Editorial

At the nexus of neuroscience and education

1. Introduction

Research on how the brain develops and learns has the potential to have a profound impact on education. Indeed, understanding the brain mechanisms that underlie learning and memory, and the effects of age, genetics, the environment, emotion and motivation on learning could transform educational strategies and enable us to design programs that optimise learning for people of all ages and of all needs. Neuroscience can already offer some understanding of how the brain learns new information and processes this information throughout life (Blakemore and Frith, 2005; Goswami, 2006; Shonkoff and Levitt, 2010). The potential link between neuroscience findings and educational practice and policy is the focus of this special issue of *Developmental Cognitive Neuroscience* on Neuroscience and Education.

Developmental cognitive neuroscience is contributing to our basic understanding of how the brain develops and changes with experience from infancy onward, as well as the neural mechanisms underlying school-based learning and how these can go wrong. As such, developmental cognitive neuroscience has the potential to contribute to education policy. Indeed, to say that neuroscience is relevant to education is an understatement. By definition, education changes the brain; the brain changes every time a child – or an adult – learns something new. Thus a deeper understanding of how the brain processes and learns shapes and sounds, letters and numbers, the neural processes underlying the maintenance and manipulation of task-relevant information, individual differences in learning, motivation and memory, and so on, is profoundly relevant to education. Understanding the biological basis of the developmental disorders that affect children's educational attainment is a critical step in developing interventions.

Inroads are being made: There are already multi-way dialogues between the fields of neuroscience and education. Educators and parents are learning about the brain, and neuroscientists are moving their research into the schools and engaging with policymakers in an effort to update educational policies as a function of what we have learned about brain development and plasticity, and about the brain basis of cognitive capacities. A new breed of students is seeking interdisciplinary training in education and neuroscience. This is surely a positive step: neuroscience must have a bigger presence in schools, and education researchers and educators must play a more substantive role in guiding neuroscience research on learning and development. This supplemental special issue highlights current work in multiple areas of interest in the context of education.

2. Bridging neuroscience and education

The special issue begins with two theoretical papers focusing on the role that neuroscience can play in the educational arena, and vice versa. David Baker, Daniel Salinas and Paul Eslinger point to the potential importance of understanding how the social environment and culture, which includes widespread formal education, influences the neurocognitive development of a population (Baker and Salinas, 2012). Their paper also discusses how findings from neuroscience can shed light on the effect of schooling on neurocognitive development. It has long been pointed out that the gap between neuroscience data and education policy is "a bridge too far" (Bruer, 1997). One of the major contributions of the paper by Baker et al. is to assess the potential contribution of social science research to bridge the gap between neuroscience and education.

Howard-Jones et al. (2012) question whether neuroscience research supports the now widely held assumption that earlier investment in an individual's education is economically optimal. The review concentrates on the intersection of human capital research, education policy-making, and neuroscience and notes that an economic model's basis in neuroscience can critically influence its policy implications and popularity. The authors focus on the economic model of James Heckman, which proposes that the earlier in life that investments are made, the greater the economic return (Cunha and Heckman, 2007). This paper critically reviews the evidence that "early is always better", and concludes that neuroscience research does not always support this assertion.

3. Foundational cognitive skills

The reviews and empirical papers in this section focus on core cognitive skills that support learning inside and outside the classroom. Many (although not all) of these core skills regulate our train of thoughts, actions, and emotional responses in a way that promotes goal-directed behavior, and are known collectively as *executive functions* or *self-regulation* or *self/cognitive control*. A recent longitudinal study, which followed 1000 individuals from birth to age 32, highlighted the importance of self-control during childhood for lifelong health, wealth, and public safety (Moffitt et al., 2011). Of particular relevance for this special issue, Moffitt and colleagues also showed that children whose parents and teachers rated them as having better self-control were less likely to drop out of secondary school. This large study complements the growing number of studies showing that performance on laboratory-based measures of executive function are correlated with, and predictive of, academic achievement (see Blair and Diamond, 2008).

One of the core self-regulatory skills is the ability to focus on relevant information, or *selective attention*. Courtney Stevens and Daphne Bavelier review the literature on the neural basis of selective attention and its development, and explain how this ability may serve as part of the foundation for the acquisition of language skills, literacy, and mathematics (Stevens and Bavelier, 2012). Then, the authors summarize evidence from several lines of research – video gaming and meditation, in particular – which suggest that selective attention can be improved with training. Finally, the authors comment on the implications of these findings for childhood education, in particular the potential role of techniques to enhance selective attention.

In their empirical paper, Stacy Espinet, Jacob Anderson, and Phil Zelazo note that there is a dramatic rise in executive functions from age 3 to 6, a period generally marked by the transition to formal schooling, during which the capacity for self-regulation is increasingly taxed (Espinet et al., 2012). A widely used measure of children's executive function is the Dimensional Change Card Sort task (DCCS; Zelazo, 2006). This task requires children to sort a series of cards into one of two bins according to a sorting rule involving one dimension (e.g., color) and then according to a sorting rule involving another dimension (e.g., shape). In this large event-related potential (ERP) study involving 99 children between the ages of 2.9–4.5, Espinet and colleagues show that the N2, a negative-going voltage deflection associated with performance monitoring, distinguishes children who do and do not exhibit the capacity to switch from one dimension to the other on the DCCS. Regardless of age, 'Switchers' exhibited smaller-amplitude N2 waveforms than 'perseverators'. These results suggest that switchers experience less conflict between competing response alternatives, as indexed by the N2, because they represent and/or implement the task rules more effectively. The authors propose that: "[r]eflecting on conflict, including gaps in one's understanding, may go hand in hand with the adoption of a more active, goal-directed, top-down approach to learning. [. . .] Further research might usefully investigate the conditions under which reflection is facilitated, in an effort not only to exercise children's executive function, but also potentially to transform the way in which children learn."

Jennifer Martin McDermott, Nathan Fox, Charles Nelson, Charles Zeanah and colleagues explore the links between early adversity and executive function in an ERP study involving children, now age 8, from their longitudinal study of the Bucharest Early Intervention Project (BEIP) (Martin McDermott et al., 2012). Through the BEIP, they have been following an initial sample of 136 children who had been abandoned early in life or placed in institutions in Bucharest, Romania. Half of these children were randomly assigned to placement in a high-quality foster care program (intervention), whereas the other half were assigned to remain in institutional care (treatment-as-usual). In this study, the researchers measured ERP waveforms during performance of a Go-nogo task for 95 eight-year-olds: 37 children from the intervention group, 29 children from the treatment-as-usual group, and 29 control children who have also participated in the longitudinal study. On the Go-nogo task, a steady stream of stimuli is presented, and participants must respond to each one in turn but inhibit responding to a specific nogo stimulus. This task taxes sustained attention and response inhibition, both key components of executive function. Children in the intervention group and in the control group exhibited better sustained attention than the children in the treatment-as-usual group, as measured by fewer errors of omission on Go trials and faster response times. These behavioral results suggest, at first blush, that high-quality early intervention can eliminate the negative effects of early psychosocial deprivation on executive functioning. However, the ERP data provide a more fine-grained picture, showing the traces of both deprivation and intervention across three commonly measured waveforms associated with executive function: the N2 (also featured in Espinet et al., 2012; Martin McDermott et al., 2012), the P3 (or P300; also featured in Hillman et al., 2012), and the error-related negativity (ERN).

The ability to store and retrieve associations from long-term memory is fundamental to learning both inside and outside the classroom. Myriam Sander, Markus Werkle-Bergner, and other researchers from Ulman Lindenberger's group review their group's two-component model of developmental changes in memory, and discuss how it is relevant for education (Sander et al., 2012). According to this model, age-related changes in two components of memory – *associative* and *strategic* – contribute to the rise and fall of long-term memory capacity over the lifespan. The associative component refers to the ability to bind the features of a singular event into an integrated memory trace, and to retrieve this bound set of representations at a later date. This component, which is tightly linked to the medial temporal lobes, is relatively mature by middle childhood. The strategic component of memory refers to the set of 'top-down' control processes that enable the organization and monitoring of memory representations. This component, most commonly linked to lateral prefrontal cortex, develops throughout childhood and adolescence. The authors note that there are large individual differences in memory development, and suggest that children's initial difficulties in strategic processing can

be overcome by environmental settings that are conducive to a more efficient combination of strategic and associative components. The authors argue that neuroscientific research on memory development has direct implications for the design of age-appropriate instructional materials.

The ability to use positive or negative external feedback to reinforce or update one's behavior, respectively, is another core cognitive skill that is central to learning. Wouter van den Bos, Eveline Crone, and Berna Guroglu report on the results of an fMRI study examining the neural basis of feedback-based learning in 13–16-year-olds during performance of a probabilistic learning task (Van den Bos et al., 2012). The authors examined the influences of IQ and educational setting (pre-vocational or pre-university studies) on feedback-based learning and associated brain activation. Higher IQ adolescents performed the task more accurately than lower IQ adolescents (regardless of educational setting, after accounting for differences in IQ between pre-university and pre-vocational students): they were more likely to benefit from positive reinforcement, adopting a 'win-stay' strategy by repeatedly choosing a stimulus that has just been rewarded. Interestingly, effects of both IQ *and* educational setting are evident in the brain – specifically, in dorsolateral prefrontal and anterior cingulate cortex responses to feedback. Thus, although one might conclude from the behavioral data that educational setting has no influence on how we learn from feedback, the neural data tell a different story.

Finally, Charles Hillman and colleagues investigate the relationship between event-related potentials during a Go-nogo task and aptitude in reading, spelling, and arithmetic, as measured by the Wide Range Achievement Test in a large sample of children aged around 8 years (Hillman et al., 2012). The results of this relatively large-scale study indicate a significant contribution of the P3 component, which reflects attentional processes involved in stimulus evaluation, working memory and inhibitory control, to reading and arithmetic achievement. The P3 amplitude explained academic aptitude beyond the variance accounted for by IQ and school grade. The authors propose that the P3 might be a biomarker for academic achievement during childhood. Further studies are needed to investigate whether the P3 can go above and beyond pencil-and-paper tests that tap the same cognitive processes (working memory and inhibitory control) and are easier and cheaper to administer.

4. Academic skills: reading, comprehension and mathematics

The first paper in this section makes an important contribution to our neurological understanding of reading and plasticity in the adult brain. Laurie Cutting and colleagues report a training study of skilled adult readers with the aim of identifying differential training effects on the neural network that supports reading (Clements-Stephens et al., 2012). The training paradigms in this combined behavioral and neuroimaging study involved either learning pronunciation and meaning of pseudowords in isolation (a more explicit approach) or learning pseudowords in sentence

contexts to allow meaning to be inferred. Several results are reported, including the interesting finding that the pattern of brain activation within the reading network for trained pseudowords was similar to that for low frequency real words, and different to that for untrained pseudowords. However, there was an interaction between training and reading proficiency such that highly skilled readers showed similar levels of neural activity regardless of the training paradigm, whereas less skilled readers showed comparable activity to highly skilled readers only for pseudowords learned in isolation. Thus, in the context of education, this study provides evidence that level of reading proficiency influences the neural response within the reading network to the type of training experienced.

In another contribution that focused on reading, Laura Barde and colleagues investigated whether 9–16 year old adolescents who were either born pre-term (mean gestational age of 28.8 weeks) or full-term, when matched on performance, would activate similar neural regions during an auditory sentence comprehension task (Barde et al., 2012). The main finding was that there was greater activation in the preterm group as compared to the full-term group in response to increasing syntactic difficulty in the middle frontal gyri bilaterally, which was not accounted for by differences in out-of-scanner language abilities, age, or receptive language skills. The authors propose that the difference in neural activation during sentence comprehension in adolescents who were born preterm compared to those who were born full-term suggests a need for educational intervention "even when formal test scores indicate normal academic achievement".

Steffen Landgraf, Reinhard Beyer, and colleagues from Elke van der Meer's group investigated the extent to which phonological processing is necessary for adults to acquire written language skills (Landgraf et al., 2012). 47 illiterate adults took part in a one-year alphabetization course and were tested before and after training on several cognitive domains relevant to phonological processing. Phonological awareness was a stronger predictor of alphabetization outcome than demographic variables such as years of education. The alphabetization training improved phonological processes, although the trained group did not reach the phonological processing level of literate controls.

To understand better the neural underpinnings of individual differences in numerical ability, Robert Emerson and Jessica Cantlon conducted an fMRI study with 4–11-year-olds (Emerson and Cantlon, 2012). They set out to test whether the strength of temporal coupling between frontal and parietal regions, assessed during free viewing of a video, would be correlated with children's mathematical ability. First, the authors used a numerical matching fMRI task to localize regions involved in processing numerical information. Then, they measured patterns of functional connectivity while children passively viewed a 30-min Sesame Street video that included math topics. As predicted, the strength of frontoparietal functional connectivity on the natural viewing paradigm was correlated with individual children's number matching ability and their scores on a standardized test of mathematical ability (TEMA). Thus, this study introduces a novel paradigm for use in measuring brain network connectivity in young

children, and also provides clues regarding the neural basis of individual differences in numerical abilities.

A paper by Sarit Ashkenazi, Vinod Menon and colleagues reports an innovative, combined behavioral-fMRI study that investigated the neural correlates of arithmetic processing in children with normal mathematical ability and in children with developmental dyscalculia (Ashkenazi et al., 2012). The experiment manipulated arithmetic complexity in order to investigate differential brain responses to simple and complex calculations in both groups of children. The results revealed that an extensive network of fronto-parietal regions were more active for complex compared with simple problems in typically developing children but not in dyscalculic children. In addition, multivariate analysis revealed that the intraparietal sulcus showed less distinct multivoxel patterns of neural activity between simple and complex problems in dyscalculic children compared with typically developing children. The results suggest developmental dyscalculia is associated with hypo-activity in key brain regions implicated in mathematical cognition, as well as less distinct neural representations for different types of arithmetic problem.

Training foundational cognitive skills

A number of neuroscientists are looking to cognitive interventions as a way to apply what we have learned over the last century about brain function, development, and plasticity. Intensive cognitive training programs that target core cognitive skills such as working memory and executive functions (as well as exercise programs that more generally enhance brain function) are being evaluated in scientific studies across multiple laboratories. Although additional research funding is needed to support large-scale, well-controlled studies on all of the promising programs, multiple research groups are beginning to show that intensive cognitive training of various forms can boost specific cognitive functions and alter brain structure and function.

This section features submissions from three research groups that are active in this area of research. First, Martin Buschkuehl, Susanne Jaeggi, and John Jonides (Buschkuehl et al., 2012) survey the growing literature on the effects of cognitive training, and in particular working memory training, on brain structure and function. In so doing, they seek to explain why working memory training can yield benefits on a range of cognitive tasks – i.e., which neural changes can account for *transfer* to untrained tasks. To this end, the authors review studies that have shown that training leads to changes in activation patterns, resting state functional connectivity, brain structure, or neurochemistry. Faced with this variegated set of findings, they argue that no single mechanism of neural plasticity can account for training and transfer at the cognitive level. Given that the litmus test of understanding is the ability to make accurate predictions, we propose that further research should be aimed at trying to predict the magnitude of training and transfer effects on the basis of a number of neural indices of change.

Dietsje Jolles, Eveline Crone and colleagues, scanned 12-year-olds and young adults before and after 6 weeks of practice on a task that required participants to manipulate – i.e., reorganize – information in working memory (Jolles et al., 2012). On trials requiring pure maintenance, they had to maintain the memory of a set of items (pictures of nameable objects) in the order in which they had been shown; on trials requiring both manipulation and maintenance, they had to reverse the order of these items in working memory (Crone et al., 2006). Both 12-year-olds and adults improved with practice, and these benefits were maintained after 6 months. Both before and after practice, adults engaged the lateral fronto-parietal network more strongly at the time when they are expected to reverse the items in working memory vs. simply maintain them. By contrast, 12-year-olds did not ramp up this working memory network for the more demanding task until the second time they were scanned, after 6 weeks of practice. Thus, these results suggest that practice led 12-year-olds to approach the task more like adults, thereby emphasizing the role of experience in development.

Rosario Rueda, Puri Checa, and Lina Cómbita assessed the behavioral and neural effects of 10 sessions of computerized attention training in 5-year-olds, comparing a trained group with a passive control group (Rueda et al., 2012). They measured performance on a wide range of cognitive tasks, and collected high-density electroencephalography (EEG) data before and after 5 weeks of training, as well as 2 months later. The behavioral effects of this intervention were modest, but – interestingly – the ERP data revealed that training resulted in more efficient neural processing. Indeed, Rueda et al. show a training-related shift in the latency to peak as well as the topographical distribution of the N2 component (see papers by Espinet et al., 2012; Martin McDermott et al., 2012) The fact that the ERP data showed stronger effects of training than the behavioral data supports the intriguing possibility that changes can be detected at the neural level *earlier* than at the behavioral level; i.e., they might indicate that an individual is on the right track towards a behavioral change with additional training, and/or that a behavioral change could be observed with a more sensitive, or more appropriate, behavioral measure.

We conclude this overview by noting that the area of 'cognitive training' or 'brain training' is plagued by dangerously high levels of both skepticism and enthusiasm; both of these attitudes are ultimately detrimental to the research enterprise. We have a responsibility as scientists, journal reviewers, and editors to publish not only the studies that show strong beneficial effects of cognitive training, but also those showing weak or negative effects of training. Such findings will help the research community to determine the boundary conditions of training: How much can we expect the brain to change? In which population(s)? Over what time frame? Moreover, it is critical that we remain realistic about the possibilities and limitations of cognitive training. Should we expect that focused training of a specific cognitive skill will generalize to improved performance on a wide array of real-world settings, or that the effects of a brief intervention will last for years? Probably not. The better we understand the cognitive challenges that we wish to

address – for example, poor performance in 7th grade algebra – the better we can design or identify programs that can help children to prepare for these specific challenges.

Conflicts of Interest

The authors declare no conflicts of interest.

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