Neuromythologies in education

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Background: Many popular educational programmes claim to be ‘brain-based’, despite pleas from the neuroscience community that these neuromyths do not have a basis in scientific evidence about the brain.

Purpose: The main aim of this paper is to examine several of the most popular neuromyths in the light of the relevant neuroscientific and educational evidence. Examples of neuromyths include: 10% brain usage, left- and right-brained thinking, VAK learning styles and multiple intelligences.

Sources of evidence: The basis for the argument put forward includes a literature review of relevant cognitive neuroscientific studies, often involving neuroimaging, together with several comprehensive education reviews of the brain-based approaches under scrutiny.

Main argument: The main elements of the argument are as follows. We use most of our brains most of the time, not some restricted 10% brain usage. This is because our brains are densely interconnected, and we exploit this interconnectivity to enable our primitively evolved primate brains to live in our complex modern human world. Although brain imaging delineates areas of higher (and lower) activation in response to particular tasks, thinking involves coordinated interconnectivity from both sides of the brain, not separate left- and right-brained thinking. High intelligence requires higher levels of inter-hemispheric and other connected activity. The brain’s interconnectivity includes the senses, especially vision and hearing. We do not learn by one sense alone, hence VAK learning styles do not reflect how our brains actually learn, nor the individual differences we observe in classrooms. Neuroimaging studies do not support multiple intelligences; in fact, the opposite is true. Through the activity of its frontal cortices, among other areas, the human brain seems to operate with general intelligence, applied to multiple areas of endeavour. Studies of educational effectiveness of applying any of these ideas in the classroom have failed to find any educational benefits.

Conclusions: The main conclusions arising from the argument are that teachers should seek independent scientific validation before adopting brain-based products in their classrooms. A more sceptical approach to educational panaceas could contribute to an enhanced professionalism of the field.

Keywords: neuromyths; brain-based; cognitive neuroscience; education

Introduction

Neuromythologies are those popular accounts of brain functioning, which often appear within so-called ‘brain-based’ educational applications. They could be categorised into neuromyths where more is better: ‘If we can get more of the brain to “light up”, then learning will improve . . .’, and neuromyths where specificity is better: ‘If we concentrate...
teaching on the “lit-up” brain areas then learning will improve...’. Prominent examples of neuromythologies of the former include: the 10% myth, that we only use 10% of our brain; multiple intelligences; and Brain Gym. Prominent examples of neuromythologies of the latter include: left- and right-brained thinking; VAK (visual, auditory and kinaesthetic) learning styles; and water as brain food. Characteristically, the evidential basis of these schemes does not lie in cognitive neuroscience, but rather with the various enthusiastic promoters; in fact, sometimes the scientific evidence flatly contradicts the brain-based claims.

The assumption here is that educational practices which claim to be concomitant with the workings of the brain should, in fact, be so, at least to the extent that the scientific jury can ever be conclusive (Blakemore and Frith 2005). A counter-argument might be posed that the ultimate criterion is pragmatic, not evidential, and if it works in the classroom who cares if it seems scientifically untenable. For this author, basing education on scientific evidence is the hallmark of sound professional practice, and should be encouraged within the educational profession wherever possible. The counter-argument only serves to undermine the professionalism of teachers, and so should be resisted.

This is not to say that there is not a glimmer of truth embedded within various neuromyths. Usually their origins do lie in valid scientific research; it is just that the extrapolations go well beyond the data, especially in transfer out of the laboratory and into the classroom (Howard-Jones 2007). For example, there is plenty of evidence that cognitive function benefits from cardiovascular fitness; hence, general exercise is good for the brain in general (Blakemore and Frith 2005). But this does not mean that pressing particular spots on one’s body, as per Brain Gym, will enhance the activation of particular areas in the brain. As another example, there are undoubtedly individual differences in perceptual acuities which are modality based, and include visual, auditory and kinaesthetic sensations (although smell and taste are more notable), but this does not mean that learning is restricted to, or even necessarily associated with, one’s superior sense. All of us have areas of ability in which we perform better than others, especially as we grow older and spend more time on one rather than another. Consequently, a school curriculum which offers multiple opportunities is commendable, but this does not necessarily depend on there being multiple intelligences within each child which fortuitously map on to the various areas of curriculum. General cognitive ability could just as well play an important role in learning outcomes across the board.

The generation of such neuromythologies and possible reasons for their widespread acceptance has become a matter for investigation itself. In particular, the phenomenon of their widespread and largely uncritical acceptance in education raises several questions: why has this happened?; what might this suggest about the capacity for the education profession to engage in professional reflection on complex scientific evidence? And one cannot help but wonder about the extent to which political pressure for endless improvement in standardised test scores, publicised via school league tables, drives teachers to adopt a one-size-fits-all, brain-based life-raft when their daily classroom experience is replete with children’s individual differences.

To gather some data about these issues, Pickering and Howard-Jones (2007) surveyed nearly 200 teachers either attending an education and brain conference in the UK (one brain based, the other academic) or contributing to an OECD website internationally. All respondents were enthusiastic about the prospects of neuroscience informing teaching practice, particularly for pedagogy, but less so for curriculum design. Moreover, despite a prevailing ethos of pragmatism (notably with the brain-based conference attendees), it was generally conceded that the role of neuroscientists was to be professionally informative rather than prescriptive. This, in turn, points to the critical necessity for a mutually
comprehensible language with which neuroscientists and educators can engage in a genuine interdisciplinary dialogue.

The American Nobel Laureate physicist Richard Feynman, in one of his more famous graduation addresses at Caltech, warned his audience of young science graduates about ‘cargo cult science’ (Feynman 1974). His point was that, while it might accord with ‘human nature’ to engage in wishful thinking, good scientists have to learn not to fool themselves. Feynman’s warning could well be applied to the myriad ‘brain-based’ strategies that pervade current educational thinking. Whereas it is commonly stated in such schemes that the brain is the most complex object in the universe (although how this could possibly be verified remains unexplained), this assumption is then completely ignored in proposing a pedagogy based on the simplest of analyses – e.g., in the brain there are two hemispheres, left and right, therefore there are two kinds of thinking: of-the-left-brain and of-the-right-brain, and therefore there are only two kinds of teaching necessary: for-the-left-brain and for-the-right-brain. Not a very exciting universe where the most complex object has only two states! And not, fortunately, the universe in which we exist, where the complexity of the human brain has been the focus of intense investigation for over a century, but particularly over the past two decades, thanks to the invention of neuroimaging technologies.

The resulting neuroimages – brains with brightly coloured areas – are disarmingly simple, and seem to fit with a commonsense view of the brain as having localised specialist functions which enable us to do the various things we do. But such apparent simplicity is generated out of considerable complexity. In functional magnetic resonance imaging (fMRI), for example, the images are the end-result of many years’ work on understanding the quantum mechanics of nuclear magnetic resonance phenomena, the development of the engineering of superconducting magnets, the application of inverse fast Fourier transforms to large data sets and the refinement of high-speed computing hardware and software to analyse large data sets across multiple parameters. The neuroimaging picture is undoubtedly worth the proverbial thousand words, but the scientist’s words can be quite different from those of the layperson.

A crucial point that most of the media overlook, or ignore, is that neuroimaging data are statistical. The coloured blobs on brain maps representing areas of significant activation (so-called ‘lighting up’) are like the peaks of sub-oceanic mountains which rise above sea level, in neuroimaging, how much or how little activation (sea level) to reveal being determined by the researcher in setting a suitable level of statistical threshold. In fact, the most challenging aspect of most neuroimaging experimental design is to determine suitable control conditions to highlight a particular area of experimental interest and thus avoid showing how most of the brain is involved in most cognitive tasks. So, in a classroom it would be quite silly to think that only a small portion of pupils’ brains are involved in a task, just because a small area of brain activity was reported in a neuroimaging study of a similar task (Geake 2006). Neuroscience is a laboratory-based endeavour. Even with the best of intentions, extrapolations from the lab to the classroom need to be made with considerable caution (Howard-Jones 2007). As Nobel Laureate Charles Sherrington (1938, 181) warned in Oxford some 70 years ago: ‘To suppose the roof-brain consists of point to point centres identified each with a particular item of intelligent concrete behaviour is a scheme over simplified and to be abandoned.’ In other words, we have to be very wary of oversimplifications of the neuro-level of description in seeking applications at the cognitive or behavioural levels.

The central characteristic of brain function which generates its complexity is neural functional interconnectivity. There are common brain functions for all acts of intelligence,
especially those involved in school learning (Geake in press). These interconnected brain functions (and implicated brain areas) include:

- Working memory (lateral frontal cortex);
- Long-term memory (hippocampus and other cortical areas);
- Decision-making (orbitofrontal cortex);
- Emotional mediation (limbic subcortex and associated frontal areas);
- Sequencing of symbolic representation (fusiform gyrus and temporal lobes);
- Conceptual interrelationships (parietal lobe);
- Conceptual and motor rehearsal (cerebellum).

This parallel interconnected functioning is occurring all the time our brains are alive. Importantly, these neural contributions to intelligence are necessary for all school subjects, and all other aspects of cognition. Creative thinking would not be possible without our extensive neural interconnectivity (Geake and Dobson 2005). Moreover, there are no individual modules in the brain which correspond directly to the school curriculum (Geake 2006). Cerebral interconnectivity is necessary for all domain-specific learning, from music to maths to history to French as a second language. Neuromyths typically ignore such interconnectivity in their pursuit of simplicity. Steve Mithen (2005) argues that it was a characteristic of the Neanderthal brain that it was not well interconnected. This could explain the curious stasis of Neanderthal culture over several hundred thousand years, and the even more curious fact that Neanderthal culture was rapidly out-competed by our physically less robust Cro-Magnon forebears, whose brains, Mithen argues, had evolved to become well interconnected.

**Multiple intelligences**

Highly evolved cerebral interconnectedness has implications for any brain-based justification of the widely promoted model of multiple intelligences (MI). Gardner (1993) divided human cognitive abilities into seven intelligences: logic-mathematics, verbal, interpersonal, spatial, music, movement and intrapersonal. Some 2500 years earlier, Plato recommended that a balanced curriculum have the following six subjects: logic, rhetoric, arithmetic, geometry-astronomy, music and dance-physical. For philosopher-kings, additionally, meditation was recommended. Clearly MI is nothing new: Gardner has just recycled Plato. But although such a curriculum scheme is long-standing, it doesn’t mean that our brains think about these areas completely independently from one another. Each MI requires sensory information processing, memory, language, and so on. Rather, this just demonstrates Sherrington’s point that the way the brain goes about dividing its labours is quite separate from how we see such divisions on the outside, so to speak. In other words, there are no multiple intelligences, but rather, it is argued, multiple applications of the same multifaceted intelligence.

Whereas undoubtedly there are large individual differences in subject-specific abilities, the evidence which conflicts with a multiple intelligences interpretation of brain function is that these subject-specific abilities are positively correlated, as shown by Carroll (1993) in his large meta-analysis. Such a pervasive correlation between different abilities is conceptualised as general intelligence, g. The existence of g not only suggests that the same brain modules are likely to be involved in many different abilities, but that their functional connectivity is of paramount importance. In fact, the main thrust of research in cognitive neuroscience in the next decade will be the mapping of functional connectivity,
that is how functional modules transfer information, anatomically, bio-chemically, bio-electrically, rhythmically, synchronistically, and so on. A recent study along these lines sought evidence for neural correlates of general intelligence – i.e., where and how does the brain generate measures of general intelligence? Duncan et al. (2000) found a common brain involvement, in the frontal cortex of adult subjects, on both spatial and verbal IQ tests. A further meta-analysis of 20 neuroimaging studies involving language, logic, mathematics and memory showed that the same frontal cortical areas were involved (Duncan 2001). It seems unlikely that these intelligences are independent if the same part of the brain is common to all. This point is elaborated in a recent critique of MI (Waterhouse 2006, 213).

The human brain is unlikely to function via Gardner’s multiple intelligences. Taken together the evidence for the intercorrelations of subskills of IQ measures, the evidence for a shared set of genes associated with mathematics, reading, and g, and the evidence for shared and overlapping ‘what is it?’ and ‘where is it?’ neural processing pathways, and shared neural pathways for language, music, motor skills, and emotions suggest that it is unlikely that each of Gardner’s intelligences could operate ‘via a different set of neural mechanisms’ [as Gardner claims].

To explain how those same pathways support high-level general intelligence across so many different cognitive areas, Duncan (2001, 824) suggested that: ‘neurons in selected frontal regions adapt their properties to code information of relevance to current behaviour, pruning away ... all that is currently task-irrelevant.’ So, underlying our specific abilities is adaptive brain functioning. In support of this idea of an adapting brain, Dehaene and his colleagues have proposed a dynamic model of brain functioning in which these frontal adaptive neurons coordinate the myriad inputs from our perceptual modules from all over the brain, and continually assess the relative importance of these inputs such that from time to time, a thought becomes conscious; it literally ‘comes to mind’ (Dehaene, Kerszberg, and Changeux 1998). It could be predicted, then, that deliberate attempts to restrict intelligence within classrooms according to MI theory would not promote children’s learning, and it could be noted in passing that one of the ‘independent consultants’ who advocates brain-based learning strategies acknowledges teachers’ frustration with the lack of long-term impact of applying MI theory (Beere 2006).

10% usage

None of the above implies that g is all that there is to intelligence – quite the opposite. With its population age-norming, IQ might be a convenient surrogate for intelligence in the laboratory, but not even the most resolute empiricist would claim that IQ captures all of the variance in cognitive abilities. Rather, intelligence in all its manifestations illustrates the underlying dynamic complexity of its generative neural processes, with emphasis on ‘dynamic’. There is overwhelming evidence that the brain is perpetually busy, and that even when any of our brain cells are not involved in processing some information, they still fire randomly. As an organ which has evolved not to know what is going to happen next, such constant activity keeps our brain in a state of readiness. Consequently, the neuromyth that ‘We only use 10% of our brains’ could not be more in error. The absurdity has been pointed out by Beyerstein (2004): evolution does not produce excess, much less 90% excess. In the millions of studies of the brain, no one has ever found an unused portion of the brain!

It is unfortunate that teachers are constantly subjected to such pervasive nonsense about the brain, so it is worth pausing to investigate the various sources of the 10% myth
It seems to have begun with an Italian neuro-surgeon c.1890 who removed scoops of brains of psychiatric patients to see if there were any differences in their reported behaviours. The myth received an unexpected boost c.1920 during a radio interview with Albert Einstein, when the physicist used the 10% figure to implore us to think more. The myth received its widest circulation before the Second World War when some American advertisers of home-help manuals re-invented the 10% figure in order to convince customers that they were not very smart. Odd, then, that it has been so enthusiastically adopted by wishful-thinking educationists at the end of the twentieth century. It would be nice if the brains of our students had all this spare educable capacity. To be sure, the plasticity of young (and even older) brains should never be underestimated. But what plasticity requires is a dynamically engaged brain, with all neurons firing. To put it bluntly, if you are only using 10% of your brain, then you are in a vegetative state so close to death that you should hope (not that you could) that your relatives will pull out the plug of the life support machine!

**Left- and right-brained thinking**

Another pervasive example of over-simplification has been the misinterpretation of laterality studies to produce so-called ‘left- and right-brained thinking’. Historically, the original studies were of split-brain patients: patients who had the major communication tract between the two brain hemispheres, the corpus callosum, surgically severed in an attempt to reduce life-threatening epilepsy. It was found that the separate hemispheres of these patients could separately process different types of information, but only the left hemisphere processing was reported by the patients. Unfortunately, the caveat that the researchers who carried out these studies back in the 1970s did emphasise – i.e., that these patients had abnormal brains – was largely ignored. For normal people, as Singh and O’Boyle (2004, 671) point out:

> the brain does not consist of two hemispheres operating in isolation. In fact, the different cognitive specialties of the LH and RH are so well integrated that they seldom cause significant processing conflicts . . . hemispheric specialisation . . . consists of a dynamic interactive partnership between the two.

Creative thinking, in particular, requires the interaction of both hemispheric specialists, neither one can operate in isolation from the other:

Since the right hemisphere and the left hemisphere are massively interconnected (through the corpus callosum), it is not only possible, but also highly likely, that the creative person can iterate back and forth between these specialized modes to arrive at a practical solution to a real problem. If the right hemisphere were somehow disconnected from the left and confined to its own specialized thinking modes, it might be relegated to only ‘soft’ fantasy solutions, pipe dreams or weird ideas that would be difficult, if not impossible, to fully implement in the real world. The left brain helps keep the right brain on track. (Herrmann 1998, http://www.sciam.com)

This, then, has important implications for the misguided ‘right-brain’ promotion of creative thinking in the school classroom. Goswami (2004) draws attention to a recent OECD report in which left brain/right brain learning is the most troubling of several neuromyths – a sort of anti-intellectual virus which spreads among lay people as misinformation about what neuroscience can offer education. This is not to say that there isn’t abundant good evidence that much brain functioning is modular, and that many higher cognitive functions, such as language production, are critically reliant on modules which are usually found in one or other hemisphere, such as Broca’s Area (BA), usually
found in the left frontal cortex. But there are notable differences between individuals as to where these modules are located. In about 5% of right-handed males, BA is found in the right frontal cortex, and in a higher number of females, the principle function of BA, language production, is found in both the left and right frontal cortices. In left-handed people, only 60% have BA functions on the left, with the rest having their language production involving frontal areas on both sides or on the right (Kolb and Wishaw 1990). An implication of this for neuroscience research is that practically all subjects in neuroimaging studies are screened for extreme right-handedness — it is a way of maximising the probability that the group map has contributions from all subjects (that is, their functional modules involved in the study will be in much the same place in the different individual’s brains). Consequently, with a nice circularity, the data which show that language production is on the left comes almost exclusively from subjects who’ve been chosen to have their language production areas on the left.

Thus the left- and right-brain thinking myth seems to have arisen from misapplying lab studies which show that the semantic system is left-lateralised (language information processing in the left hemisphere; graphic and emotional information processing in the right hemisphere) by ignoring several important caveats. First, the left-lateralisation is in fact a statistically significant bias, not an absolute. Even in left-lateralised individuals, language processing does stimulate some right hemisphere activation. Second, the subjects for such studies are extremely right-handed. As language researchers are at pains to point out: ‘It is dangerous to suppose that language processing only occurs in the left hemisphere of all people’ (Thierry, Giraud, and Price 2003, 506). The largest interconnection to transmit information in the brain is the corpus callosum, the thick band of fibres which connects the two hemispheres. It seems that the left and right sides of our brains cannot help but pass all information between them. In fact, there is some evidence that constrictions in the corpus callosum could be predictive of deficiencies in reading abilities (Fine 2005), which obviously could not occur if language processing was an exclusively left hemisphere activity.

It would be neat if all cognitive functioning was simply lateralised, and towards such a schema some commentators have suggested that perhaps there are stylistic differences between left and right hemispheric functions, with the left mediating detail, while the holistic right focuses on the bigger picture. For example, using EEG to describe the time course of activations identified by fMRI, Jung-Beeman et al. (2004) found that the insight or ‘aha’ moment of problem solution elicits increased neural activity in the right hemisphere’s temporal lobe. Jung-Beeman et al. (2004) suggest that the this right hemisphere function facilitates a coarse-level integration of information from distant relational sources, in contrast to the finer-level information processing characteristic of its left hemisphere homologue. However, researchers in music cognition disagree (Peretz 2003). Even regarding the left hemisphere (metaphorically if not literally) as a verbal processor, music, as non-verbal information *par excellence*, is not exclusively processed in the right, but in both hemispheres (Peretz 2003). Moreover, neuroimaging studies have shown that the location and extent of various areas of the brain involved with music perception and production shift and grow with musical experience (Parsons 2003). In fact, there is a strong evolutionary argument that music plays a crucial role in promoting the growth of the inter-module connections which underpin cognitive development in infants and young children (Cross 1999).

Consequently, for the many reasons noted above, leading neuroscientists have been calling on the neuroscience community to shift their interpretative focus of brain function from modularisation to interaction. As Hellige (2000, 206) pleads: ‘Having learned so
much about hemispheric differences . . . it is now time to put the brain back together again.’ Or as Walsh and Pascual-Leone (2003, 206) summarise: ‘Human brain function and behaviour seem best explained on the basis of functional connectivity between brain structures rather than on the basis of localization of a given function to a specific brain structure.’

VAK learning styles

This emphasis on connectedness rather than separateness of brain functions has important implications for education (Geake 2004). The multi-sensory pedagogies, which experienced teachers know to be effective, are supported by fMRI research. The work of Calvert, Campbell and Brammer (2000), on imaging brain sites of cross-modal binding in human subjects, seems relevant. Bimodal processing of congruent information has a supra-additive effect (e.g., simultaneously seeing and hearing the same information works better than first just seeing and then hearing it). These findings are consistent with observed behaviour. Much good pedagogy in the early years of schooling is based on coincident bimodal information processing, especially sight and sound, or sight and speech, as demonstrated by every early years teacher pointing to the words of the story as she reads them aloud.

However, such ‘natural’ pedagogy is threatened by the promulgation of learning styles. The notion that individual differences in academic abilities can be partly attributed to individual learning styles has considerable intuitive appeal if we are to judge by the number of learning style models or inventories that have been devised – 170 at the last count, and rising (Coffield et al. 2004). The myriad ways that approaches to learning can seem to be partitioned, labelled and measured seems to know no bounds. The disappointing outcome of all of this endeavour is that, overall, the evidence consistently shows that modifying a teaching approach to cater for differences in learning styles does not result in any improvement in learning outcomes (Coffield et al. 2004).

Despite the lack of positive evidence, the education community has been swamped by claims for a learning style model based on the sensory modalities: visual, auditory and kinaesthetic (VAK) (Dunn, Dunn and Price 1984). The idea is that children can be tested to ascertain which is their dominant learning style, V, A or K, and then taught accordingly. Some schools have even gone so far as to label children with V, A and K shirts, presumably because these purported differences are no longer obvious in the classroom. The implicit assumption here is that the information gained through one sensory modality is processed in the brain to be learned independently from information gained through another sensory modality. There is plenty of evidence from a plethora of cross-modal investigations as to why such an assumption is wrong. What is possibly more insidious is that focusing on one sensory modality flies in the face of the brain’s natural interconnectivity. VAK might, if it has any effect at all, be actually harming the academic prospects of the children so inflicted.

A simple demonstration of the ineffectiveness of VAK as a model of cognition comes from asking 5-year-olds to distinguish different sized groups of dots where the groups are too large for counting (Gilmore, McCarthy, and Spike 2007). So long as the group sizes are not almost equal, young children can do this quite reliably. Now, what happens when one group is replaced by as many sounds played too rapidly for counting? There is no change in accuracy! Going from a V versus V version of the task to a V versus A version makes no difference to task performance. The reason is that input modalities in the brain are interlinked: visual with auditory; visual with motor; motor with auditory; visual with
taste; and so on. There are well-adapted evolutionary reasons for this. Out on the savannah as a pre-hominid hunter-gatherer, coordinating sight and sound makes all the difference between detecting dinner and being dinner. As Sherrington (1938, 217) noted:

The naïve observer would have expected evolution in its course to have supplied us with more various sense organs for ampler perception of the world… Not new senses but better liaison between the old senses is what the developing nervous system has in this respect stood for.

To emphasise the cross-modal nature of sensory experience, Kayser (2007) writes that: ‘the brain sees with its ears and touch, and hears with its eyes.’ Moreover, as primates, we are predominantly processors of visual information. This is true even for congenitally blind children who instantiate Braille not in the kinaesthetic areas of their brains, but in those parts of their visual cortices that sighted children dedicate to learning written language. Moreover, unsighted people create the same mental spatial maps of their physical reality as sighted people do (Kriegseis et al. in press). Obviously the information to create spatial maps by blind people comes from auditory and tactile inputs, but it gets used as though it was visual. Similarly, people who after losing their hearing get a cochlear implant find that they are suddenly much more dependent on visual speech, such as cues for segmentation and formats, to conduct conversation (Thomas and Pilling in press).

Wright (2007) points out just how interconnected our daily neural processes must be. Eating does not engage just taste, but smell, tactile (inside the mouth), auditory and visual sensations. Learning a language, and the practice of it, requires the coordinated use of visual, auditory and kinaesthetic modalities, in addition to memory, emotion, will, thinking and imagination:

To an anatomist this implies the need for an immense number of neural connections between many parts of the brain. In particular, there must be numerous links between the primary auditory cortex (in the temporal lobe), the primary proprioceptive-tactile cortex (in the parietal lobe) and the primary visual cortex (in the occipital lobe). There is indeed such a neural concourse, in the parieto-temporo-occipital ‘association’ cortex in each cerebral hemisphere. (Wright 2007, 275)

Input information is abstracted to be processed and learnt, mostly unconsciously, through the brain’s interconnectivity (Dehaene, Kerszberg, and Changeux 1998). Actually, we don’t even create sensory perception in our sensory cortices:

For a long time it was thought that the primary sensory areas are the substrate of our perception….these zones simply generate representational maps of the sensorial information….although these respond to stimuli, they are not responsible for…perceptions….Perceptual experience occurs in certain zones of the frontal lobes [where] neurons combine sensory information with memory information. (Trujillo 2006, M9)

Literally following a VAK regime in real classrooms would lead to all sorts of ridiculous paradoxes: what does a teacher do with: the V and K ‘learners’ in a music lesson/ the A and K ‘learners’ at an art lesson/ the V and A ‘learners’ in a craft practical lesson? The images of blindfolds and corks in mouths are all too reminiscent of Tommy, the rock opera by The Who. As Sharp, Byrne and Bowker (in press) elaborate, VAK trivialises the complexity of learning, and in doing so, threatens the professionalism of educators. Fortunately, many teachers have not been taken in. Ironically, VAK has become, in the hands of practitioners, a recipe for a mixed-modality pedagogy where lessons have explicit presentations of material in V, A and K modes. Teachers quickly observed that their pupils’ so-called learning styles were not stable, that the expressions of
V-, A- and K-ness varied with the demands of the lessons, as they should (Geake 2006). As with other learning-style inventories, research has shown that there is no improvement of learning outcomes with VAK above teacher enthusiasm, where ‘attempts to focus on learning styles were wasted effort’ (Kratzig and Arbuthnott 2006).

We might speculate in passing why do VAK and other ‘learning styles’ seem so attractive? I wonder if two aspects of folk psychology, where we seem to learn differently from each other, and we have five senses, have created folk neuroscience: the working of our brains directly reflects our folk psychology. Of course, if our brains were that simple, we wouldn’t be here today!

References


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Applying Cognitive Neuroscience Research to Education: The Case of Literacy

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Neuroscience has provided fascinating glimpses into the brain’s development and function. Despite remarkable progress, brain research has not yet been successfully brought to bear in many fields of educational psychology. In this article, work on literacy serves as a test case for an examination of potential future bridges linking mind, brain, and educational psychology. This article proposes a model for integrating research in the cognitive neurosciences with educational psychology and reviews how neuroscience is providing new data relevant to 3 major controversies in the field of dyslexia. This article also discusses the relevance of these findings for psychoeducational assessment and instruction and suggests innovative venues for interdisciplinary research.

For better or worse, over the last 10 years, education has begun actively and aggressively looking to the biological sciences in order to inform education policy and practice. One need look no further than the 1998 decision in Georgia to fund a program, which cost hundreds of thousands of dollars, to provide Mozart CDs to all new mothers. In establishing this policy, the governor of Georgia drew heavily on work in cognitive neuroscience conducted at the University of California, Irvine. The actions were taken in the hope of “harness[ing] the ‘Mozart effect’ for Georgia’s newborns—that is, playing classical music to spur brain development” (“Random Samples,” p. 663). Despite what the program implied, Mozart effect research, upon close examination, had little to offer education. One study, reported in *Nature* (1993), found that listening to Mozart raised the IQs of college students for a brief period of time. Another study found that keyboard music lessons boosted the spatial skills of 3-year-olds (Schlaug, Jancke, Huang, & Steinmetz, 1995). Cognitive neuroscientists responsible for this work were baffled by Georgia’s program and actions based on their work. Since this debacle, major figures in the sciences have published articles emphasizing caution and care as scientists, educators, and practitioners proceed down this exciting, but pitfall-laden road. These cautionary articles have laid the groundwork for relationships between neuroscience and education. However, there is a paucity of publications that systematically examine an area of research where conservative but confident claims can be made of the benefits of interdisciplinary research spanning the fields of neuroscience and education.

This article presents a first step for the field by providing a model example of how, by combining theory and methodology from neuroscience and education, we can simultaneously address the interest and demand for links between cognitive science, neuroscience, psychology, and education. This is done in three steps:

1. First, we review arguments for and against integrating behavioral and brain studies with the field of education as well as describe select technological approaches. Here too, we provide a template of five criteria for assessing the promise of interdisciplinary neuroscience and education research.

2. Next, we suggest a model for integrating the educational research approach and research in the cognitive neurosciences to study reading research and practice. In this section, research on reading development and specifically on reading disabilities serves as a model to examine potential links and obstacles in such interdisciplinary work.

3. Finally, we review the current challenges of connecting the fields of neuroscience and educational psychology to the study of dyscalculia.

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THE IMPORTANCE OF LINKING PSYCHOLOGY WITH PHYSIOLOGY IN THE STUDY OF HUMAN DEVELOPMENT

Neuroscience, the interdisciplinary study of the nervous system, is a field less than 40 years old. Demonstrating explosive
growth, today there are more than 300 graduate programs in neuroscience. As testament to the complexity of the brain, and the many methodological barriers that exist in the objective study of its structure and function, the development of the field has resulted in the development of many interdisciplinary neuroscientific activities, including neuropsychology, neurobiology, neuroimaging, and neurophilosophy.

The fascination that philosophers and scientists have with the human brain has historically centered on the questions of mind–brain duality (Descartes, 1850). Recently, scholars have argued persuasively that understanding the brain is not necessary for the construction of theoretical models of human cognition (Marr, 1982; Neisser, 1967). Some have even argued that although neuronal constructs are part of the explanatory vocabulary of biologists, they are not useful in psychology, which adopts a different behavior level of inquiry (Pylyshyn, 1984). Many educators and psychologists similarly feel that differences between the levels of analysis utilized in biology and psychology, and the applied issues of primary importance in education, are simply too large to bridge (see Blakemore & Frith, 2000, for a review). Bruer (1997) suggested a middle ground in which cognitive psychology could serve as a midpoint between neuroscience and education. In this article, we wish to expand on this view and argue that without experimental paradigms designed to capture relationships across levels of analysis (neuronal, cognitive, behavioral), we will never develop theories that will let us begin to test the strength of bridges between these now-distant disciplines.

Neuroscience Methodologies: Overview

Cognitive neuroscience provides a window in real time to the brain’s structures and functions. Understanding the relationship between different brain structures and their functions can help scientists understand how these relate to learning and development. A neuroscientist conducting a study on human cognition would have to articulate whether his or her research questions focused on differences in the basic brain structures of the participants or on differences in how they functionally process information. In addition, depending on the research question, a methodology that focuses either on temporal or on spatial resolution will be chosen. In what follows, we provide an introductory summary of some current methodologies used in neuroscience. Neuroscience spans molecular levels to networks of neurons acting across multiple brain regions. Studies of dyslexia have been conducted using many neuroscience methodologies including studies of genetics, postmortem structural studies, and the use of animal models. Here, we focus on neuroimaging techniques and how these might be combined with behavioral measures traditionally used in cognitive science (for a review of other neuroscience approaches applied to the study of dyslexia, see, e.g., Grigorenko, 2001).

Structural studies allow a window into gross and fine structures of the brain. The study of fine structures of the brain including neurons, cortical tracts, and cortical areas is conducted largely either through postmortem autopsy work or through the neuroimaging technology of magnetic resonance imaging (MRI). MRI is a noninvasive procedure that produces a two-dimensional view of an internal organ or structure, especially the brain and spinal cord. Multiple MRI images can be combined to effectively provide a three-dimensional reconstruction of the imaged structure. Indeed, longitudinal and cross-sectional MRI studies are beginning to provide us with four-dimensional pictures: how the brain changes over periods of months and years (Thompson et al., 2000). Functional studies can be conducted through the noninvasive techniques of electroencephalography (EEG), magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI). The moderately invasive techniques of positron-emission tomography (PET) and the related single photon emission computed tomography (SPECT) also contribute to our understanding of brain function.

The techniques of fMRI, PET, and SPECT all work through detecting how blood flow patterns change in different regions of the brain during different tasks. Changes in blood flow are an indirect measure of neuronal activity with increased blood flow corresponding to increased neuronal activity. While fMRI is considered to be completely noninvasive, PET and SPECT require the introduction of a radioactive tracer into the bloodstream, either through injection or inhalation. The radioactivity received by individuals undergoing the procedure is on the order of what they would be exposed to on a transcontinental flight. In the case that a PET or SPECT scan is a medical necessity, it is relatively easy to argue for its value as a diagnostic tool, even for a child. However, because these techniques are mildly invasive and involve radioactivity, fMRI is considered to be the preferred tool, particularly for investigating basic research questions with children as participants. (For a detailed review of PET, SPECT, and fMRI, see Scott & Wise, 2003.) This article, along with the text by Berninger and Richards (2002), provides a lengthy discussion of the specific strengths and weaknesses of these methodologies for exploring speech, reading, and numerosity.

Neuroscience Methodologies: Strengths and Weaknesses

In part because of differences in what these technologies measure, these functional imaging technologies vary in their spatial and temporal resolution, the populations and types of questions they are best suited to investigate, and logistic issues such as cost and ease of widespread use. In particular, fMRI has excellent spatial resolution, on the order of 1 cm. However, it, along with PET and SPECT, has relatively poor temporal resolution. Of the three techniques, fMRI has the best temporal resolution, on the order of 1 to 3 sec. In contrast, EEG and MEG...
both have fine temporal resolution and can indirectly measure neuronal activity over a time course of milliseconds. However, both have comparatively poor spatial resolution. MRI, the structural companion to fMRI, can be combined with results from the functional technologies including EEG–MEG to provide more precise information on the location of activated areas. EEG has the advantage of being comparatively inexpensive, and it can be somewhat portable. Preliminary research has been done that suggests EEG may be useful as a screen for identifying babies who are at risk for developing dyslexia (Guttorm, Leppanen, Tolvanen, & Lyttinen, 2003; Molfese, Narter, & Modglin, 2002).

Prior to the development of imaging technologies, post-mortem and lesion studies had implicated certain structures in the brain in reading and reading difficulties (Dejerine, 1891; Galaburda, Mednard, & Rosen, 1994). However, MRI makes it possible to investigate, on a wide scale, structural brain differences between AA and poor readers. Psychophysics measures have been used to quantitatively investigate perceptual differences between AA readers and readers with dyslexia for stimuli such as written text and other visual material as well as nonspeech and speech sounds. As EEG–MEG has been used to further explore these differences, we have seen that some of these differences can occur on the millisecond time scale, depending upon the task. For changes on the order of milliseconds, EEG–MEG represents a unique method of collecting data. Behavioral methods simply do not have the resolution necessary.

Many functional imaging study designs rely on the subtraction method. This is based on comparing two or more task conditions such that brain activity during a baseline control task (Task B) is subtracted from that OF (not from) a “higher order” cognitive task (Task A). The assumption is that after subtraction, only the activity that is related to differences between the conditions is left. This method is very good for providing information about lower level processing, mainly perception, detection, and identification of auditory, visual, and tactile stimuli. In these cases, identifying an appropriate baseline control task to subtract from the target task is relatively straightforward. Designing such combinations of baseline and target tasks for higher order processing such as inference making, and comprehension in reading, has proven to be very challenging (Caplan, 2004). Therefore, functional imaging technologies may currently be less appropriate for the examination of higher order processing such as reading comprehension, inference making, and strategy shifting (Palmer, Brown, Peterson, & Schlaggar, 2004).

However, this may be a problem not necessarily of the technology per se, but rather of our ability to adequately design experiments and interpret the results. Using experimental measures in the scanner for which the behavioral data is well understood, and for which there is strong theory connecting such data with possible neurophysiological correlates, may gradually allow us to better investigate higher order processes. In this way, dyslexia researchers can help push the envelope for neuroimaging technology in the sense that they bring with them a strong set of experimental tools, along with a strong theoretical basis for interpreting neuroimaging results when the appropriate paradigms are used. In summary, fMRI, MRI, and EEG–MEG are noninvasive procedures that can measure ongoing neurological activity through the skull and reveal the living human brain at work. PET and SPECT are mildly invasive procedures that also accomplish the task of looking in on the living brain. Each technique has its own advantages, and each provides different information about brain structure and function. For this reason, scientists increasingly are conducting studies that integrate two or more techniques. As we discuss in several places later in this article, the investigation of dyslexia using these techniques could be enhanced by combining them with such approaches as eye tracking, other psychophysics measures, and experimental paradigms that are better suited for transferring results to a clinical or educational setting. This expansion of compatible techniques can likely lead to advances not only in our understanding of dyslexia, but in our sophistication in using neuroimaging more broadly. Figure 1 describes graphically the relative spatial and temporal resolutions of these and other neuroimaging techniques. Figure 2 summarizes their relative strengths and weaknesses.

Applying Neuroscience to Educational Psychology

Carefully applying neuroscientific methods to relevant questions in educational psychology may prove a fruitful interdisciplinary venture. As a first step toward establishing collaborative research teams, intellectual dissemination of information should be facilitated. For example, at the moment, virtually all neuroscience and other biological science journals are available through electronic subscription. The digitization of many clinically oriented psychology and education journals is still lagging behind (see ERIC online databases). Moreover, universities do not always subscribe to the online applied journal in the field. In addition to simply making it easier for scholars to communicate through peer-reviewed literature, online availability affects the likelihood an article will be cited. A study of 119,924 conference articles in computer science and related disciplines found that online articles are cited 4.5 times more often than offline articles (Lawrence, 2001). In addition to affecting citation patterns, having online publication avenues that are shared by psychologists, educators, and neuroscientists could catalyze interdisciplinary discussion. This, in turn, could lead to collaborative research spanning the different fields.

In a compelling presentation of their “doctrine of multilevel analysis”, Cacioppo and Berntson (1992) argued that...
### FIGURE 1
The relative spatial and temporal resolutions of several neuroimaging techniques.

<table>
<thead>
<tr>
<th>Spatial Resolution</th>
<th>EEG/ERP</th>
<th>MEG</th>
<th>PET &amp; SPECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain regions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lobes of the brain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brain areas: 1-3 cm³</td>
<td></td>
<td></td>
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<table>
<thead>
<tr>
<th>Temporal Resolution</th>
<th>Milliseconds</th>
<th>Seconds</th>
<th>Hours-Days</th>
</tr>
</thead>
</table>

Electroencephalography (EEG) and Event-Related-Potentials (ERPs) measure electrical currents at the surface of the skull propagating from the combined activity of neuronal clusters. EEG represents unaveraged data, whereas ERPs are averaged data with segments of the data averaged together based on when a stimulus has been presented and how long brain activity associated with that stimulus continues. Magnetoencephalography (MEG) measures minute changes in the magnetic field at the surface of the skull induced by the electromagnetic activity of firing neurons. The minimum detectable cluster size of firing neurons is calculated to be about 10,000 neurons. However, there are fundamental challenges to calculating the source location of magnetic or electrical currents measured at the surface of the skull. This limitation constrains the effective spatial resolution of EEG/ERP and MEG.

Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) are both mildly invasive neuroimaging methods most useful with clinical populations who need the scans for medical reasons. It has relatively poor spatial resolutions, on the order of several centimeters, and temporal resolution on the order of tens of seconds. Like Functional Magnetic Resonance Imaging (fMRI), these methods indirectly measure neuronal activity through tracking blood flow.

fMRI, coupled with structural magnetic resonance imaging (MRI), has excellent spatial resolution, on the order of millimeters, but temporal resolution is limited to approximately 1-3 seconds. There are multiple efforts underway at labs all around the world to improve the analysis methods for each of these methods individually as well as to find ways to analyze data from multiple imaging modalities and so, effectively, increase the existing temporal and spatial resolutions of each.

MRI and DTI are both structural imaging techniques. MRI provides detailed anatomical information about the structure of the brain, primarily at millimeter resolution. A complementary technique, Diffusion Tensor Imaging (DTI), is not yet widely used, but can provide information about brain connectivity through analysis of white-matter tracts.

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**FIGURE 1** The relative spatial and temporal resolutions of several neuroimaging techniques.

**Imaging Technologies, table of strengths and weaknesses**

<table>
<thead>
<tr>
<th>Imaging Technique</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>fMRI + MRI</td>
<td>Very good structural resolution, relatively poor temporal resolution</td>
<td></td>
</tr>
<tr>
<td>fMRI, PET, SPECT</td>
<td>Better at investigating lower level processing than, higher level processing</td>
<td></td>
</tr>
<tr>
<td>PET, SPECT</td>
<td>Non-invasive, suitable for use with non-patient populations</td>
<td></td>
</tr>
<tr>
<td>MRI, MRI, PET, SPECT</td>
<td>Very expensive</td>
<td></td>
</tr>
<tr>
<td>EEG, fMRI, MRI, PET, SPECT</td>
<td>Fairly portable</td>
<td></td>
</tr>
<tr>
<td>EEG, fMRI, MRI, PET, SPECT</td>
<td>Requires significant set-up time</td>
<td></td>
</tr>
<tr>
<td>EEG, fMRI, MRI, PET, SPECT</td>
<td>Requires relatively little set-up time for each subject</td>
<td></td>
</tr>
<tr>
<td>EEG, PET, SPECT</td>
<td>Requires subjects to remain relatively still in order to get highest quality data</td>
<td></td>
</tr>
<tr>
<td>MEG, fMRI, MRI, PET, SPECT</td>
<td>Especially fMRI and MRI can be intimidating for subjects, particularly young children. However, good data are routinely acquired from children as young as 6-7 years of age in labs with experience in being child-friendly.</td>
<td></td>
</tr>
</tbody>
</table>
We agree with Cacioppo and Berntson (1992) and suggest, further, that decisions as to whether a given research domain is appropriately addressed using a multilevel approach should be based on empirical criteria. The question should not be whether neuroscience research can be applied to basic child development or applied to educationally relevant topics. Rather, the question should address whether a given issue in those fields is appropriate for interdisciplinary, multilevel research.

Bidirectional collaboration among research fields should first generate a theory-driven hypothesis regarding a specific research question. The next step should be an evaluation of the usefulness of the data collected from each field, or across fields, to either support or disclaim the theoretical model suggested. For example, brain science can and has contributed much knowledge about basic science and has contributed to the general understanding of physiology. At the same time, the interpretation of such data is often enhanced or only made possible by theoretical perspectives originating in our understanding of behavior as described by psychological literature. In the case of dyslexia, for example, theories of reading processes guide the design of neuroscience experiments and the interpretation of such data. These theories were developed primarily through a combination of behavioral assessments and experiments. Having such theories, which delineate required skills and subskills for educationally relevant tasks, is a key requirement for neuroeducation research. An additional prerequisite is that the theories suggest empirically testable connections between those behaviors and brain function.

These requirements are summarized and briefly discussed in terms of dyslexia research specifically here:

1. **Falsifiable theory** that links specific skills to specific educational goals or tasks. For example, a theory that links skills such as reading fluency or phonological awareness to the educationally relevant goal of learning to read.

2. **Falsifiable theory** that links those skills to specific brain functions and structures. For example, a theory that posits links between specific brain regions or specific neuronal processing to the skills of reading fluency or phonological awareness.

3. **Appropriate experimental methodologies and analytic techniques** to test claims. For example, noninvasive neuroimaging techniques with the appropriate temporal and spatial resolution to answer questions relevant to the theories linking behavior to brain processing. Initial responses to auditory and visual stimuli can be different for dyslexic and normal readers. Some of these differences are on the millisecond time scale, a reflection of their origins in neuronal circuit activation, and can only be investigated using EEG/MEG, as behavioral investigations do not have this temporal resolution.

4. The ability to interpret the results as they reflect on the **parent theory**, for example, the ability to argue that specific findings of neuroimaging experiments corroborate the tested theory. This is an area where adequate collaboration between representatives of appropriate fields is crucial. For example, it is important that the neuroscience and behavioral studies of dyslexia use the same sample section criteria, use adequate controls, and use complementary experimental measures and paradigms. As we review later in our discussion of neuroimaging studies of dyslexia, there is room for improvement in these areas.

5. The ability and **infrastructural support to implement and conduct follow-up assessment of those interpretations in an educational context**. For example, knowing that there are specific links between activation patterns in a given brain region and a behavior of interest may not lead directly to implications for interventions. When such implications can be reasonably made, however, it is still necessary to have appropriate funding sources and expertise to bring those interventions to a classroom setting where they can be further studied in an unbiased and scientifically rigorous fashion.

**INTEGRATING THE EDUCATIONAL RESEARCH APPROACH AND RESEARCH IN THE COGNITIVE NEUROSCIENCES TO STUDY READING RESEARCH AND PRACTICE**

**Overview of Current Neuroscientific Research on Dyslexia**

Given the escalating demands for rapid, accurate reading skills in our increasingly literate and computer-dependant society, it is essential to focus on the factors that influence reading. Many of us take the seemingly simple act of reading for granted. To a significant number of children in the United States, however, learning how to read is parallel to deciphering a highly enigmatic code. According to the National Center for Education Statistics (2003), close to 40% of U.S. fourth-grade children score below grade level on reading assessments. An estimated 10% to 20% of children have been diagnosed with dyslexia, a learning disability signaled by serious difficulty reading, writing, and spelling (Lyon, Shaywitz, & Shaywitz, 2003). Dyslexia occurs among all groups, regardless of age, race, or socioeconomic status (SES; S. Shaywitz, 2003). Further, it is present across different languages, although its manifestations vary as a function of the transparency of the phonetic structure of the written language. Many scientists in the first half of the 20th century believed that dyslexia was based on visual problems. The commonly observed “reversal of letters” in children was seen as an indicator of this. In fact, most individuals with dyslexia have normal vision and do not “see backwards.” Dyslexia is best described as a heterogeneous group of disorders, with several underlying explanations for
distinct subtypes of reading disability in students (Katzir, 2001; S. Shaywitz, 2003). Research in educational psychology has advanced our knowledge about the identification, classification, and treatment of many children with reading challenges (Lyon & Chhabra, 2004). However, despite this progress, controversy still remains in the field of reading research and practice. Great debate exists in the science and practice of reading in a few pivotal areas. First, and foremost, much has been written on how reading disabilities should be defined. Second, what are the etiological and theoretical explanations for reading difficulties? Third, what are the most appropriate reading interventions that should be implemented in schools? Recently, there has been a growing demand from researchers in the field to solve these controversies using multiple research methods in different settings (Lyon et al., 2001; Stanovich, 2003; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Lyon and his colleagues (2001) claimed that many of the debates in the field can be informed by converging scientific data. Stanovich (2003) called for integration of knowledge from qualitative and quantitative research. A common theme across researchers is that many of the persistent difficulties in developing valid classification and operational definitions of reading difficulties are due to reliance on inaccurate assumptions about causes and characteristics of the disorder. The next section describes the three major controversies in the field and how research in neuroscience is providing converging lines of evidence about potential causes and characteristics of dyslexia.

Controversies in the Field (and Some Proposed Solutions)

Controversy 1: Definitions. The concept of unexpected underachievement in reading has been reported in medical and psychological literature since the mid-19th century. Definitions of this phenomenon have evolved over the years, but most point to four shared elements: (a) an intrinsic–biological nature; (b) a significant discrepancy between learning potential (typically assessed by measures of intelligence) and academic performance; (c) heterogeneity (differences in reading, speaking, and spelling); and (d) the exclusion of cultural, educational, environmental, or other disabilities (Lyon et al., 2001).

Neuroscience could potentially help validate each of these shared elements. In the next section, we address the contribution to heterogeneity. In this section, we focus on its contribution to the intrinsic and discrepancy factors as well as the exclusion criteria. A range of neurobiological investigations, examining multiple linguistic and cultural groups, has documented the intrinsic disruption of neural systems for reading and dyslexia across languages and cultures (Lyon et al., 2003; Vellutino et al., 2004). Collectively, these studies have contributed to our general understanding of the brain regions and processes involved in normal and impaired reading. A considerable body of evidence indicates that children with a reading disability exhibit both subtle structural differences and differences in neural circuitry when compared with readers without impairment (Berninger & Richards, 2002). However, there is no definitive brain marker for dyslexia, either structural or functional, that can be used diagnostically. Instead, studies have combined to give a picture of brain differences between AA and dyslexic readers as a group. Specifically, a growing number of investigations have found regional associations between neurophysiological abnormalities and developmental dyslexia (Richards, 2001). A considerable body of evidence indicates that readers with dyslexia exhibit disruption primarily, but not exclusively, in the neural circuitry of the left hemisphere serving language (see Lyon et al., 2001, for a review). Figure 3 depicts the left hemisphere of the brain and indicates several cortical regions implicated in dyslexia in functional studies.

As such, the most recent and major contribution from neuroscience to the field of reading disabilities has been its influencing a new definition of dyslexia. Until 1998, developmental dyslexia was defined as an unexpected difficulty in learning to read in children, despite adequate to superior intelligence, motivation, and schooling (S. Shaywitz, 1998). Recently, Lyon and his colleagues (2003) proposed a new definition:

Dyslexia is a specific learning disability that is neurobiological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities. These difficulties typically result from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction. Secondary consequences may include problems in reading comprehension and reduced reading experience that can impede growth of vocabulary and background knowledge. (p. 2)

This new definition emphasizes the important links between neuroscience and education to understanding the etiology,
characteristics, and potential interventions for the 10% to 20% of children with dyslexia, or those populations who have difficulty with reading. The dual emphasis on the role of neurobiological manifestations, along with the emphasis on proper classroom experience and instruction, highlights the relationship between nature and nurture that captures findings from the past 5 years regarding the crucial role of both sides of the spectrum in this disorder: the cortex and the classroom. The discrepancy criteria have not been included in this definition.

The inclusion of the discrepancy criteria in definitions of reading disability has probably generated the most controversy in the field. There is a growing group of researchers who believe that all children who cannot read, regardless of their intellectual capacities, display similar reading outcomes and therefore should be treated similarly (Gunderson & Siegel, 2001; Stanovich, 2003). A similar, yet related, controversy is whether dyslexia represents a qualitative cognitive difference or is just the end continuum of reading ability (Kavale, 2002; Stanovich, 1991b).

The discrepancy debate has theoretical and political implications. From an etiological point of view, it raises the question, does dyslexia originate from hereditary neurological underpinnings, or is it related to environmental effects, such as low language exposure? Are discrepancy children different from no-discrepancy children, and if so, should they get different types of intervention? Should we differentiate reading disabilities from reading difficulties from developmental delays in reading?

Neuroscience holds the promise of differentiating among different etiologies that exhibit similar outcomes. The challenge for physicians today is differentiating among children with low language exposure, those who have attention-deficit/hyperactivity disorder (ADHD), or who have low intelligence, as many of them may display low reading scores. Future studies are needed to establish whether poor readers such as English language learners, children with low intelligence scores, or children with other learning challenges such as ADHD can be differentiated from readers with dyslexia based on their brain activation during reading tasks. Although not reviewed here, genetic studies also hold great promise in providing future markers for this phenomenon.

**Controversy 2: Theoretical explanations of dyslexia.** Even if we accept the neurological underpinnings as the major underlying reason for some children’s inability to read, do all children with reading challenges have similar reading-relevant neurophysiological profiles? Or, is this a heterogeneous phenomenon with different types of reading disabilities reflected by different neurophysiological profiles? In addition, do reading disabilities and their neurophysiological correlates change over the life span?

The prominent theory of the cause of dyslexia affirms the clinical observation of many educators and psychologists that many children who cannot read have deficits in the phonology system (Stanovich, 1992). Phonological processes are those involved in the representation, analysis, and manipulation of information specifically related to linguistic sounds from the level of the individual speech sound, or phoneme, all the way to the level of connected text. That is, children with dyslexia have difficulty developing an awareness that words, both written and spoken, can be broken down into smaller units of sounds, such as phonemes, onsets, rhymes, and syllables. For example, it may be difficult for them to recognize a rhyme at the end of a word, or to delete a sound from the beginning of a word. Because the heart of reading acquisition involves learning the rules of mapping letters (visual representations) to sound representations, an awareness of phonemes represents half of the necessary processes needed to learn grapheme-phoneme correspondence rules (Wolf & Kennedy, 2003).

Recent neuroimaging work has provided converging lines of evidence for this theory. Extensive research in neuroimaging studies, primarily with adults, using a range of phonological tasks, has confirmed a reduced activation of the posterior brain regions in dyslexia, along with an overactivation of anterior regions (Brunswick, McCrory, Price, Frith, & Frith, 1999; Paulesu et al., 1996; Rumsy et al., 1992, 1997; S. Shaywitz et al., 1998). The activation of anterior regions associated with articulatory coding has been interpreted as representing an effortful compensation used for phonological assembly during explicit reading (Demonet et al., 1992).

Qualitative and quantitative work by educators and psychologists has led to the extension of the phonological deficit view of dyslexia and broadened our understanding and treatment of reading disorders. Inevitably, in a process as complex as reading, reductionist hypotheses cannot explain all sources of reading breakdown with the conclusion that some children always elude diagnosis, classification, and sometimes treatment. Subtyping classification represents not a new, but rather an ongoing effort to address the heterogeneity of populations with reading disabilities and to understand children who do not fit conventional theories of breakdown. Such research differs from those studies on reading disabilities that tacitly or explicitly operate within a model of general homogeneity, that is, where single factors are assumed to explain reading failure (Badian, 1997; Carver, 1997; Compton & Carlisle, 1994; Kirby, Parilla, & Pfeiffer, 2003; Lovett, 1987; Lovett, Steinbach, & Frijters, 2000; Manis, Doi, & Bhada, 2000; Manis, Seidenberg, & Doi, 1999; Wimmer, Mayringer, & Landerl, 1998; Wolf & Bowers, 1999).

Supporting the inclusion of a heterogeneity of symptoms in the new definition of dyslexia, current research in cognitive neuroscience has led to suggestions that in addition to phonological processing deficits, many readers with severe impairment have what are called naming-speed deficits (Wolf & Bowers, 1999). That is, readers with impairment are slow to retrieve the names of very familiar letters and numbers. A naming-speed deficit reflects difficulty in the pro-
cesses underlying the rapid recognition and retrieval of visually presented stimuli. Debate exists concerning whether rapid letter naming is a phonological processing task or whether it taps additional cognitive and linguistics requirements that are not accessed within phonological processing tasks (Wagner, Torgesen, & Rashotte, 1999), supporting the notion that phonological and naming-speed deficits are independent factors, each contributing separately to reading development. A growing body of research demonstrates that there are discrete groups of children with reading disabilities characterized by either naming-speed or phonological processing deficits or by combined deficits in both areas (Badian, 1996; Compton, 2000; Compton, DeFries, & Olson, 2001; Manis et al., 2000; Wolf et al., 2002).

Advances in neuroimaging techniques offer the opportunity to investigate the neuroanatomical systems that are engaged in rapid serial letter reading and word reading. These techniques may provide insights into lines of evidence for the roles and relationships between neural structures involved in rapid naming and reading. A preliminary study using functional imaging research suggests that the same factors that are related to the connections of visual representations to phonological information are also activated in rapid letter recognition (Misra, Katzir, Wolf, & Poldrack, 2004). In this study, a collaborative team of neuroscientists and educators used the theoretical framework suggested by Wolf and Bowers (1999) and applied it to neuroimaging research in skilled readers. They found that in skilled readers, the neurological underpinnings of phonological processing and rapid letter naming differ. These findings suggest that phonological processing and rapid letter naming are discrete cognitive processes that have differential relationships to reading. Further research on the different deficits that underlie the different subtypes of reading disabilities in children and adults is rapidly progressing and may ultimately inform educators and psychologists as to what interventions are best suited for each individual. Understanding the different profiles of challenges children face in the classroom, be it decoding, rate or comprehension, and how these map to different brain structures and functions, will ultimately inform more tailored assessment and instruction practices for children struggling to learn how to read.

**Controversy 3: Appropriate interventions.** The controversies just outlined lead to the greatest controversy in the field: What are the best intervention practices for children with reading disabilities? Some educators hold the assumption that reading is a natural process and believe that reading need not be systematically taught. Others believe that reading is a complex task that we are not naturally wired for (Lyon et al., 2003; Wolf & Kennedy, 2003). Among those who prescribe systematically teaching reading, the underlying beliefs about what the manifestations and characteristics of the struggling reader are will also affect the development and implementation of appropriate interventions.

Given the tremendous variability in the quality of educational interventions on the market, and the lack of standardized criteria by which they are published, or implemented, educational practitioners are in a vulnerable position when charged with the task of choosing quality programs. In order to be critical consumers, educational practitioners must be able to sort through a myriad of such claims to decide which interventions merit considerations for their classroom and for their specific students with special needs.

The federal No Child Left Behind Act (2002) calls on educational practitioners to use “scientifically based research” to guide their decisions about which interventions to implement. However, it remains unclear, given the kinds of claims made by different programs, how practitioners are supposed to navigate through the many interventions available in order to arrive at one that is based on scientific research. Further, there is a lack of sufficient or additional infrastructure funding to support compliance with the No Child Left Behind requirements. In this sense the call to use scientifically based research is likely to have little practical good effect.

Many interventions that purport to effect dramatic gains in literacy yield only little positive and lasting change (e.g., Lyon & Moats, 1997). Brain imaging techniques (S. Shaywitz et al., 2003; Temple et al., 2003) are beginning to indicate that for some individuals with dyslexia who receive targeted intervention, there are normalizing effects (their brain activation patterns begin to look more like those of the population without reading difficulties) and compensatory effects (they show activation in other areas of the brain to compensate for difficulties in language processing). These findings may help educational psychologists understand that, even if children show behavioral improvement and look more normal, they still process written information differently. This may have implications for continued instruction of these children. Future collaborative work could potentially lead to a better understanding of the profiles of these children and to the development of a more appropriate curriculum and more appropriate assessments for them. For example, school psychologists could guide the selection of clinically and theoretically appropriate assessments that would be sensitive to identifying normalizing and compensatory effects that children may display postintervention. These should include both dynamic and standardized measures (Fischer & Rose, 2001). Educators would then build on information gained by the findings on brain activation changes, combined with the behavioral information from the fine-tuned assessment that would be tailored to specific pathways children exhibit in learning. Cognitive strategies addressing specific areas of weakness could then be combined with traditional reading instruction. Slowly, and with time, neuroscience holds the promise to offer additional methods of inquiry with which we can assess the long-lasting effects of educational interventions. It can also, however, be abused in the hands of misinformed policy makers, practitioners, and parents.
EXAMINING CURRENT DYSLEXIA STUDIES
IN NEUROSCIENCE

To examine the relevance of studies in neuroscience to the pressing issues in the field of reading disabilities, we have summarized a sample of the most recent studies and grouped them according to a few of the debated issues. First, we present etiological studies to examine the routes and neurological underpinnings of dyslexia that may contribute to the first controversy on definitions. Second, we present studies comparing children and adults with dyslexia that may shed light on the second controversy of theoretical explanations. Developmental studies will ultimately help us understand the potentially different manifestations of dyslexia across the life span. Finally, we present the cutting-edge intervention studies that add to the growing body of research on the controversy regarding best educational practices.

For each study we ask the following questions:

1. What research questions are asked in the study?
2. Who were the participants and how were they identified?
3. What tasks were used to investigate the research questions?
4. What are the results of the study?
5. What are the theoretical implications?

Etiological Studies

As it is becoming more widely accepted that dyslexia is a biological and brain-based disorder, the necessary role of neuroscience in understanding the etiology is similarly becoming better defined. Two decades of reading research have systematically found that phonological impairments are a likely mechanism leading to reading disorders with numerous studies showing a causal link between sensitivity to phonological structures of words and subsequent progress in learning to read (Bradley & Bryant, 1983; Hatcher, Hulme, & Ellis, 1994; Lundberg, Frost, & Petersen, 1988; Lundberg, Olofsson, & Wall, 1980). Reflecting the strong empirical and theoretical basis for this claim, many neuroimaging studies of dyslexia have been designed to identify and characterize the neural substrates of phonological processing in adult and child populations among both those with normal reading and those with impairment. Several such studies are described in Table 1. They implicate specific brain regions, for example the left temporal–parietal region including the angular gyrus (see Figure 3), as being important for the development of normal grapheme-to-phoneme correspondence.

Given the heterogeneity of the population with dyslexia, it is not surprising that although the centrality of phonological awareness to dyslexia is well established, there are other characteristics commonly manifested among individuals with dyslexia that likely contribute to reading impairment. As reviewed earlier, early descriptions of dyslexia focused on visual impairments; indeed, there is brain and behavioral evidence suggesting that some individuals with dyslexia have a selective deficit of the visual magnocellular system, which processes rapidly moving stimuli (Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998; Demb, Boynton, & Heeger, 1998; Eden et al., 1996; Lovegrove et al., 1982; Stein & Walsh, 1997). However, the evidence is inconclusive as to whether this deficit, which only some children with dyslexia manifest, significantly contributes to reading impairments or is related in a nondirect fashion to the disorder. For example, it is possible that this visual system deficit is related to auditory system deficits, which are hypothesized to be related to problems processing rapidly presented auditory information (Nagarajan et al., 1999; Poldrack et al., 2001; Tallal, Miller, & Fitch, 1993).

Another deficit, beyond the phonological, subtle visual, and auditory deficits already described, is a deficit in the processes underlying naming speed (Wolf & Bowers, 1999). This deficit has been shown to be predictive of later single-word reading, connected text, and comprehension (Katzir, 2002; Meyer & Felton, 1999; Meyer, Wood, Hart, & Felton, 1998; Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000). However, the relationship between this deficit and phonological processing has not yet been well established and is an active area of research (Meyer & Felton, 1999; Stanovich, 1991a; Torgesen, Wagner, & Rashotte, 1994; Wolf & Bowers, 1999).

A growing number of neuroimaging studies are separately examining each of these proposed etiologies (phonological, temporal processing, or rapid-naming deficits). However, it will also be important for interdisciplinary groups consisting of educators, psychologists, and neuroscientists to collectively first develop appropriate content-based tasks to be used in these studies. Useful tasks would be those stemming from theoretical frameworks that tap into the perceptual, linguistic, and cognitive tasks that have to be integrated in higher order complex tasks in reading (Wolf & Katzir-Cohen, 2001). In this way, we can build an understanding of the brain processes involved not only in the subskills associated with reading and learning to read but also in the brain processes involved when combinations of subskills are required by a given task. This will be an important step toward developing paradigms that yield interpretable brain data and better represent the complicated task of reading.

Developmental Studies

The comparison of skilled and novice readers can inform us about the developmental nature of literacy across the life span. It can help differentiate what is learned versus what is present at the beginning of the process. Finally, it will shed light on what systems are involved in what stage for different profiles of readers. Jeanne Chall (1983) proposed one of the first developmental stage models of reading, which provides a macroscopic view of the major transitions in reading acquisition. Her model is characterized as a “stage model” because each stage is seen as differing qualitatively from the other.
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<tr>
<td>What is the spatiotemporal brain activation profile associated with phonological decoding in dyslexic children? Brain activity was measured using MEG.</td>
<td>21 children. Two subgroups: Readers with impairment: 11 children, 7 males, age range = 10–17 years. Scored under 20th percentile on Word Attack subtest of the WJ–R battery. AA readers: 10 children, 7 males, age range = 8–16 years. Scored at or over the 80th percentile on Word Attack subtest. All children had IQ greater or equal to 85.</td>
<td>Rhyme matching. Children were presented with two pseudowords (e.g., kume–noom) and asked to indicate if the words rhymed or not.</td>
<td>Readers with versus without impairment showed aberrant activation maps, with reduced activity in TMP areas in the left hemisphere and increased activity in the right homotopic region. However, in temporal brain regions where activation typically precedes that of the TMP areas where differences were found, children did not differ in degree of activity. Degree of activity in the left versus right TMP areas was a good predictor of behavioral performance on the rhyme-matching task. Similarly, the onsets of left TMP activity and behavioral performance were also correlated—earlier onset of activation was associated with better performance.</td>
<td>MEG is a valuable tool for investigating spatiotemporal activation pattern differences in a pediatric population. This study leaves open the question as to whether the differences found are related to an organic functional deficit in the left TMP regions or if the left TMP differences reflect reading exposure–practice differences between the subject groups. Findings confirm that behavioral differences in phonological decoding are reflected in both spatial and temporal properties of neuronal activation patterns.</td>
<td>Simos et al. (2000)</td>
</tr>
<tr>
<td>Does fMRI show differences between impaired and AA readers on nonreading, auditory language processing tasks involving phonological awareness and lexical judgment?</td>
<td>16 male children. 8 impaired readers, ages 10–13 years, all had &gt; 1 SD discrepancy between verbal IQ and reading skills, had scores higher than 90 verbal IQ and differed significantly from AA control participants on WRMT–R Word ID and Word Attack subtests. 8 control participants did not differ significantly from children with dyslexia in age or in verbal ability based on WISC–II Vocabulary.</td>
<td>Two auditory judgment tasks with processing demands not required in ordinary conversation and verbal reasoning. Phonological judgment: Children compared a pair of words (real, pseudowords, or mixed real and pseudoword pairs) to decide whether they rhymed. Lexical judgment: Children compared word pairs (same combinations as described earlier) and made a decision if both words in the pair were real words.</td>
<td>Behavioral performance showed all participants performed well above chance. Those with dyslexia were less accurate in the lexical judgment and on an auditory tone judgment task; groups did not differ in reaction times. Significant differences in brain activation between the two groups were found in multiple regions. Participants with dyslexia showed reduced activity in bilateral insula activity, left inferior temporal gyrus, and bilateral inferior frontal gyrus. Controls showed the reverse pattern compared to those with dyslexia, with more activity in the left planum temporale. Controls showed greater activation in the left superior parietal lobule.</td>
<td>Readers with impairment differ from AA readers on auditory language processing tasks that do not require reading. Readers with impairment may process semantic differences differently when there is also a requirement that they suppress or ignore phonological information as in the lexical decision task. Participants with impairment and AA reading differ in phonological processing and also in lexical access. This might be part of the manifestation of lexia in dyslexia and in the deficit in single-word reading.</td>
<td>Corina et al. (2001)</td>
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Do children with dyslexia show disruption in the TMP response to phonological processing of visual letters?

39 children. 15 children with AA reading. 24 children with dyslexia, age range = 8–12 years. Children did not differ significantly in verbal or performance IQ. Children with dyslexia performed less well on WJRM Word ID, Word Attack, and passage comprehension subtasks.

Rhyme letters, match letters, and match lines tasks. Participants viewed instructions “rhyme” or “same” and indicated whether (a) presented pairs of letters rhymed or were the same or they (b) indicated whether presented lines were of the same or different orientation.

Children with dyslexia showed reduced left TMP activation during the rhyming task as compared with controls. Left frontal activation was comparable in both groups. These findings parallel prior results in fMRI studies of adults with dyslexia.

Compared to AAs, participants with dyslexia showed reduced posterior activation during both the phonological and orthographic processing of single letter pairs.

Examination of subgroups of the children with dyslexia children so that IQ was and was not matched with the control group showed the main results were unchanged.

For children with dyslexia whose IQ falls in the AA range, this study suggests that IQ is unrelated to the phonological deficit and corresponding lack of left TMP activity.

Findings suggest that dyslexia is characterized by impairments in the neural underpinnings of both phonological and orthographic processing and that these impairments are likely to be causes of reading difficulties rather than compensatory responses.

Does fMRI show differences between impaired and AA readers on tasks requiring phonological assembly skills? How do the patterns of activation in children compare with those found in previous studies with adults?

144 right-handed children. 70 with dyslexia, 21 girls, 49 boys, age range = 7–18 years. 74 readers without impairment, 31 girls, 43 boys, age range = 7–17 years.

Participants made same or different judgments for two items in five conditions designed to make progressively greater demands on phonological assembly skills. Stimuli were visually presented.

Compared with controls, older, not younger, individuals with dyslexia showed overactivation of left and right inferior frontal gyrus during the most phonologically demanding task. Readers without impairment showed greater activation across multiple left hemisphere sites compared to with participants with dyslexia.

This supports claims that children with dyslexia manifest an organic dysfunction in left hemisphere posterior reading circuits not ascribable to experience as poor readers.

B. Shaywitz et al. (2002)

Note. MEG = magnetoencephalography; WJ-R = Woodcock–Johnson battery–Revised; AA = average achieving; TMP = temporo–parietal; fMRI = functional magnetic resonance imaging; WRMT–R = Woodcock Reading Master Test–Revised; WISC–II = Wechsler Intelligence Scale–2nd edition; WJRM = Woodcock–Johnson Reading Mastery.
stages. Subsequent reading models expanded the stage view to incorporate dynamic processes that develop as a child learns to read (Fischer & Rose, 2001; Juel, 1991).

The current findings from developmental neuroscientific studies support many of the hypotheses raised by educational psychologists. Recent research suggests that the degree of specialization of cortical regions for reading, as well as the pattern of regional interactions that support this specialization, may change with age (Schlaggar et al., 2002; Simos et al., 2001; see Table 2 for overviews of both studies). There are both age- and performance-related regions that function in adults and in children. The age-related regions most plausibly reflect brain maturation and indicate that, in part, children use different neuroanatomy than adults performing on the same task. One explanation is that because of experience, children have not yet incorporated the processing resources in the left frontal region into a strategy for performing the reading tasks (Schlaggar et al., 2002; Simos et al., 2001).

These findings can begin to provide converging lines of evidence for theoretical models of reading development (Adams, 1990; Chall, 1983) that facilitate a transition from focusing on reading accuracy to reading fluency. They also indicate that several systems have to mature and be able to be coordinated in order to process written language. Similar to other studies in neuroscience, the reviewed studies were conducted with small samples with a wide age range. Confining the age range to map the different stages of reading development will enhance the validity of these studies, as well as help pinpoint direct brain-related changes in relation to age, proficiency, and specific reading tasks. Another challenge to be addressed in using MEG and fMRI for studying reading-related tasks is the refinement of experimental paradigms and the incorporation of more traditional behavioral and psychophysics measures. For example, if eye-tracking equipment is used during imaging studies of reading-relevant tasks, we can better correlate imaging data with what the participant was visually attending to. In this way, we may improve our ability to interpret imaging data in terms of known results from behavioral studies. The combined use of eye-tracking and imaging technology is in its infancy with few labs having the capability and equipment to carry out the studies. Having a family of research questions related to reading, which could be explored in this way, is an example of how collaborative research among neuroscientists and educational researchers can serve as a “zone of proximal development” for both fields (Vygotsky, 1978). Educational researchers would have new data to interpret and modify their models accordingly. Neuroscientists would be challenged to further develop their research paradigms and their methodological frameworks to reflect increased compatibility with future applied research.

Pre–Post Studies

Pioneering work in evaluating potential brain-related changes pre- and postintervention is slowly beginning to make progress in bridging education and neuroscience. In the following sections, we highlight the promise and caution about these studies, and we outline the next methodological steps the field should take in order to extend the validity and reliability of these studies.

Table 3 summarizes two of the most influential neuroscientific studies in pre–post intervention. The first study examines the difference of compensated versus persistently poor young adults who had reading difficulties as children (S. Shaywitz et al., 2003), the second examined brain activity patterns of children with reading difficulties before and after receiving an intense intervention (Temple et al., 2003).

S. Shaywitz’s (2003) work sheds new light on the controversy regarding the role of intelligence in the definitions of dyslexia. S. Shaywitz and her colleagues compared the neurological functioning of adult “compensated readers” (accuracy of word reading is improved, but readers remain nonfluent) with persistent poor readers (both accuracy and fluency remain deficient in reading) and found that individuals with higher IQs were more likely to become “compensated readers” than were those with lower IQs. The neurophysiology of individuals within both groups of readers with dyslexia differs from that of typical readers. S. Shaywitz suggested that the results provide some support for the idea that cognitive abilities may provide for some degree of compensation for reading disabilities.

In her study, different pathways in the brain were indicated for the compensated compared to the persistently poor readers. Different activation patterns may indicate different reading strategies that the two groups use, ultimately helping teachers better understand the learning process and, potentially, the adequate teaching methods for these different populations. This finding sheds some light on the definition controversy, beginning to suggest that a child with a higher learning potential may learn to read in a different manner than a child with lower learning potential. Additional collaborative research could help design studies that target more specifically how response to intervention is defined (Foorman, Francis, Fletcher, Schatschneider, & Mehta, 1998)—for instance, how to tease out environmental effects from intrinsic factors such as the degree to which IQ scores reflect SES in the sample studies, immigration status, or instructional background. As neuroscientists, educators, and psychologists work together to track etiological and experience-based differences, knowledge will become more convergent on why some children resist specific treatments and how to change their outcomes.

To ameliorate reading problems, almost a quarter of a million children are participating in a training program derived from neuroscience research. These children receive a program developed by Scientific Learning Corporation (http://www.scilearn.com/), a publicly traded company, founded in 1996 by neuroscientists Paula Tallal (Rutgers) and Michael Merzenich (“Editorial,” 2004). The company sells computer software based on research showing that intensive training can improve auditory processing deficits that...
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<td>To what extent do functional neuroanatomy reading tasks performance differ in adults and in children?</td>
<td>19 children ages 7–10, average readers. 21 adults ages 18–35, average readers. Two subgroups were created: Matched children and adults who were close in their accuracy and reading reaction times. Nonmatched adults and children who had big gaps in the accuracy reading and reaction time.</td>
<td>Single-word reading</td>
<td>Children and adults had both overlapping and difference in activity in left frontal and left extrastriate cortex. Activity in one left cortex region and in the more posterior left extrastriate cortex was performance related (showing greater activation in children in the nonmatched group). Other left frontal and left extrastriate regions were found to be age related (showing more robust activity in the extrastriate and less activity in the left frontal in all children).</td>
<td>There are both age- and performance-related differences. However, related regions function similarly in adults and in children. The age-related regions most plausibly reflect brain maturation and indicate that children use differential neuroanatomy in part than adults performing on the same task.</td>
<td>Schlaggar et al. (2002)</td>
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<td>Can differences between the two groups be attributed to performance differences or brain maturation differences?</td>
<td>27 adults (ages 23–41) and 22 children (ages 8–15) that were skilled readers.</td>
<td>Single-word reading, Pseudoword reading</td>
<td>For both tasks, in both age groups there was left-hemisphere preponderance. Children displayed less pronounced asymmetries, especially in response to the pseudoword task. In contrast to adult activation, children showed very sparse activity in inferior frontal gyrus during the pseudoword task, and during the word task. The temporal course of activity of adults and children was similar for the word reading task; it differed for the pseudoword task, where adults showed a pattern that was similar to the word reading task, and children showed a different pattern.</td>
<td>The degree of specialization of cortical regions for reading, as well as the regional interaction that support this specialization, may change with age. Increased activity in left temporo-parietal areas displayed in children may reflect increased reliance on phonological decoding on both reading tasks.</td>
<td>Simos et al. (2001)</td>
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<td>Do adults and children activate similar regions in the brain when reading words and pseudowords?</td>
<td>No information on their reading scores within groups.</td>
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<td>Is the time course of the activation patterns for the two groups similar?</td>
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<td>Whether and how two groups of young adults who were poor readers as children differed from readers without impairment</td>
<td>Three groups all between ages 18-23:</td>
<td>At each grade, participants were defined as poor readers if their FS &gt; 80 and actual score on Woodcock Johnson decoding composite was 1.5 SD below predicted score (discrepancy definition) or decoding composite was &lt; 90 (low achievement).</td>
<td>Pseudoword rhyming</td>
<td>Both PPR and AIR underactivate posterior reading systems compared to NI.</td>
<td>Persistent differences in brain activation patterns even for compensated readers.</td>
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<td>Reading real words</td>
<td>PPR activate posterior reading systems but engage them differently from NI readers.</td>
<td>PPR children engage differently than NI, appearing to rely more on memory-based learning rather than analytic word identification strategies.</td>
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<td>2. AIR (were poor in 2nd or 4th grade and not in 9th or 10th grade). Were accurate but not fluent readers (n = 29).</td>
<td></td>
<td></td>
<td>AIR activate more right superior and temporal regions as well as left cingulated gyrus.</td>
<td>Divergent compensation pathways for children with higher cognitive abilities</td>
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<td>3. NI readers (n = 27).</td>
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What is the extent to which disruption in neural responses observed in dyslexia can be changed through remediation?

20 children with dyslexia and 10 controls, ages 8–12

The group with dyslexia had either 1 SD below average on either the Word Identification or the Word Attack scores on the Woodcock Johnson decoding composite.

Children with dyslexia children were evaluated pre- and postintervention (Fast For Word, Scientific Learning Corporation). They were administered behavioral language and reading measures and scanned on two related tasks:

**Phonological:** A letter-rhyming task in which a child saw two letters and had to determine whether they rhymed.

**Nonphonological:** A letter-matching task where children pushed a button if the two letters presented were identical.

Behavioral results:

Significant group gains were shown for the group with dyslexia on reading and language measures. However, for 9 children, minimal gains were made on the reading measures; for 10 children, minimal gains were made on the language measures.

Following the intervention, children with dyslexia showed increased activity in multiple brain areas. Increases occurred in left temporo–parietal and frontal regions as well as in right-hemisphere frontal and temporal regions as well as in the anterior cingulate.

Some children with dyslexia show both remediation effects (brain activation patterns that are close to normal-reading children) mainly in the right hemisphere and in the bilateral anterior cingulate following intensive intervention.

**Note.** PPR = Persistently poor readers; AIR = Accuracy Improved readers; NI = nonimpaired. FS = Full Scale.

Temple et al. (2003)
may underlie reading difficulties such as dyslexia. In principle, this represents a major achievement in translating basic scientific research into educational practices. However, since educational programs do not have FDA approval, it is essential to evaluate the effectiveness of these programs in a rigorous manner.

Temple et al. (2003) examined both the cognitive—behavioral, as well as the neurological, impact of the Fast ForWord training on children with dyslexia. After remediation, brain activation of children with dyslexia while performing a rhyming and letter-matching task in the scanner showed both normalizing and compensating effects (Temple, 2002; Temple et al., 2001). As a result of the cognitive—behavioral and neurological findings in this study (Temple et al., 2003; see also Temple et al., 2000), the researchers concluded that specific remediation programs targeted at auditory temporal processing deficits could alter the functioning of the brain.

Although the results from both studies show great promise, there are several central issues that have to be addressed before future implications can be drawn from them. The first step in validating an intervention program is to evaluate the theoretical rationale for the program. Fast ForWord designers describe it as a theoretically brain-based program. Tallal, Miller, Jenkins, and Merzenich (1997) argued that the phonological difficulties of children with reading problems may reflect broader auditory processing impairment that includes processing of nonverbal tones. Although these findings have been replicated in some instances, other researchers have failed to find a relationship between temporal processing deficits and phonological processing in AA and poor readers (McAnally, Hansen, Cornelissen, & Stein, 1997). These findings question the theoretical basis on which Fast ForWord was developed.

Temple et al.'s (2003) study is one of the first that used both standardized behavioral reading measures such as word identification and reading comprehension outside of the scanner as well as experimental tasks inside the scanner. However, the tasks used for the psychological and neuroscientific testing conditions did not match. The tasks that were used in order to assess brain activation changes pre and post were a letter-matching task and a letter-rhyming task, which are not reading tasks per se. Although they are related to reading, in the future, including age- and reading-level-appropriate tasks designed by a reading specialist could greatly benefit our understanding of the neuronal changes that occur because of the intervention. The challenge of designing a comprehension task that can be used in the scanner prevented both research teams from including it in their studies. The need to understand the complexity of reading comprehension should serve as a vehicle toward the development of more advanced technologies that can help us understand complex cognitive processes.

A further issue in this study is one that plagues nearly all neuroimaging studies of dyslexia. The sample size used in this study was small and not representative of the classic individual with dyslexia. As a group, the children with dyslexia scored within (as opposed to below) the average range on a decoding task. Also, variability existed in the level of reading difficulty both pre- and post intervention. These issues could be addressed either by using a larger sample or by investigating a more homogeneous group. Further, there was no control group of individuals with dyslexia who either did not receive the intervention or received a different type of intervention (see work by Hook, Macaruso, & Jones, 2001, for comparison).

As a group, the children participating in the program showed significant mean difference improvement. However, with regard to individual children who benefited from the program, many of the individuals did not make significant educational gains. Specifically, Temple's work suggests that some children respond to some interventions, and others do not.

The small size of the sample, the great variability in scores, and the lack of a control group with dyslexia that did not receive an intervention challenge the strength of the results in bridging the findings to broader populations. Although the research techniques allowed for innovative types of findings that can shed light on differences that are not observed through traditional educational paradigms, the design of the study could benefit from closer collaborations with reading specialists and educational psychologists with clinical experience in assessment and remediation of children with reading challenges. An educational psychologist would be able to contribute in the selection of children who fit the current criteria for having a diagnosed reading disability. A reading specialist could help design age- and instruction-appropriate reading tasks to use in the scanner, and educational methodologists could help in the experimental design.

Funding presents a great challenge for pre- and post-intervention research in general, and particularly for those studies with a neuroimaging component. The difficulty is that such studies are very demanding to conduct and generally involve obtaining consents, creating learning environments within schools, and dealing with attrition. Recent work in computational modeling of successes and failures of intervention for readers with disabilities hold great promise as a first step in preparing for applied work in school environments (Harm, McCandliss, & Seidenberg, 2003). The need to examine the effectiveness of different reading interventions has pushed researchers in computational science to develop models that can simulate responsiveness to particular interventions. These innovative models allow for the analysis of direct causal effects without the real-life confounds that can make it difficult to interpret behavioral results, and thus complement empirical studies.

In conclusion, pre–post intervention studies help validate differences in brain activity related to enhanced reading. These findings may also point to brain plasticity in children. This review also indicates that tighter collaborations among researchers could enable the development where hypotheses are first tested in computational models, and then moved to school settings, and finally a neuroimaging component could
be added to them. This would allow for responsible funding for promising research directions. Collaborative research will also foster broader research questions within the field of dyslexia, for instance, regarding different subtypes of children with reading disabilities, more cross-linguistic research, and questions that relate more to higher order cognitive functions such as reading comprehension and vocabulary development.

CONNECTING THE FIELDS OF NEUROSCIENCE AND EDUCATION TO THE STUDY OF DYSCALCULIA

We have argued that dyslexia specifically, and the development of reading skills more generally, represents a fertile area of research for connecting neuroscience and education. Key reasons underlying this claim include the following: There are several strong hypotheses linking specific skills, such as phonemic awareness and performance on fluency tasks, to reading performance. In addition to behavioral research linking performance on these skills to performance in reading, there are testable hypotheses, some generated from behavioral work, others from work in neuroscience, which link these skills to brain function and structure. Together these two types of hypotheses can be combined to guide research programs that explore connections between the behavioral and brain bases of the development of reading skills. In this section, we briefly describe the status of dyscalculia research. We argue that as in the field of reading disabilities, the field of dyscalculia research is also poised to begin making connections between neuroscience and education. With further development of cognitive models delineating skills underlying mathematical performance, exploration of testable neurocognitive hypotheses interpreting the brain, and behavioral findings in terms of their educational implications, there is the potential for advancement in this growing field and area of inquiry.

Dyscalculia: Prevalence and Characteristics

Similar to the process of receiving a diagnosis of dyslexia, children with otherwise normal intelligence who show isolated problems with arithmetic but whose other abilities are in the normal range may be diagnosed with dyscalculia. In addition to the similarity of their definitions, both disorders share a heterogeneous presentation and a considerable instance of comorbidity with other learning disorders. One large-scale study found that 17% of children diagnosed with dyscalculia also held a diagnosis of dyslexia and that 26% carry a diagnosis of ADHD (Gross-Tsur, Manor, & Shalev, 1996). In this work, Gross-Tsur and colleagues found the overall prevalence of dyscalculia to be 6.5% with equal representation among girls and boys. This rate puts it in the same range as some estimates of the incidence of dyslexia.

As with reading disabilities, the incidence rate for mathematics disorders varies with the criteria used in studies for determining whether a participant has a math disability. The Gross-Tsur et al. (1996) study, which found a 6.5% prevalence, relied on the criterion that the child be two math grades below chronological age; other studies, which found 10.9% incidence in Norway (Ostad, 1998), and 3.6% in England (Lewis, Hitch, & Walker, 1994), used registration for special long-term help and discrepancy between arithmetic tests and nonverbal IQ, respectively. As in studies of dyslexia, we see that there are an unfortunate variety of criteria used for characterizing participant populations as having an arithmetic disorder. This lack of consistency makes comparisons across studies difficult. It also reflects the lack of an accepted model of the development of numerical and arithmetic competence from infancy to adulthood. Such an accepted model would serve as a springboard from which to develop appropriate tests of the basic skills underlying mathematical performance.

The study of math disabilities share many of the same controversies as the field of reading disabilities. There is argument about the definition of dyscalculia (Landerl, Bevan, & Butterworth, 2004). There is a lack of clarity regarding the theoretical explanations of these challenges. And finally, there is great debate on what should be appropriate interventions for children who struggle with math. We argue that unlike in the field of reading, which has more advanced theoretical and practical knowledge and is therefore more “prepared” to be informed from research in neuroscience, the field of math disabilities has to first develop a more theoretical cognitive understanding of math before fitting designs can be applied to neuroimaging experiments.

Challenges to the Study of Dyscalculia

The preceding section introduced the methodological issues associated with participant selection criteria, and the lack of an integrated model from which to develop testable hypotheses of the neurocognitive development of mathematical competencies. Both of these issues represent challenges. Next, we describe some of the foundational work, already done, which is contributing to the development of an explicit model of basic, testable skills that are associated with the development of mathematical skills.

The lack of an accepted model of the development of numerical competence represents an important hurdle to overcome in the study of mathematical cognition (Ansari & Karmiloff-Smith, 2002). The lack of such a model is complicated by an apparent split between the quantitative competencies children have without instruction during infancy and preschool years and the subsequent quantitative competencies taught as part of mathematical training in schools. At least two of the most productive scholars working in this field (i.e., Dehaene, 1997; Geary, 2000) have demonstrated evidence of such a split.

Geary (2000) argued that there is a specific and universal biological basis for the emergence of the first and biologically primary category of mathematical competencies. Such
competencies include numerosity, ordinality, counting, and simple arithmetic. He argued that there is substantial cross-cultural, behavioral, and neurocognitive evidence and that their emergence follows a universal—that is, pan-cultural—developmental process, which implies that the skills have a fundamental biological basis. In contrast, the mathematical training in schools is culturally determined, and although higher level competencies are built from the more primary systems identified earlier, there exist no universal normative patterns for such abilities.

Dehaene (1997) similarly argued that there is considerable evidence that humans have a “number sense” with which Geary’s four primary competencies are compatible. He proposed that such a number sense is evident in various forms in different animal species and that it is supported by a specific cerebral substrate. He discussed how these biologically based number representations then can interact with cultural and linguistic factors throughout schooling. This implicitly acknowledges a two-tiered system of quantitative competencies, one based in more innate numerical capacities and another that links those capacities to the demands of higher level mathematical tasks.

As this understanding is created through the combined and ongoing efforts of studies of both the brain and behavioral bases of dyscalculia and normal and impaired performance on basic numeracy skills, it is important to simultaneously work on the links between these basic skills and the related scholastic demands. To facilitate more rapid progress in our understanding of atypical number development, Ansari and Karmiloff-Smith (2002) recommended the use of psychophysical paradigms. These have the attractive feature of allowing systematic manipulation of numerical stimuli so that reaction time and accuracy norms can be established. These norms would be useful in providing a basis for characterizing participant populations and making comparisons across studies that rely on these norms. As such, psychophysical studies are well suited for both behavioral and noninvasive neuroimaging studies. We also recommend this approach on the basis that it can help refine and produce hypotheses linking brain and behavioral bases of numerical cognition. To be effective, the development of such appropriate psychophysical paradigms would be based in the kind of neurocognitive or cognitive model of numerical and arithmetic processing we have described the need for earlier. Recent research by Landerl et al. (2004) used such psychophysical measures to study basic numeric processing skills and their possible role in dyscalculia. For example, they used timed number reading, number size assessment, number writing, and counting. Their work led them to conclude that specific disabilities in basic numerical processing underlie dyscalculia.

A primary candidate for a basic skill in arithmetic processing is the ability to use and understand the central conceptual structures such as the number line (Griffin, Case, & Capodilupo, 1995). Work by Dehaene, Piazza, Pinel, and Cohen (2003) supports the idea that there is a neural system analogous to an internal number line. They suggest that this circuit, in conjunction with two others, is primarily responsible for number processing. It is interesting that such foundational work to develop our understanding of the subskills necessary for fluent numeracy is being done, in some cases, concurrently in both behavioral and combined brain and behavioral studies. With this groundwork being laid, progress should be rapid in developing testable theories linking arithmetic subskills with their neural correlates. From there, the challenge is to understand how to leverage this combined knowledge of brain and behavior relationships associated with numeracy and dyscalculia in order to inform pedagogy.

**DISCUSSION**

Neuroscience has provided fascinating glimpses into the brain’s development and function; advances in our knowledge of the brain hold promise for improving the education of young children. When applied correctly, brain science may serve as a vehicle for advancing the application of our understanding of learning and development. Reciprocally, education may serve as an important vehicle in formulating important research questions for neuroscientists and in providing more precise guidelines for behavioral measurements used in neuroscience. Brain research can challenge common-sense views about teaching and learning by suggesting additional systems that are involved in particular tasks and activities.

Three major contributions of knowledge to education can be gained by neuroscientific research:

1. The new research methods used in neuroscience can serve as vehicles to provide converging lines of evidence for what has been found in traditional educational and psychological methods (Kosslyn & Koenig, 1992; Sejnowski & Churchland, 1989). In the case of reading, they have confirmed the role of phonological processes in reading (Perfetti & Bolger, 2004).
2. New findings often help researchers decide among competing rival approaches (e.g., Are there different subtypes of dyslexia? Is there a genetic component? How might genetic predispositions to dyslexia combine with environmental experiences produce different possible subtypes?).
3. Neuroscience research allows for the generation of new hypotheses that could not be generated without some knowledge of the brain (e.g., even after achieving reading scores in the average range, some children with dyslexia still process written information differently than their peers).

However, and not surprisingly, progress bridging the gaps between basic research and classroom needs has not, and cannot, come swiftly. Part of the challenge is in fostering fruitful collaborations between neuroscientists and educational researchers. In order to have true interdisciplinary collabora-
tions, in any field, at least two premises must be met. First, the collaboration must be guided by the goal of fostering interprofessional interactions that enhance the practice of each discipline. Second, such interdisciplinary education should be based on mutual understanding and respect for the actual and potential contributions of the disciplines.

Without such collaborations, the neuroscience research may be relevant to learning broadly but is unlikely to directly address specific educational issues. An examination of the citation patterns in these different bodies of literature reveals that it is only occasionally that there are cross citations between neuroscience articles on dyslexia and articles in the education and clinical literature. There are two key factors to increasing such occurrences: the theoretical topics addressed in neuroscientific research and the methods used to answer these questions.

For example, a classic problem manifests itself in participant selection. Dyslexia is enormously heterogeneous. It is common in neuroimaging studies of adults with dyslexia to recruit participants based on their self-report of having had trouble learning to read. Adequate assessment to classify such participants according to their profile of reading-related deficits and strengths is necessary but not always done. Without such testing, it is not appropriate to generalize from those studies to the larger population even though thresholds for statistical significance have been reached.

These potential confounds can stand in the way of making progress in effectively combining neuroscience and education, and, of importance, they can stand in the way even when the criteria for successful interactions between neuroscience and education have the potential to be met. We have described in this article the theoretical and actual ways that neuroscience and education can interact in the case of dyslexia and dyscalculia. The five criteria points introduced earlier are described here again, with brief examples of how dyslexia does and dyscalculia does not yet meet them:

1. Falsifiable theory that links specific skills to specific educational goals or tasks. In the case of dyslexia, it is well established that phonological processing skills are a key predictor of reading performance. There are other candidate subskills or abilities, which also seem to contribute to, or be predictive of, reading performance. In combination, these represent a base from which to begin investigating the brain bases of these skills. In the case of dyscalculia, there is no core deficit that has been established as being highly predictive of later mathematical difficulties. This is further complicated by a split between the mathematical competencies, which seem to be biologically based and pan-cultural (Feldman, 1994), and those mathematical skills that are important academically and can vary considerably across cultural and national boundaries.

2. Falsifiable theory that links those skills to specific brain functions and structures. In the case of dyslexia, there are a number of hypotheses linking brain structure and function to the core phonological awareness skills associated with reading and also to other relevant subskills (e.g., rapid automatized naming, single-word reading, low-level auditory and visual processing). For dyscalculia, the development of our understanding of the core skills necessary for numeracy, and the development of our understanding of the brain functions, are being explored in tandem. This represents a somewhat different model of neuroscience and education than that which is currently playing out in the case of dyslexia. This approach is also promising, however, and will likely move the field toward meeting these criteria and becoming a next good example of how to successfully integrate neuroscience and education.

3. Appropriate experimental methodologies and analytic techniques to test claims. It is exciting that the noninvasive neuroimaging tools now available have been proven useful with a pediatric population. The combined strengths of the different techniques to identify changes in structure, function, connectivity patterns, and spatiotemporal patterns of activation will allow unprecedented access to the development of AA individuals.

4. The ability to interpret the results as they reflect on the parent theory. Of importance, we still face significant danger of sabotaging our own efforts if we ignore the confounds that have so far frequently hampered our ability to generalize from many of the studies conducted to date. We must work to establish clear guidelines for participant selection so that we can more confidently compare results across studies. It is also important to establish reproducible experimental paradigms that are flexible enough to be manipulated to examine multiple features of either reading or math skills and that are also transportable, so that they can be meaningfully used in both the classroom and the neuroimaging laboratory.

5. The ability and infrastructural support to implement and conduct follow-up assessment of those interpretations in an educational context. Of importance, the first four criteria represent a minimum for scientific inquiry of this kind. After meeting those criteria, there is still more to be done to translate results from the journal page to the classroom chalkboard. Having the appropriate infrastructure in place includes, but is not limited to, having the funding sources and expertise to bring brain and behavioral research-based interventions to the classroom setting. And, once in this setting, it is important that further unbiased and scientifically rigorous studies be carried out. The medical model of clinical trials can be a useful paradigm to explore for this phase.

In the model case of dyslexia, brain research may also help in the early identification of children who may be at risk for learning challenges. Integrating behavioral and brain studies in an interdisciplinary manner can lead to a rich source of useful information about how we learn, and what differential causes may be contributing to why some children have difficulties learning.
A review of converging lines of research on dyslexia supports cautious optimism regarding the bridge from neuroscience to education collaborations. Presuming a reciprocal research collaboration among the various fields of neuroscience, cognitive science, and education, at least, we anticipate that interdisciplinary, multilevel brain and behavioral research will likely have first successes in the area of clinical and diagnostic improvements, and eventually for curriculum development and evaluation. Beyond those described earlier, we anticipate additional broad benefits of an interdisciplinary, multilevel research approach that connects neuroscience and education. Such research will allow deeper insights into the possible connections between educationally relevant skills and the neuronal, genetic, and other biological factors that may underlie them. A second benefit is that by necessity, in conducting such research with collaborations between scholars and scientists of different disciplines, measures that are comparable across those different disciplines will be developed. This, too, will aid in hypothesis development, as single or interdisciplinary studies that have incorporated comparable measures can be interpreted jointly.

In these ways, neuroscience can join qualitative, ethnographic, and behavioral studies in providing converging lines of evidence to better understand the processes involved in learning to read. Specifically, we believe that they can inform us about neuronal organizations that may lead to, and affect the course of, cognitive and linguistic development in diverse populations. Combining neuroscience and education represents a new frontier in science; as such it will take time and diligence to develop our foundational knowledge in this new field of mind, brain, and education studies.

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1. INTRODUCCIÓN

Este trabajo surgió a partir del año en que tuve como alumno a Luciano, un ser especialísimo. Bueno, dulce, cariñoso, servicial, muy hábil con las manos, con gran pasión por la naturaleza, la vida y el trabajo rural, pero con enormes dificultades para resolver situaciones lógico-matemáticas, extraer ideas principales de un texto, leer, redactar.

Me pregunté una y mil veces qué o cómo hacer para que aprendiera esos temas. Probé con las más variadas actividades, leí toda clase de bibliografía de la biblioteca escolar, comprada o prestada, hasta que me topé con las Inteligencias Múltiples. El tema me atrapó y decidí investigar más. Entonces quise volcarlo en un escrito para compartirlo con otros docentes que como yo, se encuentran ante situaciones similares y no tienen un equipo de profesionales a quien acudir en busca de ayuda.

Desgraciadamente Luciano ya no es más mi alumno, como la edad se lo permite, tiene 16 años, trabaja de día y concurre, por ahora, a la escuela nocturna para obtener su certificado de terminación de estudios primarios. No sé si hubiese podido ayudarlo, pero seguramente lo hubiese comprendido más y tal vez los dos nos hubiésemos sentido mejor.

2. ¿DE QUÉ SE TRATA?

En 1979 Howard Gardner, como investigador de Harvard, recibió el pedido de un grupo filantrópico holandés, la Fundación Bernard Van Leer, de dedicarse a investigar el potencial humano. A pesar de que Gardner ya había estado pensando en el concepto de “muchas clases de mentes” desde por lo menos mediados de la década del setenta, la publicación de su libro *Frames of Mind (Estructuras de la mente)* en 1983 marcó el nacimiento efectivo de la teoría de las inteligencias múltiples:

“En mi opinión, la mente tiene la capacidad de tratar distintos contenidos, pero resulta en extremo improbable que la capacidad para abordar un contenido permita predecir su facilidad en otros campos. En otras palabras, es de esperar que el genio (y a posteriori, el desempeño cotidiano) se incline hacia contenidos particulares: los seres humanos han evolucionado para mostrar distintas inteligencias y no para recurrir de diversas maneras a una sola inteligencia flexible.”

(Gardner, *Estructuras de la Mente*, 1994: 11)

“La teoría de las inteligencias múltiples puede describirse de la manera más exacta como una filosofía de la educación, un actitud hacia el aprendizaje, o aún como un meta-modelo educacional en el espíritu de las ideas de John Dewey sobre la educación progresiva. No es un programa de técnicas y estrategias fijas. De este modo, ofrece a los educadores una oportunidad muy amplia para adaptar de
manera creativa sus principios fundamentales a cualquier cantidad de contextos educacionales". (Armstrong, Las inteligencias múltiples en el aula -12)

“Desde mi punto de vista, la esencia de la teoría es respetar las muchas diferencias que hay entre los individuos; las variaciones múltiples de las maneras como aparecen; los distintos modos por los cuales podemos evaluarlos, y el número casi infinito de modos en que estos pueden dejar una marca en el mundo”. (Gardner, prólogo de Las inteligencias múltiples en el aula de Armstrong.)

La orientación crítica de Gardner hacia el concepto tradicional de inteligencia, está centrada en los siguientes puntos:

- La inteligencia ha sido normalmente concebida dentro de una visión uniforme y reductiva, como un constructo unitario o un factor general.
- La concepción dominante ha sido que la inteligencia puede ser medida en forma pura, con la ayuda de instrumentos estándar.
- Su estudio se ha realizado en forma descontextualizada y abstracta, con independencia de los desafíos y oportunidades concretas, y de factores situacionales y culturales.
- Se ha pretendido que es una propiedad estrictamente individual, alojada sólo en la persona, y no en el entorno, en las interacciones con otras personas, en los artefactos o en la acumulación de conocimientos.

Estamos acostumbrados a pensar en la inteligencia como una capacidad unitaria o como abarcativa de varias capacidades. Sin embargo, en oposición a esos enfoques de perfil más bien reduccionista, Gardner propone un enfoque de *inteligencias múltiples*. Se trata de un planteamiento sugerente, y acaso también provocativo, que permite problematizar sobre el fenómeno de la inteligencia más allá del universo de lo cognitivo.

Para este autor una inteligencia es la "capacidad de resolver problemas o de crear productos que sean valiosos en uno o más ambientes culturales", (1994; 10). Lo sustantivo de su teoría consiste en reconocer la existencia de ocho inteligencias diferentes e independientes, que pueden interactuar y potenciarse recíprocamente. La existencia de una de ellas, sin embargo, no es predictiva de la existencia de alguna de las otras.(1)

Al definir la inteligencia como una capacidad Gardner la convierte en una destreza que se puede desarrollar. Gardner no niega el componente genético.

Todos nacemos con unas potencialidades marcadas por la genética. Pero esas potencialidades se van a desarrollar de una manera o de otra dependiendo del medio ambiente, nuestras experiencias, la educación recibida, etc.

Ningún deportista de elite llega a la cima sin entrenar, por buenas que sean sus cualidades naturales. Lo mismo se puede decir de los matemáticos, los poetas, o de la gente emocionalmente inteligente.

Howard Gardner añade que igual que hay muchos tipos de problemas que resolver, también hay muchos tipos de inteligencia. Hasta la fecha Howard Gardner y su equipo de la universidad de Harvard han identificado ocho tipos distintos:
Inteligencia Lógico-matemática, la que utilizamos para resolver problemas de lógica y matemáticas. Es la inteligencia que tienen los científicos. Se corresponde con el modo de pensamiento del hemisferio lógico y con lo que nuestra cultura ha considerado siempre como la única inteligencia.

Inteligencia Lingüística, la que tienen los escritores, los poetas, los buenos redactores. Utiliza ambos hemisferios.

Inteligencia Espacial, consiste en formar un modelo mental del mundo en tres dimensiones, es la inteligencia que tienen los marineros, los ingenieros, los cirujanos, los escultores, los arquitectos, o los decoradores.

Inteligencia Musical es, naturalmente la de los cantantes, compositores, músicos, bailarines.

Inteligencia Corporal - kinestésica, o la capacidad de utilizar el propio cuerpo para realizar actividades o resolver problemas. Es la inteligencia de los deportistas, los artesanos, los cirujanos y los bailarines.

Inteligencia intrapersonal es la que nos permite entendernos a nosotros mismos. No está asociada a ninguna actividad concreta.

Inteligencia interpersonal, la que nos permite entender a los demás, y la solemos encontrar en los buenos vendedores, políticos, profesores o terapeutas.

La inteligencia intrapersonal y la interpersonal conforman la Inteligencia emocional y juntas determinan nuestra capacidad de dirigir nuestra propia vida de manera satisfactoria.

Inteligencia Naturalista, la que utilizamos cuando observamos y estudiamos la naturaleza. Es la que demuestran los biólogos o los herbolarios.

Naturalmente todos tenemos las ocho inteligencias en mayor o menor medida, (tal y como explica Fernando Lapalma en este artículo). Al igual que con los estilos de aprendizaje no hay tipos puros, y si los hubiera les resultaría imposible funcionar. Un ingeniero necesita una inteligencia espacial bien desarrollada, pero también necesita de todas las demás, de la inteligencia lógico matemática para poder realizar cálculos de estructuras, de la inteligencia interpersonal para poder presentar sus proyectos, de la inteligencia corporal - kinestésica para poder conducir su coche hasta la obra, etc.

Si la inteligencia es el conjunto de capacidades que nos permite resolver problemas o fabricar productos valiosos en nuestra cultura, la inteligencia emocional es el conjunto de capacidades que nos permite resolver problemas relacionados con las emociones. Con nuestras emociones (inteligencia intrapersonal) y con las de los demás (inteligencia interpersonal).

Daniel Goleman dice que "tenemos dos mentes, una que piensa y otra que siente" Otra manera de entenderlo es que el pensamiento es un proceso con muchas caras. Las emociones son una de las facetas de ese proceso, una parte tan integral del mismo como el pensamiento lógico, lineal y verbal del hemisferio izquierdo. De la misma manera que no pensamos sólo con un único hemisferio, sino que los dos son necesarios, tampoco nos limitamos a procesar la información, además la sentimos.

A la hora de andar por la vida es más importante saber descifrar nuestras emociones que saber despejar ecuaciones de segundo grado. Las empresas lo saben bien y cuando contratan a alguien no piden sólo un buen currículo, además buscan un conjunto de características psicológicas como son la capacidad de llevarse bien con los colegas, la capacidad de resolver conflictos, la capacidad de comunicarse, etc.
que tengamos o no esas cualidades o habilidades va a depender del grado de desarrollo de nuestra inteligencia emocional.

Cuando hacemos un examen de poco nos sirve saber las respuestas si nos ponemos tan nerviosos que no somos capaces de contestar las preguntas adecuadamente. Naturalmente tampoco es suficiente estar tranquilo, hay que saber las respuestas del examen y saber mantener la calma.

Pero mientras que normalmente pasamos mucho tiempo aprendiendo (y enseñando) las respuestas del examen no solemos dedicarle ni un minuto a aprender (o enseñar) cómo controlar los nervios o cómo calmarnos.

Nuestro sistema educativo no es neutro, no le presta la misma atención a todos los estilos de aprendizaje, ni valora por igual todas las inteligencias o capacidades. No hay más que mirar el horario de cualquier escolar para darse cuenta de que la escuela no le dedica el mismo tiempo a desarrollar la inteligencia corporal - kinestésica y la inteligencia lingüística, por poner un ejemplo.

En cuanto a la inteligencia emocional (la capacidad de entender y controlar las emociones) la escuela simplemente la ignora. No es tanto que no la considere importante, es que su aprendizaje se da por supuesto.

El colegio no hace más que reflejar la visión de la sociedad en su conjunto. A nadie le extraña que un alumno tenga que hacer muchos ejercicios para aprender a resolver ecuaciones, sin embargo, no nos planteamos la necesidad de adiestrar a nuestros alumnos en como prestar atención durante una conversación, por ejemplo, o concentrarse como lo hacen en la cultura oriental.

Naturalmente, además, no sabemos como hacerlo. Mejor dicho, porque nunca lo hemos considerado parte de nuestra tarea no hemos aprendido a hacerlo. Lo que se está planteando ahora por primera vez es que, de la misma manera que practicamos y desarrollamos la capacidad de escribir o la capacidad de hacer deporte podemos desarrollar y practicar el conjunto de capacidades que nos permiten relacionarnos de manera adecuada con el mundo exterior y con nosotros mismos, es decir la inteligencia emocional. (2)

3. ¿UNA O MUCHAS?

Gardner ha declarado que cuando formuló en 1983 la teoría de las inteligencias múltiples, encontró poca acogida entre sus compañeros de profesión: "Mi teoría gustó a unos cuantos psicólogos, desagrado a unos pocos más y la mayoría la ignoró", (1995; 14). Un rasgo llamativo de esta situación es que cuando ya se encontraba convencido de que su proposición estaba condenada al olvido, como tantas otras en la historia de la disciplina, inesperadamente comenzó a recibir una gran atención de los educadores: "Existía otro público con un auténtico interés por mis ideas: el público de los profesionales de la educación", (1995; 15).

Este episodio no es meramente anecdótico. Detrás de este hecho late una cuestión de carácter epistemológico que merece un comentario. La teoría no recibió en ningún momento una aprobación al interior de la disciplina en que se originó, ya sabemos que los miembros del ámbito la ignoraron. Ni siquiera fue debatida en forma amplia y rigurosa. Sin embargo, despertó un interés positivo en otro ámbito, y
rápidamente comenzó a ser consumida y aplicada, lo que derivó en la aparición de nuevas prácticas pedagógicas e institucionales.(3)

Lamentablemente, a pesar de su valor intrínseco y sus perspectivas de aplicación, la teoría de Howard Gardner se presenta como una propuesta no totalmente clara desde el punto de vista científico. Si bien muchos de los argumentos gardnerianos sostenidos en su libro Estructuras de la mente (1994) parecen coherentes y siguen las propuestas planteadas por otros científicos; hay algunos puntos oscuros en la misma.

El constructo de inteligencia propuesto por Gardner supone -entre otros criterios- la existencia de un correlato neurofisiológico que justifique la existencia de ellas. De esta manera cada una de las ocho inteligencias, está ubicada en un lugar determinado de la corteza cerebral y -si este llegara a dañarse- se evidenciaría en una disminución de dicha capacidad. Su postura está muy acorde con algunos descubrimientos llevados a cabo en el campo de la neurobiología que parecieran indicar la posible localización de ciertas funciones en el cerebro. Así por ejemplo, se sabe que el hemisferio izquierdo está más relacionado con las capacidades lingüísticas, mientras el derecho lo está con las espaciales y musicales. No obstante, la total ubicación de cada inteligencia, en los términos que Gardner utiliza, es todavía incierta.

Existen otros puntos teóricos en los cuales la propuesta de Gardner ofrece puntos flacos. Uno de ellos puede ser la noción de modularidad, que sirve para fundamentar la total independencia de cada capacidad. Dicha noción fue tomada en préstamo de la propuesta de Jerry Fodor, quien sostiene la existencia de ciertas capacidades modulares que constituyen la mente humana, como el lenguaje o la percepción. No obstante, la noción gardneriana guarda poca o ninguna relación con la descripción inicial que este autor realiza de los módulos de la mente. Para Fodor ellos funcionan como mecanismos automáticos y predeterminados, mucho más fijos y ciegos que las inteligencias propuestas por Gardner.

Pero sobre todo, en lo que las ideas de Gardner parecen ser más frágiles es en la medición de cada una de estas inteligencias en la actuación real de cada sujeto.

Ahora bien, ¿cómo puede medirse habilidades "teóricamente separadas", pero "realmente" tan integradas unas con otras? Uno de los instrumentos de medición desarrollados en los últimos años, fue el MIDAS (Multiples Intelligence Development Assessment Scales) creado por el Dr. Branton Shearer del Multiple Intelligence Research and Consulting, de Ohio. El MIDAS es una entrevista en la cual el sujeto se refiere a sus habilidades y preferencias y a partir de esa información -corroborada a veces por padres o maestros- se observa la distribución de cada habilidad. Como parte de una investigación llevada a cabo en el seno de la Universidad Católica de Valparaíso, dicho instrumento fue traído a Chile en 1995 y traducido al español.

Al analizarse los puntajes pudo verse que las distintas inteligencias se encontraban altamente correlacionadas entre sí. En otras palabras, un individuo tendría a tener puntajes igualmente altos e igualmente bajos en casi todas las capacidades rotuladas como inteligencias. Dicha interrelación de los factores, no permite hablar de una independencia tan radical como Gardner la propone. Más bien podría hablarse de grandes tendencias generales que parecen evidenciarse en la conducta del sujeto. En otras palabras, sea cual sea el estatus teórico de la teoría de Gardner, su medición empírica carece de claridad.
Si bien es posible hablar de habilidades humanas diferentes, es necesario cuestionarse las afirmaciones últimas de esta propuesta: ¿son dichas habilidades tan independientes y autónomas como Gardner sostiene? ¿Pueden considerarse con una importancia tan medular para la actividad intelectual al punto de ser denominadas inteligencias? (4)

4. ¿QUÉ DIFICULTADES OFRECE?
Todo este andamiaje de las inteligencias múltiples trae a la realidad unas aplicaciones que no se pueden dejar pasar por alto ya que a la vez afectan al alumno y al maestro.

- Implantar estas ideas dentro de un currículo tradicionalista no es fácil de lograr.
- Necesidad de adiestramiento en servicio.
- El programa de clases y los horarios rígidos han de mortificarse para darle paso a horarios más flexibles.
- La necesidad de tiempo extra para preparar lecciones y materiales didácticos.
- Necesidad de más personal docente en algunas escuelas.
- La necesidad de un currículo que tenga al estudiante como centro del proceso enseñanza aprendizaje y que este sea considerado como un individuo.
- El alumno tiene que prepararse para que pueda trabajar con estos nuevos enfoques.
- El estudiante ha de evaluarse en forma distinta a la que está acostumbrado.
- El uso de las inteligencias múltiples como herramienta de instrucción.
- Necesidad de más tiempo para que el estudiante pueda trabajar en una forma diferente a la acostumbrada.
- Temor de ponerle "sellos" al estudiante.
- Uso de la tecnología y materiales concretos.

Frente al inicio de un nuevo milenio, éstas ideas presentan un reto a los educadores. ¿Se sigue dando vueltas en la búsqueda de nuevas alternativas sin detenerse a pensar o se agilizan formas "atrevidas", con los pies puestos en tierra, que puedan ayudar a formar un individuo que en verdad pueda ser útil a su familia, a su comunidad y a la sociedad en que vive? Todo cambio en la educación tiene que contar con el maestro de la sala de clases y lógicamente con el alumno que es el centro de todo proceso educativo.

Si la inteligencia es la capacidad que le permite al ser humano resolver problemas, ¿por qué no le brindamos a éste la oportunidad de desarrollarla a plenitud en la medida que lo permita su condición particular? (5)

5. ¿CÓMO EMPEZAR?
Con antelación a la aplicación de cualquier modelo de aprendizaje basado en las inteligencias múltiples, debemos en primera instancia aplicárnoslo a nosotros mismos como educadores y estudiantes.
adultos, porque si no tenemos una comprensión de la teoría íntimamente ligada a la experiencia y hayamos hecho nuestro este conocimiento, es decir estemos en condiciones de aplicarlo, no como copia, sino como modelo propio, no podremos trasmitirlo con éxito.

Por lo tanto el primer paso es determinar la naturaleza y calidad de nuestras propias inteligencias múltiples y buscar las maneras de desarrollarlas en nuestras propias vidas. Cuando nos abocamos a esta tarea se pondrá de manifiesto como nuestra particular fluidez o falta de ella afecta nuestras competencias como educadores. Esta no es una tarea fácil, por cuanto no existe una herramienta de medición que nos asegure cual es el grado o el cociente alcanzado en cada una de las inteligencias, por lo que debemos ampliar nuestro campo de observación y a través de una evaluación realista de sus desempeños en las muchas clases de actividades, tareas y experiencias que se asocian con cada inteligencia es que obtendremos indicadores sobre el nivel alcanzado en cada una de ellas.

Esta teoría es una herramienta especialmente útil para observar nuestras fortalezas y debilidades en las áreas que utilizamos los docentes, porque nos permite observar todas las actividades que realizamos para alcanzar nuestros objetivos, y también cuales acciones dejamos de lado por cuanto no nos sentimos cómodos al ejecutarlas.(6)

Desarrollar hasta un grado aceptable de competencia cada una de las inteligencias, depende según Armstrong de tres factores principales:

- **Dotación biológica**, incluyendo los factores genéticos o hereditarios, y los daños o heridas que el cerebro haya podido recibir antes, durante o después del nacimiento.

- **Historia de la vida personal**, incluyendo las experiencias con los padres, docentes, pares, amigos y otras personas que ayudan a hacer crecer las inteligencias o las mantienen en un bajo nivel de desarrollo.

- **Antecedente cultural o histórico**, incluyendo la época y el lugar donde uno nació y se crió, y la naturaleza y estado de los desarrollos culturales o históricos en diferentes dominios.

6. ¿CÓMO PLANIFICAR?

Haciendo un diagnóstico de las potencialidades de los niños y teniendo en cuenta esta grilla, podremos seleccionar las actividades a realizar.

<table>
<thead>
<tr>
<th>AREA LINGÜÍSTICO-VERBAL</th>
<th>DESTACA EN</th>
<th>LE GUSTA</th>
<th>APRENDE MEJOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lectura, escritura, narración de historias, memorización de fechas, piensa en palabras</td>
<td>Leer, escribir, contar cuentos, hablar, memorizar, hacer puzzles</td>
<td>Leyendo, escuchando y viendo palabras, hablando, escribiendo, discutiendo y debatiendo</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LÓGICA - MATEMÁTICA</th>
<th>DESTACA EN</th>
<th>LE GUSTA</th>
<th>APRENDE MEJOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matemáticas, razonamiento, lógica, resolución de problemas, pautas.</td>
<td>Resolver problemas, cuestionar, trabajar con números, experimentar</td>
<td>Usando pautas y relaciones, clasificando, trabajando con lo abstracto</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ESPACIAL</th>
<th>DESTACA EN</th>
<th>LE GUSTA</th>
<th>APRENDE MEJOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lectura de mapas, gráficos, dibujando, laberintos, puzzles.</td>
<td>Diseñar, dibujar, construir, crear, soñar</td>
<td>Trabajando con dibujos y colores, visualizando, usando</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Imaginando cosas, visualizando</td>
<td>Despierto, mirar dibujos, dibujando</td>
<td>Su ojo mental, pintando</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td><strong>CORPORAL - KINÉSTÉSICA</strong></td>
<td>Atletismo, danza, arte dramático, trabajos manuales, utilización de herramientas</td>
<td>Moverse, tocar y hablar, lenguaje corporal</td>
<td>Tocando, moviéndose, procesando información a través de sensaciones corporales</td>
</tr>
<tr>
<td><strong>MUSICAL</strong></td>
<td>Cantar, reconocer sonidos, recordar melodías, ritmos</td>
<td>Cantar, tararear, tocar un instrumento, escuchando música</td>
<td>Ritmo, melodía, cantar, escuchando música y melodías</td>
</tr>
<tr>
<td><strong>INTERPERSONAL</strong></td>
<td>Entendiendo a la gente, liderando, organizando, comunicando, resolviendo conflictos, vendiendo</td>
<td>Tener amigos, hablar con la gente, juntarse con gente</td>
<td>Compartiendo, comparando, relacionando, entrevistando, cooperando</td>
</tr>
<tr>
<td><strong>INTRAPERSONAL</strong></td>
<td>Entendiéndose a sí mismo, reconociendo sus puntos fuertes y sus debilidades, estableciendo objetivos</td>
<td>Trabajar solo, reflexionar, seguir sus intereses</td>
<td>Trabajando solo, haciendo proyectos a su propio ritmo, teniendo espacio, reflexionando</td>
</tr>
<tr>
<td><strong>NATURALISTA</strong></td>
<td>Entendiendo la naturaleza, haciendo distinciones, identificando la flora y la fauna</td>
<td>Participar en la naturaleza, hacer distinciones</td>
<td>Trabajar en el medio natural, explorar los seres vivientes, aprender acerca de plantas y temas relacionados con la naturaleza</td>
</tr>
</tbody>
</table>

Cuadro traducido por Nuria de Salvador de *Developing Students' Multiple Intelligences*.


Por otra parte, Armstrong, en su libro *Las inteligencias múltiples en el aula*, muestra un la forma de planificar y llevar adelante clases sobre la base de IM, propone variados ejercicios, modelos de clases y una excelente información para ayudar al docente.
Este es un ejemplo de esquema de planificación que propone:

7. ¿DÓNDE SE APLICA?
Según Fernando Lapalma, ya existen instituciones educativas trabajando con las inteligencias múltiples aquí y en otros países. Estados Unidos, tanto a nivel privado como a nivel estatal, (con sus escuelas Key y otros proyectos como Spectrum, para nivel inicial y Arts Propel para nivel medio), Canadá, Israel, Venezuela, Italia, Australia, Nueva Zelanda, entre otros son los que han tomado la delantera en este cambio. Siendo en algunos de ellos ya oficial su aplicación.

Luego de diez años de aplicación quedan como corolario los siguientes:

- Minimización de los problemas de conducta
- Aumento de la autoestima
- Desarrollo de la cooperación
Incremento del número de líderes positivos
Crecimiento del interés y afecto por la escuela y el estudio
Presencia constante del humor
Incremento del conocimiento en un 40% (7)

8. CONCLUSIONES
En nuestra realidad educativa, no todo es válido ni todo es equivocado, en las reformas educativas latinoamericanas se deben conocer las distintas teorías y experiencias educativas en el mundo para poder reformularlas o adaptarlas a nuestras necesidades.

Independientemente de la polémica de considerar “inteligencias”, “capacidades” o “fortalezas” a esas facultades más o menos desarrolladas en las personas, a los docentes nos resulta de suma utilidad diagnosticarlas en nuestros alumnos, ya que nos permite comprenderlos más y delinear las actividades más apropiadas para obtener los máximos aprovechamientos. Claro que para eso debemos informarnos, recibir ayuda, disponer de tiempo extra, institucionalizar el trabajo y comprometer a toda la comunidad. Tarea para nada fácil pero no imposible.

El docente intuitivamente ya hace adecuaciones y actividades variadas y especiales, falta fundamentarlas, sistematizarlas, incorporarlas a la tarea diaria y, a la hora de evaluar tenerlas en cuenta. No podemos sólo hacerlos cantar y bailar y después evaluarlos por escrito.

Por otra parte, debemos tratar de desarrollar las facultades que no lo están y creo que allí está el mayor desafío. La capacidad de inventiva y creatividad, siempre puesta de manifiesto por los docentes, sólo necesita ser “activada” por un estímulo que bien puede ser éste.

Si seguimos encontrando culpables fuera de nosotros mismos y no buscamos las formas de cambiarnos y cambiar a nuestros alumnos, no hay futuro para los países latinoamericanos.

NOTAS
2- Extractado de un artículo publicado por Fernando Lapalma, autor del proyecto ÍMPETU y de diferentes cursos y seminarios sobre el tema.
3- Del trabajo de Ricardo López Pérez.
5- De la Conferencia pronunciada en el SIMPOSIO INTERNACIONAL DE EDUCACIÓN EN LA DIVERSIDAD, celebrado en panamá, del 28 al 30 de enero de 2000 por Magíster Joaquín Padovani, Departamento de Matemáticas y Ciencias Aplicadas. Universidad Interamericana de Puerto Rico.
7- Del trabajo de Fernando Lapalma
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OTROS SITIOS RECOMENDADOS

Juego didáctico basado en Inteligencias Múltiples

Juego Didáctico. Fracciones Mágicas de AutoMind. ¡Nunca pensé que era tan fácil. 1. Composición de Piezas: El juego tiene dos conjuntos de piezas: ...
   http://www.automind.cl/FRAC.HTM

INTELIGE

Aplicando Inteligencias Múltiples. ANTECEDENTES DEL CURSO. 1.- NOMBRE DEL CURSO: Aplicando Inteligencias Múltiples. 2.-FUNDAMENTACIÓN ...
   http://www.automind.cl/INTELIGE.HTM

Test de Inteligencias Múltiples

Test de Inteligencias Múltiples Esta herramienta ha sido adaptada de la obra de Howard Gardner en el tema de inteligencias múltiples e incluye una ...
   http://www.fleming.edu.pe/spn/testintelig.htm
Contactar

Revista Iberoamericana de Educación

Principal OEI
Cognitive Neuroscience: implications for education?

JOHN GEAKE, Oxford Brookes University, UK
PAUL COOPER, The University of Leicester, UK

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
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 con-
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 morphogenesis, 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.

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 neurogenesis 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 neurogenesis. 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 naïve 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 naïve 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 reinforce-
ment 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 relation-
ships 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 professionalism 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 professionalism 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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Annual review

Neuroscience and education

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

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

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

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

Teaching

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

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

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

By the age of around 10 years, brain metabolism reduces to adult levels for most cortical regions. The general pattern of brain development is clear. There are bursts of synaptogenesis, peaks of density, and then synapse rearrangement and stabilisation with myelinisation, occurring at different times and rates for different brain regions (i.e., different sensitive periods for the development of different types of knowledge). Brain volume quadruples between birth and adulthood, because of the proliferation of connections, not because of the production of new neurons. Nevertheless, the brain is highly plastic, and significant new connections frequently form in adulthood in response to new learning or to environmental insults (such as a stroke). Similarly, sensitive periods are not all-or-none. If visual input is lacking during early development, for example, the critical period is extended (Fagiolini & Hensch, 2000). Nevertheless, visual functions that develop late (e.g., depth perception) suffer more from early deprivation than functions that are relatively mature at birth (such as colour perception, Maurer, Lewis, & Brent 1989). Thus more complex abilities may have a lower likelihood of recovery than elementary skills. One reason may be that axons have already stabilised on target cells for which they are not normally able to compete, thereby causing irreversible reorganisation.

It is important to realise that there are large individual differences between brains. Even in genetically identical twins, there is striking variation in the size of different brain structures, and in the number of neurons that different brains use to carry out identical functions. This individual variation is coupled with significant localisation of function. A basic map of major brain subdivisions is shown in Figure 1. Although adult brains all show this basic structure, it is thought that early in development a number of possible developmental paths and end states are possible. The fact that development converges on the same basic brain structure across cultures and gene pools is probably to do with the constraints on development present in the environment. Most children are exposed to very similar constraints despite slightly different rearing environments. Large differences in environment, such as being reared in darkness or without contact with other humans, are thankfully absent or rare. When large environmental differences occur, they have notable effects on cognitive function. For example, neuroimaging studies show that blind adults are faster at processing auditory information than sighted
controls, and that congenitally deaf adults are faster at processing visual information in the peripheral field than hearing controls (e.g., Neville & Bavelier, 2000; Neville, Schmidt, & Kutas, 1983; Röder, Rösler, & Neville, 1999).

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

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

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

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

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

**Selected studies from cognitive neuroscience with interesting implications for education**

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

**Language**

Despite sharing 98.5% of our genome with chimpanzees, we humans can talk and chimps cannot. Interestingly, genes expressed in the developing brain may hold part of the answer. For example, a gene called FOXP2 differs in mouse and man by 3 amino acid differences, two of which occurred after separation from the common human-chimp ancestor about 200,000 years ago (Marcus & Fisher, 2003). This gene is implicated in a severe developmental disorder of speech and language that affects the
control of face and mouth movements, impeding speech. Neurally, accurate vocal imitation appears to be critical for the development of speech (Fitch, 2000). Hence when linguistic input is degraded or absent for various reasons (e.g., being hearing impaired, being orally impaired), speech and language are affected. Studies of normal adults show that grammatical processing relies more on frontal regions of the left hemisphere, whereas semantic processing and vocabulary learning activate posterior lateral regions of both hemispheres. For reasons that are not yet well understood, the brain systems important for syntactic and grammatical processing are more vulnerable to altered language input than the brain systems responsible for semantic and lexical functions. ERP studies show that when English is acquired late due to auditory deprivation or late immigration to an English-speaking country, syntactic abilities do not develop at the same rate or to the same extent (Neville et al., 1997). Late learners do not rely on left hemisphere systems for grammatical processing, but use both hemispheres (Weber-Fox & Neville, 1996). ERP studies also show that congenitally blind people show bilateral representation of language functions (Röder et al., 2000). Blind people also process speech more efficiently (Hollins, 1989), for example they speed up cassette tapes, finding them too slow, and still comprehend the speech even though the recording quality suffers.

**Reading**

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

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

Although to date neuroimaging studies have largely confirmed what was already known about reading and its development from behavioural studies, neuroscience techniques also offer a way of distinguishing between different cognitive theories (e.g., whether dyslexia has a visual basis or a linguistic basis in children). Neuroimaging techniques also offer a potential means for distinguishing between deviance and delay
when studying developmental disorders. For example, our preliminary studies of basic auditory processing in dyslexic children using ERPs suggest that the phonological system of the dyslexic child is immature rather than deviant (Thomson, Baldeweg, & Goswami, in preparation). Dyslexic children show remarkable similarity in N1 response to younger reading level controls, while showing much larger N1 amplitudes than age-matched controls. Finally, PET studies have shown that the functional organization of the brain differs in literate and illiterate adults (Castro-Caldas et al., 1998). Portuguese women in their sixties who had never learned to read because of lack of access to education were compared with literate Portuguese women from the same villages in word and nonword repetition tasks. It was found that totally different brain areas were activated during nonword repetition for the illiterate versus literate participants. Learning to read and write in childhood thus changes the functional organization of the adult brain.

**Mathematics**

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

This last observation may suggest that the neural areas activated during finger-counting (a developmental strategy for the acquisition of calculation skills) eventually come to partially underpin numerical manipulation skills in adults. If this were the case, then perhaps finger counting has important consequences for the developing brain, and should be encouraged in school. In any event, neuroimaging techniques offer ways of exploring such questions. They can also be used to discover the basis of dyscalculia in children. For example, dyslexic children often seem to have associated mathematical difficulties. If dyslexia has a phonological basis, then it seems likely that the mathematical system affected in these children should be the verbal system underpinning counting and calculation. Dyslexic children with mathematical
difficulties may show neural anomalies in the activation of this system, but not in the activation of the parietal and premotor number systems. Children with dyscalculia who do not have reading difficulties may show different patterns of impairment. Knowledge of the neural basis of their difficulties could then inform individual remedial curricula.

**Direct effects of experience**

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

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

**Sleep and cognition**

The idea that sleep might serve a cognitive function dates from at least the time of Freud, with his analysis of dreams. Recent neuroimaging studies suggest indeed that Rapid Eye Movement (REM) sleep is not only associated with self-reports of dreaming but is important for learning and memory. Maquet and colleagues (Maquet et al., 2000) used PET to study regional brain activity during REM sleep following training on a serial reaction time task. During task learning, volunteer students were trained to press one of
6 marked keys on a computer in response to associated visual signals on the computer screen. Training lasted for 4 hours, from 4 p.m. until 8 p.m. The participants were then scanned during sleep. Controls were either scanned when awake while receiving the training, or were scanned when asleep following no training. It was found that the brain areas most active in the trained awake group when performing the task were also most active during REM sleep in the trained participants. They were not active during sleep in the untrained participants. Hence certain regions of the brain (in occipital and premotor cortex) were actually reactivated during sleep. It seems that REM sleep either allows the consolidation of memories or the forgetting of unnecessary material (or both together). When tested again on the computer task on the following day, significant improvement in performance was found to have occurred. Although the cellular mechanisms underlying this are not understood, it seems likely that memory consolidation relies on augmented synaptic transmission and eventually on increased synaptic density – the same mechanisms that structure the developing brain. Again, this suggests substantial plasticity even in adulthood, supporting educational emphases on life-long learning.

**Emotion and cognition**

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

**Neuromyths**

The engaging term ‘neuromyths’, coined by the OECD report on understanding the brain (OECD, 2002), suggests the ease and rapidity with which scientific findings can be translated into misinformation regarding what neuroscience can offer education. The three myths given most attention in the OECD report are (1) the lay belief in hemispheric differences (‘left brain’ versus ‘right brain’ learning etc.), (2) the notion that the brain is only plastic for certain kinds of information during certain ‘critical
periods’, and that therefore education in these areas must occur during the critical periods, and (3) the idea that the most effective educational interventions need to be timed with periods of synaptogenesis.

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

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

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

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

Another neuromyth is the idea that ‘implicit’ learning could open new avenues educationally. Much human learning is ‘implicit’, in the sense that learning takes place in the brain despite lack of attention to/conscious awareness of what is being learned (e.g., Berns, Cohen, & Mintun, 1997, but see Johnstone & Shanks, 2001). Almost all studies of implicit learning use perceptual tasks as their behavioural measures (e.g., the participant gets better at responding appropriately to ‘random’ letter strings in a computer task when the ‘random’ strings are actually generated according to an underlying ‘grammar’ or rule system which can be learned). There are no studies showing implicit learning of the cognitive skills underpinning educational achievement. These skills most likely require effortful learning and direct teaching.
Conclusions
Clearly, the potential for neuroscience to make contributions to educational research is great. Nevertheless, bridges need to be built between neuroscience and basic research in education. Bruer (1997) suggested that cognitive psychologists are admirably placed to erect these bridges, although he also cautioned that while neuroscience has learned a lot about neurons and synapses, it has not learned nearly enough to guide educational practice in any meaningful way. This view is perhaps too pessimistic. Cognitive developmental neuroscience has established a number of neural ‘markers’ that can be used to assess development, for example of the language system. These markers may be useful for investigating educational questions. Taking ERP signatures of language processing as a case in point, different parameters are robustly associated with semantic processing (e.g., N400), phonetic processing (e.g., mis-match negativity or MMN), and syntactic processing (e.g., P600). These parameters need to be investigated longitudinally in children. Certain patterns may turn out to be indicative of certain developmental disorders. For example, children at risk for dyslexia may show immature or atypical MMNs to phonetic distinctions (Csepe, 2003). Children with SLI (specific language impairment) may have generally immature auditory systems, systems resembling those of children 3–4 years younger than them (Bishop & McArthur, in preparation). Characteristic ERPs may also change in response to targeted educational programmes. For example, the MMN to phonetic distinctions may become sharper (as indexed by faster latencies) in response to literacy tuition in phonics (see Csepe, 2003). If this were to be established across languages, education would have a neural tool for comparing the efficiency of different approaches to the teaching of initial reading. For example, one could measure whether the MMN to phonetic distinctions sharpened in response to literacy tuition based on whole language methods. This is only one example of the creative application of currently available neuroscience techniques to important issues in education. Educational and cognitive psychologists need to take the initiative, and think ‘outside the box’ about how current neuroscience techniques can help to answer outstanding educational questions.

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Marriage Education and Neuroscience: Forging New Directions

Thomas W. Roberts

ABSTRACT. The purpose of this paper is to review recent findings in neuroscience for offering suggestions for further revisions of marriage education programs. Suggestions include paying more attention to the history of each partner; understanding the attachment styles of each partner; using both explicit and implicit learning; helping couples understand the role of emotions in rational decision making; promoting activation of the left hemisphere of the brain; focusing on process instead of content; increasing religious experiences and spirituality; the use of humor, absurdity and unordered material; and creating self-directed, technologically advanced modules that can be used as periodic checkups.

KEYWORDS. Explicit memory, implicit memory, learning, marriage education, neuroscience, couple relationship

The purpose of this paper is to review research studies on marriage education in light of recent findings in neuroscience. The main focus is to determine if advances in neuroscience offer new directions for developing and conducting marriage education programs. Recent findings in neuroscience have been applied to many areas of study, including child development, mental disorders, and education. To date, no application of brain research has been made to marriage education.
Marriage education is defined as a preventive/educational training approach for couples planning to be married (Sayer, Kohn, & Heavey, 1998). It includes specific skill development in such areas as communication, problem solving, and conflict negotiation (Bagarozzi & Rauen, 1981). Various methods of training are used to develop these skills, including lecture and group experiences. Marriage education has existed in some form for over sixty years (Schumm & Denton, 1980), and most marriage education participants report satisfaction with outcomes (Center for Marriage and Family, 1995; Stanley & Markman, 1997; Sullivan & Bradbury, 1997).

The aim of marriage education is to reduce the occurrence of a beautiful wedding turning into two warring factions a few months or years down the road. Stanley, Blumberg, and Markman (1999) described the typical scenario of how couples develop problems. Couples become attracted to each other from spending time together and sharing activities and interests. Over time they form a bond that is qualitatively different from other bonds leading to a long-term committed relationship. As time passes, the day-to-day activities of living together and mishandling normal conflicts that arise can begin to erode the bond that holds them together. Forgiveness and attempts at resolutions of problems give way to negative interpretations of the partner. As positive communications and commitment to each other wane, the decision to stay or leave the relationship becomes paramount.

With a current divorce rate of about 50%, family professionals, researchers, and clinicians have been sounding an alarm that couples need greater support to keep the marriage intact. Many states have initiatives that are aimed at prevention to support marriage. Many marriage education experts are touting the belief that much is to be gained by preventing divorce before it happens. Marriage education is one of the weapons in the arsenal to strengthen marriage.

Marriage education in the early years focused on such topics as parents-in-law, living arrangements, and physical exams (Schumm & Denton, 1980; Bagarozzi & Rausen, 1981). About half of the programs reviewed included topics on communication skills, problem solving, and conflict resolution. David Olson (1983) found that most pre-marriage programs lacked an inventory of questions about marriage and that clergy conducted about 25% of the marriages.

In recent years, marriage education has applied research on couple relationships to marriage education programs (Stanley, 2001). The logic for integrating research findings into training models of marriage education is simple; if we know which behaviors contribute to good
relationships and which ones contribute to bad relationships, we may be in a better position to prevent future disruption of families. The main tenet of these programs is to give people the skills they need to create strong lasting relationships.

Recent models in marriage education include Couple Communication (Miller, Wackman, & Nunnally, 1983); Relationship Enhancement (Guerney, 1977); and PREP (Stanley, Markman, St. Peters, & Leber, 1995; Trathen, 1995), a risk reduction approach based on skill building underscoring findings from marriage researchers such as John Gottman (e.g., Gottman & Krokoff, 1989). The Couple Communication program has been used in many different formats and with varied subjects (Wampler, 1990). Results show that participants improve their communication compared with the control group (Russell, Bagarozzi, Atilan, & Morris, 1984). The Relationship Enhancement program has been effective with a wide range of ages and types of couples (Heitland, 1986; Ridley, Jorgensen, Morgan, & Avery, 1982). Considerable research has been done on the PREP program and most studies have shown clear-cut evidence of its effectiveness (Cullen, 1999; Hahlweg, Markman, Thurmaier, Engl, & Eckert, 1996; Markman, Renick, Floyd, Stanley, & Clements, 1993).

While PREP has generated more positive outcomes than other approaches, some research findings have been negative. A study conducted in Holland with high risk couples found no difference with control subjects (Van Widenfelt, Hosman, Schapp, & van der Staak, 1996). Sullivan and Bradbury (1997) found that there was no difference on marital outcomes in those who participated in marriage education from those who did not. Other researchers have found that the selection factor may affect the outcome as well (Stanley & Markman, 1997).

There is no doubt that current models of marriage education are improvements over models used twenty and thirty years ago because we now have a better understanding of the causes of distress in couple relationships. There is still much to be learned and it is hoped that applying recent research on the brain will further the progress in creating more effective programs in marriage education.

**RELEVANT FINDINGS FROM NEUROSCIENCE**

Recent neuroscience research in the areas of learning, memory formation and retrieval, emotional memories, and relationship formation and maintenance are extremely important for applying to marriage edu-
cation. Most of the neuroscience findings have been made in the past decade and have not been integrated into clinical or educational practice.

First, in terms of learning, brain researchers have concluded that we are our synapses (LeDoux, 1996). Learning is the result of forming and strengthening specific synaptic connections in the brain. Existing neurons grow through linking dendrites that project from neurons. There is evidence that neurons grow and change through experiences. The growth of neural connections is what is understood as brain plasticity, or the ability of change throughout life. This change is dependent on the neural connections involved and the types of challenges encountered.

Learning involves the brain integrating various disjointed stimuli and fashioning a consistent outlook about what is taking place (Ramachandran & Blakeslee, 1998). New input must be flawlessly integrated into the preexisting belief system. Consequently, one’s belief system remains fairly static over time as new information is merged into the preexisting belief system. While the worldview remains stable because the brain forces new information to conform to preexisting beliefs, it is not necessarily accurate (Ratey, 2001). The brain is capable of changing, however. Researchers have demonstrated that when new information is inputted in the brain, about 80% of how the brain processes this information is stored in the brain and the remaining 20% comes from the new information (Marchese, 2000).

David Sousa’s (1995) brain-based education suggests teaching school children through a process that engage both hemispheres of the brain. It is relevant to apply research on learning in children to learning in adults since brain processes are very similar and researchers have found that plasticity extends throughout one’s lifetime (Kotulak, 1997). The right hemisphere is considered the creative intuitive hemisphere, while the left hemisphere is the center for language, verbal ability, and problem solving. To some degree gender differences have been based on laterality, or left-right brain differences. Left hemisphere-dominant individuals are more likely to be better problem solvers, verbal, and female. Males, on the other hand, are more likely to use visual-spatial situations. Learning environments tend to be highly left brain-oriented and therefore, more comfortable for females. Laterality is viewed as task-specific rather than as an absolute type of difference. According to Sousa (1995), learning should involve both verbal and visual imagery. Teachers and instructors generally spend little time in developing visual cues.

While brain-based education has been severely criticized by Bruer (1999) and lateralization has been questioned by Gackenbach (1999), both brain-based education and lateralization may have some merit in
understanding how the brain is integrative and works as a whole. For example, some researchers have focused on the role the left hemisphere plays in fitting new information into existing models (Ramachandran & Blakeslee, 1998). The right hemisphere questions the status quo and causes revisions in the belief system. This finding suggests that the best way to challenge beliefs and established patterns in the brain may be to overwhelm it with inconsistencies in order for the right hemisphere to initiate revisions in the learning process. This inconsistency will start the brain scanning for more efficient way to represent the information.

Neuroscience researchers continue to discover new findings about human learning that can be valuable when applied to education models. For example, researchers have found that learning seems to be enhanced when persons are self-directed. A learning environment in which students actively participate in the process greatly increases what they retain (Abbott, 1997). Learning is a process where the instructor slowly guides the participant toward self-direction in their learning. Engaging the whole organism through social interaction allows students to work individually and together in solving problems. Any model of education, including marriage education, could be more effective if it allows individuals self-direction and engages the whole person.

In addition, creating mental imagery of what is being learned enhances learning. Visualization seems to vastly improve what is being learned. Furthermore, movement helps integrate the brain and increases learning in young children (Languis, Sanders, & Tipps, 1980) and exercise reduces depression in adults. Finally, learning that takes place in a certain situation will be recalled better under a similar situation. This is called state-dependent learning (LeDoux, 1996). This finding suggests that for adult learners in marriage education programs, the setting of the training should be very closely related to the future setting where the new skill is needed.

Researchers have found that learning is not permanent and can be changed by a strong desire to change and by practicing new behaviors (Ratey, 2001). By deliberate attempts to create new patterns, one can force the brain to develop new pathways. New responses can be learned through practicing exercises that simulate real life experiences.

Two other useful areas of brain and learning research are relevant. First, the brain seems to tire with repetition and actually shuts down input that is repetitive. In other words, the brain recognizes familiar input and ignores it (Ratey, 2001). For persons to remain engaged in active learning, material must be revised by using different visual cues and new concepts.
Not only does the brain have to be stimulated with novelty, but some researchers believe that new technology of computers and video games also have created different brain connections in younger people. In effect, their brains have been wired in such a way that visual cues are inseparable to the learning process. While older learners may learn with a lecture format, young adults, raised on video games and interactive computers, must be engaged with technology.

A second relevant finding from neuroscience is about the relation between emotions and learning. Learning has been viewed as primarily a function of the neocortex, or the part of the brain generally linked to cognition and logical and abstract thinking. Beliefs about learning are no longer viewed as an exclusively cognitive process. We know from child studies that negative emotions can contribute to poor learning and that positive ones can benefit the learning process (Izard, 1984). Antonio Damasio (1994) has argued that there are no cognitive (or higher) and emotional (or lower) brain centers. He claims that the neocortex does not function adequately without emotional input. He believes that there is a collection of systems in the brain that are well integrated with a full-body involvement of the endocrine system, heart, and other body regulators that affect cognition and emotion. He views thinking and emotions as integrative functions that are dependent on each other.

Not only are emotions and cognitions dependent on each other, there is also some evidence that the appraisal theory, which states that emotions are the product of being labeled after passing through the cognitive part of the brain, is not supported by new brain research. According to LeDoux (1996) sensory information is carried from the thalamus to both the neocortex where cognition takes place and to the amygdala, the center of emotional response. His findings suggest that learning takes two different paths—one path of learning involves sensory perceptions that go to the neocortex and then to the emotional center and one in which sensory perceptions pass through the emotional center of the brain before they are processed in the neocortex. If a sensory stimulus can go directly to the amygdala and bypass the neocortex, it means that we can react before we recognize what we are reacting to. This implies that emotional learning can take place implicitly outside of consciousness. Memories can be formed without conscious awareness creating an automatic emotional response.

Not only can we have emotional responses before we know what we are responding to, but also emotions that are central to the learning of conscious explicit information. A person is much more likely to recall something abstract if it involved an emotional response (Goleman,
Events that take place during an emotional state tend to be retained. Emotional learning may be the key to long-lasting effects of marriage education programs. Instead of keeping emotions under wraps, marriage educators should find ways to increase emotional content.

Cahill and McGaugh (1998) found that men and women access different parts of the brain in forming an emotional memory. The right-hand side of the amygdala is activated in men during an emotional memory and the left-hand side of the brain in women. They found that men tend to remember the big picture or global details of an emotional experience, while women remember more of the specific details. This difference accounts for much of the disagreements between women and men about emotional content.

Some input into the brain is not retained because the brain makes the judgment that it is not needed. Long-term memory is stored in bits and pieces and the brain brings them together when a memory is recalled (Ratey, 2001). For an event to be retained in memory there must be a change in the structure of the brain. Daniel Schacter (2001) studied people trying to recall a list of names and later asked which words they remembered. He found through brain imaging that people remembered words where there was an increase in brain activity. When words or images come into consciousness in an effort to remember them, they enter the brain through the posterior parahippocampal cortex and proceed to the hippocampus. There is more activity in the neurons for words that are remembered. A process called long-term potentiation (LTP) is activated when something moves from short-term to long-term memory.

Researchers at the University of Geneva found that “exercising” the brain improves memory and learning (Shimura et al., 2001). The researchers photographed neuron connectors when a memory was formed, showing tiny spines on a synapse that strengthen memory. They concluded that the formation of memory involves duplication of synapses involved in the original memory. Long-term potentiation is the change that takes place in a chain reaction. When a synapse is stimulated by a neighboring synapse, a fundamental change occurs in the structure.

In addition, researchers have found that memory is enhanced when it is recorded by more than one of the senses, such as visual, auditory, and kinesthetic (Sylwester, 1995). The different senses are retained in different memory networks allowing for easier access and greater recall. This finding suggests that learning is enhanced when instructors use various means and engage all the senses in presenting material.

Likewise, researchers have found that problem solving is enhanced by applying non-traditional approaches. Putting down a problem and
coming back to it later can be valuable to finding a solution. In adult learning situations, persons may have better recall where they are attempting to solve more than one problem at a time. The accepted belief is that one should focus on one problem until it is completed, but doing so may reduce problem-solving ability.

Third, Davidson, Putnam, and Larson (2000) conducting research on human affect concluded that positive emotions and goal-directed thinking are centered in the left-hand side of the prefrontal cortex. Withdrawing, inhibiting, and negative emotions are associated with the right-hand side of the prefrontal cortex. He has supported his findings through positron emission tomography (PET), a type of brain imaging. Davidson and colleagues have found that people are consistent across time in the way they respond. His research shows that people with left-hand side activation are more positive, content, and happier than those with right-hand side activation.

Davidson and colleagues (2000) have found that by the end of the first year of life, there is a noticeable difference in infants. These early patterns become the building blocks for later development of personality and even pathology. They hypothesize that emotional health is related to difficulty in activating brain circuitry that shuts down negative emotions. Emotional stability may be related to balance along a particular network of neural circuits involving the amygdala, the prefrontal cortex, and the hippocampus. A particular concern is shrinkage in the hippocampus due to overexposure of the stress hormone cortisol.

One of the outgrowths of the Decade of the Brain was a linking of attachment theory, neuroscience, and infant psychiatry (Schore, 2001). Research is beginning to confirm that trauma early in life alters the maturation of the brain and creates attachment disorders that continue throughout one’s life. The attachment relationship is the foundation for the maturation of our experience-dependent brain interfering with the structural systems that regulate affect and coping with stress. This exposure to extreme stress alters the brain and results in vulnerabilities throughout life for poor adjustment.

While moderate levels of stress heighten awareness and tend to increase learning, prolonged excess stress causes exposure to glucocorticoids, a chemical related to dendrite degeneration. Degeneration of the hippocampus is extremely problematic because of the hippocampus’ role in storage of explicit memory and learning. Persons with hippocampal shrinkage resulting from excessive stress have much difficulty learning and retaining new facts.
NEUROSCIENCE AND MARRIAGE EDUCATION PROGRAMS

The purpose of marriage education is to build skills that both enhance relationships and lessen the probability of breakup (Carroll & Doherty, 2003; Stahmann & Hiebert, 1997). Neuroscience offers some interesting, new ways of thinking about marriage education, which is generally based on skill-building exercises. A focus on a structured skill-building program suggests that all persons are the same and will benefit equally from the training. Individual differences affecting how a person can integrate or use the skill-building exercises are ignored. In this sense, skill development appears to require only the right kind of program to be successful. The content of the program is most important.

From the standpoint of neuroscience, making changes in attitude or behaviors occurs because of long-term memory. Skill building is creating a synaptic connection that has become part of long-term memory in each person. Learning that takes place only in short-term memory will not be retained or affect future behaviors. This fact is illustrated in that marriage education researchers have found that the closer to the wedding date, the more effective is any type of program and that learning over a longer period is more effective than a shorter period even if the total number of hours in the training are the same.

Second, skill-building programs are based on the belief that learning skills in the present will affect future behavior. From the perspective of neuroscience, this assumption raises particular questions because behavior results from how sensory input is stored and processed in the brain. The present is composed of working memory, which allows the person to recall recent mundane events and address issues that come into consciousness (LeDoux, 1996). Consciousness can also include recalling past memories. Future actions occur as a person retrieves from his or her repertoire of memories to guide appropriate actions. This bank of memories is different for each person and is what marriage educators call skills.

The literature on attachment illustrates that different intimate styles of relating to others are internal and biological processes of the individual. Attachment is primarily an automatic, non-conscious process that kicks into action without conscious cognitive awareness. In the same manner, conscious cognitive awareness deals with explicit memory, which is not the same process as implicit memory. For example, one does not have to think, “I am getting angry about this,” before finding oneself in the middle of an angry outburst. The awareness of the angry
outburst is not the process that produced it (LeDoux, 1996), rather it is an automatic reaction to the stimulus that occurred.

Third, researchers in marriage education state that programs are educational rather than therapeutic and much of the effort is on teaching skills, such as communication and problem solving. This type of teaching is an explicit process aimed at imparting specific information that can be recalled as future events unfold. From the standpoint of neuroscience, implicit memory cannot be addressed from conscious cognitive states (LeDoux, 1996). How we have learned to relate to others occurred through implicit learning. It would seem, therefore, that addressing implicit memory educationally with the belief that we can change it through explicit conscious processes is problematic and may account for the lack of strong outcomes on the effectiveness of marriage education.

LeDoux (1996) has noted that what we can process in consciousness is only what was known to us through awareness. If we can think about it, we have experienced it consciously. On the other hand, how we form relationships through attachment processes and how we handle relationship issues generally happen non-consciously. Most educational programs, including marriage education, attempt to change individuals by explicit means by bringing into conscious awareness relevant content. According to LeDoux, this process would be difficult because we are attempting to change something that was formed non-consciously.

Fourth, another implicit process in relationship formation, which seems largely unexplored in marriage education, is love and attachment bonds. In marriage education literature, there is little or no mention of love and romance except generally as emotions and behaviors that will change over time. While no one would dispute that romantic feelings change as the relationship matures, it seems that marriage education should not minimize the underlying reason why most people marry. Without sexual and romantic attachments, many people would not even bother to marry. As in attachment to a partner, romantic and sexual feelings are for the most part implicit and not amenable to conscious thought (Roberts, 1992). This point is illustrated very clearly in the knowledge that we cannot make ourselves love someone and we cannot make ourselves not love someone through conscious or rational thought processes.

Fifth, neuroscience sheds new light on the process of decision making, challenging marriage education programs that promote rational processes as superior to, and separate from, emotional processes. Decision making, for example, is viewed as mainly a cognitive process. Neuroscience has shed new light on the process of making rational deci-
sions. In the past the view was that the neocortex, or rational part of the brain, was tainted by emotional input. To make good decisions, one needed only to think logically and not be overrun by emotions. As mentioned earlier, neuroscience has demonstrated that rationality and emotionality are intertwined. Imaging research supports the idea that in every decision-making process a person makes a better decision when he or she “feels” the emotional outcome of each choice (Damasio, 1994). This feeling of the outcome allows for implicit and non-conscious input to guide one to make the best choice. When persons make decisions that affect their lives they access emotional parts of the brain even though the decision may not seem emotional in nature. In other words, ordinary decisions are made on the basis of how we would feel about the outcomes.

When a couple makes a decision about how much to spend for a new sofa, it is actually an emotional choice because spending too much money may affect the quality of life and this is an emotional idea. Researchers have found through fMRI (functional magnetic resonance imaging) that when making a personal decision there is more activity in the ventromedial frontal lobe, which is related to emotional input. So, when this couple very carefully makes plans to purchase this sofa based on the cost, how much the payments will be and whether it really goes well with the curtains they have are emotional inputs that actually guide their choice. The list of “pros” and “cons” they made to rationally guide the process appears to be the reason for the purchase when, in fact, they would be unable to act rationally without the emotional input.

**NEUROSCIENCE AND NEW MODELS OF MARRIAGE EDUCATION**

In this section, new ideas will be offered for future development of marriage education by integrating findings from neuroscience in the same way that findings from couples research has been integrated in the past. It should be noted that marriage education programs have undergone periodic revisions that have made them more effective. Applying research from neuroscience is the application of another body of knowledge about human behavior and interaction that might offer some helpful suggestions for program revisions.

First of all, a marriage education program must pay attention to the history of each partner. The program should neither be therapy nor educational, but a neuro-psychoeducational approach. The brain structure
in each partner is actually what is of utmost concern when two people attempt to be intimate. One’s pattern of relating to the other is more than skills or lack of skills—it reflects the very structure of the brain. For example, if one’s partner is depressed and this depression is leading to interactions that are unpleasant and unproductive, it will take more than a brief cognitive reframe to change it. Depression actually causes brain shrinkage which effects memory and thinking. New learning must be of the kind that will begin the self-corrective steps that will allow the brain to mend itself.

A case could be made for the need for an awareness of the attachment style of each partner and a procedure to address these styles as part of the training. Addressing attachment issues would require more initial assessment of each person. Attachment styles are formed prior to the development of language and are largely from implicit learning (Schore, 2001). Persons may learn to be consciously aware of their attachment style, which can help relating in more adaptive ways.

In an extensive review of marriage education programs, Carroll and Doherty (2003) noted a gradual decline in effectiveness of marriage education programs over time. They speculated that this decline could be the result of developing generic programs that assume that all couples are the same. Instead, they suggest tailoring programs to meet individual needs. The author of this paper is suggesting that this tailoring of programs should go far beyond content and should focus on the underlying biosocial factors of attachment styles and emotional regulation of each partner.

Second, models should incorporate both explicit and implicit types of learning. Relationship formation and maintenance are largely accomplished through non-conscious implicit learning. As stated earlier, training based on explicit learning fails to influence relationship processes, which are primarily implicit. PREP incorporates fun and sexuality in the program, which provides some link to implicit learning. However, implicit learning goes far beyond these topics and may be much more important than topics related to explicit learning. The author suggests that marriage educators could devise a similar process to that of attachment in which couples have a significant emotional experience that could facilitate implicit learning. They may not know how their relationship improved; just that it is at a different place after the intervention.

Third, more emphasis should be placed on helping couples understand the importance of emotional expression and emotion regulation for learning and long-term memory activation. Teaching couples the role that emotions play in informing them about events in their marriage
and about how emotions are processed in the brain would be very helpful. Explaining emotions in this way would provide both implicit and explicit learning in that couples would understand consciously how emotions are processed, and they might change their behavior simply from this experience without fully understanding it. If emotional health is related to feeling deeply and then coming back into balance, a model of training that attempts to minimize emotional expression may inadvertently lead to more distrust of emotional expressions.

Marriage education should focus more on creating healthy brains of both partners. Activation of the left hemisphere of the brain through sensory stimulation could be very helpful in increasing positive outcomes (Davidson, Putnam, & Larson, 2000). If persons are taught how to develop and maintain healthy brains, the by-product would be more effective intimate relationships. Increasing the repertoire of emotional expressions is one way to improve intimate relationships. For example, helping couples understand the wide range of emotions and the interconnections between emotions and logical thinking may help couples learn a greater appreciation for their partner’s unpleasant moods.

Fourth, from a neuroscience perspective, there are important reasons for focusing on the role of religious and spiritual experiences in intimate relationships. Some models include religious beliefs and a greater understanding of how one fits into a larger system of meaning. From a neuroscience point of view, including religion and meaning in marriage education is commendable, but would go beyond social or cultural reasons. Religious beliefs from the standpoint of neuroscience are important for what they do for the brain (Newberg & d’Aquili, 1999, 2002). The brain seems to be hot-wired for religious expression. When one is engaged in religious ritual or worship, something different is taking place in the brain than at other times. Activity is increased in the frontal lobes, an area where attention is processed, and decreased in the posterior superior parietal lobe where orientation to space is processed. These neurological changes in the brain use similar neural pathways in sexual activity and are linked to health benefits of religious persons who have lower blood pressure and who recover from severe illnesses more readily. Perhaps marriage education could broaden its emphasis on religious experience to improve individual and relationship functioning.

Fifth, marriage education programs should develop training modules that can be given as check-ups or practice of existing skills (Carroll & Doherty, 2003). Check-up exercises or practice would increase the likelihood of success because persons would strengthen their memory of training materials. These exercises should be in a natural setting and use
various presentation formats to reduce waning attention. Exercises could also incorporate new technology such as computer interactive software. A series of interactive disks could be developed that help couples practice the material learned in the training workshop. Exercises could also be developed on CDs for periodic check-ups.

Sixth, in marriage education programs, decision making should be addressed from the standpoint of emotional content. In order to make logical decisions the emotional center of the brain, specifically the amygdala, must be activated and must provide input about how one feels about the competing alternatives (Damasio, 1994). Training exercises should be developed in a way that couples can learn to link emotional and rational content.

Seventh, it would be helpful to address the differences in how men and women process emotional information. Helping men see details and women see the big picture of an emotional experience could facilitate greater understanding of each other. It could also reduce the tendency to automatically react.

Eighth, training modules should allow for self-direction in training. Allowing couples to choose the modules that they feel would be most helpful to them may increase learning and the activation of long term memory. Furthermore, modules should challenge beliefs and patterned thinking, creating incidences where participants must make order out of chaos. Humor and the use of absurdity can help accomplish this goal.

As more research becomes available about learning the role of cognition in conscious and non-conscious states, applying these concepts to adult learners will be clearer. It remains to be seen how brain research will be utilized in the learning situations. The caveat is that there is so much still unknown that it would be a mistake to reify what is now known as the answer. However, it seems clear from the evidence presented in this paper, that there is considerable room for improvement in marriage education programs by applying neuroscience research. Future findings in neuroscience are expected to continue to revise knowledge about learning and memory and improve our methods of applying this information to couple relationships.

REFERENCES


