks. It interprets high-level descriptions of the mind (such as psychological theories and symbolic descriptions) and lower level data (about the activation of neural networks in the brain) and low-level theories (for example, about neuronal function) within a common framework (Szűcs and Goswami, 2007).

3. What is currently known from neuroscience about education

Despite these advances, the current state-of-the-art is limited (Bruer, 1997; Goswami, 2004, 2006; Howard-Jones, 2007). We know a certain amount about some of the electrochemical activity that is correlated with educational performance, but not very much. Most studies have focused on two central aspects of educational performance: literacy and numeracy. Despite claims and expectations in the popular media, almost nothing is known about other aspects of learning that make a difference in the classroom, such as creativity. Indeed, it is far from clear which physiological variables could be measured in order to study something like creative problem-solving, where different participants are likely to use different strategies.

Although other aspects of education such as the understanding of core concepts in science are amenable to neuroscientific study, empirical work is lacking. This probably reflects the fact that neuroscience is expensive, and that the most informative studies are longitudinal.

3.1. *Literacy*

Regarding literacy, neural imaging shows that the brain develops essentially similar neural networks to support reading in different languages (e.g. Paulesu et al., 2001). Many studies (of adults) identify three, critical neural regions for reading, namely left posterior temporal, left inferior frontal, and left occipitotemporal. At a very simple level, semantic processing is thought to occur in temporal and frontal areas, articulatory processing in left inferior frontal areas, auditory processing in temporal areas, and visual processing in occipital areas.

The left occipitotemporal regions include a neural area labelled the visual word form area (VWFA, e.g. Cohen and Dehaene, 2004). The VWFA becomes more active as reading develops (Pugh, 2006; Shaywitz et al., 2007). Despite its name, the VWFA is not a logographic recognition system, rather it learns spelling-sound connections. It responds not just to whole words, but to fragments of familiar words such as orthographic rimes (e.g. 'ight' in 'light') and to 'nonsense words' such as 'tegwop'. Very young readers do not engage the VWFA, but rather depend on left posterior superior temporal cortex, a core area for phonology (Turkeltaub et al., 2003). Thus, neural data suggest that beginning readers rely on letter-sound recoding, and that an orthographic lexicon of familiar word forms develops gradually during the first years of reading acquisition.

Reading acquisition across languages depends on 'phonological awareness', which is a cognitive description of the brain's ability to distinguish and represent the sound structure of language (Ziegler and Goswami, 2005). As well as confirming the importance of phonological awareness in early reading acquisition, neural imaging studies also show its core role in developmental dyslexia. Activity in left posterior superior temporal cortex during reading is modulated by the level of children's phonological skills.

Studies of children with developmental dyslexia reveal difficulties with both the phonological aspects of reading and with the development of an orthographic lexicon. For example, studies across languages report reduced activation of left occipitotemporal networks and increased activation of left inferior frontal areas (Shaywitz et al., 2007; Kronbichler et al., 2006). Atypically, right temporoparietal cortex continues to be used during reading by children with dyslexia. Imaging studies have also shown that successful interventions for dyslexia improve brain activity in the key areas for phonological recoding. For example, dyslexic children given 80 hours of an intensive phonology-based intervention showed a dramatic increase in the activation of left temporoparietal regions, predominantly in the left posterior superior temporal gyrus – the cell assemblies thought to support letter-sound recoding in typically-developing readers (see Simos et al., 2002).

3.2. *Numeracy*

So far as numeracy is concerned, the key neural structures are networks that code non-numerical magnitude, primarily in the parietal (spatial) cortex, and networks that store memorised arithmetic facts, primarily in the angular gyrus (the language system). These mental representations enable the cognitive understanding of symbolic number and the manipulation of numerical symbols (Dehaene et al., 2004; Dehaene 1997; Szűcs and Goswami, 2007). Again, almost all relevant neuroscience studies have been conducted with adults.

The parietal network has been seen as particularly important developmentally, as it appears to correspond to an analogue magnitude representation or evolutionarily-driven 'number sense' that is also present in babies and animals (Dehaene et al., 1998). This intraparietal area is thought to be particularly concerned with knowledge of numerical quantities and their relations. For example, Dehaene et al. (1999) compared brain activation for two arithmetic tasks in adults, one involving exact addition (such as 4 + 5 = 9) and one involving approximate addition (4 + 5 = 8). They reported that, during exact calculation, participants showed greatest relative activation in a left-lateralised area in the inferior frontal lobe, traditionally regarded as a language area. During approximate calculation, participants showed greatest relative activation in a bilateral parietal area involved in visuo-spatial processing.

The researchers also tracked the precise time course of brain activation. They found that the electrical signals (ERPs) to exact *versus* approximate trial blocks were already different by 400 milliseconds, before the possible answers to the additions were displayed. Dehaene et al. argued that their data supported the idea that exact calculation relies on knowledge of 'number facts' or verbal associations stored in the language areas of the brain. Approximate calculation, on the other hand, relies on visuo-spatial parietal networks, which support a language-independent representation of quantity.

Cantlon et al. (2006) used neuroimaging to study the activity of these visuo-spatial parietal networks in 4-year-olds. They concluded that the intraparietal sulcus was recruited for non-symbolic numerical processing even at four years, before formal schooling has begun. This makes it likely that individual differences in numerical understanding will be linked to individual differences in the functioning of the neural analogue magnitude representation. Indeed, it has been argued that dyscalculia reflects a deficient analogue magnitude representation (i.e. atypical processing of quantity by the cell assemblies in intraparietal sulcus, see the Foresight Dyscalculia review by Butterworth).

The potential offered by neuroscience for understanding the development and characteristics of the mental representations underpinning educational performance is clear. Yet even in core areas such as reading and number, there are still very few studies and the data are essentially correlational. Longitudinal studies of typically-developing children are likely to be most informative with respect to causal factors. Neuroimaging techniques also offer the potential to study the effects of different learning environments on the electrochemical activity comprising mental representations, such as different kinds of instructional programme (e.g. The effects of teaching reading by 'synthetic phonics' *versus* 'analytic phonics' on the mental representations supporting printed word recognition). Almost no such studies are currently available.

4. Neuromyths and the popular media

In principle, the effects of different medications (e.g. Ritalin for ADHD), food additives or supplements (e.g. fish oil), and potential toxins (e.g. foetal exposure to alcohol) on educational performance can also be studied using neuroscience methods. Indeed, there are a variety of confident claims about the brain benefits of different food supplements (such as fish oils) and different commercial instructional programmes intended to exercise the brain flourishing at the current time. Such claims are usually given enthusiastic media coverage (see Goldacre, 2006), and may end up in local educational authorities spending significant amounts of money. A number of 'neuromyths' – beliefs that have little if any scientific support – appear to be remarkably persistent within education (Goswami, 2004, 2006; Howard-Jones, 2007).

One persistent neuromyth is 'left brain' *versus* 'right brain' learning (e.g. Smith, 1996). Teachers are told that children should be identified as either 'left brained' or 'right brained', because each individual prefers one type of processing – the 'logical' or the 'artistic'. Thus, teaching should ensure that learning experiences are 'left- and right-brain balanced'. Another neuromyth is that of learning styles. Teachers are advised that children's learning styles can be either visual, auditory or kinaesthetic (VAK), and that children should be taught according to their perceptual style.

Howard-Jones (2007) discusses commercial exercise packages "intended to improve learning by integrating different brain areas". As Howard-Jones comments, the explanations and concepts used to support such packages are unrecognisable to neuroscientists.

The idea that nutrition will affect brain function, and therefore learning, must be correct at a simple level, as the brain requires glucose to function effectively. Furthermore, fatty acids appear to be important for myelination, the process whereby protective sheaths build up around neuronal axons and increase electrical transmission speeds. However, it does not necessarily follow that if children ingest essential fatty acid (EFA) supplements such as omega-3 EFA and omega-6 EFA, their brain function will improve. Large US government-sponsored meta-analyses in psychiatry suggest that there may be a protective effect of omega-3 EFA intake for affective disorders such as depression and bipolar disorder. But these analyses reported no strong evidence as yet for cognitive disorders such as ADHD (Freeman et al., 2006).

Specific claims have been made that EFAs are deficient or imbalanced in developmental dyslexia (e.g. Cyhlarova et al., 2007). However, in their study of dyslexic adults, what Cyhlarova et al. actually found was a correlation between low cellular omega-3 levels and reading attainment, for both dyslexics and typically-reading controls. This does not establish a specific relationship with dyslexia. The dyslexic participants did not show lower membrane fatty acid levels for any of the 21 fatty acid measures reported by Cyhlarova et al. (2007). The correlation found with reading may be due to a third factor that has not been measured. Indeed, no plausible mechanism is proposed to link EFA levels to the specific cognitive skill of reading.

One problem with many studies undertaken to support putative brain-based interventions or other commercial packages is that research designs are poor. Often, control groups are absent or inadequate. Further, in educational research, it is well-established that correlations do not establish causes, and that any classroom intervention is vulnerable to so-called Hawthorne Effects. These arise not from specific changes due to targeted interventions, but from the generalised motivational and self-esteem effects of participating in something extra and unusual. These motivational effects can apply both to the teachers implementing a particular new method as well as to their students, and may well lie at the heart of some of the gains that do appear to arise when some of the currently-popular commercial packages are first introduced into classrooms (see Benedetti et al., (2005) for a discussion of the neurobiological mechanisms of placebo effects).

5. Neuroscience and education: the future

The beginning of this review stressed that a neuroscience approach was particularly promising with respect to education in three areas: (1) understanding the neural basis of the mental representations that underpin learning in school and beyond; (2) discovering neural markers for educational risk and; (3) evaluating debates in education that have not been resolved on the basis of behavioural data.

As the mental representations important for learning can be studied directly using neuroscience methods, neuroscience investigations can throw light on developmental factors. For example, an EEG study of the neural timing of the activation of the analogue magnitude representation important for number in 5-year-old children and adults showed that, surprisingly, the magnitude information associated with numbers was activated equally rapidly in both groups. They all showed a change in the amplitude of event-related electrical brain potentials when making magnitude-related decisions, within 200ms (Temple and Posner, 1998). However, the children took three times as long as the adults to organise their task-relevant responses, that is, to decide which hand to use to indicate whether a particular Arabic numeral or group of dots was smaller or larger than five. This suggests that the developmental differences in task performance observed in the study depended on 'executive functions' such as response organisation, rather than on the cognitive understanding of numerical magnitude.

Indeed, further neuroimaging studies with children have shown that the executive resources controlling behaviour are taxed to a much larger extent in children than in adults during the processing of numerical information (Szűcs et al., 2007). Without neuroimaging, it would have been concluded that the age differences that are found in many behavioural studies indicated immature numerical discrimination skills in 5-year-old children. Furthermore, the many demonstrations that the amplitude of event-related electrical brain potentials varies in response to numerical distance means that this response can be considered a neural marker for magnitude processing (Szűcs and Goswami, 2007). This marker can, therefore, be compared in children of different ages and in children with mathematical difficulties.

Given that the analogue magnitude representation is thought to be present in infancy, the discovery of neural markers such as this may be able to provide early indications of later educational risk (e.g. for mathematical difficulties). Similar neural markers have been discovered in language development (see Friedrich's *Foresight* review). For example, the brain's responsivity to speech sounds can be measured in sleeping babies (e.g. Cheour et al., 1997). One such marker is the 'N100', the early increase in the amplitude of electrical negativity when sounds are registered, as recorded by electrodes placed on the scalp. Neural markers such as the N100 can provide data on the neural representation of speech sounds when there are no cognitive or behavioural variables at all. Therefore, aspects of language function can be measured very early, and without requiring attention. As Friedrich (see Foresight review) demonstrates, a variety of neural markers may be useful in determining early risk for specific language impairment.

Finally, neuroscience offers methods for evaluating long-standing debates in education, by showing how the brain actually learns what is being taught. For example, teachers have long believed in the value of multi-sensory teaching methods, yet the VAK debate about learning styles recommended a uni-sensory approach to teaching (using either V, A or K). Given that different types of information will be learned by different regions of the brain, which will all be inter-connected to form a particular mental representation, multi-sensory teaching seems likely to lead to multiple representations of the same input which theoretically should *strengthen* learning. Neuroscience offers the research methods for finding out.

As one demonstration of this potential, James (2007) reported preliminary data on the effects of learning to trace and write letters (motor or kinaesthetic learning) on the visual recognition of letters by very young children. Brain scans (using fMRI) to *visual* presentation of the letters to be learned were taken both before and after the training. James (2007) reported that, prior to receiving writing training, presentation of the letters either caused no activation in left fusiform gyrus (the putative Visual Word Form Area, see Cohen and Dehaene, 2004), or modest activation. Following training, visual presentation of the letters not only activated the VWFA, it also led to novel activity in ventral premotor areas. Control children who did not receive training did not show activity to the letters in either neural area. The activation of *motor* areas during a *visual* task (letter recognition) suggests that the writing experience created multi-sensory mental representations. This opens up the possibility of studying whether letter knowledge is indeed more robust for these children.

6. Conclusion

The key potential of educational neuroscience for education is that brain imaging technologies can be used to measure mental representations in the *typically-developing* human brain (Szűcs and Goswami, 2007).

Longitudinal studies from early in development are essential, and will enable the documentation of typical developmental pathways for learning in a detail that has been impossible to achieve prior to neuroscience. Mapping and understanding normative development is an enterprise whose payoff will have positive benefits for the lives of millions of children. Nevertheless, so far current neuroscience research has little to translate into classroom practice.

The most exciting aspects of future educational neuroscience are likely to be a deeper understanding of plasticity and learning via the study of the development of mental representations, the identification of neural markers of risk that will enable very early interventions to change children's developmental trajectories, and the ways in which new neuroscientific technologies can make unique contributions to longstanding educational questions.

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