1 Educational Neuroscience

Why Is Neuroscience Relevant to Education?

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Educational neuroscience is an emerging field whose goal is to translate new insights, garnered from the study of neural mechanisms underpinning learning, into practical applications in the classroom in order to improve educational outcomes. The field began in the 1990s, the so-called 'decade of the brain' (Jones & Mendell, 1999), when technological advances in brain imaging spurred progress in the scientific understanding of how the brain supports the mind and its facility to learn. The field is also referred to as 'mind, brain, and education' and as 'neuroeducation', and now supports a range of societies, research centres, conferences, and journals. It falls under the broader banner of the 'Science of Learning'.

While educational neuroscience is founded on the intuition that new findings on the neural mechanisms of learning may be helpful for teachers in the classroom, educational neuroscience is not intended to be reductionist—it does not maintain that brain-level explanations are the best, nor seek to reduce education from its intrinsic nature as a societal and cultural enterprise. Its contribution is intended to be more modest: an understanding of mechanisms of learning may help improve some learning outcomes.

As we believe the diverse contributions contained within this volume show, educational neuroscience has great potential to propel advances in educational practices. However, the current cultural context presents challenges. Teachers are often enthusiastic about techniques that are 'brain-based', but some of these techniques are advocated by companies where the neuroscience is only window dressing for a commercial product, and the techniques are not supported by scientific data (Simons et al., 2016). In amongst a public understanding of how the brain works there have appeared myths (e.g., that we only use 10% of our brains, or that some children are left brain learners while others are right brain learners[1]). These 'neuromyths' have frequently led to classroom practices, again without scientific support (e.g., visual-auditory-kinaesthetic learning styles; Pashler, McDaniel, Rohrer, & Bjork, 2009). In addition, while educational policymakers have proved keen to inform their decisions with neuroscience evidence (e.g., Thomas, 2017; Willetts, 2018), researchers must be careful to ensure that recommendations do not exceed the current level of scientific understanding (Bruer, 1999). Moreover, while it is important to educate the public about neuromyths or ineffective educational approaches, it should also be acknowledged that despite knowledge translations, ineffective methods may continue to be used.

This volume presents the latest research in educational neuroscience. Across seventeen chapters, there are four main areas of focus. The first is on individual differences: what makes children perform better or worse in the classroom. Note this is a slightly different question to the theoretical puzzle of how education-relevant skills are acquired. It is the distinction between asking, say, what makes children better or worse at mathematics, compared to asking how can humans learn something like mathematics at all. The second focus is to consider this question at different stages in development—from the early years, through mid-childhood, adolescence, and into adulthood. Each age range can pose different challenges for teachers and offers different opportunities to modify approaches. Our consideration of individual differences considers their respective origins in genetic and environmental causes (the latter particularly focusing on the contribution of socioeconomic status). The chapters following address individual differences in *discipline-specific abilities*, including literacy, numeracy, and science, and then in *discipline-general abilities*, including executive functions and social and emotional development.

The third focus of the book, represented by a collection of six chapters, considers *cognitive enhancement*, summarising research that has investigated activities that might give general benefits to cognition. These include action videogame playing, mindfulness training, the role of sleep in learning, aerobic exercise, learning a second language, and learning a musical instrument. These chapters assess which of these activities (if any) have proven to have widespread benefits that extend to educational achievement.

The fourth focus of the book is on the translation of research findings into classroom practices, and broader ethical issues raised by educational neuroscience. Offering the teachers' perspective, one of our contributors argues:

> we are the professionals and understanding learning and the implications it has for our teaching should be the basis of our practice. Just as we would expect doctors to understand how the body works and keep up to date with new techniques, for example in treating cancer, teachers need to understand how learning takes place.
>
> (Bell & Darlington, Chapter 19)

Yet what exactly do teachers need to know about neuroscience that will actually change their day to day practice—for example, how they plan a lesson? Do teachers need to know how a brain scanner works? What neurotransmitters do? How the brain consolidates memories? The final section of the book seeks to answer this question.

How Does Educational Neuroscience Work?

Neuroscience interacts with education via two routes, shown in Figure 1.1. It can interact indirectly via psychology, whereby evidence from neuroscience

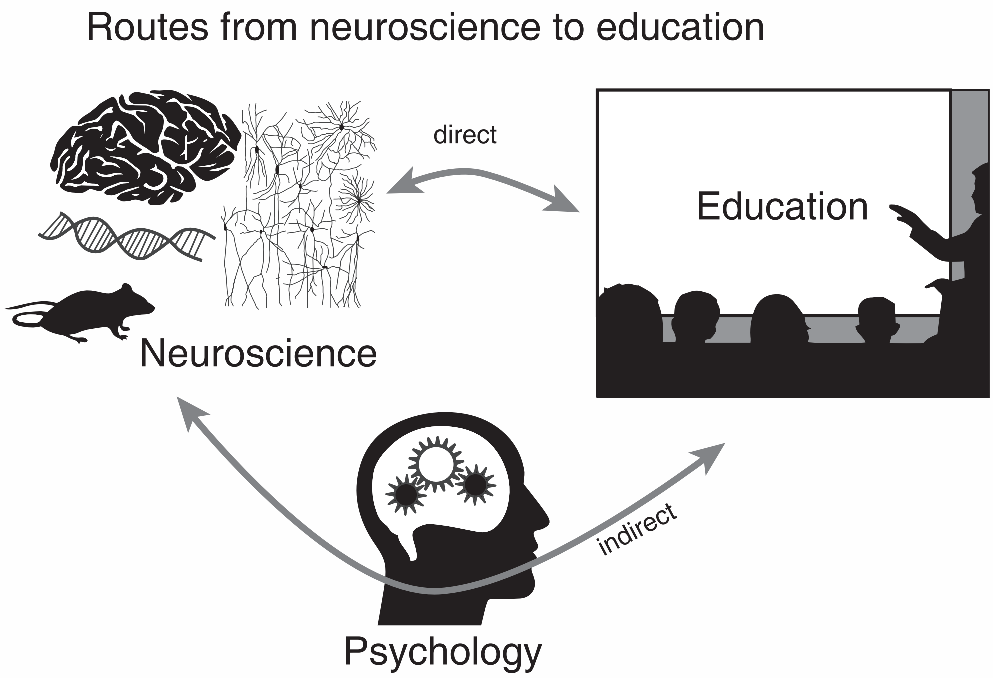

Figure 1.1 Two Bi-directional Routes Linking Neuroscience and Education

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is used to advance psychological theory. Under this view, as an isolated discipline, psychology produces theories of learning that are too unconstrained, speculating on how cognitive systems *might* work rather than focusing on how our actual cognitive system works given the constraints of delivering it in real-time through brain function (Thomas, Ansari, & Knowland, 2019). Neuroscience and education can also interact directly, by virtue of the fact that the brain is a biological organ and therefore subject to metabolic constraints. Factors such as energy supply, nutrition, response to stress hormones and environmental pollution can potentially influence brain function, including learning. Thus, while educational neuroscience generally places psychology at its centre, research on the impact of non-psychological factors on educational outcomes, such as aerobic fitness, diet, and air quality, also falls within its remit. The direct route can be thought of in terms of 'brain health'—placing the organ in the optimal condition to maximise the individual's learning when he or she enters the classroom.

Even if educational neuroscience can offer insights into mechanisms of learning, it should also be recognised that learning is only one part of education. Educational outcomes need to be thought of in terms of the nested constraints that encompass the individual, classroom, school, family, and society. For example, the effect of home conditions is often more powerful in influencing educational outcomes than what occurs in school, suggesting that school practices are not always the limiting factor on performance. Figure 1.2 borrows

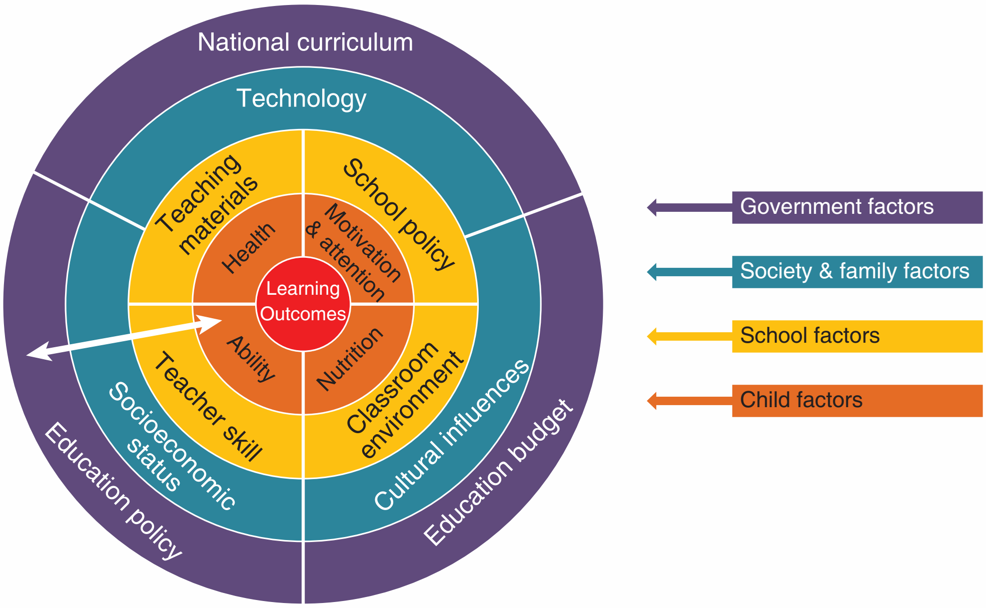

Figure 1.2 Proximal and Distal Factors That Support and Constrain Change in Learning Outcomes, Following the Layered Influences on Behavioural Change Proposed by Michie, van Stralen, and West (2011), and the Interactive Relationships Between an Individual and His or Her Environment as Proposed by Bronfenbrenner (1992). The white arrow reflects bidirectional influences between layers.

Source: Reproduced with permission from Thomas et al., 2019.

from Bronfenbrenner's ecological systems theory (Bronfenbrenner, 1992) to identify some of the nested factors constraining educational outcomes. It places learning outcomes at the heart of education, but illustrates the range of other factors—child-internal, societal, institutional, and governmental—which make up the broader picture. In line with Bronfenbrenner's view, the factors that influence a child's learning outcomes operate at vastly different degrees of proximity to the learning process and should be seen as an interactive, interconnected system. The potential impact of educational neuroscience is to improve educational outcomes by changing the most proximal factors to learning outcomes as shown in Figure 1.2: ability, motivation and attention, health and nutrition. However, its scope to do so depends on the range of barriers to change that may be encountered beyond learning itself.

The Job of Educational Neuroscience Is a Difficult One

Part of the challenge of educational neuroscience is that translation from basic science to practical application is difficult, even for a mature discipline such as psychology. Roediger (2013) observed that despite a hundred years of psychological evidence on learning and memory, there were still techniques used in the classroom even though a body of evidence exists that they are ineffective (e.g., highlighting/underlining text to aid memorisation), and techniques with good evidence of their effectiveness that were not used in the classroom (e.g., learning through testing) (see Dunlosky, Rawson, Marsh, Nathan, & Willingham, 2013). It is not straightforward to translate an understanding of how learning occurs in the brain into ways to improve learning outcomes through instruction. Such translation requires investment into structures and mechanisms that can facilitate it.

A second challenge is that even though 'learning' may seem like a unitary construct—something that hopefully happens in the classroom, or through study—its realisation in the brain is highly complex. As a product of evolution, the human brain has a number of priorities. Its first is to support motor movements by integrating perceptual information. Its second is to purse basic goals built into its very structure in the systems that support emotions, in what one might call the eight Fs (fear, fight, flight, freeze, feed, fun, frolic, and forty-winks).[2] As the brain of a social primate, its third priority is other people, be they parents, siblings, mates, friends, or enemies. The brain dedicates many systems to processing other people's identities, actions, emotions, and intentions. Its fourth priority—*only* the fourth—is high-level cognition, the kind of knowledge and reasoning skills that are the target of education. There is much, then, that could get in the way of learning.

Learning itself is the interplay of perhaps eight different neural systems (Thomas et al., 2019[3]). These are depicted schematically in Figure 1.3 (see Chapter 2 of this volume for an overview of actual brain regions and functional networks). The eight are:

1. A system for memorising individual moments, which produces *episodic or autobiographical memory*. This is realised by the hippocampus and the structures around it. This system can change its connections very quickly to record snapshots.
2. A system for learning *concepts*. The brain learns associations between perceptual information and motor responses, spotting complex spatial and temporal patterns. This happens within the cortex, where changing connections takes seconds, minutes, and hours.
3. A system for *classical conditioning*. Some associations are unconscious and involve the emotion (limbic) structures further inside the brain. These are associations between stimulus and response, such as when a particular food made you sick and puts you off it thereafter. These associations can form over seconds and minutes.
4. A system for *control*. The brain learns to control content-specific systems in the posterior cortex so that they are activated in the appropriate contexts. This system learns strategies and when to apply them. Control also involves the prefrontal cortex, which also interacts with limbic structures to integrate planning with emotion.

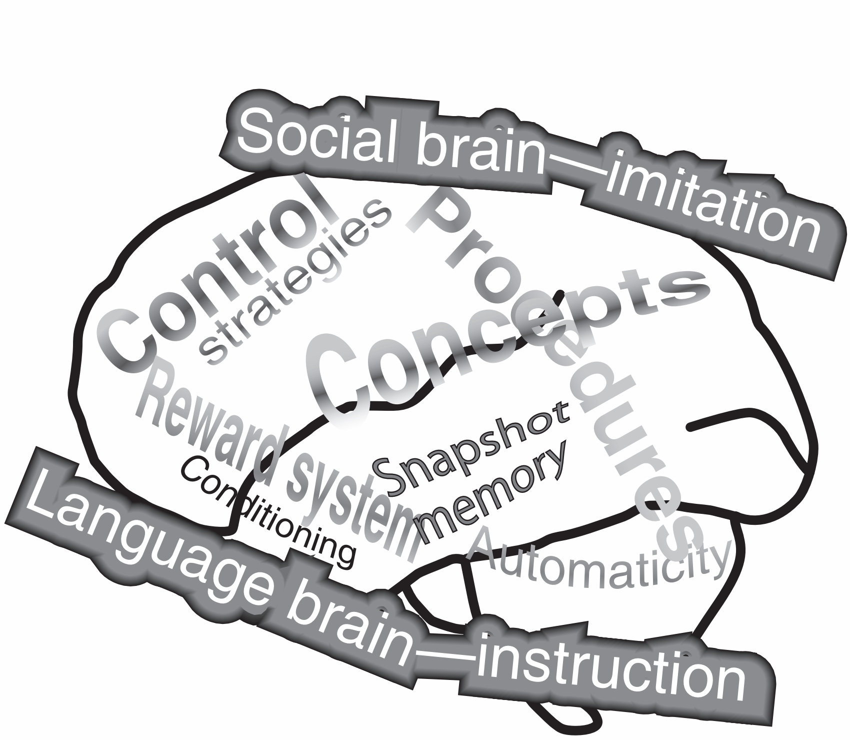

Figure 1.3 A Schematic of Eight Neural Systems for Learning, Whose Interplay Produces the Phenomenon of 'Learning' in the Classroom (From the Centre for Educational Neuroscience Resource www.howthebrainworks.science). See Chapter 2 of this volume for overview of actual brain regions and networks.

5. A system for learning how to get *rewards*. This system works out what we have to do to get what we want, to make nice things happen and avoid bad things happening. It operates over seconds and minutes. The system is based deep within the brain (the ventral tegmental area in the midbrain), where neurons release a neurotransmitter called dopamine that tracks the presence or absence of rewards and in turn influences the operation of other systems.
6. A *procedural learning* system for learning activities that we perform frequently and often unconsciously, such as tying shoelaces, reading or driving a car. These automatic skills can take tens or hundreds of hours to learn through practice. The structures involved are the cerebellum and the looping outer-to-inner circuits connecting the cortex through the basal ganglia to the thalamus and back again.
7. The *social-learning system*. The brain can take advantage of its widespread circuits for perceiving, understanding, and imitating other people, so that skills can be learned simply by watching other people do them.
8. The *language system*. The brain can take advantage of its widespread circuits for using language to construct new concepts and plans, so that skills can be learned through instruction.

In addition to these multiple systems, a broader principle operates: make all processes automatic, so they occur quickly, smoothly and without need for cognitive effort or even awareness. The more knowledge/skills are used, the more they become automatic. With automatized skills, there is increasing involvement of basal ganglia and cerebellar structures and decreasing involvement of prefrontal cortex. In contrast, the less often skills or knowledge are used, the more likely they are to be lost. Forgetting happens at a different pace in different learning systems: for instance, factual knowledge crumbles more quickly than motor skills, such as riding a bicycle.

All of these systems work in an integrated fashion. They respond differently over time and prefer different regimes of training. And they can be differentially modulated by factors such as motivational and emotional states. In face of this complexity, understanding the implications of this constellation of mechanisms for the term ‘learning’ as construed by educators represents a huge challenge.

Educational Neuroscience Is Still Controversial

Educational neuroscience remains controversial in some quarters. Some researchers feel that neuroscience data are simply too remote from the classroom to be of educational value, and approaches that focus more overtly on behaviour, such as psychology, are more appropriate (e.g., Bowers, 2016). Some feel that claims that neuroscience data can be of use in diagnosing developmental disorders or predicting individual outcomes are overstated, and these methods are not currently practical or viable (e.g., Bishop, 2014). There have been recent, lively debates on these issues in leading psychology journals (e.g., a critique by Bowers, 2016, and a response by Howard-Jones et al., 2016, in *Psychological Review*; or a critique by Dougherty and Robey [2018], and a response by Thomas [2019], in *Current Directions in Psychological Science*).

Educational neuroscience is a fledgling field, and there are indeed legitimate criticisms that can be made of it. For example, educational neuroscience must amount to more than a re-labelling of phenomena already well known from behavioural psychology with the names of brain structures—such as re-labelling ‘executive function’ with ‘prefrontal cortex’, or ‘episodic memory’ with ‘hippocampus’. Educational neuroscience must progress psychological theory, and it must point to ways to improve brain health.

Bishop (2014) is correct to argue that neuroscience methods are still limited in their sensitivity and specificity as screening or diagnostic tools for deficits. They can only complement more traditional behavioural and social markers of risk. However, some neuroscience measures may be available earlier, such as infant electroencephalographic measures of auditory processing to predict later dyslexia risk (Guttorm, Leppänen, Hämäläinen, Eklund, & Lyytinen, 2009); or, in the future, available-at-birth DNA measures to predict possible educational outcomes (Plomin, 2018). Early availability increases the opportunity for intervention or simply more targeted monitoring of traditional risk markers in tracking the progress of individual children.

Lastly, educational neuroscience needs to improve the quality of the dialogue between teachers, psychologists, and educators to ensure that the discussion is genuinely bidirectional, for example, through co-designing studies with teachers to improve the relevance of research and increase the chance of changing practices in the classroom. It is essential that the dialogue be as much about teachers stimulating research directions and thinking about how new findings may be useful in the classroom as it is about researchers communicating the findings of their cognitive neuroscience studies.

There are also distracting but spurious criticisms. One is that to contribute to education, the insights of neuroscience must be brand new and revolutionary (otherwise the retort is, 'But we already knew that!'). While there may be pre-existing folk theories about, say, the importance of sleep ('my old granny always said a good night's sleep was good for you!'), this does not undermine the possible contribution that the neuroscience of sleep can bring through, for example, its investigation of consolidation effects on learning during the interactions between hippocampal and cortical structures (see Sharman, Illingworth & Harvey, this volume). Neuroscience can tell us not only that sleep is good but how much sleep is required (e.g., Wild, Nichols, Battista, Stojanoski, & Owen, 2018). Even when behavioural effects are already known, they can be improved by understanding mechanisms at lower levels of description.

Another spurious criticism is that neuroscience explanations are dangerous because they have a 'seductive allure' (Weisberg, Keil, Goodstein, Rawson, & Gray, 2008), that is, they make psychologists and teachers more likely to believe new proposals for teaching techniques irrespective of supporting evidence. While that may be true (unfortunately), when neuroscience is used merely as window dressing, it is a contextual framing effect, not a reflection on the progress of the discipline of educational neuroscience itself (Farah & Hook, 2013; Scurich & Shniderman, 2014).

An Overview of the Chapters

The volume unfolds as follows. For those who are coming to this volume unfamiliar with neuroscience, the next chapter by Dumontheil and Mareschal gives an introduction to key concepts and methods within neuroscience—the broad anatomy and functioning of the brain, how it changes across development, the main regions that are referred to in subsequent chapters, as well as the leading brain imaging methods such as magnetic resonance imaging and electrophysiology. This is the place to familiarise yourself with the key terminology and what abbreviations like MRI and EEG mean.

Section 1 includes two chapters on *Genetic and Environmental Factors*, tackling genetic and environmental contributions to individual differences in educational achievement. In Chapter 3, Donati and Meaburn explain how genetic methods have been increasingly applied to educational abilities. The focus here is on emphasising that not all differences between children and adults are environmental in origin. Educational achievement, intelligence, and personality dimensions run in families to some extent—as revealed by the traditional behavioural genetic method of twin studies, yielding the heritability of these traits. Breakthroughs in molecular genetics now allow measurements of actual DNA variations between individuals, and how these correlate with variations in high-level abilities such as reading or mathematics. Donati and Meaburn discuss how the results of these so-called genome-wide association studies can be used in education, such as using DNA to predict educational outcomes via polygenic risk scores. Notably, they declare that genetic outcomes are not inevitable (genetic effects may change in magnitude in different environments) and that 'genes for education simply do not exist' (p. x)!

In Chapter 4, Hackman and Kraemer consider the nurture side of the equation, and how environmental factors contribute to individual differences in educational outcomes. One of the most predictive and readily available measures of the environment is the socio-economic status (SES) of the families in which children are raised. Hackman and Kraemer review current research on the effects of SES on brain and cognitive development. They conclude that 'many of the same aspects of neurocognitive performance that are associated with SES are also predictive of educational outcomes' (p. x). Although these are individual-level factors, Hackman and Kraemer emphasise how the findings point to the centrality of social and systemic factors in education. However, SES is a proxy for multiple potential causal pathways of environmental influence, and the chapter carefully unpacks how SES effects might operate on educational outcomes—stressing that even though their impact is measurable in the brain, SES effects are by no means immutable or deterministic.

Section 2, *Discipline-Specific Abilities*, considers the contribution of educational neuroscience to understanding *discipline-specific abilities*. These include literacy, numeracy, and science. Chapters 5 and 6 both address reading. In Chapter 5, Tong and McBride-Chang give a broad overview of how reading develops in the brain—given that as a recent cultural invention, reading must involve re-purposing other neural systems for object recognition, oral language, and meaning to fashion a system dedicated to literacy. Tong and McBride-Chang show how different imaging methods have been used to reveal these brain pathways. They show how both structure and function differ in cases of dyslexia, and how brain pathways may be modified by the language (and script) that children are learning, such as in a comparison of English and Chinese. Notably, measures of electrical brain activity in infants in response to auditory stimuli are able to predict language and literacy skills some eight years later, indicating the early origin of differences in literacy skills.

In Chapter 6, Goswami takes a deep dive into one skill underlying language and literacy, one that is particularly implicated in dyslexia: phonology. Understanding the brain mechanisms that underpin this skill points to an unexpected possible avenue of remediation for dyslexia: practising playing on the bongo drums, and reciting poetry. How can this be? The child's early learning of phonology—via a home or pre-school environment rich in language—involves constructing a hierarchy of the linguistic information available in the speech stream. Much of the key information involves rhythm. The brain's processing of rhythm can be investigated through the auditory system's tendency to entrain its activity to the different rhythms present in language input. Neurons actually fire in tune with different beats! In dyslexia, there appears to be a particular problem in detecting the rhythmic 'envelope' not just of words but whole sentences, compromising the child's later ability to match phonology to the written form of language. Goswami argues that interventions which focus on metrical language activities, such as nursery rhymes and rhythmic music, may aid the brain's construction of the appropriate phonology to prepare for reading acquisition. Since these activities are appropriate for pre-school, they permit an early intervention for children who are flagged as at risk of developing literacy problems.

In Chapter 7, de Smedt focuses on mathematics and asks why learning mathematics is so easy for some but so hard for others. De Smedt considers the virtues and disadvantages of understanding school-taught skills at the biological level. Mathematics involves the integration of many different mechanisms in the brain, and mathematics problems frequently involve many steps. This makes mathematical skills difficult to study with current brain imaging methods, which either average together activity over several seconds or pull it apart into milliseconds. De Smedt focuses on arithmetic development—adding, subtracting, multiplying and dividing whole numbers. Here, it turns out that different strategies are available to solve the same problem, and the strategies that children have available depends on the way that they are taught, as well as individual preferences. Often it appears that strategy, not problem type (e.g., single digit vs. multidigit arithmetic), modulates the brain regions that are correlated with doing arithmetic. But there is also developmental change—for example, fact retrieval is mediated by temporal-parietal cortex in adults (conceptual) but is more hippocampal (episodic) in children. De Smedt considers whether there are particular core skills that serve as constraining factors in learning arithmetic, and concludes that symbolic magnitude processing (that is, understanding how numerical symbols, such as Arabic numerals, represent numerical quantities/sets of objects), 'is as important to arithmetic as phonological awareness is to reading'.

In Chapter 8, Tolmie and Dündar-Coecke consider science education, and the lifespan development of the conceptual skills that underpin scientific knowledge, from the early years, mid and late childhood, adolescence and into adulthood. They note that in childhood, perceptual knowledge of how the physical world behaves seems separate from conceptual knowledge: 'by the time they have reached the age of 11 children show acute perceptual awareness of variables that genuinely affect outcomes, even if this is conflated with false beliefs about other factors' (Chapter 8, p. x). They argue that talk in science class is essential, because language is key in closing the gap between perceptual and conceptual understanding—language-provoked mechanistic ideas focus attention on relevant perceptual properties to understand how physical systems work. However, elaborated concepts emerge at different rates in different areas, depending on the extent and nature of environmental input. Adolescence is marked by the addition of detail, the linking up of knowledge and the connection to procedures and application. In adulthood, there are multiple systems of knowledge, flexibly used, but expertise is now more important than age. Notably, prediction and explanation skills can still separate—one study of undergraduates described by Tolmie and Dündar-Coecke on the path of rotating objects found the correlation between prediction and explanation was close to zero. The implication is that science skills and knowledge are fractured, and a key aspect of science learning is integrating knowledge and correctly applying it.

Section 3, *Discipline-General Abilities*, focuses on individual differences in abilities that may affect performance *across disciplines*. In Chapter 9, Peters considers executive functions, and how they develop across childhood and adolescence. She considers the main components of cognitive control, including working memory, inhibition, and flexibility and the extent to which these skills are trainable. Peters argues that the brain substrates underpinning executive functions take a long time to mature, which explains the poor executive function skills of young children. Importantly, she argues that not all classrooms and education programmes are currently well tailored for the level of neural development and executive function skills that children possess at that age. In adolescence, by contrast, executive function skills are more advanced, but pubertal changes impact decision making around risk taking, particularly in a social context, with associated adverse health outcomes. However, Peters also identifies opportunities in adolescence, including the heightened sensitivity of reward systems to feedback and to social environments. The teenage years may be a window of opportunity for learning, but also a time when individual differences are exaggerated since the brain is more influenced by affective and social context.

In Chapter 10, Immordino-Yang and Gottleib focus on the emotions. They address the question of why learning is such an emotion-dependent process, and what this means for teachers and schools. They answer:

> students' abilities to recognise, understand and manage their emotions; to build and maintain a sense of interest and curiosity; to persist through challenges and uncertainty; to embrace new experiences; to imagine alternative futures for themselves and their communities; and to feel purposeful . . . all of these powerfully influence personal and academic success.
>
> (p. x)

Despite the key role of emotion in learning—and indeed recent government focus on Social Emotional Learning—Immordino-Yang and Gottleib argue that the message is frequently misconstrued by teachers, for example that focusing on emotions in the classroom is a luxury when time affords, or is simply about ensuring students are 'having fun'. They argue that emotions are key to learning but need to be relevant to what is being learned, otherwise they will interfere with learning outcomes (for instance, as is the case with anxiety around mathematics). Immordino-Yang and Gottleib (Chapter 10) explain how brain systems for sensing the gut (including the insula) are co-opted for emotional experiences, but that 'gut feelings' reflect extensive learning rather than naïve intuitions. Even when people experience a complex emotion like admiration, this still appears to involve activation of the insula! Finally, the authors consider cross-cultural differences, in particular to how individuals report feelings of emotionality in response to otherwise equivalent activation of body sensory systems in the brain.

Section 4, *Leading Methods for Cognitive Enhancement*, contains six chapters that evaluate various forms of *cognitive enhancement*. On the whole, training cognition produces what is called 'near transfer'—gains on the task that is trained on, smaller gains on similar tasks, but little or no improvement on very different tasks, referred to as far transfer (e.g., Sala et al., 2019). However, researchers continue to seek evidence for techniques that confer general benefits across cognition. This section uniquely brings together in one place evaluations of several such approaches, including action videogame playing, mindfulness training, the role of sleep in learning, aerobic exercise, learning a second language, and learning a musical instrument, each of which, at one time or another, has been claimed to produce either general benefits for cognition or improved educational outcomes.

One must be cautious in this area: some researchers have reservation about the very notion of 'cognitive enhancement', both in the goal that it implies and the necessity of measurement of aspects of education that are not readily quantifiable (Cigman & Davis, 2009). For example, Cigman (2009, p. 174) argues that

> the enhancement agenda is not simply about getting children to perform better. It is about getting them to *feel* better—more motivated, more confident, happier—and about the idea that feeling good in these ways leads to success at school and in life generally.

but Cigman notes that 'it is not obvious that one can identify particular feelings as unconditionally good, so that more is necessarily better' (p. 174). Nevertheless, to the extent that cognitive abilities can be measured, education as a whole can be said to act as a cognitive enhancer, with one meta-analysis reporting a gain of approximately one to five IQ points for each additional year of education attended (Ritchie & Tucker-Drob, 2018).

In Chapter 11, Altarelli, Green and Bavelier consider the impact of sustained playing of *action video computer games* on cognition. These games are fast paced and engaging, involving rapid motor responses to fast changing visual scenes. Some teenagers and young adults spend a great deal of time playing these games, and games have been found to have the capacity to powerfully alter brain and behaviour. Meta-analyses reveal uneven effects on cognition, mostly influencing top-down attention, spatial cognition and visual attention. Altarelli and colleagues reveal the key properties that these games must have to be effective: fast pacing to force decision making under time constraints, pressure to divide attention and monitor multiple sources of information, a requirement to switch flexibly between divided attention and focused attention states, adaptive tailoring of difficulty (not too easy, not to hard), and rich and variable experiences. Because action video games are so engaging, it has been an ambition among educators to exploit these properties for educational purposes—to 'gamify' education. However, Altarelli and colleagues comment that most educational games focus on content and are unsuccessful in capturing the game mechanics that trigger engagement. They also note that there is as yet little evidence base for cognitive effects of action video games in younger children (where there is also a risk of age-inappropriate content, such as violence). Yet there remain intriguing findings, such as the possibility that action video game playing can improve the reading skills of some children with dyslexia.

In Chapter 12, Semenov, Kennedy and Zelazo consider mindfulness training in children and adolescents, and its potential impact on executive function skills in the classroom. Meditation is often connected to religious practice, most notably Buddhism, but it has recently been exploited as a secular method to enhance health and wellbeing. As Ven. Ajahn Sumedho says, within Buddhism 'all the teachings are for encouraging and directing our attention, investigating and examining experience in the present moment. To do this, you need to be fully awake. You have to pay attention to life as it happens' (Panawong Green, 2001, p. 8). Semenov and colleagues consider the role of mindfulness training for improving both hot (emotion regulation) and cold (cognitive control) aspects of executive function such as attention. They emphasise its potential to improve internal regulation by preventing bottom-up influences (such as emotional responses) overriding and interfering with goals and attention. While cognitive training usually only produces near transfer, Semenov and colleagues argue mindfulness training has the potential for far transfer because it supports metacognition through reflection: metacognitive awareness of skills and their range of application can be a vehicle for far transfer. The neuroscience of mindfulness training—mostly in adults—points to the importance of the anterior cingulate cortex (ACC), a brain system that monitors current performance against goals. Notably, studies report that the ACC is *more* active when expert meditators are practising mindfulness, but *less* active than non-meditators during regular cognition—suggesting that the filtering out of distractions may become automatic with practice. In an educational context, Semenov, Kennedy and Zelazo consider the potential benefits of mindfulness not only for children but also for teachers, where it may aid wellbeing in a stressful job.

In Chapter 13, Sharman, Illingworth and Harvey consider the neuroscience of sleep and its relation to educational outcomes. They review how sleep works in the brain—how cycles of sleep are revealed by electrical brain activity—and how sleep is linked to the circadian rhythm. Particular attention is paid to the shift in circadian rhythm in adolescence of around three hours, with teens staying up later at night and waking later in the morning. As yet, the cause of this shift is unknown. But later bedtimes combined with the same fixed start time for school translates to reduced amounts of sleep for teenagers. Sleep is associated with psychosocial functioning and emotional/behavioural regulation, and so reductions in sleep may influence students' wellbeing, their ability to get on with their peers and teachers, and their behaviour at school (though the direction of causality has not yet been completely clarified). Not only may teenagers be more 'tired and emotional' (p. x), cognition may be impacted and so too quality of learning. Sharman and colleagues consider the role of sleep in memory and learning in the brain, with cycles of replay, consolidation, reorganisation, and integration of memories. They note that sleep efficiency may turn out to be more important than duration—children need to sleep well! The authors then evaluate the parallel possibilities of altering school start times to fit better with adolescent circadian rhythms, or of sleep education, improving students' understanding of behaviours that encourage good sleep (such as avoiding use of screen-based media devices close to bedtime; see e.g., Mireku et al., 2019) in order to maximise sleep efficiency.

In Chapter 14, Wheatley, Wassenaar and Johansen-Berg consider the possible benefits of aerobic exercise for improving educational outcomes. It seems a no-brainer that exercise is good for you, in this age of concerns around obesity. But the focus here is less on health benefits and more on potential effects on cognition, particularly on executive function skills such as attention. Wheatley and colleagues carefully consider cross-sectional studies, evaluating whether those undertaking more aerobic exercise have better educational outcomes, and then intervention studies, where the target is to improve existing fitness levels. The story becomes complex: is exercise about 'acute', immediate improvements so that, say, children perform better in a mathematics class after a PE lesson? Or about 'chronic' improvements, acting via sustained improvements in fitness? Are improvements to do with cardiovascular fitness or better motor skills (e.g., better flexibility, balance and speed)? What are the brain mechanisms underpinning observed improvements? Animal studies point to the involvement of improved brain connectivity, growth of new blood vessels, greater expression of chemical 'growth factors' such as Brain Derived Neurotropic Factor (BDNF), and even the generation of new neurons in the hippocampus. What kind of exercise is better? Moderate to vigorous physical activity (MVPA) seems a favourite. There are suggestions that aerobic fitness activity may be more effective in the primary years than for teenagers, and there may be diminishing returns for children who are already fit. 'On balance,' Wheatley and colleagues conclude, 'young people's executive functions can be improved by physical activity' (p. x), before they turn to consider the practicalities of how this activity can be fitted into the school day, and who should be in charge (turns out specialist PE teachers aren't required!).

Chapter 15 turns to consider the possible cognitive benefits (and disadvantages) of bilingualism and multilingualism. Phelps and Filippi address this question both for children and also across lifespan—given suggestive evidence that learning a second language could be a protective factor against the cognitive decline associated with ageing. Research on bilingualism and cognition seems like a rollercoaster—in the first half of the 20th century, bilingualism was deemed to have a negative effect on IQ; in the latter half of the century, it was thought to enhance cognition. This conclusion is now contested; meanwhile, in the educational sector (at least in the UK) English as an Additional Language (EAL) is viewed as a risk factor for poorer outcomes with such pupils in need of support. The picture is confused by a lack of 'random allocation to condition' (p. x). Because it is not randomly decided who will be monolingual and who bilingual, there may be systematic differences between these groups that depend on historical and cultural factors—for example, in some country or region, bilingual groups may have higher (or lower) SES than monolingual groups; as we have seen, SES is itself associated with differences in cognition. Phelps and Filippi sift the behavioural and brain evidence: There is stronger evidence that bilingualism produces benefits for attention in processing language, while the evidence is more mixed that the demands of controlling two language systems produce general benefits on cognition. Part of the problem is that bilinguals are so variable in their abilities and experiences, and wider benefits may only surface in children and ageing populations, rather than in young adults whose cognitive skills are at their strongest. This diversity prompts Phelps and Filippi to argue that it is time for a new theoretical framework. Their strongest messages are that there is no evidence for 'mental overload' for children learning two languages (even for children with autistic spectrum disorder or ADHD)—indeed, the wider cultural contact afforded by two languages offers greater opportunities for support. And that the EAL profile is not atypical—it is not like developmental language disorder—and educators should abandon the negative connotations associated with EAL status.

In Chapter 16, the final chapter in the cognitive enhancement section, Schellenberg considers whether music training can raise IQ levels. He asks whether music training has systematic consequences that extend beyond music knowledge and ability to non-musical cognitive abilities. Once more, a frequent lack of 'random allocation to condition' (p. x) poses problems. Schellenberg observes that children who take music lessons are a select group, and randomly allocating children to a 'music lesson group' (p. x) in an intervention study is not realistic, since children need to commit to practise beyond the classroom to progress in musical training. Schellenberg views the positive claims made for music training in the face of these experimental challenges as a 'kind of radical environmentalism' (p. x): a focus on brain plasticity has led researchers and educators to ignore pre-existing individual differences between children who do and don't undertake musical training, and has encouraged a tendency to interpret correlational findings as evidence of causation. In this, he views educational neuroscientists as particularly guilty. Since they are studying the brain—a mechanism—it is all too easy for these researchers to see correlational evidence as causation. But Schellenberg points out that common factors may cause children to both persist with musical training and to have higher IQs: for example, supportive middle-class families, or genetic differences in intelligence and willingness to persist with practise. Schellenberg reviews the evidence and finds little convincing support for improvements in cognition. However, there are intriguing findings, such as the possibility of improvements in speech processing and in reading for dyslexics—a hypothesis we saw put forward by Goswami (see Chapter 6). At the end of the chapter, we come full circle to reservations about the cognitive enhancement agenda. Why should the goal be to achieve measurable improvements in IQ?, asks Schellenberg. Music training improves musical skills, music promotes social bonding, 'music listening often makes us feel good, and making music often makes us feel good together. Isn't that enough?' (p. x).

Section 5, *Into the Classroom*, enters the classroom. Up to this point in the volume, teachers might legitimately say, 'this research is all very interesting but . . . how do I use it in the classroom?' In Chapter 17, Howard-Jones, Ioannou, Bailey, Prior, Jay and Yau attempt to answer this question. Their focus is on the quality of teaching, pointing out that 'a teacher in the top 16% of effectiveness, compared with an average teacher, has been estimated to produce students whose level of achievement is somewhere between 0.2 and 0.3 standard deviations higher by the end of the school year (p. x).' However, they argue that good teaching is not simply about applying best practice but knowing how and when to apply each practice. They argue that the sciences of mind and brain enrich education by informing the processes by which teachers critically reflect upon and develop an understanding of their own practice. The goal of these authors is to select core scientific concepts that will aid in this reflection, and to demonstrate their relation to established educational practices. Howard-Jones and colleagues settle on three key categories of the learning process: (1) Engagement with Learning, (2) Building of New Knowledge, and (3) Consolidation of Learning, characterised in terms of the key brain systems involved. These concepts are then systematically linked to published 'Principles of Instruction' and 'Principles for Emotion and Learning' within education. The authors ground this cycle in examples such as classroom instruction and teacher emotions, guiding student practice, and daily review. Crucially, the utility of these concepts for teachers is road tested in a postgraduate course for teachers being developed at the authors' own university.

In Chapter 18, Knowland tackles the ethical issues raised by classroom research in educational neuroscience, given that the targets of its interventions are usually children. Within neuroscience and psychology, the ethical bar is set higher in considering research with children. Yet one could argue that education as a whole concerns authority figures changing children's brains. The issues are potentially emotive. For example, in the context of how much discretionary screen time children should have, Sigman (2019) argued for the precautionary principle: until we know the full impact of screen time on children's health and development, health care professionals should err on the side of caution and advise low limits. To ignore the precautionary approach of child health professions, Sigman says, 'promotes a hubristic picture of psychology and 'educational technology' researchers knowing better than the many paediatric and public health professionals what is best for protecting child health' (p. x). Knowland takes a hypothetical but stark example to consider the question of cognitive enhancement. If we knew that neuromodulation was effective in enhancing cognition (e.g., via psychostimulants, such as Ritalin used to treat attention deficit hyperactivity disorder; or via transcranial electric stimulation of the brain) should we use it on children? Don't we have a duty to improve educational outcomes for kids? Out of fairness, shouldn't we then target such interventions to the least advantaged of society, to level the playing field? What of possible side effects? What of the fact that these kinds of interventions work for some kids but not for others? What age should we intervene—should we be using neuromodulation with infants, because their brains are more plastic? Or perhaps the pre-school years shouldn't be within the remit of educational neuroscience at all? The issues here are complex, as are our intuitions. In one study probing the attitudes of adults, any pharmacological enhancement to improve academic endeavours, employment, and personal relationships was deemed to be morally unacceptable—yet participants judged a hypothetical 'smart pill' to improve intelligence to be more morally wrong than taking a 'motivation pill' that would improve an individual's ability to work hard. The brain systems that the hypothetical pills targeted altered people's judgement of their moral worth!

Chapter 19 presents the view of teachers practising in the classroom. Bell and Darlington offer their view on all the preceding chapters. They consider why teachers should try to understand learning in the first place: 'the first reason for understanding learning and teaching,' say Bell and Darlington, 'is that we are the professionals; the people who have responsibility for a significant part of children's education . . . [we] need to keep up to date with new evidence on ways of improving the learning experience for all students' (p. x). They step through how an understanding of learning might better inform practice, addressing the environment and context of learning, the process of learning, as well as emotional welfare and mental health. On the lifespan perspective, they say 'each setting and age range requires approaches based on sound principles and evidence . . . understanding the developmental changes that take place across the lifespan potentially has differing implications for individual teachers at each stage of education' (p. x). They embrace Howard-Jones and colleagues' three categories of the learning process: engage, build, and consolidate, but also emphasise a fourth, the application and transfer of learning. Although the general pattern of near transfer does not augur well for automatic application of learning to new situations, the authors emphasise the potential of developing metacognitive skills alongside the domain-specific knowledge and skills, and identify a role for teachers in modelling transfer skills. They seek to identify concrete classroom activities that would capture the (now) four categories of learning. And finally, they identify half a dozen features of learning, and list questions for teachers to consider guiding reflection on practice.

In the concluding chapter, Chapter 20, the editors pull out the main themes of the volume, and look to the future of educational neuroscience. They in particular address two questions.

What's the Added Value of Neuroscience?

Part of the debate around the field of educational neuroscience is the added value of the neuroscience itself. Isn't behaviour the most important feature of education, that is, children's learning outcomes? How does the understanding of brain mechanisms help? What more does neuroscience add than is contributed by psychology? All the authors to this volume were asked to finish their chapter with a consideration of just this question.

What's the Concrete Implication of Research for the Classroom?

Given that educational neuroscience is an intrinsically translational field, the second challenge posed to the authors was to identify the concrete implications of research and opportunities for translation in the classroom.

How well the authors answer these two questions is a good indicator of current progress in the field of educational neuroscience.

Notes

1. www.educationalneuroscience.org.uk/resources/neuromyth-or-neurofact/
2. Forty-winks = sleep. It turns out that there are few synonyms for sleep beginning with F.
3. www.howthebrainworks.science

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