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Educational neuroscience

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Introduction

Given the progress that has been made over the last 30 years in understanding how the developing brain works (e.g., Johnson & de Haan, 2015), it seems only natural to assume that this new knowledge should somehow impact on the way we deliver teaching in the classroom. However, the joining of education and neuroscience has historically been viewed as a 'bridge too far' (Bruer, 1997), and simply wishful thinking. The solution to this problem is to see cognitive neuroscience as an island between these two disciplines, one that enables two bridges (one from basic neuroscience to cognitive neuroscience and the other from cognitive neuroscience to education) to join and span between these two disparate disciplines. Discovering the underlying neural and genetic mechanisms of learning will provide a more detailed explanation of the academic process, enabling more effective and targeted educational interventions. Thus, educational neuroscience is a new scientific discipline bringing together education, psychology, and neuroscience, with the common goal of promoting better learning (see Fig 1). Although it chimes well with the ideas of Neuroconstructivism (Mareschal *et al.*, 2007), it is less of a theoretical framework, than a methodological approach consistent with many pedagogical theories. By weaving together education, psychology, and neuroscience, it becomes possible to describe learning processes and the interactions between the environmental, cognitive, and neural levels as they operate in and out of the classroom.

Figure 1 about there

That said, **educational neuroscience** (defined and described for inclusion in the Glossary) is not just concerned with learning in childhood; it recognizes that development, learning, and education start in infancy and continue through adolescence and beyond. It also encompasses typical and atypical learning, in fields across the academic curriculum, such as language, reading, science, and mathematics. Beyond traditional academic subjects, educational neuroscience is also concerned with social and emotional development and cognitive abilities more generally, particularly as they impact on school performance. A good understanding of the underlying processes involved in learning will allow us to optimize timing, regimes, and learning contexts for all kinds of individuals.

In this entry, we will first introduce the range of methods used to study learning in the brain. This will then be followed by an overview of the discoveries made in language development, reading, science learning and mathematics. We will finish with a discussion of the issues currently facing the young field of educational neuroscience.

Exploring the brain

Educational neuroscience draws on a number of non-invasive imaging techniques that complement the traditional behavioral research methods associated with studying child development. The recent growth in the use of neuroimaging methods to explore brain structure and function has led to a greater understanding of typical and atypical development from infancy to adolescence. These can be broadly separated into *indirect measures* that measure oxygenation and blood flow in specific parts of the brain, rather than direct brain activity, and *direct methods* that directly measure the electrical activity of neural tissues. These two classes of methods offer complementary views of brain function. In contrast, *brain stimulation* techniques enable us to observe the affects of directly impacting on brain activation.

Indirect measures of brain function

Perhaps the most well-known neuroimaging technique is magnetic resonance imaging (MRI), see the chapter *Magnetic resonance imaging*. MRI is considered powerful, flexible, and safe, but comes with a number of practical difficulties when used with children and adolescents. Scanning sessions can last up to 60 minutes, which is a long time for children to stay awake, still, and concentrating. Moreover, dental braces may exclude a large proportion of adolescent populations. Functional near infrared spectroscopy (fNIRS) is a particularly useful neuroimaging technique for use with infants and young children, see the chapter *Functional near infrared spectroscopy*. Like functional MRI, it can provide insight into brain functions while the participant is engaged in some cognitive activity. **Functional transcranial doppler ultrasonography** (fTCD) uses ultrasound in order to determine gross neural characteristics such as hemispheric laterality (Bishop, Badcock, & Holt, 2010). While cheaper and more portable than other imaging methods, it is relatively lacking in resolution.

Direct measures of brain function

Electroencephalography (EEG) is one of the most widely used methods for measuring brain activity. Passive electrodes on the scalp measure electrical activity caused by the firing of large groups of neurons in response to a stimulus. The voltage difference between two electrodes is recorded to show changing brain activation over time. EEG does not require an overt response from the participant, and is therefore one of the most practical methods for examining the brain activity of infants. However, this method is sensitive to movement and eye blink artifacts, which can skew the results. Magnetoencephalography (MEG) is a more recent tool that records magnetic fields produced by electrical activity in response to a stimulus, see the chapter *Fetal and neonatal magnetoencephalography*.

Brain stimulation

Two methods of brain stimulation have recently garnered interest with the view to improving learning. **Transcranial direct current stimulation** (tDCS) generates an electrical current while **transcranial magnetic stimulation** (TMS) uses magnetic field pulses to induce an electrical current in the brain. Inducing these currents in the brain is thought to increase the firing rate of neurons, and thus may improve learning. TDCS has attracted the most interest, and has shown some promising results in enhancing basic sensory abilities, memory, attention, language ability, mathematics ability, and problem solving (Cohen Kadosh *et al.,* 2012). Although these stimulation techniques are regarded as non-invasive, side effects and long-term effects in the developing brain are still unknown, rendering stimulation controversial for a child's education.

Genetic analyses

Behavioral genetic research has shown that individual genetic profiles lead to variation in academic achievement. Twin studies compare the differences between monozygotic (identical) and dizygotic (non-identical) twin pairs to make an estimate of the heritability of a trait or skill, while **genome-wide association studies** (GWAS) can identify specific marker genes of traits or skills. However, genetic effects identified are not deterministic or stable; rather they affect development and educational outcomes through a complex interplay between genes and environment. In fact, the quantitative trait loci (QTL) hypothesis argues that each DNA marker of a complex trait has only a tiny effect on behavior. Thus, it is the combination of many genetic markers that contributes to a certain educational outcome, even for a very well defined target skill (Asbury & Plomin, 2014).

Putting it all together again

Computational modeling provides one means of combining all of these different levels of constraints (genetic, neural, behavioral) into one consistent causal framework (Thomas, Forrester, & Ronald, 2013). The construction of a computational model relies on precise definition of all factors considered in the model. This means that terminology and theories must be well defined. An effective model should simulate human behavior, explain a *range* of behaviors, help explain why the behavior occurs, and generate novel predictions that lead to new human research. The clarity demanded by this method encourages researchers to think carefully about theories and mechanisms of learning; putting many levels of explanation together to form a coherent theory.

We now turn to a survey of some key areas in which findings from developmental cognitive neuroscience have impacted on our understanding of academic skills. This is necessarily a ‘whistle stop tour’, and is intended more to give the reader a flavor of the work done in this area rather than a comprehensive review.

Understanding language and reading

Language underlies learning in all educational disciplines due to its inherent involvement in the accessing of material. Atypical development in language or reading can therefore have a hugely detrimental impact on education (Tallal, 2004). The aims for research in these related fields are to identify those at risk of impairment, uncover limitations in the underlying mechanisms, and inform the design of appropriate training programs to improve language and reading ability.

By the time children start school, most will have good receptive and expressive language ability. Yet there are still substantial variations between individuals, the origins of which are a combination of factors. Phonological development and neurobiological maturation, both intrinsic to the individual, contribute to the development of language skills. Phonemes are the smallest units of speech sounds, and must be effectively processed and categorized. The acquisition of phonemes is mirrored by neural maturation, as cortical areas become specialized through exposure to speech sounds. Low socioeconomic status (SES) is associated with a less enriching linguistic environment, which constrains language development. SES also affects language learning through indirect processes such as the interaction between SES and attentional control. In other cases, such as specific language impairment (SLI), severe language impairments may occur in the absence of a known cause (Tallal, 2004) such as low SES.

Substantial changes in the brain regions associated with language development occur throughout childhood and into adolescence, even after language ability may appear stable or comparable to that of adults. Increasing activation in the temporal cortex is seen throughout development in response to speech sounds. The lateralization of neural language systems changes over temporal and frontal regions during adolescence. Despite these changes in neural systems during development, children with SLI tend to keep their language difficulties throughout adolescence and into adulthood (Clegg, Hollis, Wawhood, & Rutter, 2005). This highlights the need for educational interventions that can be targeted not only at pre-schoolers and young children, but also older children and adolescents.

Learning to read is different to language learning, since direct instruction and hard work are required. The competent reader must convert orthography (notation on the page) into meaningful words and sentences. Dyslexia is the diagnosis given to an individual who has difficulty reading with no known cause such as low intelligence (Tallal, 2004). Although SLI and dyslexia are distinct disorders, they often co-occur, or indeed occur with other developmental disorders. Neuroimaging studies suggest that there is a left-lateralized network for reading that shows only subtle differences between typical adult readers and those with dyslexia. Developmental work indicates that children with dyslexia show reduced activation in the brain networks that typical readers use, and compensate by engaging other, slower brain networks. Reading researchers are now using neuroimaging tools to try and predict which children will have reading difficulties, in order to provide extra help at the earliest signs of impairment.

Understanding science

Scientific reasoning involves domain-general cognitive abilities and domain-specific knowledge (Zimmerman, 2007). Causal reasoning, deductive reasoning, and analogical reasoning are domain-general processes that support the scientific discovery process in scientists and non-scientists alike. Since these three domain-general abilities are thought to be similar across scientific subjects, they have been the focus for a great deal of research. Each will be addressed here.

Through causal reasoning, a principal aim in scientific investigations can be achieved: the discovery of causal relationships. Causal *perception* can be dissociated from causal *inference*: the former refers to events that appear to be directly linked, such as physical collisions, while the latter concerns events such as learning that a switch turns a light on and off (Michotte, 1963). The testing of causal relations between variables requires detection and processing of information that contradicts existing knowledge. One theory of causal reasoning is that pre-potent, perceptually-based responses need to be inhibited to allow reflective processing, a skill that develops through childhood (Houdé *et al.*, 2000). But in some cases, the inhibition of perceptual input can lead to the incorrect answer, as too much emphasis is placed on prior beliefs and expectations. In overcoming scientific misconceptions, which are prevalent in students, inhibition of incorrect responses can relate to both perceptual cues and expectations.

Deductive reasoning is the process through which we assess whether a conclusion follows logically from the premise. This is an important skill to acquire as much scientific reasoning involves drawing conclusions from what is already known. Deductive reasoning is dramatically affected by the context in which a problem is presented. An abstract deductive reasoning task (Fig. 2) has consistently found that 90% of adults fail to act rationally (Wason, 1968), compared to 25% in a similar concrete task (Griggs & Cox, 1982). Similarly, when judging the validity of scientific evidence, college students will engage different neural circuits and draw different conclusions depending on the familiarity of the hypothesis being tested (Fugelsang & Dunbar, 2005).

Figure 2 about here

Analogical reasoning is a tool that can aid scientific thinking. Using information from one known domain and applying it to another domain is a skill that goes beyond the classroom and has been a successful strategy in a number of scientific discoveries. Superficial analogies focus on similarities between surface features, while structural analogies focus on deeper relationships between disparate domains. Analogies are goal-driven, with superficial analogies used in problem solving, and structural analogies used in the formulation of new ideas. Although scientists use analogies in this way, students do not readily notice analogies, so problem solving improves when students are explicitly shown analogies (Reed, Ernst, & Banerji, 1974). Thus, analogies are useful for scientific problem solving, but students may not recognize them without guidance.

Neuroimaging studies have examined the brain regions that are associated with these domain-general reasoning skills (Masson, Potvin, Riopel, & Foisy, 2014). The areas that are consistently associated with scientific reasoning include multiple regions of the prefrontal cortex (PFC) and the anterior cingulate cortex (ACC). The prolonged development of scientific reasoning skills through childhood and adolescence is unsurprising given the protracted development of the PFC through this age range. The suggestion here is that increasing error detection (mediated by the ACC) and frontally (PFC) mediated inhibitory control with age are key factor in the improvement of scientific reasoning skills across the school years.

Understanding mathematics

It is widely acknowledged that mathematical competence is of importance not only for individuals in terms of employment and wellbeing, but also for the economy, thus making it a key priority for education. Formal mathematical abilities are underpinned by key numerosity skills that are present in individuals to varying degrees. When discriminating between two numbers, a larger distance between the numbers results in a faster response; this is known as the *distance effect*. The *problem size effect* refers to faster and more accurate responses when arithmetical problems use smaller numbers. The strength of these effects can be diagnostic of mathematical difficulties as they identify whether or not representations of numerical magnitude have been evoked (De Smedt, Verschaffel, & Ghesquière, 2009). An individual who does not show these effects may have an underlying problem in magnitude representations.

Behavioral studies (e.g., visual preference paradigms with infants) have shown sensitivity to differences in numbers of objects even in the first few months of life. By school age, distance effects can be measured and are indeed seen at all ages with variation in the extent to which individuals show the effect. The size of the distance effect can predict math performance in childhood and adolescence, even after controlling for other sources of individual variation such as intelligence and working memory.

What are the neural systems underpinning these abilities? Parietal regions of the cortex have consistently been related to arithmetic and number (Dahaene, Piazza, Pinel, & Cohen, 2003). Differences in brain structure and function in these regions are seen in individuals who have the mathematical disorder *dyscalculia*. Particular parietal regions involved in mathematical ability include the intra-parietal sulcus (IPS), which is involved in the representation of number symbols, the left angular gyrus (AG) involved in number fact retrieval (Delazer *et al*., 2005), and the posterior superior parietal lobule (SPL) involved in relating number to space. Application of tDCS during novel symbol learning, where the symbols are designed to be comparable to numbers, led to improved learning, even six months later (Cohen Kadosh *et al*., 2010). This finding not only further corroborates the role of parietal cortex in mathematics, but also has exciting potential implications for improving performance in mathematics learning.

Current challenges in educational neuroscience

The field of educational neuroscience presents a number of theoretical, practical, and ethical concerns. Although the rationale and aims of the field are clear, the reality of uniting three distinct subjects is challenging.

One of the practical challenges is the field's goal of translational research. In order to achieve this aim, a number of key players must be involved. Beyond scientific researchers of diverse communities, the enterprise must also engage educators, speech and language therapists, educational psychologists, and policy makers. It must be a collaboration among all stakeholders, whereby each community can learn from the others. Educators can use their insights from the classroom to inform the direction of research. The conversation between educators and scientists must be two-way, moving away from the traditional model in which scientists impart their knowledge to teachers. Educators have a huge amount of relevant knowledge and engaging with them will move the field forward in unforeseen directions.

There are also some ethical considerations. The first concern is the unknown long-term safety associated with brain stimulation techniques in developing populations. Scientists are so far divided on whether it is ethical to try these procedures in children when we are unsure of their safety. The second major ethical consideration concerns the potential implications of finding genetic or biological markers for high or low academic ability. Once these have been discovered, should extra help be targeted at those who are less able, in order to improve their performance? Or to those who are more able and could achieve even greater things? These are difficult questions, and highlight one of the reasons that scientific advances should not be carried out in isolation from the rest of the community. It is the public and policy makers who should debate the ethics of what do with the research findings once they have been made. Conversely, educational neuroscience can help scientists to fulfill their moral duties. There is a duty to the taxpayer for scientists to conduct research that is relevant and for which there is an appetite (as neuroscience is sought by educators), and to share scientific findings widely with those who could benefit. There is also the moral duty to give the best possible education to children who go to school five days a week for nine years of their lives.

Conclusions

The provision of reliable research findings from scientists is the first step in opening up the dialogue between interested communities and offering evidence-based directions for action. The future of the field is likely to involve more intervention studies where we can assess the effectiveness of different modes of training and teaching: do children learn better through certain technologies? Do they learn better with regular short training or less frequent longer sessions? What is the best age to target certain skills? The field will continue to investigate all levels of description – from the genetic and neural to the behavioral and social – in the pursuit of a holistic understanding of learning that will allow for the enhancement of learning for all individuals. A key dimension will be gaining and understanding of the impact of new educational technologies on children’s learning and their developing (e.g., Bavelier, *et al.*, 2012).

See also:

Learning theories; Fetal and neonatal magnetoencephalography; Fetal ultrasonography; Magnetic resonance imaging; Functional near-infrared spectroscopy; Twin method and related designs; Connectionist modeling; Attention; Cognitive development beyond infancy; Intelligence; Memory and learning; Language acquisition; Reading and writing; Schooling and literacy; Speech development; Early childhood education; Handwriting; Brain and behavioral development; Cognitive neuroscience; Social neuroscience; Dyscalculia; Dyslexia; Behavioral genetics; Connectomics; Linguistics; Systems neuroscience

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Glossary

Educational neuroscience: A scientific discipline that brings together psychology, pedagogy, and neuroscience, with the goal of improving teaching and learning in individuals of all ages.

Functional transcranial doppler ultrasonography (fTCD): An indirect neuroimaging tool that uses doppler ultrasound to measure cerebral blood flow during cognitive tasks.

Genome-wide association studies (GWAS): A method that scans common genetic markers to identify genetic variants associated with a phenotype.

Transcranial direct current stimulation (tDCS): A non-invasive brain stimulation technique that induces a weak electrical current, which is thought to increase the firing rate of neurons in the cortex.

Transcranial magnetic stimulation (TMS): A non-invasive brain stimulation technique that used magnetic field pulses to induce an electrical current, which is thought to increase the firing rate of neurons in the cortex.

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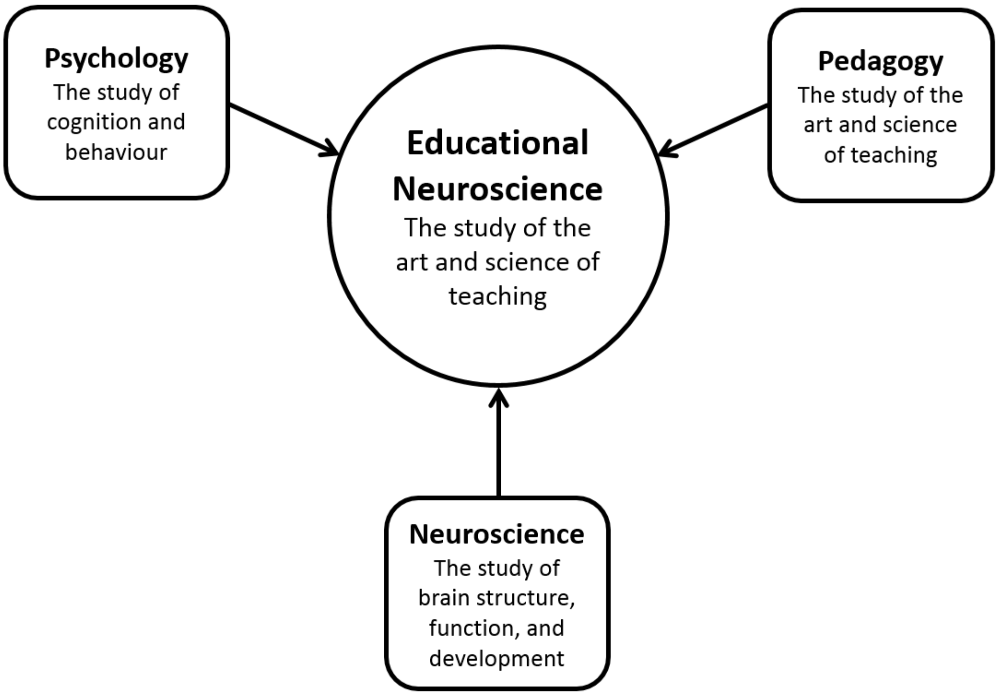
Figures



Abstract Form

You have been hired as a clerk. Your job is to make sure that a set of documents is marked correctly, according to the following rule: "If the document has a vowel on one side, then it must have an even number on the other". You have been told that there are some errors in the coding of the documents, and that you need to find the errors. Each document has a letter rating on one side and a numerical code on the other. Here are four documents. Which document(s) do you need to turn over to check for errors?

A	D	4	7

Concrete Form

You have been hired as a bouncer in a bar and you must enforce the following rule: "If a person is drinking beer, then they must be over 19 years old". The cards below have information about four people in a bar. One side of each card shows a person's age and the other shows what she or he is drinking. Which card(s) do you need to turn over to make sure no-one is breaking the law?

Drinking beer	Drinking Coke	22 Years of Age	16 Years of Age

Figure legends

Figure 1. Educational neuroscience brings together psychology, pedagogy, and neuroscience.

Figure 2. The abstract and concrete forms of the Wason four-card selection task. The correct response in the abstract form is to choose the vowel and the odd number. The correct response in the concrete form is to choose beer drinking and the 16-year-old.