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Cognitive Neuroscience: implications for education?

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ABSTRACT *Research into the functioning of the human brain, particularly during the past decade, has greatly enhanced our understanding of cognitive behaviours which are fundamental to education: learning, memory, intelligence, emotion. Here, we argue the case that research findings from cognitive neuroscience hold implications for educational practice. In doing so we advance a bio-psycho-social position that welcomes multi-disciplinary perspectives on current educational challenges. We provide some examples of research implications which support conventional pedagogic wisdom, and others which are novel and perhaps counter-intuitive. As an example, we take a model of adaptive plasticity that relies on stimulus reinforcement and examine possible implications for pedagogy and curriculum depth. In doing so, we reject some popular but over-simplistic applications of neuroscience to education. In sum, the education profession could benefit from embracing rather than ignoring cognitive neuroscience. Moreover, educationists should be actively contributing to the research agenda of future brain research.*

Introduction

We have written this article in response to the current high level of general interest in brain functioning (Greenfield, 1997; Pinker, 2002) and its potential applications to the social sciences (Carter, 2000; Levine, 2002), especially education (Geake, 2002). We are aware that many of our readers have already joined one of two diametrically opposed camps: that neuroscience should keep its nose well out of educational affairs, or, that an even stronger case should be made for a future reliance of education on neuroscience than the current assortment of initial misguided enthusiasms such as left and right-brain thinking. We unapologetically take a middle path, but with cautious optimism that the relationship between cognitive neuroscience and education will be for the long term.

In this article, we propose that some recent experimental findings in the cognitive neurosciences can be interpreted or generalised to suggest possible implications for learning, cognitive development and pedagogy in formal educational settings. Our motivation to undertake such an endeavour is driven by the potential for cognitive neuroscience to contribute to educational discourse, and possibly shed some new light on hitherto intractable educational problems. As John Bruer (1994) notes:

> We send our children to school to learn things they might not learn without

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> formal instruction so that they can function more intelligently outside school. If so, recommendations for school reform should explicitly appeal to and implement our best, current understanding of what learning and intelligence are. In the public debate on school reform, this is seldom the case. Common recommendations—raising standards, increasing accountability, testing more, creating markets in educational services—are psychologically atheoretical, based at best on common sense and at worst on naive or dated conceptions of learning. (p. 273)

Here, we suggest that cognitive neuroscience could in principle, and may in practice, inform our conceptions of learning. We see this as the addition of a level of understanding to educational discourse, towards the creation of a holistic bio-psycho-social framework, and not a regression to some earlier bio-deterministic position. Cognitive psychology is replete with black-box models of brain functioning. Cognitive neuroscience may be able to prise open the lid just a little to afford a glimpse inside. Such insights may, in turn, be helpful in either supporting long-regarded best educational practice, or in deciding between competing cognitive models and their veracity in educational settings.

In this article, we explore possible relationships to school learning of more recent cognitive neuroscience, both experimental and theoretical. First, we sketch some landmarks in the field of cognitive neuroscience for readers unfamiliar with that territory. Next, we offer a rationale for our endeavour *per se*, i.e., that cognitive neuroscience may offer helpful insights for all educationists in and out of the classroom. Then, by way of example, we provide a very brief outline of a relevant area in cognitive neuroscience: Hebbian synaptic plasticity. In this section, we offer some conjectural implications for educational theory and practice, and make some suggestions for research which might provide evidence to support or refute such conjectures. Finally, we make a plea in the light of our initial concerns for educationists to give our case a fair hearing. In sum, our argument is predicated on our conviction that education should start with an understanding of what and where people are, and where they might/like to go—before somebody else decides where they ought to end up.

To that end, we note that the relationships between education and cognitive neuroscience have begun to be explored, not by educationists, but by the neuroscience community. In a special edition of *Educational Psychology Review* (10(3), 1998), the article by Byrnes and Fox, 'The educational relevance of research in cognitive neuroscience' (Byrnes & Fox, 1998a; but also see Byrnes & Fox, 1998b), attracted a variety of cautiously supportive responses from other cognitive neuroscientists (Berninger & Corina, 1998; Brown & Bjorklund, 1998; Geary, 1998; Mayer, 1998; O'Boyle & Gill, 1998) and educational psychologists (Schunk, 1998). The arguments advanced in this collection rehearse many of the issues which we present below.

An Outline of Cognitive Neuroscience

Cognitive neuroscience is a wide field embracing a rich variety of experimental paradigms and approaches, from the biomolecular to the behavioural (see Rugg, 1997; for a rigorous introduction to neuroscience, see Zigmond, *et al.*, 1998; for a more general introduction see any of the brain science books listed below; for a school student text, see Hayward, 1997). Areas of experimental interest include vision, spatial cognition, audition and music, emotions, imitation, memory, motor function, language, and consciousness, most (if not all) of which can inform our understanding of cognitive behaviours relevant to education, for example, intelligence, learning, memory, motivation, literacy, creativity (see Detterman, 1994; Huettner, 1994). At its broadest level, this research has produced evidence for brain function along a number of non-exclusive polarities:

- modularisation and connectionism;
- localisation and distribution;
- cellular reductionism and adaptive plasticity;
- genetic determinism and nonlinear indeterminism;
- phylogenic similarity and individual differences.

Data are gathered by a wide range of experimental techniques, such as biochemical assay, autopsy, single cell spike train recordings (i.e., neuronal electrical activity), positron emission tomography (PET) scans, thermal imaging, functional magnetic resonance imaging (fMRI) (Frith & Friston, 1997), and electroencephalograph (EEG) and magnetoencephalograph (MEG) recording, especially evoked related potentials (ERP) (Kutas & Dale, 1997), across a range of animal species. The overarching aim is to chart mappings of neural functions which correlate with cognitive behaviours (e.g. Vallar, 1991).

These data from the past decade have been particularly informative about functional modularity—that different discrete areas of the brain, especially within the cortex, are critically involved in mediating various cognitive behaviours (Phillips, 1997). For example, PET scans have revealed different cortical language-related areas in the dominant cerebral hemisphere for reading, speaking, writing and comprehending words (see Calvin & Ojemann, 1994; Howard, 1997). As these tasks are often performed simultaneously, the less understood issue of synchronisation, the so-called 'binding problem', is predicted as being the focus of cognitive neuroscientific research for the current decade (Phillips & Singer, 1997).

Whereas the brain contains an estimated 100 billion neurons (Changeux, 1985), functional modularisation is strongly supported both by neurophysiological evidence that the units of brain function are neuronal groups (Edelman, 1992), and by neuroanatomical observations that the neurons are more strongly connected locally than distally (see Zigmond *et al*., 1998). Neuronal connections are made via synapses, a small space between an axon discharging an action potential (efferent) and a dendrite of another neuron whose electrical activity (afferent) is stimulated by the release and uptake of neurotransmitters (biochemicals) released by the axon and diffused across the synapse. As neurons typically have many dendrites (pyramidal neurons may have thousands), the total number of synapses in an adult brain is estimated at around 100 000 billion (Greenfield, 1997).

Although the general course of neurological development is well prescribed, neuroscience has identified many sources of difference between individual brains (Edelman, 1987). These include:

(a) developmental primary processes, e.g., cell division, adhesion, differentiation and death;
(b) cell morphology, e.g., shape and size, dendritic and axonic aborizations;
(c) neuronal connection patterns, e.g., number of inputs and outputs, connection order with other neurons;
(d) cytoarchitectonics, e.g., cell density, thickness of cortical layers, layout of columns;

(e) neurotransmitters, both spatial (some cells and not others) and temporal (some times and not others) variance;
(f) dynamic responses, e.g., synaptic electrochemistry, synaptic reinforcement, neuronal metabolism;
(g) neuronal transport, e.g., ion channel efficacy;
(h) interactions with glia.

In sum, due to nonlinear indeterminent molecular and cellular processes during morphogenisis, it can be said with certainty that no two human brains are, have ever been, or ever will be identical. This applies to identical twins, who are not identical people, and for that matter to any other possible human clones. Politicians who are quick to condemn cloning experiments should note that it is impossible to replicate exactly the brains of Hitler, Einstein, or of any other individual from the past. For a classroom teacher, this simply underpins that uniqueness of each child in his/her care.

However, whereas generic neural processes are necessarily idiosyncratic in their application, the underpinning neurological functioning *can* produce similar behaviours across individuals in response to the same stimulus. As Changeux (1985, p. 249, emphasis in original) notes: 'different learning inputs may produce *different* connective organisations and neuronal functioning abilities but the *same* behavioural capacity'. In other words, much human behaviour can be predicted and controlled, again, as is commonplace in classrooms. As teachers well know, it is this mix of the predictable with the unintended that makes classroom teaching such a complex task (McIntyre, 1998).

Historically, neuroscience has been driven by the more immediate concerns of neuropathology, where 'deficit-functioning' has informed various models of cognition. Recent improvements in the spatial resolution of fMRI and the temporal resolution of ERPs have informed models of cognition with 'normal-functioning' data. Nevertheless, a valid map of neural correlates still remains largely elusive, especially for aspects of higher order cognition such as truth or beauty, and some contemporary descriptions of brain function (Penrose, 1989) deny its possibility. However, neither in-principle nor actual limitations to the determination of neural correlates affect our consideration of what cognitive neuroscience has achieved, and what those achievements might suggest for education. With a pragmatism perhaps typical of educationists, we can remain agnostic over whether neural correlates of all human thought will ever be found.

Nevertheless, the search is attracting an increasingly attentive audience. With an estimated 50,000 neuroscience researchers in Europe, and a similar number in the USA (editorial, *Nature Neuroscience*, 1998), perhaps it is little wonder that a plethora of populist brain science books covering topics from memory to consciousness to perceptions of reality have been the decade's top sellers in 'good' bookshops. A sample of these which feature various perspectives, such as Jean-Pierre Changeux (1985) *Neuronal Man*, Steven Rose (1992) *The Making of Memory*, Michael Gazzaniga (1992) *Nature's Mind*, Antonio Damasio (1994) *Descartes' Error*, Gerald Edelman (1992) *Bright Air, Brilliant Fire*, William Calvin (1996) *How Brains Think*, Susan Greenfield (1997) *The Human Brain: A Guided Tour*, Richard Cytowic (1998) *The Man Who Tasted Shapes*, Edmund Rolls (1998) *The Brain and Emotion*, Steven Pinker (1998) *How the Mind Works*, Rita Carter (2000) *Mapping the Mind*, Walter Freeman (1999) *How Brains Make Up Their Minds*, Antonio Damasio (2000) *The Feeling of What Happens*, Frank Tallis (2002) *Hidden Minds*, and Steven Pinker (2002) *The Blank Slate* (among very many others), have offered a multi-level but potentially coherent approach to understanding brain functioning, especially perception and learning.

Cognitive Neuroscience in the Classroom?

It is an interesting exercise, as an educationist, to consult the indexes of the books cited in the previous paragraph. There are multiple references to learning, knowledge, memory, motivation, cognitive development and so on, but none whatsoever to education, schooling, children as pupils or pedagogy. A recent and welcome exception is Ann and Richard Barnet's *The Youngest Minds* (1998), at least with respect to cognitive neuroscience and pre-schooling. We argue that as cognitive neuroscience advances our understanding of the very basics of learning, so there is a need for educationists to appropriate this research with regards to implications and applications for teaching in formal educational settings, especially school classrooms (Geake, 2000). Such a return to the fundamentals of teaching and learning might even help to reclaim the education agenda from those politicians and board room directors whose predominantly instrumental objectives for schooling and further education have caused such dismay within the teaching profession of late (Walden, 1996; Johnson & Hallgarten, 2002; Woodhead, 2002).

In other words, a good reason for educationists to embrace cognitive neuroscience is the hope that such an endeavour might stem the increasing marginalisation of teachers as pedagogues. We can only agree with Johnson and Hallgarten (2002), that 'teachers must be empowered once again … to design curricula and pedagogies, because they are in the best position to judge how to engage young people' (p. 12). Our argument is that some knowledge of cognitive neuroscience should be included in the knowledge base which underpins such re-empowerment.

This may be all the more urgent given current global political and commercial pressures, particularly from the information and communication technology (ICT) industry, to replace human teaching with on-line information retrieval. We assume that education will remain largely a human endeavour and, to that end, teachers will always be interested in gaining a better understanding of the multitude of factors which govern the learning of their charges. Such teacher professional development, we suggest, should embrace an understanding of developments in cognitive neuroscience. Therefore, we propose that education adopt an interactive bio-psycho-social model, which can only come about if educationists engage cognitive neuroscientists in dialogue to share each other's professional knowledge.

Such a dialogue should focus on those insights from cognitive neuroscience which have the potential to help educationists address a range of fundamental and pressing questions that affect the ability of societies to deliver educational services effectively (Geake, 2000). These questions can be summarised in the form of the following composite question: what are the educational practices most conducive to the promotion of optimum social, cognitive, affective and moral development of children and young people in ways that prepare them for active participation in post-industrial societies?

There seems to be a growing consensus about the qualities required for such participation. Schooling must produce graduates who are skilled in the art and science of learning. Primarily, they must be able to adapt rapidly to changing social and economic circumstances by abandoning outmoded procedures and ways of thinking in favour of new ways of thinking and the development of new skills. Thus, the key task of educators is to produce students with knowledge and skills in the discovery and creation of knowledge (Reich, 1991; Hargreaves, 1998).

The range of abilities required of individuals as a result of this vision of contemporary educational imperatives is vast. Not only are school graduates required to have the age old skills of literacy and numeracy, but they also are required to demonstrate higher-level reasoning skills as well as self reliance and emotional resilience in the face of a socially fragmented, unstable and unpredictable world. This is a world which rewards initiative, independence, self motivation and self reliance over obedience to authority and conformity. It should come as no surprise, therefore, to note that the current era is also marked by unprecedented levels of psychological and behavioural disorders among young people (Blau & Gullotta, 1996; Rutter & Smith, 1995).

Our contention is that understanding of this complex of inter-relating factors will be facilitated by an approach that recognises the contribution that biology makes to the development of human social, behavioural and psychological characteristics. We are aware that such an approach may be perceived as antagonistic to some established ways of thinking about educational and other social and political issues. We agree with Degler's (1991) observation that both social and natural scientists of the second half of the twentieth century have often rejected biological explanations of human nature in favour of socio-cultural explanations. Degler illustrates the way in which this rejection is rooted in the laudable ideological commitment to the power of social and political reform to make the world a 'freer and more just place' (p. viii). By denying the validity of arguments for the influence of biology in human social and psychological development, the way would be made clear for the creation of social conditions which would offer opportunities for 'self-realisation' to all. Degler, however, demonstrates that such anti-biological arguments are deeply flawed. First, they co-exist, often within the same minds, with an acceptance of the view that human beings are, like all living things, the product of the evolutionary process of natural selection, first described by Darwin. Second, and more importantly, the anti-biological arguments often depend on an immutable identification of the application of socio- and psycho-biology with repellent ideologies such as Nazism, which promote such ideas as racism, sexism and eugenics. This misrepresentation of evolutionary approaches ignores the modern applications of evolutionary research, such as in the field of evolutionary psychiatry, which concerns 'the environmental provisions necessary for healthy development and for the prevention and treatment of mental disorders' (Stevens & Price, 1996, p. 10).

Interestingly, as media reports have illustrated, in order to provide learning environments conducive to healthy development, a number of UK schools are embracing 'brain gym' programmes (see 'How to improve your child's brain power', *The Sunday Times*, 18 October, 1998; 'Just One Chance', *BBC2*, 10 November, 1998). This immediately suggests a preliminary programme of research. As a starting point, what is the current level of knowledge of cognitive neuroscience amongst the education community? (*The Sunday Times* article claims 1000 schools in the UK are using 'brain-based' strategies for learning enhancement.) To what extent do school teachers base any of their practice on their understanding of cognitive neuroscience? In particular, is there a describable folk psychology of school teachers regarding genetic heritability of intelligence and learning abilities, and genetic correlates with classroom environment? To what extent do university educationists in teacher preparation programmes incorporate cognitive neuroscience into their courses? To what extent do parents expect teachers to employ cognitive neuroscientific evidence-based practice? To what extent do students perceive their teachers as being in or out of touch with modern developments in understanding brain function? Another topic for research could be a rigorous evaluation of existing interventions in schools which claim to be based on neuroscientific evidence, e.g., brain gymnastics which purport to increase cerebral blood flow. Would a psychometric analysis of a well-designed (e.g., using matched controls) quasi-experiment find the same level of benefit in school performance that anecdotal reports indicate?

The Education-Neuroscience Argument

Some commentators, however, argue that the education-neuroscience argument, while well meaning, is basically flawed. John Bruer in his article 'Education and the Brain: a bridge too far' (1997), argues that education cannot be directly informed by neuroscience, as the former is unable to generalise from detailed specifics of neural functions to the cognitive behaviours observed in classrooms or with young children's learning.

Bruer's argument is largely based on one particular over-interpretation of neuroscience: that neurogenisis in animals implies critical periods of educational priming for young children. The critical-stage argument proposes that some of the apparently effortless learning of very young children, particularly in learning to speak their native language, is indicative of a window of opportunity which closes with the retardation of early neurogenisis. The difficulty Bruer points out is that too little is known about the process to be predictive of what stage is attained at what age for any individual child. In our view, this is an issue for research, and not the basis for an in-principle objection. As a critical matter for educational policy making, the need for some neuroscientific insight into critical staging underscores our argument that educationists should be influencing the directions of cognitive neuroscientific research.

We agree with Bruer that mis-interpretations of the science are problematic, perhaps even potentially dangerous, and certainly counter-productive for informed consideration of educational issues. Recent appeals based on misinterpretations of laterality studies for teachers to educate half the brain of their pupils (usually the right half) should be too ridiculous to flatter with serious consideration, save that they appear with increasing frequency in popularist, if not mainstream, educational literature (see Edwards, 1982; Williams, 1986). Apart from overlooking the fact that a small but significant proportion of the normal population does not exhibit left-dominant right-non-dominant laterality, for example up to 25% of left-handed females (Kolb & Wishaw, 1996), and that young children with brain injury display compensatory lateral plasticity (Stiles, 1998), this half-brain literature seems to ignore the research focus of laterality studies, viz. split-brain patients, and the consequent important caveat of this research that normally the two cerebral hemispheres are massively interconnected (see Barnet & Barnet, 1998).

This is not to contradict the evidence of both EEG and neuroimaging studies for modularisation, indeed lateralisation. But, as noted above, these modules function in concert with one another: cerebral modularisation has evolved to facilitate efficacious connectionism. This can be seen in the activities of a school lesson, where at any one moment a child may use some or all of these modules in a highly correlated fashion. In an fMRI study of the brain functioning required for arithmetic, Dehaene (1997) reports some half-dozen areas of cortical activation across both hemispheres. These active functional modules include those involved in the identification of digits, quantity representation, verbal articulation, and strategic planning.

The point here is that past over-simplifications of some neuroscientific findings do not *a priori* exclude an education-neuroscience nexus, but rather compel us to proceed with due caution, as usually exercised in the natural sciences if not in the popular media, especially when it comes to education. Moreover, this field is advancing at an exponential rate. For example, whereas a few years ago Bruer seemed to be on firm ground in pointing out that neural patterning is more likely to correlate with cognitive behaviour rather than more prosaic measures of brain structure such as neural density, recent reports of some fMRI research indicate significant positive correlations between dendritic length and dendritic segment counts in the brains of children and the number of years spent in formal education (Jacobs, *et al.*, 1993). Schooling does make a difference to the brains of children, and cognitive neuroscience can show how, and how much.

Adaptive Plasticity

Adaptive plasticity is the capacity of the brain to change at a neurophysiological level in response to changes in the cognitive environment. We suggest that a cognitive neuroscientific understanding of this characteristic has implications for pedagogical issues concerned with learning, including the necessity of reinforcement and the problem of erroneous learning, and for curriculum issues of breadth and depth.

The most fundamental problem which has taxed educational philosophers over the centuries since Plato has been the nature of learning. From a neuroscientific perspective, we can frame the problem thus: when we learn, what changes in the brain so that later we can recall an item of knowledge or perform a rehearsed behaviour? Over 50 years ago, Donald Hebb proposed that it was the strength of synaptic functioning, i.e., the efficacy of inter-neuronal communication, that changed (Hebb, 1949). Importantly in Hebb's model, such functional neural plasticity was enacted by repeated coincident firings of the particular synapses involved in 'processing' the information about a particular stimulus. The result may either be stronger excitatory or stronger inhibitory functioning, i.e., a permanent physiological change. The power of this model is that it can explain how functional neuronal circuits in the brain can learn. Neuronal groups, which can often be found as cellular columns in the cortex, are responsible for particular information processing, for example, a specific edge orientation, or a specific sound frequency, or a specific phoneme (see Edelman, 1992). Neuronal circuits are the feedforward and feedback pathways between the various neuronal groups, and can themselves 'learn' via Hebbian rules: synchronised neural pathways become more efficient in response to repeated coincident stimulation of the synapses along the route.

Perhaps the most important implication for education is that Hebb's model strongly supports what teachers have long known: that repetition is necessary for effective learning. This in turn may hold implications for curriculum development, especially where there is considerable pressure to reduce depth for breadth as schools become society's agents for an increasing range of learning that was once the province of family or other community groups. From a Hebbian perspective of a school curriculum, depth might deserve some privilege over breadth, and core knowledge some priority. The over-crowded curriculum could mitigate against high general levels of basic skills, or frustrate permanent change in children's naive concepts, as commonly reported in science education (see Driver, *et al.*, 1985). If contemporary society requires an ever increasing breadth of enculturation, then perhaps more responsibility for this should be falling on extra-school agencies, not less. It could also be noted that frustration in not being able to select curriculum is cited as one of the current difficulties with the teaching profession by resigning teachers (Johnson & Hallgarten, 2002).

Moreover, the Hebbian model can not only account for inefficiencies in learning, but can also explain why 'erroneous' learning is so hard to eliminate, or counter-act. Music teachers know full well that what a student practises is what that student plays, regardless of its musical correctness (St George, 1990). From a cognitive neuroscience perspective, those brain circuits in the motor cortex which get reinforced to produce an automatic sequence of finger and other body movements may be quite neurally distal in the brain of a music novice from any musical 'censor' located in the frontal cortex. That is, the binding between these modules has not been reinforced, hence the importance of performing new pieces slowly and carefully, and learning the technically difficult passages with much patient repetition, before attempting the piece up to speed. A corollary to this is that concepts learned in childhood can be very resilient to change later in school. This has been well researched with children's naive science concepts, for example, the belief that the Moon's phases are due to its changing shape (Baxter, 1989). The proportion of adults in the UK and the USA who hold naive science constructs from their childhood, and thus seem immune from the effects of school science, despite many hours of science lessons, can be as high as 80% depending on the issue (McClosky, 1983). This may be of little importance for science concepts which do not impact directly on daily life, but ignoring Newton's laws of motion when driving can lead to tragic consequences.

Another feature of Hebbian reinforcement is that specificity is facilitated by objective-oriented or context-facilitated activity (Kay & Phillips, 1997). That is, learning is more efficient if the same synapses of the same neural circuit are stimulated for each instance of the same learning experience. Distractions, wild guesses, misleading concepts and so on are all threats to learning efficiency. This is well known in pedagogy; it is also the case neurophysiologically. A distraction, for example, will likely affect another neural circuit than the one required for learning the item of content or skill at hand. Context-dependent learning can be explained, then, by associated neural circuits being reinforced. A common example from classrooms is seen with teacher-dependent recall or performance. All together, this supports what practitioners of the complex art of teaching have long known, that, among other things, clear learning objectives need to be set at each stage of learning in the classroom.

We suggest that this maxim could be taken a step further in a way that might appear counter-intuitive from a traditional pedagogic perspective. So that Hebbian reinforcement can be well focused during the initial stages of learning a new topic, answers could be provided as student learning targets (as distinct from pedagogic targets such as preferred method). For example, in a new topic in secondary mathematics, say, simultaneous equations, the teacher or the text book could provide solutions to the initial problem sets as learning targets, rather than let students get wrong answers, since wrong answers will also reinforce neuronal group connections just as well as right answers. This would be the equivalent of, in music, playing through a new piece very slowly and carefully in order to begin with an accurate rendition lest initial errors be learned through repeated mistakes while practising. Importantly, the effectiveness of such an answers-as-targets approach is testable with a usual quasi-experimental design.

What cognitive neuroscience does not know about adaptive plasticity is whether there is a threshold of stimulation for permanent learning (Phillips & Singer, 1997). However, the considerable range of variables contributing to individual neurological differences would suggest that there are individual learning thresholds, which in turn supports teachers' common knowledge that some children 'get it' much quicker than others. With this line of argument we are not, we must stress, advocating a return to exclusive drill-and-practice. Rather, we are wanting to emphasise the necessity of clear relationships within learning contexts. For young children, for example, a period of free or directed play may be the most efficacious strategy for generating a repertoire of relationships with the learning material prior to introducing anything so formal as a learning target.

Concluding Remarks

In this article we have proposed some implications for education that could be drawn from the few areas of cognitive neuroscience which we considered. There are many caveats, which we hope our readers will forgive. First, the article is deliberately conjectural. For this we are not apologetic; perhaps in this we have shown excessive zeal, but at the same time we have indicated some directions for research which might reveal which of our conjectures deserve further scrutiny. However, we do take heart from the recent publication of Edward Wilson (1998) *Consilience*, in which the case for the urgent construction of a bio-psycho-social nexus is presented in far more detail than we can hope to manage in one article. Second, we make no claims for analytic exhaustion; doubtless many other implications, some perhaps even contradictory to those offered here, may be drawn from cognitive neuroscience. Third, cognitive neuroscience is, as indicated in the Introduction, a vast interdisciplinary venture, and obviously we have only touched on some aspects. It will be interesting to read of similar analyses of other aspects of cognitive neuroscience—perception, motor skills, executive functioning—and of implications for education of contemporary research in genetics.

Nor should a cognitive neuroscience-education nexus necessarily be a one-way street: there are education policy questions which might one day be profitably asked of cognitive neuroscience (Harrison, personal communication, 1998). For example: what is the best age to begin formal schooling? and its accompanying corollaries: what is the best age for early education? What are the 'right' things for a parent to be doing at home before their child commences school? Is there a natural order of intellectual development for verbal and non-verbal reasoning? Is there a critical age beyond which the foundations for adolescent literacy and numeracy is passed? These questions are critical for policy makers. After all, the ages for commencing formal education vary widely in Western countries, even in Europe, from 3 to 6 years. Another large concern for those who manage educational budgeting (and, of course, those parents and teachers involved) is the effectiveness of high-cost remedial interventions. For children who suffer an educational disadvantage of some kind, for example, socio-economic and/or genetic, what sorts of specific interventions will be effective?

Then, there are the eternal questions that teachers confront every day in the classroom: why do some children learn more easily than others? Is there a genetic component to intelligence? Why do females and males appear to think differently? We have suggested that cognitive neuroscience may contribute to the search for some helpful answers. Moreover, as we hope we have shown *inter alia*, teachers should not fear the findings of cognitive neuroscience, as many of these might support intuitive high-quality teaching practices. We believe this position is supported by a growing public (especially, school teacher) interest in the findings of cognitive neuroscience, as evidenced through media attention (see Robert Winston's *A Child of Our Times*, BBC2, 2002) and the sales of popularist accounts of brain science (see Greenfield, 1997; Pinker, 2002).

Moreover, cognitive neuroscientists are showing an increasing interest in such general topics as learning and memory, their manifestation in literacy and numeracy (for example, the research programme at the University College London Institute of Cognitive Neuroscience), and their application to children with learning difficulties—all issues which are (or were) of central concern to educationists. Or to be less gracious, cognitive neuroscientists are already researching on educationists' turf. This argument is admittedly one of educational self interest, but why not, especially if education is to remain the lynch pin of most political agendas for social improvement? We therefore strongly urge educationists to become involved in the cognitive neuroscientific enterprise lest educationists find themselves even further professionally marginalised than some politicians and education bureaucrats seem intent on pushing them. In other words, applying evidence from cognitive neuroscience to educational futures might provide a means for teachers to reclaim eroded professional autonomy (Johnson & Hallgarten, 2002). Furthermore, educationists should not feel at any disadvantage in engaging in a dialogue with neuroscientists. After all, scarce research funding is more readily won by proposals with explicit social applications, and what better application than genuine improvements in education? On a more positive tack, education policy makers are unlikely to base changes of policy on anything less than robust replicated evidence. Our argument is that unless the education community join the cognitive neuroscience community in dialogue, such neuroscientific evidence may not be forthcoming, or at least not in a form which readily informs educational policy and practice.

In sum, our position is that, caveats not withstanding, there *are* implications and applications for education in cognitive neuroscience. As noted above, the positive effects of time at school on neuronal dendrite growth in children has been demonstrated (Jacobs *et al*., 1993). As Paul Fletcher from University College London conjectured on possible developments arising from the imaging of neural activation: 'One day there might be enough known about brain activity to show the process of learning, and whether it was taking place efficiently' (*The Daily Telegraph*, 8 September 1998). To that end, we present two possible future scenarios.

The scene is a parent-teacher night at a local primary school. A parent is discussing the poor maths results of her child, Chris, with Chris's class teacher. In the first scenario, the teacher acknowledges that Chris's maths performance has been under surveillance for a while. To that end, the teacher has available Chris's event-related neuroimaging report captured in the school's neuroimaging assessment room. Here, the whole class regularly undertakes their term assessment tasks while wearing individual neuroimaging headsets. (The school bought a class set of neuroimaging head-set scanners some years ago. They've been set up in the former class computer room, long abandoned when all students were issued with hand-held computer note pads with infra-red links to their teacher's classroom PC.) The class set of individual images is statistically analysed by a dedicated computer, and parent-teacher reports generated.

After scanning Chris' report, the teacher brings her professional knowledge to bear, and recommends a course of real-time biofeedback utilising mental multi-step arithmetic problems to strengthen Chris's short-term memory circuit for number solutions, which the imaging has shown to be relatively weak. On-going neuroimaging assessment during the next month will determine the effectiveness of this individually-specific intervention.

The parent is pleased with the professionality of the teacher, especially that the teacher knew what was the matter, and could do something about it. The teacher was pleased to be able to act in such a professional manner. Her considerable training, including an M.Phil (Oxon) in education and cognitive neuroscience, had been worth it, especially her research thesis on the neural correlates of learning difficulties in mathematics.

In the second contrasting scenario, the teacher is at a loss to explain why Chris might be having maths learning problems.

> "Could it be motivation?" the teacher offers.
> "Obviously," says the frustrated parent, "but that is circular. If Chris had more maths success, Chris would be better motivated."
> "I suppose so," replies the teacher. "I barely scraped through the lowest level of maths at my School Certificate."

> "Well" says the parent, "what are you going to do about it?"
> "Me?" says the teacher. "How would I know what to do? After all, I'm only a teacher. I don't know what is causing the problem. Why don't you take Chris for an assessment with Cognitive Services Inc? Here is their card. They'll know best what to do."

In either case, the remedial intervention is undertaken by biofeedback with the subject viewing a suitable neuro-image while undertaking the remedial learning task. In the first future scenario, teachers have developed a similar professionality to that of doctors and engineers, and are accorded commensurate social status (and salary?). Obviously, there are commensurate issues regarding selection for teacher preservice courses. In the second future scenario, the professionality of teachers has been usurped by other professionals, mainly those with training in cognitive neuroscience.

Of course, writing future scenarios is a guarantee for retrospective embarrassment. But consider just this type of diagnosis of children with the learning condition of dyslexia (Shaywitz, 1996). An fMRI comparison with normals showed dyslexic subjects had reduced functioning in a part of their cortex—the inferior frontal gyrus—usually involved in phonic decoding. As Shaywitz describes, specific interventions of phonics together with whole-language improved the reading skills of these children. As subsequent fMRI analyses have shown, these improvements have not altered this weakness in brain functioning. Rather, adaptive plasticity has been utilised for educational advantage.

The change in the social status of doctors came last century with that profession's adoption of scientific evidence-based practice. The move for teachers to scientific evidence-based practice is still to come. Will it be this century? Carter (2000) suggests that future generations will use our increasing knowledge of the brain to enhance mental qualities which add meaning to our lives, and to reduce those that are destructive. As Bruer (1994) summarises:

> a reasonable position would be to admit that traditional cognitive science should be supplemented by cognitive neuroscience from below and by cognitive anthropology or cultural psychology from above. Biological theories, functional theories, and sociocultural theories proceed at different levels of analysis that for now cannot be seamlessly linked. Research at these levels should proceed in parallel, with each level looking to the other for possible constraints on its own theorising. If this is to be scientific research, all that is required is that the disciplines at each level share a belief in an external reality that can be discerned through careful use of qualitative and quantitative research methods. All participants should share a conviction that their collaborative discourse is indeed about something. (p. 289)

For us, that something is learning within formal education.

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