Pedagogical Knowledge and the Changing Nature
of the Teaching Profession

Chapter 9

Developmental cognitive neuroscience: Implications for teachers' pedagogical knowledge*

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This chapter critically considers the role that insights from research in Developmental Cognitive Neuroscience (the study of the neural underpinnings of developmental changes in psychological functioning) might play in teachers' pedagogical knowledge. The chapter reviews key findings in neuroscience with implications for learning, such as functional and structural brain development and brain plasticity. We discuss concepts such as transfer of learning from one domain to another as well as the role that neuroscience can play in the prediction of educational outcomes. In addition, we consider how such evidence might be integrated into pre-service teacher education as well as ongoing in-service teacher professional development. Finally, the chapter discusses the importance of considering Developmental Cognitive Neuroscience as an important contribution towards more evidence-based education and highlights that such information must be integrated with evidence from psychology, cognitive science and other research enterprises related to learning and education.

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Why should neuroscience inform teachers' pedagogical knowledge?

Neuroscience is a rapidly growing field of inquiry. Tens of thousands of individuals attend the annual meeting of the Society for Neuroscience,[1] and new breakthrough studies are published almost every week, increasing our understanding of how the brain works (Carlson, 2013; Kandel et al., 2013). Newspapers are filled with reports about the latest neuroscientific research and how this might impact the reader's life. As a consequence, there is growing public interest in findings from neuroscience, especially as it relates to behaviour, including learning.

Neuroscience is becoming a hub science for addressing key questions concerning humanity, such as how we develop, how we learn complex cultural skills such as reading, what drives our behaviours, how we make decisions and how our emotions influence our decisions. Neuroscience covers investigations at multiple levels of analysis, ranging from the study of how genes influence the functioning of single nerve cells through to the study of large-scale systems and networks in the brain and how these generate human behaviour. Not only do neuroscientists work at multiple levels of analysis, but their work also intersects with many other disciplines, such as philosophy, psychology, anthropology, economics, as well as education.

In education, there have been growing calls to use evidence from the study of the human brain to influence what goes on in the classroom. It has been argued that the study of how the brain develops and acquires new information has the potential to transform education (Sigman et al., 2014). As such, teacher training might benefit from integrating evidence from neuroscience. In this chapter, we highlight how evidence from neuroscience might influence how teachers conceptualise and think about learners in their classrooms, with a critical discussion of what neuroscience can and cannot do for education. In doing so, we will argue that neuroscience *is one of many pieces of evidence* that can lead to more "evidence-based" practice in education and can help empower educators to become more informed practitioners. It is critical to emphasise that neuroscience should not be considered the most valuable source of evidence to influence how teachers think about students in their classrooms, but that together with evidence from other levels of analysis (such as cognitive science, psychology and educational research) it has the potential to further enrich teachers pedagogical knowledge.

One way of bringing research from neuroscience to bear on education is to make it a fundamental part of teachers' pedagogical knowledge both through pre-service teacher education, as well as through on-going professional development. In order to present how this might be achieved and what kind of knowledge from within neuroscience would become part of teachers' pedagogical knowledge, this report consists of a non-exhaustive review of some overarching neuroscience concepts that are essential for a basic understanding of the research. Throughout, we include examples of research from within neuroscience that illustrate the implications for teaching and learning. Critically, the description of these illustrations will provide a justification for why the research should be a part of teachers' pedagogical knowledge. The aim is not to propose a framework of teachers' pedagogical knowledge that will overturn or replace existing ones, but rather to add to what are already considered as essential components of teachers' knowledge. Again, neuroscientific evidence should not be considered as being superior to other forms of evidence about learning and development, but rather as complementary to them. Indeed, often neuroscientific evidence can simply serve to confirm what we already know from evidence coming from cognitive science and psychology.

It is clear that teachers are actively seeking to learn more about the latest research and how it might impact their practice. For example, the "Learning and the Brain" conference series is attended by thousands of teachers from around the world. Similarly, the Mind Brain and Education Society (IMBES) as well as the European Association for Research on Learning and Instruction's Special Interest Group on "Neuroscience and Education" are organising conferences that aim to bring together educators and cognitive neuroscientists to discuss evidence and forge new collaborations. There are many new resources such as online courses and books (e.g. Tokuhama-Espinosa, 2011, 2014; Blakemore and Frith, 2005; Della Sala and Anderson, 2012; Howard-Jones, 2009) that are available to teachers.[2,3] This provides an important basis for the potential success of educating educators about neuroscience in an effort to inform their practice. In fact, evidence suggests that teachers believe that knowledge about brain function will aid their pedagogy by helping them to understand the mechanisms underlying their students' learning (Dubinsky, 2010; Pickering and Howard-Jones, 2007).There is already some evidence to suggest that when teachers learn about neuroscience it positively impacts their practice (Dommett et al., 2011).

While the field of neuroscience is growing rapidly, the ways in which research within this field are translated into education are not formalised. A systematic integration of neuroscience evidence into the knowledge that teachers are expected to have to optimally carry out their profession is currently lacking. Anecdotal reports suggest that evidence about how children's brains develop and learn, is not a focus of current pedagogical knowledge frameworks (Ansari, 2005; Wilson and Conyers, 2013). If teacher education programmes do include empirical research on how children learn and develop, the knowledge transmitted is based on comparatively old theoretical models (e.g. Jean Piaget, Lev Vygotsky) (Tokuhama-Espinosa, 2014). The present report argues to integrate the latest neuroscience evidence into a formalised framework of teachers' pedagogical knowledge rather than just presented ad-hoc or dependent upon the initiative of educators.

It is important to acknowledge that the notion that neuroscience can play a role in education has been heavily criticised. For example, in a recent paper (Bowers, 2016) contends that neuroscience has no role to play in education and that only evidence from psychological experiments that examine behaviour is relevant to education. We argue that such a perspective is unnecessarily narrow and that educators can benefit from multiple levels of analysis (brain, behaviour, social environment, etc.). There is no need to pit neuroscience and psychology against one another and to be forced to choose which level of explanation is superior to the other in terms of informing education (Howard-Jones et al., 2016). In Developmental Cognitive Neuroscience, evidence from neuroscience and behaviour meet on a level playing field and mutually constrain one another. Indeed, that is why we emphasise that it is Developmental *Cognitive* Neuroscience that has potential to be meaningful to teachers' knowledge and thereby fully acknowledge the important and critical role played by behavioural and cognitive evidence. Therefore, both levels of explanation (in addition to others) can inform teacher's thinking and practice in meaningful ways.

It is important to emphasise at the outset that the aim is not to integrate knowledge that is prescriptive in terms of teaching practice. The proposal being put forth here is that information about how learner's brains learn, develop and change as a function of experience will help educators to become more informed practitioners and to see the children in their classrooms in the light of evidence about child development and learning. It is the integration of this knowledge with their experience that will influence teachers' practice. The analogy with medical education can be useful here (Thomas, 2012). All doctors in training take courses on molecular and cellular biology and it is accepted without question that an understanding of cell biology most likely improves a doctor's probability of correct diagnosis. Yet it is also clear that this knowledge is not going to lead to clear prescriptions in medical practice, but rather form an important aspect of multiple knowledge sources that inform the practice and decision-making of doctors. The present report argues that the research from within neuroscience can serve a similar, important function in informing educational professionals by serving as part of the broader knowledge that educators bring to the task of teaching. Furthermore, by instilling a culture of evidence-based practice, educators will be better equipped to critically evaluate programmes and seek out evidence-based approaches.

Moreover, by making this kind of knowledge part of teachers' overall professional knowledge, it is hoped that bidirectional relationships between educators and developmental cognitive neuroscientists will be established. Interdisciplinary approaches to problems, including how to teach better, may yield more comprehensive and efficient solutions. There is currently a divide between neuroscientists working on problems related to children's learning and skill acquisition and teachers or education professionals working with children having to learn these new skills and concepts. Bidirectional relationships between researchers and educators will improve the integrated knowledge base and lead to research questions that are educationally relevant and results that are increasingly more informative for educators.

Finally, we argue that educating teachers about neuroscience can help to prevent the damaging influence of so-called "neuromyths" – apparent facts about the functioning of the brain and its role in learning for which there is, in fact, poor quality, little or no evidence (Ansari, De Smedt and Grabner, 2012; Dekker et al., 2012; Pasquinelli, 2012). Having an understanding of neuroscience would enable educators to evaluate misconceptions about the brain and avoid accepting information or commercial products that are not evidence-based (Dekker et al., 2012; Goswami, 2006).

At the same time, the increasing public interest in neuroscientific findings raises the importance of neuroscientists becoming involved with efforts to diffuse accurate knowledge into the public consciousness and bringing about ethical challenges of the implications that can and are being derived from neuroscience research on the human condition (Illes et al., 2010; Morein-Zamir and Sahakian, 2010). For example, new insights into how measures of brain activation predict educational outcomes need to be carefully reported to avoid that misconceptions arise (e.g. the mistaken notion that because measures of brain structure and function predict educational outcomes, there is nothing that educators can change). In other words, scientists need to provide balanced accounts that take into account the scientific literacy of the audience and guard against misconceptions and potential misapplications of the evidence. As is evident, neuroscience is a highly complex science and handling the implications of neuroscience for individuals and society at large is a complex and multi-level endeavour.

Defining neuroscience and its sub-disciplines

In the domain of human neuroscience, fuelled by the advent of non-invasive neuroimaging methods, such as functional Magnetic Resonance Imaging (fMRI) and many other methods, it has become possible to look at how the brain functions and to study the neural correlates of complex human behaviours, such as problem solving and the processing of emotions (Immordino-Yang, 2011). Consequently, a new, interdisciplinary field of inquiry has flourished over the past quarter of a century: cognitive neuroscience. Cognitive neuroscience represents the integration of cognitive psychology and neuroscience. Put simply, the aim of cognitive neuroscience is to study how the brain enables the mind (Gazzaniga, Ivry and Mangun, 2008). In other words, cognitive neuroscience provides biological constraints on our understanding of human psychology. This field of interdisciplinary inquiry is rapidly growing and is beginning to investigate questions relevant to virtually all aspects of human behaviour. Today, departments of psychology at universities throughout the world are becoming increasingly populated with researchers who integrate neuroscientific methods and approaches into their study of psychological processes. Indeed, many departments of psychology have renamed themselves to acknowledge the growing role that neuroscience plays in psychological research and are now called 'Department of Psychological and Brain Sciences' or 'Department of Behavioural and Brain Sciences' and even 'Educational Neuroscience'.

As part of this field, researchers have gained unprecedented insights into human brain development through neuroimaging studies with children. Such studies have looked at age-related changes in both the structure and functions of the brain (Casey, Giedd and Thomas, 2000). The term brain "structure" refers to variables such as the volume of certain brain areas and other measures that quantify neurophysiology in the absence of its relationship to psychological processes (e.g. attention, emotion). Brain "function", on the other hand, is used to refer to variables that are correlated with psychological processes, such as the signals derived from functional Magnetic Resonance Imaging (fMRI) where the brain's response during psychological processing is investigated. Of course, structure and function are intimately linked with one another, so the terms "structure" and "function" refer to the level at which the brain is being measured. By studying both brain function and structure, it has become possible to investigate how the brain changes over developmental time and how experiences influence brain structure and function, often referred to as studies in developmental cognitive neuroscience (Johnson, 2001; Munakata, Casey and Diamond, 2004). Developmental cognitive neuroscientists study how the brain changes as a function of experience and how this varies over the course of learning and development. By doing so, developmental cognitive neuroscientists study how children learn complex skills such as reading (Dehaene, 2009; Schlagger and McCandliss, 2007) and arithmetic (Ansari, 2008; Ashkenazi et al., 2013) and how the acquisition of these skills is influenced by other cognitive functions such as working memory (Diamond, 2013), attention (Posner and Rothbart, 2007) and exercise (Hillman, Erickson and Kramer, 2008), to mention just a few.

Researchers in developmental cognitive neuroscience also address questions such as adolescent risk-taking (Blakemore and Robbins, 2012; Steinberg, 2008) and how arts education affects cognitive functions (Winner, Goldstein and Vincent-Lancrin, 2013), which are just a few of the topics that are investigated by researchers in this quickly growing field. In this context, it is also important to note that developmental cognitive neuroscience is not simply concerned with topics typically associated with the study of cognition, such as reasoning, problem-solving and thinking, but also encompasses the study of social behaviours and the influence of emotional factors, such as motivation and reward processing (Blakemore, 2008, 2010; Somerville and Casey, 2010), in an effort to better understand the interface between emotion and cognition and their interactive neural substrates.

Notwithstanding strong critics (e.g. Bruner, 1997), over the past 15 years or so, the enthusiasm for a new "science of learning" that combines insights from cognitive science, neuroscience and psychology to inform education has grown exponentially (Carew and Magsamen, 2010; Goswami, 2004; Sigman et al., 2014; Varma, McCandliss and Schwartz, 2008), thanks in great part to advances in imaging technology and co-operative efforts by neuroscientists with educators and psychologists. Terms such as "neuroeducation", "educational neuroscience", and "mind, brain and education" have been used to describe these efforts. In the present report, we use the term "developmental cognitive neuroscience" in reference to this field of research.

Neuroscientific findings with implications for learning

In this section, we provide an overview of the overarching concepts that, according to the argument put forward in this chapter, should become part of teachers' knowledge base. An understanding of these concepts will turn teachers into more informed practitioners and decision-makers in an age where evidence from developmental cognitive neuroscience is, for better or worse, increasingly being drawn upon to help inform many problems that humanity faces, including how best to educate our learners. A clear understanding of key concepts and their limitations will, in combination with their everyday classroom experiences, help teachers optimise their practice.

One key neurobiological process that will be discussed below is that of brain plasticity. Early neurophysiological studies revealed that sensory deprivation or enrichment (i.e. adding toys and/or other animals to a cage of an animal that was previously isolated) changes the brains of animals, revealing that experience shapes the brain (Buonomano and Merzenich, 1998). Plasticity refers to how the brain responds to experience and changes its structure as a consequence of alterations in the environment. In other words, experiences embed themselves into the way in which the brain functions. This occurs at the level of connections between neurons. Plasticity changes in the brain occur when new connections are formed, existing connections are eliminated or existing connections are strengthened. Today, we can study the effects of complex environmental and experiential differences, such as cross-cultural and socio-economic variability, on brain structure and function (Ansari, 2012; Hackman, Farah and Meaney, 2010; Noble et al., 2006). Meaning, while research with other species has been important in providing fundamental insights into neuronal plasticity and its mechanisms, the availability of non-invasive neuroimaging methods has enabled researchers to study plasticity in the human brain. Mounting research suggests that the brain is more plastic than we originally thought (though, importantly, within constraints) and that our brains continue to be capable of functional and structural changes into adulthood. This is the second key neurobiological process, and it has potential implications for life-long learning, a topic of much interest in many ageing Western societies (for a recent review see May, 2011).

Plasticity is key to education: Without the ability of the brain to change in response to experience, education would not be possible. If our brains were static organs or had very limited ability to change in response to information, then our ability to learn would be severely compromised. The brain allows humans to be educated and, at the same time, puts constraints on the effects of education. For learning to occur, the brain needs to be able to encode, retrieve and process information and this requires physical changes within brain circuitry. This type of change in the brain architecture in response to experience is often referred to as "experience-dependent brain plasticity". Experience-dependent plasticity represents the key mechanism by which individuals learn to adapt to their unique socio-cultural niches and function successfully within them (Greenough, Black and Wallace, 1987). Thus, in order for children to learn, experience-dependent plasticity needs to occur.

Even though most may not be aware of it, teachers are tasked with finding the best way to induce experience-dependent brain plasticity in order for students to encode knowledge, make connections between different pieces of information and acquire essential skills, such as reading, writing and mathematics. It follows from this that teachers are the orchestrators of their students' neuronal plasticity during classroom time. Hence, if teachers possessed a greater understanding of neuroscience, their practice would be significantly enriched. More specifically, accurate information translation from neuroscience to teacher education will, in deep interaction with their experience, affect and inform teachers' pedagogical decision-making.

Higher-level brain functions continue to develop into adulthood

The basic building blocks of the human brain

The mature human brain contains over 80 billion neurons. *Neurons* are the nerve cells that are thought to underlie brain functions. The basic units of a neuron are its cell body (containing the nucleus), an *axon* (an extension through which the neuron sends electrical signals away from the cell body) and *dendrites* (extensions away from the cell body through which the neuron receives information from other neurons). Neurons connect with one another. The points at which neurons connect are called *synapses*. The most common type of synapse in the brain is the so-called "chemical" synapse. In this type of synapse there is no actual direct physical contact between one neuron and another, but the synapse represents a junction between two neurons into which chemicals (known as *neurotransmitters*) are released from one neuron (referred to as the presynaptic neuron) and taken up by another neuron (referred to as the postsynaptic neuron). Neurotransmitters can inhibit or increase (*potentiate*) activity. The brain is a highly interconnected network of neurons. The cell bodies of the neurons make up what is commonly referred to as the *grey matter*. *White matter*, on the other hand, consists of axons that extend from the cell bodies and enable both short and long-range connectivity between neurons (via synapses). The brain also contains other cell types, such as *glial cells*. These cells are involved in supporting neuronal function through, for example, being involved in the insulation of neurons (*myelination*) to allow for more efficient neuronal communication.

Pre- and postnatal brain development

The human brain undergoes tremendous changes over the course of both pre- and postnatal development. During prenatal (before the child is born) development neurons are "born" (*neurogenesis*) and migrate from the innermost parts of the brain to form the different parts of the brain. Furthermore, during prenatal development the two hemispheres of the brain are formed. The hallmark of postnatal brain development (occurring after the child is born), in contrast, is not so much the birth of new neurons (though this also occurs; there is currently much effort being made to better understand the mechanisms that guide postnatal neurogenesis), but instead a burst in the connections (*synapses*) that neurons make followed by a period of the elimination (or *pruning*) of some of these synapses.

Put differently, postnatal brain development is primarily about connections between cells and the fine-tuning of connections both within and between local neuronal circuits.

There are, to date, no methods available to non-invasively measure developmental changes in brain structure at the level of the synapse and therefore such research needs to be carried out with animals or on the basis of the analysis of postmortem brains. However, while it is not possible to directly measure developmental changes in the number of synapses in humans, structural neuroimaging methods, such as MRI, have been used to quantify changes in brain volumes (where the unit of measurement includes tens of thousands of synapses) and these studies have provided convergent evidence (for a review, see Giedd and Rapoport, 2010).

The process of synaptogenesis is then followed by a developmental time period in which synapses are eliminated. In other words, following an overgeneration of synapses, the total number of synapses in the brain is reduced. However, it is important to note that synaptogenesis and pruning overlap during development and throughout the lifespan. In other words, while synaptogenesis occurs first, pruning does not replace synaptogenesis in a categorical way. Interestingly, both synaptogenesis and pruning differ substantially across brain regions. Specifically, brain regions associated with basic sensory motor processing, such as basic visual, auditory and motor cortex functioning, undergo these processes relatively earlier than brain regions associated with higher-level cognitive and emotional functions, such as the prefrontal and parietal cortices. Thus, in brain development there is not one, but multiple time-scales that differ between regions.

There are several important takeaways from the developmental changes described above. The first one is that postnatal development involves the initial overgeneration of synapses and their elimination. Secondly, these two processes (synaptogenesis and synaptic pruning) are not uniform across the brain but they differ by regions. More specifically, it appears that regions associated with basic sensory functions undergo these developmental processes earlier than regions involved in higher-level functioning *and therefore regions whose functions will be affected by learning and education*. Thirdly, it is evident that human brain development is protracted. *The brain is not fully developed by the time children reach 'culturally' defined adulthood*. The evidence pointing to brain development well into the early adulthood years has had a profound influence on the way in which we now think about adolescence. In particular, studies using structural measures of the brain, such as MRI, are revealing that the brain continues to change in structure during adolescence and into emerging adulthood (Gogtay et al., 2004; Houston, Herting and Sowell, 2013). Fourthly, in addition to synaptogenesis and synaptic pruning, there is another process referred to as *myelination*. Myelination is characterised by the "insolation" of axons that connect neurons to one another. This is achieved by *glial cells* (specifically oligodendrocytes), which wrap an insulating tissue (myelin) around these axons, allowing for faster transmission of neuronal signals between brain regions and also between the brain and the peripheral nervous system.

It is important to note what can and cannot be inferred from these findings. First of all, these changes are changes in the *structure* of the brain over the course of development (i.e. the amount of physical connections between neurons). Therefore, they cannot directly inform us about developmental changes in brain *function* (i.e. the degree to which such changes in the structure of the brain relate to changes in children's learning). Physical changes in the brain structure do not necessarily reflect functional changes, as in behaviour. This is an important distinction. Too often have these findings been interpreted to tell us about when environmental inputs should be made (e.g. when the brain should be stimulated) and educational products proclaiming to be based on neuroscience often make a leap from such data to the timing of educational inputs. For example, it has been speculated in the popular press that children are "sponges" and "can learn anything" in the early years because they have more brain cells, which quickly deteriorate (are pruned away), justifying early stimulation products and a "critical period" for learning. Neuroscientists know that we cannot derive such implications from these findings, and it is critical that educators are aware of these explanatory limitations (for more discussion of this issues, see the section on sensitive and critical periods below). These findings are all about structural changes and reveal only that the structure of the brain continues to change over the course of postnatal development and that these changes differ in timing across brain regions and over the lifespan. In other words, in order to link changes in the structure of the brain to the emergence of new behaviours, the correlation between structure and behavioural/psychological variables needs to be demonstrated rather than inferred through evidence revealing structural changes alone.

Learning changes the brain

Brain plasticity

Connections in the brain (synapses) are not static once formed but rather they change as a function of synaptic activity. This notion that the connections in the brain change is referred to as "synaptic plasticity". When two neurons connect via the synapse, this leads to physical changes in the neurons and influences the subsequent activity at the synapse (*long-term potentiation* and *long-term depression*). Synaptic plasticity is thought to be one of the primary mechanisms by which the brain changes as a function of experience and results in learning.

Beyond the level of the synapse, there is also evidence showing that the organisations of large-scale neuronal networks are capable of change. Work with animals has shown that manipulating the experience of the animal affects the organisation of their brain. For example, it has been revealed that depriving animals of visual input changes the organisation of their visual system (for a review see Buonomano and Merzenich, 1998). One of the key principles of neuronal organisation in the sensory cortices (visual, auditory, somatosensory) is that these brain regions have a topographic representation of the sensory information. For example, the motor cortex is organised in such a way that different parts of this brain region represent the hand compared to, for example, the feet. Moreover within the region of the motor cortex that represents the hand there are different parts that represent each finger.

When one of the fingers is stimulated more than the others, it will be overrepresented relative to the other fingers (meaning that more neurons in the motor cortex will respond to the stimulated finger compared to the non-stimulated ones). Results similar to those from animals have been obtained from string instrument players in whom the cortical representation of the fingering hand is larger than that of their other hand or the hands of non-playing individuals (Pantev et al., 2003). Findings such as these demonstrate that the organisation of the brain is changed by experience, and this is what is meant by neuronal plasticity. Furthermore, evidence such as this demonstrates that the pioneering work on brain plasticity in animals is convergent with data from humans (using modern, non-invasive brain-imaging methods).

Another seminal finding showing experience-dependent plasticity in the human brain is the finding that second language learning affects the structural neuroanatomy of the left parietal cortex (Mechelli et al., 2004). Specifically, it was found that bilinguals have greater grey matter volume in the left inferior cortex, a region associated with verbal fluency. Moreover, the researchers found that the volume of this brain region was related to the age at which the second language had been learnt in such a way that relatively early bilinguals had greater amounts of grey matter in this region than comparatively late bilinguals. In addition to these findings, the authors also reported that the amount of proficiency in the second language correlated with the amount of grey matter. More specifically, bilinguals who had the greatest proficiency in their second language were also those who had the largest amount of grey matter in the left inferior parietal cortex. These data therefore show that age of acquisition and individual differences in proficiency affect brain structure.

One of the most striking examples of how educational experiences drive experience-dependent neuronal plasticity is the acquisition of reading skills. It has been shown that learning to read involves changes in the neural correlates of auditory, visual and language processing (Dehaene, 2009). For example, it has recently been shown that regions in the higher-level visual cortex of the brain that are specialised for processing print in adults (for a review see McCandliss, Cohen and Dehaene, 2003) become sensitised to print as soon as children learn the associations between letters and speech sounds, thereby providing strong evidence that learning a critical skill for reading leads to change in the way in which the brain responds to input (Brem et al., 2010).

Modern neuroimaging methods, such as structural and functional neuroimaging, have allowed cognitive neuroscientists to investigate neuronal plasticity in humans. There are now countless studies that show that experiences modulate the structure and function of the brain. Furthermore, it has been shown that brain plasticity can even be found in the adult brain (for a review see May, 2011). There are numerous examples showing that training (such as working memory training, learning how to juggle, learning how to navigate complex spatial environments and even video-game playing) can lead to changes in both the grey and white matter of the brain and changes in the amount of activation within brain regions. What these data are revealing is that different experiences lead to changes in different regions and to varying extents. That is, plasticity is not a uniform process, but specific experiences change the structure and function of particular neuronal circuits. Furthermore, while there are data to demonstrate plasticity in the adult brain, the evidence does point to a gradual age-related decline in neuronal plasticity (Thomas and Knowland, 2009). In other words, the potential for neuronal plasticity is greater early in development and declines gradually over the lifespan, though learning can and does occur into old age.

The notion that the potential for brain plasticity decreases with age has led to the suggestion that there are *critical periods* for the development of particular abilities or brain circuits and the concept of "critical periods" is often discussed in education. A critical period is a window of development within which experience must occur, and if it does not, a functional deficit occurs. It should be noted that while there is some evidence for windows of opportunities for the optimal organisation of certain brain circuits (such as speaking one's first language), most neuroscientists now prefer the use of *sensitive periods,* because the evidence suggests that the windows during which plasticity can occur are not as rigid as suggested by term "critical period" (Thomas and Johnson, 2008). Furthermore, it needs to be noted that most of what is known about such windows of opportunity comes from research on the effects of experience on the neuronal organisation of the sensory modalities (e.g.

vision). Much less is known about the time windows of optimal plasticity of brain circuits that underlie higher-level brain functions such as problem-solving or literacy, for example, and many agree that there are no critical periods for an academic subject (Thomas and Johnson, 2008; Tokuhama-Espinosa, 2011). In other words, there is no clear evidence on any precise developmental time points at which plasticity for higher-level functioning is enhanced. Taken together, while there is much evidence on sensitive periods for basic sensory functions, such as vision and audition, almost nothing is currently known about the best timing for experiences that go on to shape higher-level functions. This means that while curriculum structures may appear logical in sequence, it is not yet known whether or not the age of introduction is optimal given developing neurocognitive structures.

In this context, a distinction between two types of plasticity is useful. Specifically, Greenough and colleagues argued that plasticity should be divided into: *experience-expected* and *experience-dependent* plasticity (Greenough, Black and Wallace, 1987). This distinction has been very influential on subsequent research and has been widely cited. Experience-expectant brain plasticity refers to changes in the organisation of the brain that are ubiquitous to individuals within a species, such as light and sound. These kinds of experiences are likely to be had by members of a species within certain windows of development. In contrast, experience-dependent brain plasticity occurs in response to experiences that vary between members of a species, such as the language that is being spoken within the environment of the individual or the skills they acquire in their classrooms, such as learning how to read, do math, or appreciate the history of their country. Put differently, experience-dependent plasticity allows individuals to adapt to their unique environments.

Experience-dependent plasticity represents the study of how the environment impacts the biological organisation of the brain. Recent work suggests that complex variations in the environment (and therefore the individual's experience) affect brain structure and function. For example, it has been documented across several studies that individual differences in children's socio-economic status (SES) and the environment in which a child grows affect the brain circuits underlying functions such as those underlying literacy (Hackman, Farah and Meaney, 2010; Noble et al., 2006). These findings show that the environment in which children grow up affects their brain development. Another example of how environments impact the organisation of the human brain comes from research showing that the brains of individuals growing up in urban environments show a different response profile to stress than do the brains of individuals growing up in rural environments (Lederbogen et al., 2011).

Data such as these show that the particular socio-cultural niche in which learners find themselves affects the way in which their brains function. Variables, such as education and culture, are influencing the study of brain plasticity. In other words, cognitive neuroscience now finds itself in a position to move beyond the study of how sensori-motor experiences change the brain to gaining a better understanding of how socio-cultural environments shape the brain.

When discussing neuronal plasticity, it is important to note that plasticity does vary between individuals. In other words, experience will not have the same effects on the brain circuits of all individuals. Genetic variability between individuals interacts with experience to shape neuronal plasticity. An example of this interaction between experience-dependent plasticity and genetically constrained *variability* was provided through a neuroscience study by Golestani and colleagues (Golestani, Price and Scott, 2011). These authors studied expert phoneticians (individuals who transcribe speech as part of their professional lives). These individuals clearly receive many hours of training in transcription, raising not only the question of whether their brains change as a function of this intense training, but also whether certain individuals show brain circuitry that makes them different from those who do not go on to become phoneticians and might therefore predispose them to engage in such activities.

What the authors found was that, consistent with the notion of experience-dependent plasticity, a region in the left hemisphere was positively correlated with the years that individuals had spent transcribing speech. However, in addition to this region, they found that the expert phoneticians differed from non-experts in the morphology (structure) of their auditory cortex and that this structural difference did not correlate with years of experience. In view of these data, the authors concluded that certain brain structures might vary between individuals for genetic reasons and thus predispose these individuals to engage in certain activities. These predispositions then interact with other brain circuits that exhibit experience-dependent brain plasticity, revealing the interactive role of genes and experience in shaping individual development and preferences.

Similarly, it is now well-understood that experience alters both biological and genetic mechanisms (for a review see Zhang and Meaney, 2010). This notion is well-described by the concept of *biological embedding* (for a review, see Hertzman, 2012), which postulates that the environment influences biology (such as mechanisms of gene expression) and that such processes are further modulated by individual differences (whereby the degree of biological embedding varies across individuals). Put differently, *neuronal plasticity is the result of a complex interplay between experience, biology and individual differences*. This is an important point for educators to be aware of because it shows that the knowledge and behaviour of students in their classrooms is not the result of one variable alone, but a complex interaction of experiential and biological factors. This can help to explain why certain teaching interventions resonate with some students and not with others.

Examples of cognitive neuroscience with relevance to education

In the above we reviewed some of the key concepts and terms in neuroscience that should, according to the proposal of the present chapter, become part of teachers' professional knowledge. Furthermore, we considered some recent innovative approaches to put this into practice, which show promising results of teaching teachers about neuroscience, but require further implementation and evaluation. In what follows, we now consider some insight from cognitive neuroscience that can be applied across domains of learning and therefore have relevance for education and could also be integrated into teacher training. This is not meant to be an exhaustive review of all the cognitive neuroscience research that is of relevance to educators, but covers a few topics and subjects of study that could impact the way that teachers think about learners in their classroom and the way in which they evaluate evidence and evidence-based products with which they may be presented.

Executive functions

In addition to studying how the brain represents specialised cognitive functions such as reading, language and mathematics, cognitive neuroscientists study brain systems that function across domains in order to enable learning. These systems represent the "gatekeepers" of learning since they determine how information is processed, encoded and retrieved. Cognitive neuroscientists have postulated many different systems that constrain how information is learnt. Terms such as *working memory* (the ability to hold information in a temporary storage while operating upon it), *attention* (the ability to direct focus to a particular stimulus while ignoring or inhibiting other types of information) and *inhibitory control* (the ability to inhibit responses and select among different stimuli that are presented) are frequently used to refer to neurocognitive systems that constrain our ability to focus on information, mentally manipulate that information, select some information while inhibiting others and to encode information into long-term memory.

The aim of this chapter is not to discuss the subtle nuances of theories regarding the different constructs (although this should be part of any pre-service or on-going professional development programme), but rather to highlight the importance for educators to be aware of the existence of these general constraints on learning that may help them to better understand learners in their classroom, their behaviours and individual differences therein.

To describe these general constraints on learning, we adopt a recent classification put forward by Diamond (2013). Specifically, Diamond contends that the most superordinate category of neurocognitive systems that help us to control our thinking, learning and behaviour can be referred to as *executive functions* (henceforth EFs). Executive functions such as working memory influence what can be held in memory while students solve problems. Consider for example a student solving a complex multi-digit multiplication problem. To execute the processes necessary to resolve the problem, the student needs to hold information in mind temporarily, such as intermediate solutions, while at the same time engaging on the online process of calculation. The ability to hold information in memory temporarily and to operate on that information (e.g. problem-solving) is sub-served by working memory. While solving the problem the student might be distracted by other stimuli and would therefore need to exert inhibitory control to be able to inhibit other information that is being presented but is irrelevant to the task of solving the multiplication problem. This example illustrates that many components of executive functions are drawn upon during everyday tasks and therefore also during classroom activities. A consideration of EFs by educators can help them understand why some students might struggle in certain classroom activities. It may not be because they have an inability to grasp a particular subject or concept, but rather because they struggle to exert the necessary EFs to be able to engage with the material, hold in in mind, operate upon it, and select the relevant information, while at the same time inhibiting information that will not inform their understanding, but rather interfere with it.

It has long been known that individual differences in EFs are related to educational outcomes such as literacy ability (e.g. Blair and Razza, 2007) and maths achievement (for a recent review, see Cragg and Gilmore, 2014). The relationship between EFs and important educational outcomes shows that these neurocognitive functions are related to learning and skill acquisition.

EFs serve as an umbrella term for a broad set of neurocognitive functions. It is therefore not surprising that there is no single brain region that subserves EFs. In general, tasks that tap into executive functioning are subserved by a network of brain regions encompassing not only the frontal and parietal areas of the brain but also subcortical regions of the brain, showing that a large network is engaged during executive function execution. From a developmental perspective, it is important to recognise that the neural networks underlying EFs change over the course of an individual's development with networks undergoing age-related increases in activation (for a review see Morton, 2010). Furthermore, it has been shown that the neural networks underlying EFs are changeable. Results of studies that have trained EFs, such as working memory, have shown that such training results in changes in the structure and function of the brain. Such findings imply that EFs are changeable and plastic rather than static.

Box 9.1. **Attention systems**

Just as there are multiple neural pathways associated with memory systems in the brain, so there are multiple circuits and pathways associated with attention (Petersen and Posner, 2012; Posner, 2012a; Posner, 2012b). Just as memory systems are vital for learning, so are attention systems; without memory or attention, there can be no learning. Posner and colleagues have identified at least three distinct neural pathways for attention that contribute to efficient learning (Posner & Rothbart, 2013). The altering and orienting system calls attention to stimuli; the sustaining system permits a learner to stay focused; and the executive functions permit the learner to choose the right things to pay attention to in any given moment. In order for efficient school learning to take place, all three systems must be working properly (Sarver et al., 2012). For effective teaching, teachers must be aware of how to get a students' attention (alerting system) and how to keep them on task (sustaining system) and how to help them develop criteria about what is of most importance (executive functions system).

Learning problems can be based in memory deficiencies, attention deficiencies, a combination of both, or neither. A high percentage of learning problems, however, are associated with problems of attention or attention and memory (see Lufi, 2013; Sarver et al., 2012 for examples). Some studies suggest that cognitive difficulties can arise due to chemical imbalances, which may be affected by diet or living conditions for example, which can affect attention systems as well as potential to learn (see Bhang et al., 2013 for an example). One pertinent example of chemical imbalances affecting attention and learning capacity is attention deficit hyperactivity disorder (ADHD). Individuals who present with ADHD tend to have a lower threshold for stimuli, suggesting their alerting systems are on high, and show low abilities for sustained attention through difficulties maintaining focus on specific tasks. The catecholamine hypothesis of ADHD suggests a dysregulation of two chemicals in the brain, norepinephrine and dopamine, which results in a diminished ability of the prefrontal cortex to fine-tune attentional processes, such as the directing or maintaining of attention on current activities (Curatolo et al., 2010). Issues such as chemical imbalance can be remedied through pharmacological intervention, for example in the case of ADHD through dextroamphetamine or methylphenidate, which are two of the more commonly used stimulants used to manage symptoms (Mash and Wolfe, 2012), or through lifestyle interventions such as increasing rates of aerobic exercise, which has been implicated in increases in attention-mediating neurotransmitters in the prefrontal cortex (Wigal et al., 2012). Proper diagnosis of the roots of learning problems is key to remediation, and teachers can play a key role in identifying issues or difficulties associated with attention.

Transfer of function across neurocognitive domains

In view of the finding that EFs are plastic, there has recently been a lot of interest in the possibility that such training can lead to improvements not only in EFs but can also improve functioning in neurocognitive domains that require EFs. More specifically, it has been argued that domain-general functions such as EFs can be trained through computerised games and that the effects of such training will result in participants becoming better at that task/game or tasks/games that are closely related to it. For example, engaging in working memory training makes individuals better at the task/game that they are being trained and on games that also train working memory or measures of working memory. Far transfer, on the other hand, refers to effects of training that extend beyond those that are directly being trained. For example, given that solving complex mathematical problems involves EFs, it might be hypothesised that training them results in improvements in mathematical problem solving. If training EFs lead to changes in mathematical problem solving, then this would be a demonstration that the training of EF leads to transfer to domains that were not directly trained but are related to EF. While there have been some reports of far transfer, such as an effect of working memory training on (fluid) intelligence (e.g. Jaeggi et al., 2008), such findings have not been replicated in other studies (e.g. Harrison et al., 2013). Indeed, there are now several large-scale studies that provide no evidence for far transfer of so-called "brain-training games" that purport to train functions such as working memory and attention. What these studies consistently report is that such training improves performance on very similar tasks/games that simply use different materials but that they do not lead to changes in performance on tasks that tap into related but different processes (e.g. Owen et al., 2010; Shipstead, Redick and Engle, 2012; Egeland, Aarlien and Saunes, 2013; Dunning, Holmes and Gathercole, 2013).

There is similar, conflicting data on the effects of music training on non-musical abilities. While some studies have shown that music training leads to positive changes in IQ (Moreno et al., 2011; Schellenberg, 2004), others do not show evidence for such far transfer (Mehr et al., 2013).

The notion of training domain-general neurocognitive functions (such as EFs) is a relatively new concept. Thus far, the evidence is clearly conflicting, and there is not a lot of support for the notion that training on EF tasks leads to improvement in non-trained neurocognitive functions (e.g. that working memory training improves reading abilities). Yet, the possibility of such transfer effects should not be excluded *a priori*, since their absence may reflect a need to improve the training programmes to yield far-transfer effects or to look at a broader set of potential targets for far-transfer effects. As it stands, no firm conclusions about the effects of so-called "brain-training" can be made. There certainly is no quick fix, no magical "brain training" package, even though some companies would make you believe so in their advertisements. It is important that educators are aware of what the data currently says and to understand the distinction between near- and far-transfer. This will allow them to ask questions about training programmes or new educational tools that might be suggested to them and thereby become more informed and critical users. Being able to engage in such critical reflection will eventually benefit the learning of students in their classrooms.

Finally, it is important to note that the data on "brain training" show that just because one variable correlates with educational outcomes, such as EFs, that does not necessarily mean that training EFs will improve educational outcomes. In other words, demonstrating a relationship between a given neurocognitive function and learning in educational settings does not necessarily imply that training the function will lead to improvements in learning.

Box 9.2. **Memory systems**

Memory systems (short, working, long-term, among others) are vital for learning. Without memory, there is no learning (Baddeley, 2013). Memories are created when information passes through short and working memory into long-term storage, and recall is accessed to link old to new (Alberini, 2011). The ability to rapidly recuperate information stored in the brain is based on both how easy it is to find due to accessible placement, as well as how quickly it can be recalled (Baddeley, 2013). The location of storage is primarily based on mode of learning, how easily linked prior information is to new information due to past association, and the development of networks that chain different types of learning into whole circuits (Winocur, Moscovitch and Bontempi, 2010). The speed of recall is based on how well the information has been rehearsed; the more rehearsal, the quicker the recall (Ericsson, Krampe and Tesch-Römer, 1993).

To strengthen memory systems, significant learning experiences and practice are necessary. In schools, the use of classroom tests can enhance memory systems. But memory systems can also be enhanced through mechanisms of "self-testing", such as when students practice while studying (Roediger and Butler, 2011; Roediger and Karpicke, 2006). Holding frequent tests in the classroom setting, for example, encourages students to maintain a study regime throughout the duration of the course, rather than promoting small periods of concentrated study, which is more likely to occur when a teacher sets only a few tests per semester. Some research has also indicated that rates of retention could be higher with more frequent testing than if the student spent the equivalent amount of time purely engaging in studying. While testing may produce some negative effects, such as recall interference or the negative suggestion effect (i.e. when a teacher sets a multiple choice or true/false test, there are options that are correct and incorrect, subsequently students may endorse the incorrect answer on the first test and continue to do so on future evaluations), testing seems to generally be a robust mechanism for enhancing learning and memory (Roediger and Karpicke, 2006).

Neurocognitive predictors of educational outcomes

One area in which data from cognitive neuroscience is having a growing influence on education is the area of predicting academic outcomes from brain imaging data. For instance, there are several studies using event related potentials (ERPs) to record the brain responses of neonates and infants which have revealed that the infant's brain responses to sounds predict individual differences in reading years later (Guttorm et al., 2001; Guttorm et al., 2010; Molfese, 2000; Pihko et al., 1999). In other words, these data show that brain signature in infancy recorded during speech processing predict reading scores later in life, thereby potentially giving parents and teachers an early indication that a child may need special attention to learn how to read fluently. Such data show that the pre-reading brain of infants who will go onto experience difficulties in reading respond differently to those who will develop normal literacy skills and thereby draw attention to the early building blocks of reading, resulting in many potential implications for early diagnosis and remediation. In this context, it should also be noted that these kinds of data are difficult to obtain with any other measure traditionally used in behavioural research with young infants and children and that there are few studies currently available, thereby demonstrating the potential added value of using neuroimaging methods.

In studies with older children using both structural and functional neuroimaging, researchers have been able to demonstrate that structural variables, such as brain volume and white matter integrity, as well as functional measures of brain activation during reading-related tasks (e.g. rhyming), predict significant variability in children's reading scores. It could be said that this is not a surprising finding and that it is far more cost-effective to use traditional behavioural measures as predictor variables. However, Hoeft and colleagues demonstrated that the combined used of behavioural and neuroimaging measures as predictors of reading (specifically, decoding skills) explains significantly more variance than either measure used in isolation (Hoeft et al., 2007). Thus, neuroimaging and behavioural measures each explain unique variance, which leads to overall better prediction of reading outcomes. In other words, the combination of neuroimaging and behavioural data predicts success and failure in a better way than either measure alone.

In a more recent study, Hoeft et al. asked whether neuroimaging data could predict who will go onto show gains in reading performance over time. Both behavioural and neuroimaging data were acquired from children with and without developmental dyslexia. The same children were tested again 2.5 years later. Behavioural data suggested that while some children with developmental dyslexia exhibited significant gains in reading abilities, another group of children demonstrated no change on behavioural tests of reading competencies. By using the behavioural and neuroimaging data acquired at the outset of the study to predict who ended up showing reading gains compared to children who did not, the authors were able to show that structural and functional neuroimaging measures were able to predict which children end up exhibiting gains in their reading abilities.

In striking contrast, none of the behavioural variables were able to predict which children exhibited gains (Hoeft et al., 2011). These data point to the possibility of undertaking "neuroprognosis" and also demonstrate that, in some cases, neuroimaging measures (both structural and functional) may be a more sensitive way in which to predict later outcomes (given that the behavioural data did not exhibit such predictive power). It should be noted that in this context the data does not imply that the children who did not benefit from the particular intervention could not, in principle, benefit from another intervention. Instead, the data show that these children did not respond to the intervention used. Put differently, this kind of evidence cannot be used to classify children into those for whom education does or does not work. However, they can be used to predict who will gain most from a particular intervention. Therefore, it is possible that, in future, such analysis could be used to determine which kind of intervention is optimal for which child (i.e. individualised education).

In addition to providing evidence to suggest that neuroimaging measures can be used to predict change in educationally-relevant outcomes (e.g. gains in reading ability), Hoeft et al. found that individual differences in the structure and function of the right inferior frontal cortex were particularly predictive of such gains. This represents an intriguing finding because reading is typically associated with a predominantly left-lateralised network of brain activity and structure (Dehaene, 2009). However, there have been other studies suggesting that the right hemisphere plays an important role in response to intervention and may represent compensatory neural mechanisms (Temple et al., 2003). Thus, individuals who are better able to use these right-lateralised compensatory mechanisms may show greater gains in reading ability.

This finding provides a significant constraint on our understanding of the mechanisms that drive individual differences in improvements in reading abilities. It is not as though we necessarily see the normalisation of disrupted brain circuits, but instead it appears that the recruitment of regions not typically associated with reading is what is associated with the recovery of impaired reading skills. This is not only important from the point of view of understanding the mechanisms underlying the recovery of reading abilities, but it may also help to constrain how reading interventions are designed. In other words, future efforts may be directed at better understanding what mechanisms drive the recruitment of such compensatory neural processes and how these might be optimally harnessed. In this way, neuroimaging provides a novel constraint on recovery of cognitive function by revealing the mechanisms that can guide future intervention programmes.

The data reviewed above suggest that neuroimaging can play a role in predicting individual differences in educational achievements and can help to better understand who will benefit from intervention. Furthermore, neuroimaging methods acquired early in development can predict future outcomes. While these data are certainly exciting, their application in mainstream education seems hard to imagine at least at this point in time. There will likely never be MRI scanners in schools to help understand individual differences in response to educational interventions or for the use of predicting who might be at risk of academic failure (leading to a host of neuroethical questions as well, which go beyond the scope of this chapter). However, one might imagine that cheaper measures such as electroencephalogram (EEG) could be used in certain circumstances to help increase the precision of prediction in the future. After all, in the year 2001, when the first sequence of the human genome was published, nobody would have imagined that today it is possible to sequence a human genome in less than a day at a cost that is rapidly falling. Thus, while such neuroimaging methods to predict and track educational outcomes are currently not ready for mainstream use, it is possible that technological advances may make these useable in the future. In view of this, teachers should become aware of these future possibilities.

Furthermore, the kinds of brain networks that are revealed to predict individual differences in performance and change in performance over time inform our understanding of the neurocognitive mechanisms that are associated with improvement. By doing so, these findings will inform the design of training and intervention programmes. For example, the finding that responses to math tutoring are predicted by the volume of the hippocampus and its functional connectivity with the prefrontal cortex might indicate that individual differences in the general circuits underlying memory and learning rather than regions specifically associated with arithmetic processing are related to improvements in mathematics.

Box 9.3. **Emotion regulation and education**

There is much evidence for the interdependence between learning and emotion. Over 2000 years ago, Plato stated that learning inherently has an emotional base (Hinton, Miyamoto and Della-Chiesa, 2008), and in more recent literature the science has been focusing on the prevalence and development of social-emotional skills and competences in students. There are a number of competing schools of thought regarding the definition of emotions, although one commonly touted biological definition suggests emotions to be a system of response through which experience is appraised and actions are prepared based on a set of circumstances, and experience and meaning are infused (Cole, Martin and Dennis, 2004). Emotions are comprised of many dimensions, such as cognitive, experiential, behavioural and physiological (Gross, 1999).

Box 9.3. **Emotion regulation and education** *(continued)*

In the human brain, there are a number of neural networks associated with learning, one of which is the affective network, which tends to be involved in the more emotionally-based aspects of learning such as stress, motivation and interest (Hinton et al., 2008). This brain network encompasses regions such as the limbic system, which is considered to be the "seat of emotion" and consists of structures such as the hippocampus and amygdala (MacLean, 1949), which relay information to various cortical regions of the brain (LeDoux, 2000). This allows for a bidirectional flow of emotional information and cognitive processing, which allows the higher cognitive centres to be involved in the shaping and regulation of emotion, as well as the ways in which emotion can influence both cognition and behaviour. Emotion regulation is a highly adaptive skill that allows humans to reappraise various events through interpreting them in manners that change emotional responses to them (Gross and Thomson, 2007; Giuliani and Gross, 2009). Self-regulation of emotions encompasses a wide range of processes through which an individual can influence the emotions they have, how they experience and express the emotions, and when they have them using techniques such as reappraisal, rationalisation and suppression (Gross, 1999; Hariri et al., 2000).

According to an OECD report published in 2007, the ability to regulate one's emotions can be predictive of academic outcomes. This is consistent in much of the scientific literature, stating that self-regulatory skills and academic achievement are closely linked (e.g. Blair and Razza, 2007; Duncan et al., 2007; Payton et al., 2008). Emotion regulation has been shown to be positively correlated with teacher-reported academic success, productivity in the classroom environment, as well as scores in math and literacy (Graziano et al., 2007). One potential explanation for this finding could be that learning new information results in an arousal of emotions in children, which could range, for example, from anxiety to frustration. A student who is unable to cope with these emotions may become agitated or frustrated when trying to do an assignment, resulting in inaccurate completion (Graziano et al., 2007). Those students who are more apt at self-regulating their emotions also tend to show higher levels of resilience, fewer behavioural problems, and are more likely to have stronger social networks, including more positive relationships with teachers (OECD, 2007; Graziano et al., 2007). Student-teacher relationships are related to academic success, with more positive relationships indicating a higher likelihood for higher achievement potentially due to providing more motivation for children to succeed and please their teachers (Pianta and Stuhlman, 2004; Urdan and Maehr, 1995).

Children who are able to recognise and label their emotions also seem to have higher academic performance and are better socially adjusted, with similar findings reported for preschool-aged children (Izard, 1971; Walden and Field, 1990). Emotion knowledge skills may be exhibited more in children who are older and do not come from socially disadvantaged backgrounds, as well as those who are superior in self-regulation (Denham et al., 2012). Emotion knowledge as well as the ability to self-regulate seem to be important precursors to fostering academic achievement, social capital and a pro-social classroom. As these are skills and traits that can be developed, there is room for the introduction of social-emotional learning programmes in an educational context in order to enhance the capacity for self-regulation and emotion knowledge.

Does learning about brain development and plasticity improve teaching?

Educators play a critical role in driving experience-dependent changes in brain function. Put differently, because it is through education that individuals adapt to their environments and become members of their culture, education can be said to be a vehicle through which experience-dependent brain plasticity occurs. From this it might be hypothesised that if educators had a better understanding of brain plasticity and the role they play in this neurobiological process, changes in their teaching would occur.

Indeed, recent evidence in support of this notion comes from the work of Janet Dubinsky and her colleagues at the University of Minnesota. Since 2000, this team of neuroscientists, educators and educational psychologists have developed and run a professional development programme called "Brain U" for in-service teachers at primarily the middle school level of instruction. The philosophy behind the "Brain U" professional developmental programme is that teaching teachers about fundamental concepts in neuroscience, especially brain plasticity, will change their understanding of the processes of learning and therefore learners in their classroom. This in turn will make them better teachers. As Dubinsky et al. put it: "The goal of bringing the neuroscience of learning to in-service teachers provides a new perspective on instruction, one where teachers come to see themselves as designers of experiences that ultimately change students' brains" (Dubinsky, Roehrig and Varma, 2013, p. 318). In this way the philosophy of "Brain U" is very closely related that which forms the core of the present framework for integrating neuroscience into teacher education.

The content of "Brain U" is based on the Society for Neuroscience's core concepts.[4] These core concepts are taught using an inquiry-based approach that was developed in collaboration between the neuroscientists, educators and educational psychologists behind the "Brain U" programme. One key aspect of "Brain U" is that the focus is on learning the neuroscience concepts. The programme does not focus on discussions of the relevance of these concepts for education and pedagogy, nor is it deliberately focused on covering a discussion of whether or not neuroscience can inform education and at what level. Instead, key concepts about the brain and how the brain learns and changes through learning are acquired through inquiry-based pedagogical approaches such as experiments, group discussions and model building. In this way, the programme does not involve direct instruction of neuroscience concepts through lecture formats, but instead involves activities that enable in-service teachers to collaboratively construct their understanding of core concepts in neuroscience.

As one might expect, teachers who participated in this programme gained a better understanding of neuroscience. In other words, the investigators found a significant difference in their neuroscience knowledge when comparing it before and after their participation in "Brain U". This finding is promising because it shows that teachers' knowledge of neuroscience increases, which may also make them less susceptible to inaccurate statements about the brain or so-called "neuromyths" (Dekker et al., 2012).

While such data clearly show that the "Brain U" professional development programme was effective when it came to enhancing teachers' understanding of the brain, such findings do not speak to the central prediction behind "Brain U", which is that, as the authors clearly state: "The neurobiology of learning, and in particular the core concept of plasticity, have the potential to directly transform teacher preparation and professional development, and ultimately affect how students think about their own learning" (Dubinsky, Roehrig and Varma, 2013, p. 317). To address this prediction, Dubinsky and her colleagues asked independent observers to code for categories of quality of classroom instruction in both classrooms taught by teachers who had been students in "Brain U" as well as a comparison group of teachers who had not yet taken part in "Brain U" professional development. The results of these observational studies suggest that participation in "Brain U" had a positive effect on broad indicators of classroom instruction such as developing students' "deep knowledge", "making connections to the world" and developing "higher-order thinking skills". In other words, the observers coded the classrooms taught by teachers who had been students in "Brain U" as higher on these categories compared to classrooms taught by the control teachers (those who had not yet participated in "Brain U").

While these results are promising and appear to support the central motivation behind the professional development programme, it should be noted that there are several limitations that point towards the need for future development. One of the key limitations, which Dubinsky and her colleagues acknowledge themselves, is that "Brain U" involves both the teaching of neuroscience concepts as well as partaking in inquiry-based pedagogical approaches to do so. In other words, it is possible that teachers who participated in "Brain U" absorbed some of the pedagogical design principles behind this professional development programme and used these in their future instruction, quite independently from the neuroscience content. While this possibility cannot be fully excluded, it seems somewhat unlikely given that teachers repeatedly reported that understanding core concepts in neuroscience bolstered their teaching beliefs through showing them that teaching changes the brain and motivated them to teach their students more about neuroscience in order to enhance their motivation to learn (by showing students that if you learn your brain changes – learning does not simply involve using the brain, it entails continually changing the brain to deal with new content and information).

Another closely related limitation of "Brain U" is that it did not use an active control group. To further pinpoint the specific effects of "Brain U" or similar professional development programmes it will be necessary to have a control group of teachers who also underwent professional development during the summer months, but participated in professional development programmes that did not focus on neuroscience but used similar pedagogical principles (i.e. inquiry-based pedagogy). The comparison between the effects of "Brain U" and such a control condition is absolutely critical to enable a better understanding of whether neuroscience instruction specifically leads to the observed changes in classroom practice, independently of the pedagogical approach used to instruct it.

It should be noted that "Brain U" has thus far been used in professional development with teachers who were predominantly from middle-school classrooms. Therefore, there is a need to also use this or a similar programme with elementary school teachers. In addition, it should be explored, as stated previously in this chapter, whether making neuroscience part of pre-service training has the same effect. The disadvantage of professional development is that it may not be available to all teachers. If neuroscience were to be integrated into pre-service teacher training, it could reach a larger group of teachers and could influence their practice from the very beginning.

In this context it will also need to be carefully considered exactly how the information will be taught. In "Brain U" an inquiry-based approach is used. This is a laudable strategy, but one that does require relatively small classes of teachers. Such a way of instruction may not be feasible for pre-service training in neuroscience and other means of delivery, including multi-media approaches to the delivery of materials. Therefore, there is a need to develop additional frameworks for the integration of evidence from cognitive neuroscience into pre-service education and to test the efficacy of such approaches for improving teaching and teachers pedagogical knowledge.

Summary

The last two decades have seen a tremendous growth in our understanding of the functioning of the human brain and how the brain relates to the way we think, feel and learn. Moreover, by studying human brain function across the lifespan, researchers are improving our understanding of how changes in brain function underpin developmental changes in cognition and emotion. In view of this growth in our understanding, there have, and continue to be, calls for this scientific knowledge to inform education. In the above, we consider how the study of how the brain relates to cognition and learning and how this relationship changes over development might impact educators. It is clear that new evidence from studies in developmental cognitive neuroscience does not generate findings for teachers that are prescriptive. It would be naïve to assume that it is possible to go straight from "brain scan to lesson plan". Knowledge transfer involves a complex, collaborative and iterative process between researchers and stakeholders. In this way, it is necessary to provide the infrastructure that will enable researchers working on enhancing our understanding of brain development to work collaboratively with educators and educational researchers.

We contend that an important part of creating a new, evidence-based, collaborative culture in education that is, among other scientific areas, grounded in what we learn from developmental cognitive neuroscience, is the systematic integration of such evidence into teacher training to impact their pedagogical knowledge. We contend that such knowledge can give teachers better grounding to the decisions that they make in their classroom and a fuller understanding of their students. Such findings need to be translated. In the above, we provide examples of the kind of research findings and empirically-supported theories that could be included into teacher training. Research from developmental cognitive neuroscience and allied disciplines can support teachers' professional judgment and help them rethink the way they practice (e.g. if they learn about neurocognitive functions, such as the effect of working memory on learning, they may change practice in their classrooms). But research can only be translated if teachers actually have an understanding of the evidence base that exists, what to trust and how to evaluate it. They must play a role in the translation, as many neuroscience researchers may have no experience of pedagogy.

This paper is not meant be prescriptive in that it tells teachers that this piece of science translates to that kind of practice. Rather it argues for the potential integration of basic principles of developmental cognitive neuroscience and development into teacher training in order to foster teachers' knowledge that, in combination with their professional judgement and skills, may support their teaching activities.

Notes

1. Society for Neuroscience (www.sfn.org).
2. The OECD is not endorsing any specific conferences or books in connection with this research.
3. www.learningandthebrain.com; www.learner.org/courses/neuroscience/about/about.html
4. www.brainfacts.org/about-neuroscience/core-concepts/.see

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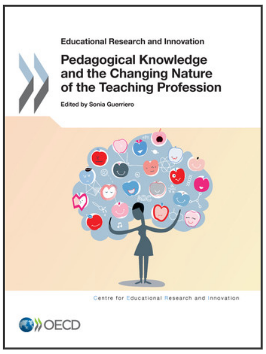

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