Potential educational developments involving neuroscience that may arrive by 2025

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Introduction

Educational innovation involving valid neuroscientific concepts is a relatively new phenomenon and the challenges involved are considerable, but it can be expected that progress in this area will accelerate with the growth of scientific understanding of the brain and mind. This report attempts to identify where changes are likely to occur by 2025. It deals first with those changes that are probable through neuroscience and education working together, reviews educational issues associated with neuroscience that may arise even in the absence of such positive collaboration, and then briefly considers the effect of such changes on the professional development of teachers.

While these first three sections deal with what may happen by 2025, the rest of the report is concerned with what is improbable by 2025. This includes a section on advances that may occur in the far distant future but, based on our current state of knowledge, appear unlikely to occur by 2025. The final section reviews the many neuromyths in education. This is included because such concepts are known to influence educators' expectations of what to expect from neuroscience in the coming years but, lacking a valid scientific basis, are not likely to give rise to future innovation.

Keywords: brain, education, innovation, neuroscience

Probable educational advances involving neuroscience

Some insights regarding brain function tend to resonate with existing educational attitudes and concepts, and may be helpful in strengthening and consolidating existing practice. Examples of such insights arise from research on

- *Brain plasticity*. This emphasises the extent to which the structure and function of the brain can respond to environmental influences including education. Such studies tend to emphasise the general importance of educational influence on neurocognitive development, and will always find favour amongst those who feel passionate about the value and promise of education. (eg Immordino-Yang presented two complimentary case studies of boys who had undergone the surgical removal of an entire brain hemisphere (Immordino-Yang, 2007). Both were able to develop language and social skills far beyond expectations, by developing individual processing strategies that exploited the functionality associated with the remaining hemisphere).
- *The role of phonological processing skills* which includes an understanding of reading processes and reading difficulties. Studies have linked dyslexia to reduced functioning in areas of the brain associated with phonological processing, and have demonstrated that both the reading difficulties and thus reduced functioning are amenable to remediation using approaches that emphasise sound-spelling relationships (Shaywitz et al, 2004).[1] Ongoing research continues to emphasise the importance of modern "phonics" approaches in the classroom.
- *Creativity* that shows that the inclusion of remotely associated concepts increases activity in brain regions linked to creative effort, supporting the use of such strategies as a means to foster creativity (Howard-Jones et al, 2005).
- *Visualisation* that shows visualising an object recruits most of the brain areas activated by actually seeing it (Kosslyn, 2005), supporting the use of visualisation as a learning tool.

However, although such neuroscientific studies may play a vital role in consolidating *existing* educational attitudes in some areas, perhaps the more salient influence of neuroscience in education will arise from more counter-intuitive findings. That is, it may be the educationally-relevant findings about brain function that are more surprising in their content and implications that stimulate the more dramatic *changes* in educational thinking and practice.

By definition, however, it is difficult to predict surprises. Yet, there are some areas of neuroscience research where results already appear to challenge the types of assumptions teachers work with, and may soon give rise to new directions. These areas will, therefore, now be given particular focus.

Early Numeracy

The acquisition of much formal mathematics relies on our ability to learn rules and procedures. This has been demonstrated by a neuroimaging study involving adults who were asked to calculate answers exactly. Researchers observed increased activity in areas of the brain involved in word association and language activity, the left frontal and angular gyri (Dehaene et al, 1999), as these adults pursued mathematical procedures by following formal mathematical steps that could be linguistically encoded. However, when the same individuals attempted to estimate answers, bilateral activity in the intraparietal sulci was linked to our more ancient and language-independent ability to approximate. Such an ability appears early in development. Even at six months, most of us can approximately differentiate between large numbers of items for ratios of between 1:2 and 2:3 (Starkey and Cooper, 1980) and it seems that we share this approximate

[1] I have included dyslexia in this list because present understanding in neuroscience tends to support much existing practice, although it could be argued that this is due to existing practice *already having been influenced* by cognitive psychology and cognitive neuroscience.

number sense with other animals (Boysen and Capaldi, 1993). Such early mathematical ability is likely to have a critical role in 'bootstrapping' our capacity to formally grasp exact differences and procedures (credited to Spelke and Carey in Johnson, 2004; see also Carey, 2004), and should provide an improved basis for developing initial mathematical understanding of number and for remediating pupils' difficulties in achieving this. For example, dyscalculia has been linked to a deficit in our 'premathematical' estimation abilities (Butterworth, 2008) and a study of low birth-weight adolescents with numerical difficulties revealed less gray matter in an area of the intra-parietal sulcus (Isaacs et al, 2001). Further research is needed to confirm the direction of cause and effect in such studies, but insights from brain imaging research are contributing to models of mathematical development useful in developing interventions. For example, in one intervention based on these concepts, it was demonstrated that children with dyscalculia showed considerable improvements in a broad range of calculation abilities when basic numerical and conceptual knowledge were focused upon at an early stage of mathematics education (Kaufmann et al, 2003). Dehaene has also used his own findings to develop educational software aimed at remediating dyscalculia. The software is based on the hypothesis that dyscalculia derives from a core deficit in number sense, or in relating number sense to numerical symbols (Wilson et al, 2006)

Another example of the potential influence of neuroscience on mathematics education comes from research into the role of fingers in early mathematical development. Since one might consider mathematics as a cognitive ability, the use of fingers to support calculation can be looked down upon as evidence of mathematical weakness. However, finger gnosis (being able to differentiate between different fingers in response to, say, one or more being touched) has been identified as a strong predictor of mathematical ability (Noel, 2005). Links between finger discrimination and mathematical ability have been studied in both children and adults. A functional Magnetic Resonance Imaging (fMRI) study has shown that, although behavioural outcomes can be the same, the activities produced when fingers are involved in approximating tasks vary with age (Kaufmann et al, 2008), suggesting their contribution varies with development. Eight year-old children produce an increase in activity in the intraprietal sulci when fingers are involved, but not adults. Kaufmann suggests fingers represent concrete embodied tokens involved in the estimation of number magnitude – an intimate involvement with our basic "number sense". On this basis, children should not be discouraged from using fingers and teachers may be able to exploit their natural role more fully (Kaufmann, 2008). For example, in one intervention based on such ideas, new arrivals at three Belgian schools were identified as having poor finger gnosis and some of them received two-weekly 30 minute sessions of finger training for eight weeks (Gracia-Bafalluy and Noel, 2008). After training, these children were significantly better at quantification tasks than those who had not received the training.

Research on the relationship between our "animal number sense" and the early learning of mathematical concepts has only just begun. However, the concepts emerging are sufficiently well established and different to previous ideas of mathematical development to suggest the potential for improved educational practice in primary school classrooms in the next 1-2 decades.

Adolescence

It may be natural to consider that a teenager is essentially a young adult, with a fully formed brain but lacking the social experiences of his/her elders. However, scientific investigation has revealed a very different picture, with frontal and parietal regions still undergoing radical structural changes until the late teens, relative to other areas of the brain which appear more fully developed. Synaptic pruning (the cutting back of neural connections) and myelination (improving the efficiency of neural connections) also continue throughout adolescence (Sowell et al, 2003) in frontal regions. Such change in specific regions suggests the teenage brain may be less ready than an adult brain to carry out a range of specific processes, including directing attention, planning future tasks, inhibiting inappropriate behaviour, multitasking, and a variety of socially-orientated tasks. Although more research is needed, some psychological research backs this up, even showing a "pubertal dip" in some areas of performance, such as matching pictures of facial expressions to descriptors. In this task, 11-12 year olds perform worse than younger children (McGivern et al, 2002). Discontinuities have also been shown in abilities underlying social communication, such as taking on the viewpoint of another person, or so-called 'perspective-taking' (Blakemore and Choudhury, 2006; Choudhury et al, 2006). Some parts of what might be described as a "social brain" network are also activated differently in teenagers compared with adults when thinking about intentions (Catherine et al, 2008) and brain regions responsible for the control of impulses appear less well functionally connected in adolescents' than in adults' brains (Steven et al, 2007). Teenagers also appear to activate different areas of the brain from adults when learning algebraic equations, with this difference associated with a more robust process of long-term storage than that used by adults (Luna, 2004; Qin et al, 2004). Adolescents, then, are not simply older children or younger adults, and cognitive development cannot be expected to proceed in a continuous linear manner. Apart from explaining some of the difficulties teenagers experience, such changes also suggest how and why adolescence can be a potentially sensitive period for learning, within and beyond academic contexts. For example, teenagers often tend to perceive risks as smaller and more controllable than adults, and they are generally more vulnerable than adults or children to a range of activities which are inappropriately risky, such as gambling and drug taking. Appropriate decision making appears to require a balanced engagement between harm-avoidance and reward orientating processes that is regulated by processes within the prefrontal cortex, where teenage development may lag (Ernst et al, 2005). Imaging studies comparing adults and adolescents show reduced activity in these prefrontal areas when making risk-based decisions (Bjork et al, 2007; Eshel et al, 2007), and this reduced activity correlates with greater risk-taking performance (Eshel et al, 2007). Such studies provide new insights into how adolescent risk taking may be linked to neuro-maturational events and these insights may influence educational perspectives on teenage behaviour, helping to understand a potentially problematic, and sometimes even dangerous, period of children's development (Baird et al, 2005).

It seems likely that these and future findings from neuroscience may generate new educational approaches in future years (eg strategies that take a more informed account of the temporary lagging of cognitive function in some areas). Findings on the adolescent brain are potentially illuminating and should stimulate educational changes, although the rate at which these will occur is difficult to predict. Paus believes that "the time is right for evidence-based, large-scale studies of interventions aimed at facilitating youth development. Neuroimaging-based approaches hold considerable promise, providing both the evidence as well as novel insights about the role of the environment in shaping the adolescent brain" (Paus, 2008). However, do such beliefs reflect an awareness of the considerable ethical, social and political issues that would be involved with such studies? Neuroimaging studies of interventions aimed at remediation of difficulties associated with dyslexia have already been carried out, but remediation of character (one of the five "c"s of positive youth development (Lerner, 2005)) would take neuroethical dilemmas to a new level.

Motivation

A burgeoning number of findings from neuroscience has supported some fresh educational thinking about motivation, including the type of intense engagement provided by computer gaming (Gee, 2003). Previous explanations of gaming motivation involve issues of fantasy, challenge and curiosity (Malone, 1981) but these appear inadequate in explaining the attraction of some traditional games such as "snakes and ladders" and "bingo", or simple (but popular) computer games such as *Tetris*. This attraction may be due more to elements of chance-based uncertainty. The attraction of uncertainty is now gaining closer neuroscientific investigation, but it is a phenomenon well established by psychological experimentation (Atkinson, 1957) which has shown moderate risk taking (50% chance) heightens motivation.

Recent neuropsychological understanding of reward[2] involves consideration of 'wanting' and 'liking' as two dissociable components, with the wanting of a reward being coded by levels of dopamine release in mid brain areas (Berridge and Robinson, 2003). The predictability of an outcome has been shown to influence this activity. In primates, it has been shown that maximum dopamine is released when the likelihood of receiving reward for success is about half way between totally unexpected and completely predictable, ie 50% likely (Fiorillo et al, 2003). Dopamine levels in this area of the human brain have been linked to our motivation to pursue a variety of pleasures, including sex, food, gambling (Elliot et al, 2000) and computer gaming (Koepp et al, 1988). The link between the predictability of an outcome and mid-brain dopamine activity is, therefore, helpful in explaining why humans are so attracted to activities involving elements of chance (Shizgal and Arvanitogiannis, 2003). Activity in this area has been studied non-invasively in humans during gaming using fMRI. These fMRI studies have shown that patterns of dopamine activity are predicted less by reward in 'real' absolute terms and seem more to do with winning the particular game being played. Activity can increase with reward size (Knutson et al, 2001) but, rather than being proportional to absolute monetary reward, activation peaks at the same level for the best available outcome in different games (Nieuwenhuis et al, 2005). The complex relationship between reward and motivation is thus strongly mediated by context.

When uncertainty is encountered in more real world instances, there are potentially more complex effects of context created by the social environment. These are illustrated by the way our natural attraction to uncertainty falls off when the task is perceived as educational. Students generally prefer low levels of academic uncertainty and choose problems well below moderate (<50%) challenge (Clifford, 1988; Harter, 1978) unless these are presented as games, when students will take greater risks (Clifford and Chou, 1991). This may suggest that individuals can be deterred from tackling academic tasks with higher levels of uncertainty due to the implications of failure for social status and esteem. In research involving classroom-based applications, these concepts provide a means to understand how learning games with elements of pure chance can increase uncertainty without impacting negatively on self-esteem, thereby raising motivation (Howard-Jones and Demetriou, in press - now published on-line). Neurocomputational modelling is now providing the tools to study the reward system in more detail (Elliott and Deakin, 2008).These techniques allow estimation of how dopaminergic activity in the reward system varies with the progress of a game. Such activity also mediates attention in the short term, and these models can predict when declarative learning (the type of greatest interest to educators) will occur during an educational game (Howard-Jones et al, 2009).

Neuroscience is providing concepts that are proving useful in understanding learning games and motivation in the classroom, particularly amongst males (Hoeft et al, 2008). However, introducing chance-based uncertainty into learning can conflict with the principle of reward consistency that is traditionally valued by education (OfSTED., 2001). Our increasing understanding of this region of the brain has, therefore, the potential to prompt a significant departure from present educational thinking.

Early screening for some developmental disorders

[2] Note that reward is being used here in the psychological sense, i.e. as a process, or set of processes, by which behaviour is reinforced.

Event-Related Potentials (ERPs) refer to a set of distinct electrical signals emitted by the brain and detectable using a non-invasive technique involving the attachment of electrodes to the scalp. Some ERP waveforms of newborn infants have been identified that can differentiate between children who will later, at eight years old, be poor readers or be dyslexic (Molfese, 2000). Measurement of ERPs has been shown as an effective method of predicting dyslexia in new-borns with and without a family history of dyslexia (Guttorm et al DATE) and such techniques could form the basis of very early screening, so that children at risk of dyslexia are able to benefit as quickly as possible from suitable intervention(s). See also discussion by Friedrich of neural markers and specific language impairment (Friedrich, 2008). Such techniques and possibilities are not limited to literacy. Another type of ERP has been identified that is sensitive to children's response to numerical distance (Szucs et al, 2007) that may be a helpful neural marker for magnitude processing in infancy. This signal may provide an early indicator of later educational risk in respect of mathematics.

The use of neural markers to provide very early detection of educational risk is an area identified by Goswami where a neuroscience approach may provide particular promise for education (Goswami, 2008).

Cognition and the Brain in the Curriculum: Curriculum Aims and Content

i) The influence of research on cognitive training ('Brain training')

There is increasing evidence to show that the cognitive training can reduce risk of Alzheimers (Wilson et al, 2002) and in normally functioning older adults. A 5-year study has shown that training can provide sustained improvements in a range of cognitive functions in this age group (Ball et al, 2002).

A study by Willis et al (2006) showed sustained improvements in targeted function over five years, following an intervention that consisted of only 10 sessions of about 60-75 minutes each. Positive effects were also been observed on daily functioning (phone, laundry, cooking etc) (Willis et al, 2006).

There is thus good evidence to show that brain function can be trained, in the sense that repeated practice on exercises that focus on a cognitive function, can produce improvement in that cognitive function. There is less evidence confirming impact on everyday functioning not specifically targeted by the training. As research continues, however, such evidence is emerging (Mahncke et al, 2006; Willis et al, 2006) and we are understanding more about the impact of training cognitive function on other, non-targeted areas. Most notably, it has been convincingly shown that fluid intelligence, which is seen as a good predictor of professional and academic achievement, can be improved by rehearsing working memory exercises, specifically an exercise based on the N-back test[3] (Jaeggi et al, 2008). Unlike most other studies which have been undertaken with older participants including those at risk of dementia, the average age of the participants in this study was 25, demonstrating the relevance of this type of cognitive training to the younger population.

In terms of developing cognitive function amongst children, it is the targeting of WM, together with the closely allied concept of attention that has again produced the most interesting results. In a study involving children with ADHD, training of WM was found to successfully transfer to non-targeted areas of behaviour, producing improved complex reasoning skills and reduced parental ratings of ADHD symptoms (Klingberg et al, 2005). Training of visual and auditory attention has been found to benefit literacy achievement for children with dyslexia (Chenault et al, 2004), and a study using ERPs with children

[3] In the type of N-back task used in this research, participants are asked to observe a sequence of digits or letters, and asked to recall the item that was N items back

with specific language impairment (SLI) showed that neural mechanisms of selective auditory attention and the associated language difficulties can be remediated through auditory attention training (Stevens et al, 2008).

The research from science converges with other forces encouraging educators to move further away from content towards thinking skills and, more specifically, the training of cognitive function. Advances in technology are likely to continue improving our access to information, with some commentators believing this will increase the need for specialisation as it increasingly places "any human knowledge at the fingertips of any human" (Stewart, 2008). Such advances may, therefore, make it desirable for learners to be better at manipulating information than encoding and recalling it, with demand for specialisation making it more difficult to predict and include the type of content that an individual may benefit from in the initial stages of their education[4]. These factors may combine with a burgeoning dialogue with neuroscience that also encourages greater emphasis upon cognitive function generally within education – since cognitive function is a central construct of cognitive neuroscience - and some way towards a redefinition of the aims of education[5] as an attempt to "nurture" the brain and its processes. Increasing interest in the training of cognitive function as a means to enhance learning potential is also reflected in current public interest in "brain training" products, although it should be noted that no quality research exists that evaluates the claims made by the manufacturers of these products, or even the design principles upon which they are based. This public enthusiasm with the commercial products has already begun to extend itself to some schools[6].

ii) Teaching about the brain

There has also been a broader interest in the development of children's cognitive function, in ways that include emotional aspects of behaviour. These include the development of "Executive Function" (EF) - an umbrella term referring to the underlying processes responsible for children's ability to direct, maintain and focus their attention, manage impulses, self-regulate behaviour and emotion, plan ahead and demonstrate flexible approaches to problem solving[7]. EF skills are predictive of academic achievement (Bull et al, 2008), and social and emotional development (Hughes, 1998). For this reason, attempts have been made to find ways of developing EF skills and some interventions in schools have reported positive results in terms of improved behaviour (Greenberg, 2006).

Unlike simple cognitive training, such programmes require learners to understand and reflect upon their behaviour in terms of a set of mental processes. They are thus delivering an explicit, if sometimes ill-defined, psychological content into the curriculum of many schools. These programmes are becoming associated with protecting the mental

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[4] Memory processes will, however, still remain of key importance in education although semantic memory (for knowing "how to") may increase its significance relative to declarative memory (explicit recall of facts and events)

[5] An extreme view of this redefinition has been provided by Koizumi: "… education should be designed to guide and inspire the construction of the basic architecture for information processing in the brain by preparing and controlling the input stimuli given to the learners." Koizumi, H. (2004) The Concept of 'Developing the Brain': A New Science for Learning and Education, *Brain and Development*, 26, 434-41. p435.

[6] For example: http://www.ltscotland.org.uk/ictineducation/gamesbasedlearning/sharingpractice/braintraining/introduction.asp

[7] WM is usually considered one component of EF

health of children[8] as well as improving academic standards and behaviour. They have been explicitly linked to neuroscience by some experts (Greenberg, 2006), although (in the opinion of the author) such links would benefit from further scientific scrutiny and consensus. What does appear clear, however, is that the school-based curriculum education is becoming influenced by attempts to directly attend to the development of executive function, in order to promote emotional well-being, mental health and academic achievement. It has been known for some time that the level of education can influence mental health in later life, but there are now growing voices for educators to become actively involved in fostering the mental health of their learners. A 2005 policy paper produced by the Sainsbury foundation (together with the NHS confederation) predicts "By 2015, mental wellbeing should be a major concern for schools, from dedicated classroom time to the overall approach of the school towards its pupils and staff" (SCMH, 2005, p13.

It can also be predicted that advances in neuroscientific understanding may broaden the aims of education further still, thereby influencing the curriculum and the ways in which it is delivered. For example, rising levels of obesity amongst children has drawn new attention to the importance of exercise in schools, but this may gain further emphasis as neuroscientific understanding emerges about the processes by which exercise is linked to learning (Hillman et al, 2008). Understanding the processes by which even short bouts of exercise improve subsequent learning (Winter et al, 2007) makes it foreseeable that regular exercise breaks during the school day will become more popular as a means of raising academic standards and fostering mental and physical health. Although it is certainly not a good example of science, evidence for the likelihood of such developments arises from the popularity of Brain Gym. The principles of Brain Gym are unscientific and bizarre (Hyatt, 2007), but its popularity in the face of unfavourable media exposure must surely derive, in part, from its associations with academic achievement and neuroscience. Such associations, in the case of Brain Gym, do not withstand scrutiny, especially in terms of neuroscience, but it is likely that the authentic value of exercise in learning will become well understood by educators in future years. It can be predicted that, by 2025, neuroscience will have contributed to developing scientifically sound and educationally evaluated methods of incorporating frequent exercise breaks into the school day and these will have become established in most schools.

Part of the success of introducing such elements into the curriculum will depend on ensuring learner motivation, and this may depend on learners understanding something of neurocognitive function. Such understanding may have other benefits. It has been reported that providing learners with a basic knowledge of the brain can, by itself, provide significant help in improving self-image and academic achievement (Blackwell et al, 2007). In this study with adolescents, researchers informed learners about the structure and function of their brain, how learning changes the brain by producing new neuronal connections and about brain plasticity, and provided the clear message that the pupils themselves were in charge of this process. This promoted a positive change in classroom motivation. Grades for the control group, who had not received the intervention, continued downward while this trend was reversed for the intervention group.

[8] Programmes through the curriculum can promote mental health … important characteristics of such programmes include those that enable children to correctly identify and regulate one's feelings..." DfEE. (2001) "Promoting Children's Mental Health within Early Years and School Settings." (Nottingham, Department for Education and Employment), p10

Neuroscience-related issues arriving without invitation

The potential changes so far discussed are expected come about through initiatives involving educators, and their final form is likely to be mediated by educational understanding, sensitivities and opinions. Some influences involving neuroscience, however, may arrive without invitation.

One such issue is the use of cognitive enhancers. In the US, students are increasingly using prescription drugs in order to provide cognitive enhancement and thereby support their studies. Usage varies widely from one university to the next, with an average figure of 6.9% of students indulging in non-medical use of prescription stimulants (McCabe et al, 2005). In another study, however, that surveyed 1811 students at a large Southeastern US university, 34% reported the illegal use of ADHD stimulants (eg methylphenidate), mostly to improve their cognitive function during periods of fatigue and stress (DeSantis et al, 2008).

The production of new and stronger drugs for cognitive enhancement is likely to increase, driven partly by efforts to combat the effects of Alzheimer's disease. One such drug is donepezil (marketed as Aricept) that increases levels of acetylcholine (ACh). ACh is thought to modulate the rate at which neural connections adjust themselves when learning, with increases in ACh thus able to bring about increases in learning rate. Donepezil reduces cholinesterase that mops up ACh, thereby increasing levels of ACh and improving cognitive function, including memory, amongst those suffering from Alzheimers (Roman and Rogers, 2004). The potential value of this drug for other users was demonstrated in a study that administered donepezil to healthy young adults for only 30 days, and revealed significant improvements in episodic memory performance (Gron et al, 2005).

Scientists have been speaking out in positive terms about the "new enhancement landscape" for healthy adults (Gazzaniga, 2005). In a recent article in *Nature*, one group of scientists suggested that the growing demand for cognitive enhancement should be responded to, and that the response should begin by "rejecting the idea that enhancement is a dirty word."(Greely et al, 2008) However, a modest UK consultation showed more ambivalence (Horn, 2008), with concerns raised that included

- possible side and long term effects including personality change
- the devaluation of 'normal' achievement and the intrinsic value of effort and motivation in learning
- inequality if such drugs are expensive
- pressure to use such drugs and the exacerbation of an already over-competitive culture.

It seems likely that the use of cognitive enhancers amongst the general UK population will increase as public sensitivity diminishes and the drugs become more socially acceptable. This will stimulate significant ethical debate amongst educators. Some educational institutions may, with parental permission, choose to introduce drug testing. Since there are few clear precedents for the issues involved with these drugs (it is debatable whether a comparison with the use of drugs in sport is helpful) there may, for some time, exist a diverse range of attitudes and practices amongst learners and educational institutions in respect of cognitive enhancers. This may impede the development of any necessary legislation.

The influence of neuroscience on educational professional development

Psychology returns, accompanied by some neuroscience, to initial teacher training

Our burgeoning understanding of the human brain and mind, particularly in regard to the issues raised above, will increase the likelihood of some elements of psychology returning to initial teacher training. When teachers consider learning processes, they consider mental rather than neural processes, although in the future we can expect constructions about these mental processes to be increasingly informed by neurobiological understanding. Neuroscience, in itself, remains largely meaningless in educational terms, except insofar as it informs our psychological concepts about the learner's mind. However, neuroscientific concepts are helpful in formulating and communicating educationally-relevant concepts about the mind (Howard-Jones, 2008).

The emergence of neuro-educational research and new types of educational professional

Although appearing under many different names (eg educational neuroscience, neuroeducational research, neuroscience and education) a field of research at the interface between neuroscience and education is becoming established. This provides some support for the prediction made by some that, in the future, hybrid professionals will emerge with expertise in both neuroscience and education (Pickering and Howard-Jones, 2007; Szucs and Goswami, 2007).

Developments that may occur in the future, but not by 2025

Genetic profiling in mainstream education

The area where genetic knowledge is first likely to impact, and appears likely to do so before 2025, is in the area of learning difficulties. Gene-based diagnoses of learning difficulties will be able to predict general learning difficulty as well as difficulties within specific areas such as maths (Plomin, 2008). Such very early predictions, combined with emerging educational understanding of effective interventions, will provide the soonest possible implementation of appropriate interventions. Genetic knowledge will provide opportunities for new levels of personalised learning and these should ameliorate or even prevent the manifestation of some learning difficulties.

Ultimately, genetic knowledge should allow educational programmes to be better tailored to suit all individuals according to their genetically-informed educational profiles. It has been suggested that, in the future, "Educogeneticists" will be able to provide informed recommendations to schools and families about how a child's education may be planned in order to optimise academic outcomes (Grigorenko, 2007). Genetics may, therefore, be considered to have considerable educational potential beyond the early identification and amelioration of learning difficulties. This wider application, however, will only add further controversy to a plethora of ethical issues and questions about using genetic knowledge in education: what may result when genetic testing proceeds without full understanding of the educational intervention that may be needed? Who makes the decisions about testing and interventions, and by what processes? What precautions are needed to prevent this new educational opportunity feeding demand for genetic engineering and eugenics?

Since biotechnology companies are now marketing genetic tests directly to the public, it is possible that this issue may arrive without educational invitation by 2025, as with cognitive enhancers. One can imagine that, by 2025, all parents will have the opportunity to independently purchase a genetic profile of their child and ask what their school intends to do about it. However, whilst the educational application of smart pills requires only that a bottle is opened and a pill consumed, there remains much educational (or "edu-genetic") research necessary in order to utilise genetic knowledge in mainstream education. This knowledge gap and the ethical issues mentioned above will provide some barrier to progress. Due to the potential benefits to individual learners, public attitudes are likely to become increasingly positive and demands for edugenetic approaches will grow, but it seems unlikely that schools will develop established approaches to genetically-based differentiation of mainstream teaching and learning by 2025.

Brain-Computer interfaces (BCIs) in mainstream education and 'brain reading'

Brain-computer interfaces have developed the potential to provide valuable aid to some profoundly disabled individuals. For example, severely paralysed patients can control prosthetic limbs and computer cursors by thought alone. Non-invasive approaches often adapt the type of technology used by ERP and EEG measurements, using a patient's electrical brain activity sensed by electrodes placed on the scalp. The EEG/ERP signal is analysed and interpreted automatically by a computer, which then produces an appropriate output. In this way, the user can generate some rudimentary signal to the outside world by producing the pre-defined type of thought that the computer is programmed to decode. For example, by imagining different body motions (eg left versus right hand), the user can generate different EEG signals that can be translated by the computer into responses to binary (yes/no) questions with high, but not perfect, accuracy (Neuper et al, 2006). As illustrated in this example, there are presently significant limitations upon the amount of information such BCI interfaces can communicate. These limitations arise from the noisiness of the signal and the variability of the signals produced by different individuals. Improvements in technology alone may not be sufficient to overcome these limitations, since significant advances may require greater neurobiological and psychological understanding of the signals themselves.

At present then, although the usefulness of non-invasive BCIs for the profoundly disabled may be possible in the next 1-2 decades, the likelihood of the wider population using them to communicate with everyday technology is something for the very far distant future when both our technology and, perhaps more importantly, our understanding of brain function is unimaginably superior than at present[9].

Similar issues limiting the advances in BCI's over coming years will also apply to 'brain reading'. Some experiments have shown that imaging technology can reveal socially sensitive and relevant information, such as racial group identity and unconscious racial attitudes. For example, white subjects with more negative evaluations of black faces showed increased amygdalic activity in response to unfamiliar black, compared with white, faces. There has also been some success in identifying the correlates of deception (Nunez et al, 2005) and such knowledge may be applied in counter-terrorism efforts in the future. Such examples, however, tend to compare a very small set of conditions, and results could only be used to differentiate between a correspondingly small set of possible alternatives regarding mental content (eg truth/lies). As with the notion of using a BCI to access one's computer in an everyday sense, the possibility of reading the everyday contents of a learner's mind will be science fiction until well beyond 2025. As

[9] Invasive BCIs involve the implantation of electrodes, produce cleaner signals and perform a little better, but clearly these are not likely to become acceptable amongst those who suffer no serious disability and so these devices are not considered here.

Farah suggests (p1126) in relation to brain-reading, "even a major leap in the signal-to-noise ratio of functional brain imaging would leave us with gigabytes of more accurate physiological data whose psychological meaning would be obscure." (Farah, 2002)

Improbable educational advances involving neuroscience

There are considerable differences between the views of educators and scientists about how neuroscience is relevant to education, although consensus is emerging in both areas that the relevance exists. Perhaps unsurprisingly, educators associate neuroscience chiefly with those brain-based concepts already commonly found in schools (Pickering and Howard-Jones, 2007). Unfortunately, these concepts are often not well supported by existing science, yet educational expectations of how neuroscience may influence education in the future are likely to be strongly influenced by these neuromyths. This was illustrated in 2000 when scientists Uta Frith and colleague Sarah-Jayne Blakemore were commissioned by the Teaching and Learning Research Programme (TLRP) to carry out a review of neuroscientific findings that may be of relevance to educators (Blakemore and Frith, 2000). This review attacked a number of unscientific myths and highlighted some scientific areas of potential interest to educators. In January 2001, to promote further discussion about a possible research agenda, the TLRP wrote to scientific and educational institutions, asking for comments on the report by Blakemore and Frith. Respondents were particularly asked to provide "identification of key research questions, … their priority … and estimate of their tractability (in terms of return on research effort)". While scientists indicated areas such as learning disorders, memory and plasticity, educational respondents identified areas such as multiple intelligences and learning styles, which are problematic as robust and well-defined scientific concepts suitable for orientating neurocognitive research. The report on the consultation concluded that no collaborative research agenda had yet emerged (Des Forges, 2001).

Indeed, perhaps the most immediate benefit of the increased dialogue between neuroscience and education has been to highlight the large number of neuromyths that have developed within education. Some of the most prominent will now be listed below, none of which are likely to receive support from neuroscience in the coming years and should become less prominent by 2025, despite the hopes of many educators.

Multiple Intelligences (MI) Theory

Gardner's MI theory proposed that, rather than a single all-purpose intelligence, it is more useful to describe an individual as possessing a small number of relatively independent intelligences (Gardner, 1983). Possible candidates for these intelligences include linguistic, musical, logical-mathematical, spatial, bodily-kinaesthetic, intrapersonal sense of self, interpersonal and Gardner has later proposed other possibilities such as naturalistic and existential intelligence (Gardner, 1999). MI theory is in direct opposition to the idea of a unitary general intelligence factor 'g', reflecting overall brain efficiency and the close interconnection of our mental skills. MI theory resonates with many educators, who see it as a robust argument against IQ-based education.

In a critical review of the evidence for MI theory, Waterhouse examined the empirical scientific evidence (Waterhouse, 2006). MI theory claims to be drawn from a wide range of disciplines including neuroscience. Indeed, Gardner has claimed "accumulating neurological evidence is amazingly supportive of the general thrust of MI theory". However, Waterhouse points out that the general processing complexity of the brain makes it unlikely that anything resembling MI theory will ever emerge from neuroscience. Cognitive neuroscience is exploring the brain in terms of processes (vision, hearing, smell, etc) but not in terms of *seeing intelligence*, *auditory intelligence* or *smelling intelligence.* In the realm of neuroscience, it neither appears accurate or useful to reduce the vast range of complex individual differences at neural and cognitive levels to any limited number of capabilities.

Despite the absence of MI theory in the neuroscience literature, teachers heavily associate MI theory with neuroscience. (To confirm this, the author returned to the data collected from the 150 UK teachers who were asked the question "Please list any ideas that you have heard of in which the brain is linked to education" (Pickering and Howard-Jones, 2007). Of those teachers who responded to this question (121), most listed no more than 2-3 ideas. Of these, MI theory occurred 17 times (14%)).

Thus, in educational terms, MI theory appears like a liberator – providing teachers with the 'scientific' license to celebrate diversity. In terms of the science, however, it seems an unhelpful simplification as no clearly delineated, limited set of capabilities arises from either the biological or psychological research.

Learning Styles

In educational terms, an individual's learning style can be considered as a set of learner characteristics that influence their response to different teaching approaches. A survey in 2004 identified 71 different models of learning styles (Coffield et al, 2004) and our own survey showed almost a third of UK teachers had heard of learning styles, with most of those who used this approach reporting it as effective (Pickering and Howard-Jones, 2007). As with MI theory, which is also often interpreted by educators as a means to identify preferred modes of learning, the promotion of learning styles has benefited from a strong association with neuroscience. Many learning style models have a distinctly biological justification, with one of their major proponents, Rita Dunn, commenting that "at least three fifths of style is biologically imposed" (Dunn et al, 1990).

Very many educational projects have pursued improvement through tailoring programmes to meet individual learning styles but, as yet, there is no convincing evidence that any benefit arises. A review of such studies, concluded that matching instruction to meet an individual's sensory strengths appears no more effective than designing content-appropriate forms of education and instruction (Coffield et al, 2004). Perhaps the best known inventory of learning styles within education is the one categorising individuals in terms of their preferred sense modality for receiving, processing and communicating information: visual, auditory or kinaesthetic (VAK). In a laboratory study of memory performance, participants' own self assessment of their VAK learning style was shown to be out of line with more objective measures, and memory scores in different modalities appeared unrelated to any measure of dominant learning style (Kratzig and Arbuthnott, 2006). There was, instead, evidence that participants' self-rating as kinaesthetic learners was related to visual performance, that they were self-rating their learning styles in ways possibly promoted by the inventory itself, and objective evidence from memory testing that suggested visual and kinaesthetic/tactile tasks were tapping the same underlying memory process. The authors concluded that educators' attempts to focus on learning styles were "wasted effort".

In approaches such as VAK, the implicit assumption appears to be that, since different modalities are processed independently in different parts of the brain, differences in the efficiency of these parts results in a clear modality-based method of classifying how learners are able to process information most efficiently. However, as pointed out by Geake, this flies in the face of what we know about the interconnectivity of the brain(Geake, 2008). Geake refers to a recent piece of experimental research in which five year olds showed themselves able to distinguish between groups of dots even when the numbers were too large for counting (Gilmore et al, 2007). They were then asked to repeat the task in auditory mode by counting clicks, and reproduced almost identical levels of accuracy. Geake points out that this is because input modalities in the brain are very interlinked. As yet, no evidence arising from neuroscience, or any other science, supports the educational usefulness of categorising learners in terms of their sensory modality or any other type of learning style. In the meantime, educators continue to be drawn to VAK as means to implement a type of differentiation between learners.

Learning styles based on these ideas are likely to diminish in their popularity as awareness grows of their ineffectiveness and lack of scientific basis. By 2025, one can be hopeful that differentiation of learners may be informed by a better understanding of the development of literacy, mathematical and other skills, and this understanding will undoubtedly be informed by insights from cognitive neuroscience. More speculatively, it is also possible in the more distant future (but not by 2025 – see above) of genetically-informed profiling of individual learners.

Left-Brain Right Brain

Another popular way of categorising learning style is in terms of "left-brain right-brain" theory(Springer and Deutsch, 1989). According to this theory, learners' dispositions arise from the extent to which they are left or right brain dominant. It is true that some tasks can be associated with extra activity that is predominantly in one hemisphere or the other. For example, language is considered to be left lateralised. However, no part of the brain is ever normally inactive in the sense that no blood flow is occurring. Furthermore, performance in most everyday tasks, including learning tasks, requires both hemispheres to work together in a sophisticated parallel fashion. The division of people into left-brained and right-brained takes the misunderstanding one stage further. There is no reliable evidence that such categorisation is helpful for teaching and learning.

Educational Kinesiology (Brain Gym)

Educational kinesiology (or Edu-K, also often sold under the brand name of Brain Gym) was developed by Paul and Gail Dennison as a means to 'balance' the hemispheres of the brain so they work in an integrated fashion and thus improve learning (Dennison, 1981). Whatever the flaws in its theoretical basis (which are many and fatal), there is a lack of published research in high quality journals to make claims about the practical effectiveness of programmes such as Brain Gym to raise achievement. Of the studies published elsewhere, the lack of information about the exercises undertaken and/or the insufficient or inappropriate analysis of the results undermine their credibility (Hyatt, 2007). However, it may also be that programmes such as Brain Gym are contributing to learning, but for entirely different reasons than those used to promote them. As discussed above, there is an emerging body of multidisciplinary research supporting the beneficial effect of aerobic exercise on selective aspects of brain function of importance to education (Hillman et al, 2008). However, these advantages appear linked to the aerobic nature of the exercise, which is low in Brain Gym.

Implicit learning

Work with artificial grammars, in which participants are able to acquire grammatical rules by observing examples of artificial language, demonstrates our ability to learn implicitly, ie without being able to report explicitly what has been learnt. Such experiments have contributed to enthusiastic calls for more educational focus on implicit learning (Claxton, 1998). However, there are considerable barriers to the practical application of such ideas, making their usefulness to education questionable and causing some scientific authorities to label them a new source of neuromyth (Goswami, 2004). A non-specialist interpretation of the phenomenon of implicit learning might involve ideas about absorbing information and concepts from the environment without attending to them, but such ideas have no scientific basis. For example, in the artificial grammar scenario, formal rules may be acquired without the learner consciously formulating them, but the learner must pay considerable attention to the examples of artificial language in order to facilitate this. In a more real world context, we may also implicitly develop understanding about, for example, the motivations of people around us, without being able to articulate how we have achieved this. Again, however, this is only possible by paying attention to the behaviour of those people. “Implicit learning” does not equate to “learning without attention”, and it seems unlikely that such concepts will become usefully applied in education in the coming years.

A brain-based science of learning?

Although researchers at the interface of neuroscience and education have done much to counter the neuromyths prevailing in schools, they may also be guilty of inadvertently creating one. There has been much enthusiasm amongst policy makers for the creation of a “new” science of learning (OECD, 2002; OECD, 2007). This may be because neuroscience seems a more secure basis for learning theory, with its images of blood flow appearing more concrete than abstract psychological concepts. Indeed, it has been experimentally determined that including references to the brain (even irrelevant ones) increases the satisfaction of a reader (Weisberg et al, 2008). However, as with social and experiential perspectives on learning, the biological perspective is, on its own, limited in terms of what it can tell us. A science of teaching and learning which is chiefly *based* upon the brain is unlikely to develop in the foreseeable future, because neuroscientific perspectives struggle with many concepts (such as meaning and autonomy) that are central to educational aims and understanding (Howard-Jones, in press). On the other hand, this brief review has emphasised that greater *inclusion* of biological perspectives in educational thinking, alongside other perspectives, is increasingly desirable and probable.

Summary

It is anticipated that the following educational developments involving neuroscience may arrive by 2025:

- New educational approaches will become established for the teaching and learning of mathematics in the early years, as a result of insights from cognitive neuroscience.
- Adolescents will become recognised as a more distinct group of learners and educational approaches will be developed that are better tailored to meet their social, emotional and educational needs
- A new understanding of motivation will be developed and new approaches to engaging learners will become established (eg in areas involving the use of games) informed by insights into the brain’s reward system
- Early screening will be available for a range of learning disorders, using neural markers and genetic testing.
- Attendance to the training of some targeted cognitive functions, including working memory, will feature across year groups in the National Curriculum
- The reflective understanding and development of executive function will feature in the National Curriculum for young learners
- Understanding of mental health issues will become a stronger feature of the curriculum, as the aims of education become broader. This will include a basic understanding of brain function, with the associated academic benefits that such an understanding may bring.
- Exercise breaks will become a feature of the curriculum, as the link between exercise and academic achievement becomes clearer, and the UK struggles with increasing levels of obesity.

- The use of drugs to enhance cognitive function will become commonplace, remaining chiefly unchecked by legislation as the government remains unwilling to intervene in the absence of clear public consensus. The attitudes and practices amongst different groups of learners and educational institutions will diverge.
- Psychology, and some neuroscience, will become an established feature of teachers' professional development and training.
- There will be no brain-based science of learning that is meaningful in educational terms, but a new field of neuro-educational research will become established, together with the development of professionals trained in both education and the relevant natural sciences (eg cognitive neuroscience, genetics). Biological perspectives will become an increasingly important component of educational understanding, practice and policy making.

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Commonly used abbreviations :

fMRI - functional Magnetic Resonance Imaging (fMRI)

OfSTED – Office for Standards in Education, Children's Services and Skills

ERP – Event Related Potential

EEG – Electroencephalogram

ADHD – Attention Deficit Hyperactivity Disorder

WM – Working Memory

EF – Executive Function

SLI – Specific Language Impairment

ACh – Acetylcholine

BCI – Brain Computer Interface

MI - Multiple Intelligences theory

VAK – Visual Auditory Kinaesthetic

SCMH - The Sainsbury Centre for Mental Health

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