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NEUROSCIENCE FOR OLD PEDAGOGY

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Abstract

In recent years there has been an increasing trend in education to seek answers for best pedagogical practice in cognitive neuroscience research. This paper reviews current cognitive neuroscience research findings and critically discusses what they can potentially add to educators' pedagogy. It argues that there is a need for the development of pre-service teacher modules on the application of cognitive neuroscience research to education so that teachers can meaningfully and accurately employ any implied pedagogy. Appropriate pre-service teacher modules need to be placed within the context of major focus areas in undergraduate teacher preparation degrees; for example within educational psychology, behaviour management, special education, literacy and numeracy teaching. This is vital for non-science secondary teachers as well as those who upon entering the profession are often too busy to engage critically with the latest neuroscience research or to evaluate the many emerging textbooks that are proclaiming to be based upon the latest cognitive neuroscience findings. In this way teachers will be able to guard against "neuromyths" and "brain-based" learning claims and pedagogy that might, ultimately, be detrimental to student learning and wellbeing.

Introduction

In a recent paper, Furlong (2013, May 2) argued that educators must do better, that there is a need to increase the relevance of teacher training to the practice of teaching so as to help pre-service teachers to engage with and produce research that can potentially shape their practice. Earlier, Geake and Cooper (2003) also stressed a need for educators to embrace new ways to enrich their pedagogical knowledge base, their understanding of learning in diverse settings with diverse learners. Observing the exponential increase of cognitive neuroscience research over the past 30 years, Geake and Cooper (2003) advocated for educators to apply the findings from cognitive neuroscience to their teaching so that they might stem "the increasing marginalisation of teachers as pedagogues" (Geake & Cooper, 2003, p.11). They reasoned that:

> 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. (p.11)

Similar calls for improving teacher competence have been articulated regularly within the context of quality teaching and quality teachers (for example, Clement, & Lovat, 2012; Lovat, Dally, Clement & Toomey, 2011). While the attributes of a quality teacher are potentially debatable given the diversity of students within any classroom, agreement exists as to the most desirable attributes of effective teachers. For example, John Hattie's (2009) meta-analysis of research studies investigating teacher influences upon student learning resulted in an identification of a range of desirable competencies for effective teachers; they included a deep knowledge of their discipline and strong pedagogical content knowledge.

Pedagogical knowledge is critical to learning and teaching; it bridges content knowledge and the practice of teaching, and as such, it is the unique province of teachers (Shulman, 1987). For example, constructivist approaches to pedagogy based on Piaget's theory emphasise exploration, discovery learning and problem solving, using problem based or inquiry learning approaches that can range from the very simple to highly complex. Vygotskian approaches to pedagogy advance these ideas by stressing the importance of contextualising learning in meaningful scenarios, based on the notion that the learning needs to be meaningful to the learner. Meaningfulness does not just imply having some prior knowledge of the task or a 'real-world' task; it encompasses values, rewards and

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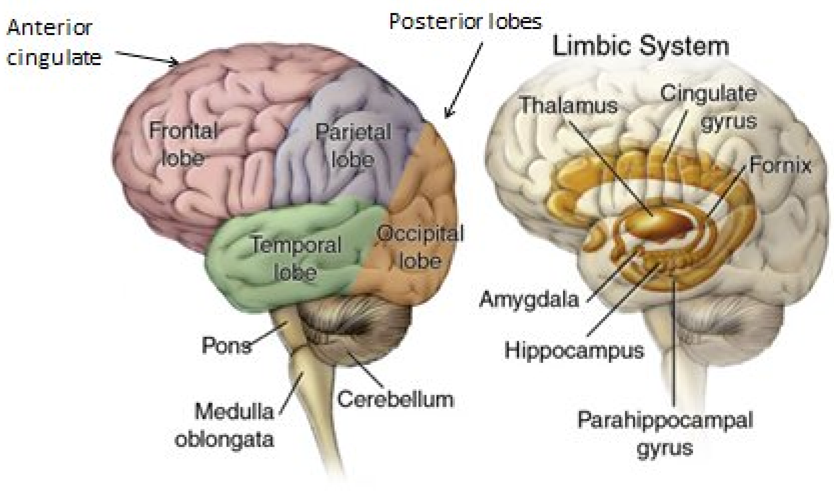
motivational factors that propel the learner into engagement with the learning situation. The suitability of pedagogical approaches for different learners is also dependent on the subject matter, so that for example, mathematics and art are likely to require different approaches.

In an endeavour to refine pedagogical knowledge educational academics have been turning to the emerging field of educational neuroscience, the assumption being that by joining brain science or neuroscience, a respected and largely uncontested science, with education, education can be grounded more solidly in research on learning and teaching (Fischer, Goswami & Geake, 2010).The new discipline, educational neuroscience, is looked upon to draw implications from the findings and theories of the neurosciences for application in educational research, theory, and practice.

This begs the question: "*what is known at present about what happens in our brains that can be used directly by educators to improve teaching and learning?*" For example, can cognitive neuroscience research direct us to the most appropriate pedagogy to teach mathematics, history or science to diverse learners? Can it point to the best way to help diverse learners to master percentages or fractions, or grammar? Much of what has emerged from cognitive neuroscience can be categorised as "macro-level" or general, qualitative knowledge, based on whole system activation of the brain or certain brain systems or areas during particular learning experiences. These learning experiences and responses are not however, able to be differentiated into specific, procedural steps neurologically that are amenable to pedagogical interventions to ensure best outcomes for the diverse student population attending schools.

Nonetheless, cognitive neuroscience has advanced our understanding of the overall process of cognition. This is because of improvements in brain imaging techniques whereby data from animals and humans are gathered using single cell spike train recordings (i.e., neuronal electrical activity), positron emission tomography (PET) scans, thermal imaging, functional magnetic resonance imaging (fMRI) and the like. Such experimentation has refined our mapping of regions of the brain which correlate with cognitive behaviours. Figure 1 shows a simplified anatomical map of the regions of an adult brain.

Figure 1. *Simplified anatomical map of an adult brain*



The sections following will review recent research and consider if and how that research can potentially enhance current pedagogical practice. Research in the areas of learning difficulties and special education, neuroplasticity, sleep, exercise and nutrition, motivation, emotion, and puberty will be examined. The paper will conclude with a discussion and proposal for the most fruitful partnership between cognitive neuroscience and education.

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Learning difficulties and special education

Research in cognitive neuroscience through the use of brain imaging techniques has illuminated processes that might be useful in the field of special education (Goswami, 2004). For example, it is known that young readers develop their skills through activation of the left posterior superior temporal cortex, an area implicated in phonological skill acquisition, and as literacy is acquired, the visual word form area in the left occipital temporal region becomes activated. Dyslexics, however, show abnormal activation of the right parietal cortex (Goswami, 2006). Likewise, parietal brain areas have been shown to be involved in representing both physical size and number concepts (Feigenson, Dehaene & Spelke, 2004). These findings may be helpful in understanding certain types of dyslexia and dyscalculia. Progress is also being made in understanding ADHD and autism spectrum disorders (Philip et al., 2012). Nonetheless, the application of these findings to education in the classroom is not entirely clear because of the nature of the experimental data (being mainly cross-sectional rather than longitudinal and with small cohorts, and in the case of ASD being limited to studies with high functioning males).

Hruby (2012) points out that while dyslexia refers to precise impairments in text decoding processes, such as rapid serial letter–sound matching and /or word-form recognition, the term dyslexia is often employed more loosely as a synonym for reading difficulty of any sort including difficulties with language comprehension. This is because neuroimaging studies have shown a similar lack of typical brain activity in diverse populations of non-readers, leading experimenters to describe this lack of activation as a neurological deficit. Because dyslexia is presumed to be a neurologically related disability, and because brain scans of poor readers show similar lack of activation in particular brain areas, they conclude that the problem is a development deficit in decoding ability due to a neurological problem. However, as Hruby (2012) points out, the lack of activation in a brain image may be a symptom rather than a cause of the lack of skill because children who have not yet learned a skill will fail to demonstrate neural activity in the regions implicated in that particular skill. This would certainly be the case given the brain's neuroplasticity. Moreover, neuroscience findings have not resolved the 'reading wars' between advocates of whole language and of phonics drilling, possibly because of the inherent difficulties involved in experimentation within laboratory settings and utilising young children as subjects. To complicate matters, most mental tasks and behaviours involve multiple brain regions. Activity in a brain region or two does not reliably indicate a particular kind of mental operation, certainly not one as multifaceted as reading.

The complexity of neural processing in learning tasks is illustrated in recent research with young children. This research demonstrated that the processes involved in number magnitude computations most probably involve higher processing centres such as the prefrontal cortex in concert with other specific brain areas (Soltész , Goswami, White, & Szűcshas, 2011). This study showed that children have more difficulties inhibiting irrelevant information under the control of the prefrontal cortex and with organising their responses, because unlike adults their prefrontal cortex has not fully developed connections with other areas of the brain. The study showed that numerical tasks are resolved when various areas of the brain are acting in concert fulfilling discrete but interconnected processes to solve a given problem. It is clear therefore that the application of such findings in the classroom, through the design of specific pedagogical strategies is rather a long way off. Conversely, results of cognitive neuroscience might even lead to teacher despondency because studies might show that biologically determined factors, i.e. genetics, are most influential for the learning process. An illustrative example follows.

Supekar et al., (2013) studied the behavioural and neural predictors of individual differences in arithmetic skill acquisition in a group of grade 3 children. These children, aged 8-9 years, were tested in response to an 8-week program of one-to-one mathematics tutoring. The children underwent structural and resting-state fMRI scans pre-tutoring. Results showed the speed and accuracy of arithmetic problem solving increased with tutoring, with some children improving significantly more than others. Superkar et al., (2013) also examined whether pre-tutoring behavioural and brain measures could predict individual differences in improvements with tutoring, but found that no behavioural measures, including IQ, working memory, or mathematical abilities, predicted

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performance improvements. The only measure that predicted improvements was pre-tutoring hippocampal volume. They showed therefore that individual differences in anatomy and functional circuitry of brain regions associated with memory formation predict math-tutoring performance improvements in primary-grade school children. These results were consistent with findings that showed children with dyscalculia demonstrate structural deficits in the hippocampus (Rykhlevskaia, Uddin, Kondos, & Menon, 2009) and they also typically have poor skills in retrieving arithmetic facts from memory. Rykhlevskaia et al. (2009) concluded that quantitative measures of brain structure and intrinsic brain organisation can provide a more sensitive marker of skill acquisition than behavioural measures. One might therefore question what the point of refining pedagogy is when biological or genetic factors are most critical in potentiating learning advances. A much more fruitful study to inform pedagogy would be to examine what sorts of specific teaching strategies enhance learning outcomes for the different children participating.

Neuroplasticity

Perhaps one of the most important consequences of cognitive neuroscience research for education is that repetition of a particular mental activity increases the synaptic connections of the part of the brain involved in that activity. This supports Donald Hebb's 50 year-old proposition that it is the strength of synaptic functioning, i.e., the efficacy of inter-neuronal communication, that changed as a result of learning. In other words the brain's ability to alter as a result of learning, or its plasticity, is a process that has been demonstrated (see Doidge, 2007 for extensive examples). Of course this strongly supports what teachers have known since ancient times: that repetition is necessary for effective learning. The plasticity inherent in the nervous system means that interventions of various types result in functional and structural changes in the brain, with concomitant changes in behaviour.

Carol Dweck (2008) stressed that students who understand that brain power is dynamic (i.e., that it can be exercised and strengthened) fare better academically than those who believe their intellectual abilities and intelligence were determined at birth and cannot be altered. The approaches she advocated, such as teaching students how brain exercises can stimulate memory and improve grades, also strengthen important executive function skills like cognitive flexibility and self-monitoring. The way that children conceive the nature of their intelligence, whether fixed, and determined by genetics, or fluid and able to be improved, can have serious implications for their motivation and in turn their academic success (Blackwell, Trzesniewski, & Dweck, 2007). The brain's neuroplasticity has potential specific applications, as we now know that it is never too late to learn new skills in a range of content areas, and the so called "critical periods" are just sensitive periods (Goswami, 2004) not absolute windows of opportunity for learning particular skills as was once thought. Nonetheless, this knowledge is once again "macro-level", general knowledge, implicating anatomical changes over time. One such example is observed in experienced London taxi drivers. Typically, some individuals have been shown to exhibit an enlargement of the hippocampus which is presumed to be a result of visio-spatial knowledge acquired as a matter of course in conducting their work (Doidge, 2007). This anatomical change in the part of the brain occurs as a result of learning, but knowing this enlargement takes place after learning geographical positions yields no clue as to the best way to learn street names or understand how to travel from A to B.

Sleep, exercise and nutrition: biological requirements for optimal cognitive function

Many new studies have emerged from cognitive neuroscience confirming the importance of sleep, exercise and nutrition for optimal learning outcomes (Medina, 2008). These are also "macro-level" general matters that help support learning, and which, though essential knowledge for parents and pedagogues, do not help educators refine their pedagogy, except at the most basic, general level. For example, learning can be facilitated by ensuring that children have exercise breaks and ensuring that the pastoral care policy of the school is designed to ensure that children's needs are monitored and intervention is employed where needed.

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Exercise has been cited as being essential for learning because it is thought to get blood to the brain, bringing it glucose for energy and oxygen for cellular respiration (Medina, 2008). Meta-analyses of 19 empirical studies on the effects of physical exercise on executive functions in preadolescent children (6–12 years of age), adolescents (13–17 years of age) and young adults (18–35 years of age) showed all groups enhanced their executive functioning as a result of acute physical exercise. The authors pointed out that these results are highly relevant in preadolescent children and adolescents, given the current increase in sedentary behaviour in these age groups (Verburgh, Königs, Scherder & Oosterlaan, 2013). Researchers have discovered that movement and exercise increase the production of brain-derived neurotrophic factor, or BDNF (Ratey, 2008). In animal studies this protein supports the survival of existing neurons, encourages the growth of new neurons, and is important for long-term memory formation. Further, movement and exercise improve mood and enhance cognitive processing.

What needs to be stressed here is that there are multiple reasons why exercise might improve cognitive gains, including the after-effects of exercise, the endorphins released, as well as the increased blood flow to the brain (in line with flow to the rest of the body). The endorphin releases improve mood, and so motivation is increased. Motivation is the most important factor in engagement with learning activities and the reward systems these activate, both necessary for memory formation and learning. Therefore, to claim that exercise is a key to improved learning, as has been promoted by some "brain based" learning programs, is to omit the vital causal link which is determined by motivation.

Similarly, regular meals have been shown to be related to better academic outcomes in children up to Year 11, even after socioeconomic status has been taken into consideration (Hye-Young et al. 2003).

Learning requires the formation of memories and the storage of these in ways that can be accessed in the future. Sleep has been found to be essential for the consolidation of learning because memory consolidation takes place during sleep (Diekelmann & Born, 2010).This is the case for both an efficient consolidation of (declarative) knowledge and (procedural) skills (Curcio, Ferrara, & De Gennaro, 2006). Does sleep provide passive protection from forgetting or does it actively shape the future of memories? In either case, the mechanism of how sleep assists learning is not as critical for educators as knowing that sleep deprived children are not as likely to engage in learning because of tiredness, and not as likely to commit their learning into memory stores. While new cognitive neuroscience research has validated the idea that sleep is needed to consolidate learning, such knowledge is not new to educators.

Motivation

The foregoing brings us to a most important concern for educators – that of motivation. For if a learner is motivated to acquire knowledge their engagement and active attention will facilitate the learning process and its storage in memory. However, human motivation is highly complex and dependent upon multiple and individualized systems of goals and anticipated rewards. The neural correlates of motivation are being studied at a simple level, for example pressing a lever for a reward, or what is better known as conditioning. Yet even when examining this basic level of learning and motivation, the most important conclusion arising from animal studies and human learning studies is the finding that a single behaviour (for example a lever press, or a choice response) can potentially arise from multiple processes that are dissociable (Dow & Shohamy, 2008) and guided by multiple forms of memory, subserved by different neural systems.

For example recent motivational studies using neurophysiological evidence from motivation studies on children with attention-deficit hyperactivity disorder (ADHD) suggest that they are subject to abnormal reward prediction signals from the midbrain dopamine system onto the frontal brain areas that implement cognitive control when compared to typical children (Holroyd, Baker, Kerns, & Müller, 2008). Dopamine has been implicated in the formation of memory that encourages behavioural responses in learning situations, including those involving movement, and drug addiction, and is generally believed to be implicated in neural "rewards" which facilitate motivation in humans. It is thought that for new synapses to be formed between cells (i.e., for synaptogenesis, the hallmark of plasticity) coding the new learning and therefore the memory, it is not enough for the local neurons to be activated in response to a behaviour. There needs to be a response from larger scale networks, the dopaminergic system, which release dopamine when reward or novelty is encountered (Otmakhova, Duzel, Deutch, & Lisman, 2013). In adult human studies the release in dopamine is subject to individual differences (Wacker et al., 2013), which are found to be genetically determined (Pearson-Fuhrhop, Minton, Acevedo, Shahbaba, & Cramer, 2013). Little is known about the control of dopamine release in humans, but research in experimental animals suggests that the prefrontal cortex plays an important role in regulating the release of dopamine in subcortical structures (Wise, 2004). This means that a learner needs to be actively attending to a learning situation AND valuing that learning – either experiencing a reward or an attention capturing novelty.

Studies have found that those with ADHD are likely to have a midbrain dopamine system dysfunction which is thought to impair their cognitive control (Holroyd et al. 2008). While an understanding of the neurochemistry of ADHD might be helpful for choosing an appropriate medical intervention for those with the impairment, behavioural studies have revealed their behavioural profiles and have been no less useful for adapting educational strategies for these students. The individual brain's developmental state, determined by age, genetics and experience can therefore have an impact upon motivational choices, which are dependent on memory and on cognitive capacities and self-regulation.

Many questions need to be answered to untangle the neurological and biochemical processes underlying motivation; not least how all these processes are executed in diverse children's brains, since much of motivational research has been conducted on animals and adults. On the other hand behavioural studies have given us an exceedingly long list of studies that can shed light on children's and adolescents' motivation. At present, a thorough grounding in educational psychology can provide an educator with more potential applications for developing appropriate pedagogies than cognitive neuroscience.

Emotion

Closely related to motivation is emotion as a primary catalyst in the learning process. This area is well known to teachers who have been exposed to the theories of Abraham Maslow and Carl Rogers. However, findings from cognitive neuroscience have given more empirical support for the role of emotion in learning and memory. Two small but powerful structures deep within each hemisphere called the amygdala regulate our emotional responses. These emotional responses have the ability to either impede or enhance learning (Hinton, Miyamoto & della Chiesa, 2008). Emotion guides students' learning, helping them gravitate toward positive situations and away from negative ones. This means, if learning experiences are positive, students will be motivated to engage in them. On the other hand, if learning experiences are stressful or associated with other negative emotions, students will jump through hoops to get out of them. In other words, "we feel, therefore we learn" (Immordino-Yang & Damasio, 2007, p. 1). In situations where we are scared, the amygdala starts a chain of physiological responses (fight, flight or fright response) to ready the body for action. Under these conditions, emotion is dominant over cognition and the rational/thinking part of the brain is less efficient.

Abundant empirical human evidence exists confirming that stress and adversity, particularly early in life, can produce enduring alterations in behaviour, mediated by changes in neural circuitry which persist throughout the life-course. The animal and human evidence is consistent in demonstrating that many forms of stress promote excessive growth in sectors of the amygdala (the "emotional" centre), whereas effects in the hippocampus (important in laying down memories and learning) tend to be opposite. Whether sensitive periods exist for plasticity in response to social influences has not been thoroughly investigated (Davidson, & McEwen, 2012). A recent study of a cohort of 1,000 participants studied from birth to 32 years of age found that childhood measures of self-control predicted physical health, substance dependence, personal finances and criminal offending outcomes at 32 years of age (Moffitt et al., 2011). The authors defined self-control as a family of processes that include delay of gratification, impulse and attention control, executive function, and willpower. In other words, behaviour is dominated by the activation of circuitry in the pre-frontal cortex areas over the emotional circuitry of the brain. They suggest that early interventions that enhance self-control might reduce a range of societal costs and promote prosperity. The educational

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implications of these findings are wide ranging particularly with respect to matters of behaviour management and academic persistence.

The school environment must be physically and psychologically safe with clear expectations and boundaries for learning to occur. Once again this research confirms what experienced educators have long known and used in their classrooms and pastoral care programs. What the research adds for these practices is an understanding of why certain procedures or school policies work so that educators no longer have to operate intuitively but can articulate and explain the rationale for what they do. The special place of emotions in learning leads us to the consideration of their effects during puberty, where swings of emotions are frequent in many adolescents.

Puberty and emotions

Many factors, seemingly unrelated to specific academic subject areas or disciplines, contribute strongly to success in school. For example, social emotional development influences academic achievement through the child's/adolescent's ability to persist with tasks and delay emotional gratification. Burnett, Thompson, Bird, and Blakemore (2011) studied the neural systems supporting social and emotional processing, specifically the development of complex social emotions during adolescence. They found that compared to children at an earlier stage of pubertal development, more developed children reported more complex emotional reactions to social scenarios, and had the capacity to understand multiple perspectives and mixed feelings. These findings are thought to be a reflection of changes observed in the developing brain. Two of the brain regions that have consistently been shown to undergo continued development during adolescence are the prefrontal cortex and the parietal cortex.

The prefrontal cortex (PFC), also known as the CEO, is that part of the brain where executive decisions are made and where ethical/moral behaviour is mediated. Imaging studies of the PFC have showed changes in white and grey matter in growing children between the ages of 4 and 22 (Giedd et al., 1999). Linear increases were observed in white matter, corresponding to myelination of neuronal axons, but nonlinear changes were observed in cortical grey matter, with a preadolescent increase followed by a post-adolescent decrease. These changes in cortical grey matter were not uniform, with frontal and parietal (centre back) lobe peaking at about age 12 for males and 11 for females, while the temporal (side) lobe peaked at about age 16-17; cortical grey matter continued to increase in the occipital (posterior) lobe through age 20. Thus, the increase in grey matter apparent at the onset of puberty (Giedd et al., 1999) might reflect a wave of synapse proliferation at this time. The gradual decrease in grey matter density that occurs after puberty in certain brain regions has been attributed to post-pubescent synaptic pruning (Giedd et al., 1999; Gogtay et al., 2004). This may explain the slow maturation of functions that are mediated by the prefrontal cortex, such as inhibitory control, planning, and decision making. In contrast to the rather slow and linear development of the prefrontal regions, data suggest that striatal brain regions underlying reward driven and impulsive behaviour may show a curvilinear developmental pattern with a peak inflection between 13 and 17 years. This is important, since the processing of reward-related stimuli (primarily in the nucleus accumbens, situated in this area, which operate with dopamine release, that promotes desire, and serotonin, which affects inhibition), may relate to increased risk-taking behaviour commonly observed in adolescents. However, competing theories exist about the reward system in adolescence. One hypothesis suggests that the nucleus accumbens is relatively hypo-responsive to rewards during adolescence, and an increase of reward-seeking behaviour is necessary to achieve the same activation as in adults. Another hypothesis says that, just the opposite, the striatal reward system is hyper-responsive, and this leads to greater reward-seeking behaviour.

In trying to understand adolescent behaviour some books and articles appearing in education websites make claims about the causes of adolescent impulsivity. For example: "Adolescents tend to use a part of the brain called the amygdala during decision-making, because their frontal lobes function poorly" (accessed Sept 7 2013 from: http://www.curriculumsupport.education.nsw.gov.au/secondary/pdhpe/prolearn/reading/pr_013.htm.) These claims are oversimplified, sometimes inaccurate, and can potentially lead to the erroneous conclusion that all adolescents are likely to be impulsive and in need of strict control. Because the neural mechanisms involved in adolescent impulsivity and risk taking behaviour are diverse and based

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not only on development but also genetics, and possibly experience, rigid ideas about neurocognitive explanations of behaviour are not a useful guide to understanding adolescent behaviour. Cognitive neuroscience studies have led researchers to conclude, for example, that risk taking behaviour can result from the dynamic interaction of the cognitive control system (medial/ventral prefrontal cortex), the reward system (nucleus accumbens), and the harm-avoidant system (amygdala).

Increased risk taking might be the consequence of either a weak control system, an easily activated reward system, or a weak harm-avoidant system, or combinations of these (Ernst, Pine & Hardin, 2008). Evidence for these conclusions was derived from a large scale study which examined differences between two groups of adolescents, those with ADHD and those who were drug users. The sample (n = 1,896) of 14-year-old adolescents showed little overlap between the networks associated with ADHD symptoms and those linked with drug use, suggesting that these problems arise from different neurobiological pathways (Whelan et al., 2012), i.e., different networks are associated with drug use (n = 1,593) and ADHD symptoms (n = 342). Hypo-functioning of a specific orbitofrontal cortical network was associated with potentially initiating drug use in early adolescence. Results overall indicated that individual's neural biochemistry and genetic variation give rise to the various manifestations of impulsive behaviour. Therefore, behavioural patterns rather than cognitive neuroscience are a better guide for understanding adolescent developmental behaviours and responding to them.

The variations observed across studies in adolescent impulsivity and self-control is evidence that prefrontal systems and the ability to recruit distributed function are present early in development. Nonetheless, recent work indicates that through adolescence the connections within these distributed circuitries increase in strength, and incorporate more long range connections (Luna, Padmanabhan & O'Hearn, 2010). The transition from adolescence to adulthood therefore can be seen as a change in mode of operation from initially relying on more regionalized processing, such as in the PFC, earlier in development, to relying on a broader network of regions that share processing in an efficient and flexible manner at the systems level. The finding that changes in brain structure continue throughout puberty and adolescence has given rise to a range of investigations into the way cognition (including social cognition) might change as a consequence. If early childhood is seen as a major opportunity–or a "sensitive period"–for teaching, perhaps the teenaged years should also be viewed as such. During both periods, neural reorganisation is taking place. Perhaps the aims of education for adolescents might be adapted to include abilities reliant upon the parts of the brain that undergo the most dramatic changes during adolescence. These include executive function-related abilities such as internal control, multi-tasking and planning (Luna et al., 2010) but also self-awareness (Sebastian, Burnett & Blakemore, 2008), social cognitive skills, (e.g., Dumontheil, Apperly & Blakemore, 2009), and the understanding of complex social emotions.

Cognitive neuroscience evidence that younger children rely on their PFC for decision making, which gradually changes as better connections are developed with the other parts of the brain, broadly corresponds with the stages of moral development that Kolhberg (1971) described. These progress from simple to more complex decisions, based on deliberations that involve social and emotional considerations, and are reflected in the utilisations of diverse regions of the brain, which adults are more likely to employ than children or adolescents.

In light of these findings, it could be fruitful to include in the secondary education curriculum some teaching on the changes occurring in the brain during puberty and adolescence. Adolescents might be interested in, and could benefit from, learning about the changes that are going on in their own brains particularly in the context of drug education and perhaps sex education.

Overall, cognitive neuroscience evidence centred on the adolescents' growing emotional and social competence gives validation to school policies that already exist in most schools in Australia. These are general pedagogical policies which target early adolescents with programs on empathy, peer support and anti-bullying as well as drug and sex education. Conversely, if oversimplified, these neuroscience findings might lead to the blanket application of unnecessarily strict behaviour management policies upon all adolescents. Since the majority of adolescents have well developed cognitive and emotional/social skills, such that they are neither overly impulsive nor reckless, this could result in alienating them from school, and suppressing their capacity for developing autonomy. Worse still, if educators believe adolescents have an "immature brain" as many popular proponents of brain based learning approaches imply (for example, "..[the adolescent brain is]…missing in action" p.9, Andrew Fuller) teachers might very well abrogate their responsibilities to teach appropriate behaviours and social responses, setting up a self-fulfilling prophecy, and observing in adolescents what they expect. The neuroscience that has shown us that the brain is able to learn at any stage is the very reason to discard claims that 12-15 year old adolescents are not capable of learning appropriate emotional and behavioural responses.

The future for the partnership between cognitive neuroscience and education

There are dangers inherent in applying cognitive neuroscience findings without understanding how they were derived and by which experimental design. Goswami (2006), Director of the Centre for Neuroscience in Education at the University of Cambridge, has written of the 'astonishing' speed with which packages claiming to be based on brain science have gained widespread currency in schools and which, not being subject to rigorous scrutiny, often represent little more than 'neuromyths', a term first coined by the OECD report on brain learning (OECD, 2002). The public clearly wants information about how the brain learns and is eager to embrace any 'magic bullet' that is even remotely associated with science. One reason for this is that the media commonly presents findings from biological methods as if they involve 'harder' more scientific-knowledge based results compared to psychological or cultural methods, which are presented as 'soft' and needing scientific validation. In the United Kingdom it was announced that 5,000 pupils would be given daily doses of fish-oil supplements to improve their exam scores, quoting trials (with no control group) showing that fish-oil supplements had improved the concentration and learning abilities of young children (BBC, 2006, Sept 6). Similarly, many state schools in the UK embraced a program called Brain Gym, which claimed that a series of simple physical movements will "integrate all brain areas and promote efficient communication among the many nerve cells" (Goldacre, 2006). The eagerness for a "scientific basis" for education appears to be global. A quick search of Education Queensland's Learning Place for educators, turned up "Anatomy of the brain: Learning to learn with the brain in mind", (John Joseph, 2009). More recently Bartlett (2011, May 23) urged Australians to embrace neuroscience to unlock the secrets of learning because of the needs of classroom teachers who depend on "the expertise of neuroscientists to design effective and practical learning techniques and tools".

A more cautious approach is advocated here, one respectful of the teaching profession. It is summarised by Van der Wyk and Pelphrey (2011):

> Looking to the future, neuroscientists should be bold in their goals, but conservative in their recommendations. The general public, including those in the educational field, are eager for and highly respectful of claims even tangentially backed by neuroscience data. This creates the situation where intentionally or not, neuroscience results, when simplified and generalized in an overly broad way, lead to the formation of pervasive 'neuromyths' that are extremely difficult to eradicate. Thus, we need to remain cognizant of the limitations of our research, especially in the difficulty of moving from laboratory to classroom, and should strive to 'first, do no harm. (p. 634)

One way to help educators not to oversimplify existing cognitive neuroscience in their application to classrooms is for tertiary training institutions to incorporate cognitive neuroscience modules in appropriate sections of the Bachelor of Education course. For example, when teaching educational psychology instruct pre-service teachers how to interpret cognitive neuroscience findings by asking key questions such as: What exactly was being tested to derive the results? How many subjects were there in the study? What were the ages and characteristics of the subjects? Was there a control group of subjects matched with the subjects in the experimental group? Are issues of causality addressed? Have results been replicated? Are there similar studies that have contradictory findings? How will results be applied in actual classrooms? What specific outcomes will be realized? Are there potential implementation problems? In other words apply research evaluation criteria to the presented neuroscience studies. This is critical as it is not currently possible to measure the real-world thought process that a child has while observing an actual school lesson. Importantly, do the findings add

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anything to existing behavioural studies, and if so, what? Such training is vital for those pre-service teachers who are not science specialists and those who will be teaching in primary and early childhood education settings.

An understanding of the methodological issues involved in experimental methods is also essential if we are to be able to discern causal relationships. For example differences between different individual's brains can lead to confusion. Blakemore and Choudhury (2006) lament the confounding effects of task performance differences between groups in fMRI studies because they point out those differences are difficult to interpret. They might cause the difference in task performance, or it might be an effect of these differences. In relation to adolescent brain changes, the directions of cause and effect remain unclear when looking at differences between adolescent and adult responses to tasks (Blakemore et al., 2006). What are urgently needed are longitudinal developmental studies.

A key matter focused upon by educational psychology is that although neuroplasticity means that the brain can change itself in response to learning (Doidge, 2007), this learning is based on personal choice and effort (Bandura, 2006). Hence the key to learning is motivation. Motivation to participate in cognitive neuroscience research can potentially have particular impacts upon learning which however, could be difficult to disentangle when evaluating pedagogies derived from such research for their efficacy.

Knowing the full developmental picture is essential when linking neuroscience findings to education. For example the identification of evidence showing that neural white matter continues to increase past adolescence and possibly in some case through to one's 20s and 30s, has given rise to an acceptance and possibly an expectation of adolescent impulsivity. However, rarely is it also noted in articles highlighting these issues in relation to adolescents, that white matter volume continues to increase in prefrontal, parietal and temporal cortices well beyond this stage and even up to the age of 60 (Blakemore et al., 2006).

There is a great need and scope to introduce cognitive neuroscience studies for special education preparation and for literacy and numeracy training. Here too it is important to train pre-service teachers to be critical and to ask those questions that will enable them to evaluate particular claims from laboratory findings, since these can sometimes lead to false generalisations. For example it is reported that those with Asperger's Syndrome, which is placed within the autism spectrum, have no understanding of others' minds (Baron-Cohen, 1995). However, individual variation shows that those with Asperger's syndrome can show insight and sensitivity for others if those others are significant to them (Vuletic, Ferrari & Mihail, 2005). Given the prevalence of specific learning disabilities (SLDs), estimated to affect up to 10% of the population (Butterworth & Kovas, 2013), teachers and school psychologists need to know how recognise SLDs and optimise the learning of individual students.

Another area where cognitive neuroscience has the potential to inform pedagogy is within behaviour management. However, knowledge of the cognitive neuroscience of adolescent development needs to be closely coupled with validated behavioural and cultural research to ensure that appropriate methods of management are implemented for diverse groups of students, for example those with ADHD, ADD and ASD.

Knowing how to interpret cognitive neuroscience findings will enable teachers to defend their practices, whether new or old, and avoid the trap of biological determinism. For cognitive neuroscience to inform pedagogy it must show how students in varying stages of development can improve their learning over time and develop their skills in reading and mathematical computation, science understanding and so on.

In closing it is hoped that the newly established research schools like the Queensland Brain Institute in Australia will ensure that teachers collaborate with neuroscientists, cognitive scientists, physicians and psychologists so that educational pragmatics inform any proposed implications for education.

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