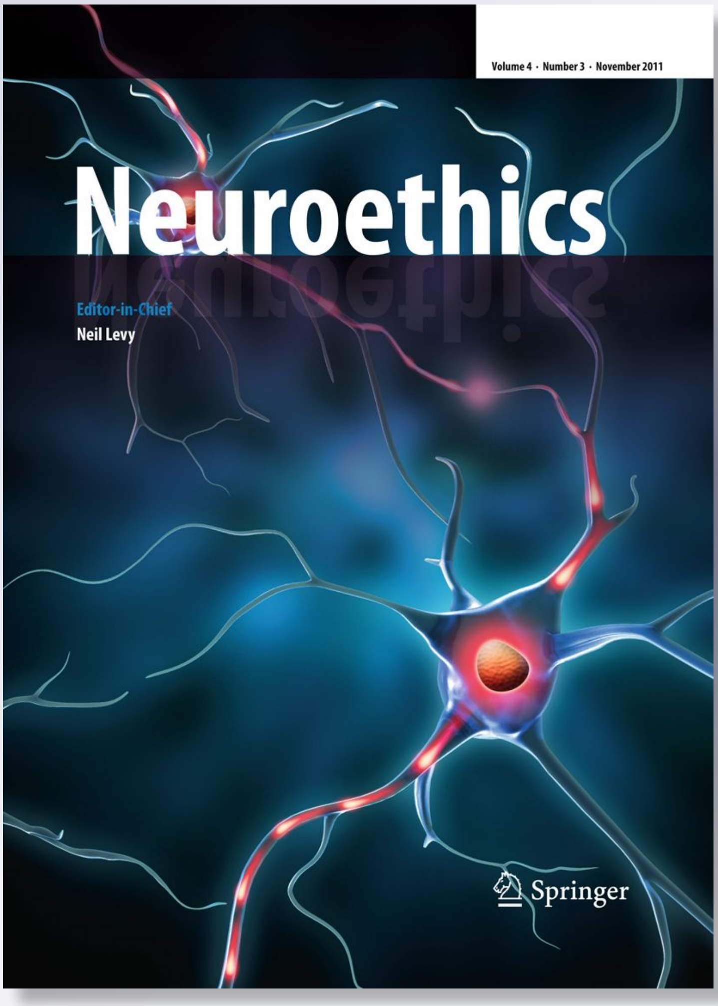
Neuroeducation – A Critical Overview of An Emerging Field

Daniel Ansari, Bert De Smedt & Roland H. Grabner

Neuroethics

ISSN 1874-5490
Volume 5
Number 2

Neuroethics (2012) 5:105-117
DOI 10.1007/s12152-011-9119-3



Neuroethics (2012) 5:105–117
DOI 10.1007/s12152-011-9119-3

ORIGINAL PAPER

Neuroeducation – A Critical Overview of An Emerging Field

Daniel Ansari · Bert De Smedt · Roland H. Grabner

Received: 15 December 2010 / Accepted: 20 May 2011

Abstract In the present article, we provide a critical overview of the emerging field of 'neuroeducation' also frequently referred to as 'mind, brain and education' or 'educational neuroscience'. We describe the growing energy behind linking education and neuroscience in an effort to improve learning and instruction. We explore reasons behind such drives for interdisciplinary research. Reviewing some of the key advances in neuroscientific studies that have come to bear on neuroeducation, we discuss recent evidence on the brain circuits underlying reading, mathematical abilities as well as the potential to use neuroscience to design training programs of neurocognitive functions, such as working memory, that are expected to have effects on overall brain function. Throughout this review we describe how such research can enrich our understanding of the acquisition of academic skills. Furthermore, we discuss the potential for modern brain imaging methods to serve as diagnostic tools as well as measures of the effects of educational interventions. Throughout this discussion, we draw attention to limitations of the available evidence and propose future avenues for research. We also discuss the challenges that face this growing discipline. Specifically, we draw attention to unrealistic expectations for the immediate impact of neuroscience on education, methodological difficulties, and lack of interdisciplinary training, which results in poor communication between educators and neuroscientists. We point out that there should be bi-directional and reciprocal interactions between both disciplines of neuroscience and education, in which research originating from each of these traditions is considered to be compelling in its own right. While there are many obstacles that lie in the way of a productive field of neuroeducation, we contend that there is much reason to be optimistic and that the groundwork has been laid to advance this field in earnest.

Keywords Neuroeducation · Mind, brain and education · Educational neuroscience · Reading · Numeracy · Arithmetic · Brain imaging · Brain training

Why Neuroeducation?

Despite early skepticism and the notion that connecting neuroscience and education represents 'A bridge too far' [1], the past decade has seen a tremendous

D. Ansari (✉)
Numerical Cognition Laboratory,
Department of Psychology,
The University of Western Ontario,
Westminster Hall,
London, ON N6A 3K7, Canada
e-mail: daniel.ansari@uwo.ca

B. De Smedt
Parenting and Special Education Research Group,
Katholieke Universiteit Leuven,
Leuven, Belgium

R. H. Grabner
Institute for Behavioral Sciences, Swiss Federal Institute
of Technology (ETH) Zurich,
Zurich, Switzerland

interest in the potential of applying insights from neuroscience to educational settings. Some refer to this emerging field of translational research as 'neuro-education', others call it: 'mind, brain and education' or 'educational neuroscience'. In the present paper, we refer to this growing field as 'neuroeducation' a term that we consider to be interchangeable with the other labels mentioned above.

A few examples serve to illustrate just how much enthusiasm and energy there has been to establish a field of 'neuroeducation'. For instance, in 1999 the Organization for Economic Cooperation and Development (OECD) launched the so-called 'Brain and Learning' initiative to bring together international researchers to discuss the potential of neuroscience for educational policy and practice. These efforts culminated in the publication of a book entitled: "Understanding the brain: Towards a new learning science" [2]. Furthermore, under the leadership of Kurt Fischer at the Harvard Graduate School of Education, where Dr. Fischer directs a Master program in 'Mind Brain and Education' (http://www.gse.harvard.edu/academics/masters/mbe/), the 'International Mind, Brain and Education Society' (IMBES) was founded in 2004 (http://www.imbes.org/). In 2007, IMBES launched an international, peer-reviewed journal entitled 'Mind, Brain and Education' to provide an outlet for empirical and theoretical work dealing with the connections between neuroscience, psychology and education, and this journal was recognized as the best new journal in social sciences and humanities in 2007. Moreover, in 2008, the then President of the Society for Neuroscience, Tom Carew, held a "Neuroscience Research in Education Summit" (http://www.sfn.org/index.aspx?pagename=NeuroEd_Summit) to bring together neuroscientists, education researchers, practitioners and policy makers to explore the potential of neuroeducation. Most recently, in 2010, we (Daniel Ansari, Bert De Smedt, Roland H. Grabner) organized a meeting of the European Association for Research on Learning and Instruction (EARLI) Special Interest Group for 'Neuroscience and Education' in Zurich (Switzerland) entitled "Educational Neuroscience: Is it a field?" at which leaders of recently established centers for neuroeducation discussed the promises and pitfalls of this developing field. In addition to such events, numerous special issues on the subject have been published including, perhaps most notably, reviews on neuroscience and education in recent special sections of high-ranking journals such as *Science Magazine* [3, 4] and *Neuron* [5, 6]. The above examples serve to illustrate the ambition of educational researchers, cognitive psychologists and neuroscientists to forge interdisciplinary collaborations.

There are numerous causes of this international drive to forge tighter, bidirectional links between neuroscience and education. Most importantly, through the wide availability of non-invasive methods to image the functions of the human brain, such as functional Magnetic Resonance Imaging (fMRI), Electroencephalography (EEG) and Near Infrared Spectroscopy (NIRS), to mention a few, it has become possible to measure which brain regions are involved in school-taught skills, such as reading and arithmetic, and how their neural correlates change over the course of learning and development. Recent studies have revealed that these changes are not restricted to brain function but can also be observed in the brain structure. For example, Keller & Just [7] revealed that 100 h of intensive remedial instruction lead to changes in the left hemisphere white matter structure of 8- to 10-year-old poor readers, suggesting that myelination had increased. On the other hand, brain maturation appears to continue well into adulthood [8, 9] and the adult brain exhibits a much greater structural plasticity to learning than was previously thought [10].

The possibility of imaging neural effects of learning is helping us to understand both the typical and atypical trajectories of development and to better characterize the limits of plasticity of brain circuits underlying cognitive functions that are shaped by education. In addition, the application of neuroimaging methods has the potential to provide incremental insights into learning-related cognitive (sub)processes at a more detailed level than on the basis of behavioral methods alone (for examples in the domain of mathematics see [11]). The hope is that more knowledge on the neural and cognitive bases of academic competencies will help to better structure learning environments that optimally foster the acquisition of these competencies that are crucial in our modern Western society.

In addition to methodological advances, there is also a practical reason to turn to neuroscience for answers to outstanding educational questions. The bedrock of neuroscience is represented by interdisciplinary research collaborations and this might be an attractive workspace in which to situate efforts to generate evidence-based educational approaches. For example, Michael Gazzaniga, the founder of cognitive neuroscience, stated that ”At the core, the cognitive neuroscientist wants to understand how the brain enables the mind [12].” In practice, cognitive neuroscience involves the collaboration of cognitive psychologists, who ask the relevant questions and situate them within existing frameworks of studying mental processes; with anatomists, who are able to understand how different brain structures relate to different aspects of processing; and physicists, who design increasingly sophisticated methods for the non-invasive imaging of the human brain, such as fMRI. Furthermore, cognitive neuroscience may also involve collaborations between cognitive psychologists and geneticists in an effort to understand the contribution of genetic variability to measures of cognitive processes or the relationship between genetic markers and brain activation during cognitive tasks. A cognitive neuroscientist is a researcher who has benefitted from interdisciplinary training allowing him or her to move seamlessly between different levels of explanation to arrive at a richer characterization of problems which would not have been possible by focusing on one level alone. There are now numerous graduate programs in cognitive neuroscience that span across departments and faculties to afford such interdisciplinary training. This long-standing history of interdisciplinary research within the broad field of neuroscience creates an ideal basis from which to grow a science of education that draws on research from neuroscience, cognitive psychology and other learning sciences.

The potential of neuroscience to serve as a platform for evidence-based education is also reflected in large investments into inter-disciplinary research programs. For example, in 2005 the German Federal Ministry for Education and Research established the ‘Neuroscience, Instruction and Learning’ funding initiative [13]. This program was partially a reaction to Germany’s relatively poor performance in the OECD’s Program for International Student Assessment (PISA). Similarly, the US National Science Foundation established the ‘Science of Learning’ funding program to establish interdisciplinary research centers to enhance our understanding of how students learn, how this learning can be optimally fostered, and how research may be brought to bear on educational problems. Many of the currently funded ‘Science of Learning Centers’ have cognitive neuroscientists as key investigators of larger, interdisciplinary research teams. Thus, neuroscience is one of the fields of inquiry that funding agencies and policy makers have turned to for answers to large-scale educational problems.

What are Some Examples of Research and Translation in Neuroeducation?

Having laid out the case for ‘neuroeducation’ we now turn to an overview of some of the key advances that have been made in this field. We do so by briefly reviewing key pieces in different areas of research. This overview is not meant to be comprehensive but merely to provide a taster of the large variety of educationally relevant research domains in which neuroscience, and in particular cognitive neuroscience, has provided new insights that constrain our understanding of learning. It is important to point out that these insights have largely originated from studies that aimed to understand the origins of specific disorders of learning to read and to calculate, i.e. dyslexia and dyscalculia, and then attempted to design appropriate educational interventions for these children. Such interventions are extremely relevant, given that academic failure puts a serious burden on one’s life success in modern western societies. More broadly, current research is also trying to unravel typical academic skill development and we will discuss some of the potentials for this research to affect teaching and education in general. One of these potentials deals with complementing, for example by means of methodological triangulation, and extending our knowledge on academic skill development that has been obtained on the basis of behavioral data only. On the other hand, neuroscience can also have indirect effects on education by drawing our attention to the importance of underlying representations, thereby setting the stage for further educational research, as we will elaborate below in the field of numeracy and arithmetic. In all, this knowledge might, in the long run, help educationalists to design appropriate learning environments.

Reading

The neuroscience of reading is perhaps the field in which the most progress has been made towards understanding the neural correlates of skills acquired over the course of formal education. Most importantly, cognitive neuroscience research has gleaned insights into which brain circuits are disrupted in children with dyslexia [3]. A set of brain regions has been identified whose activation patterns respond differently during basic reading tasks, such as rhyming or reading of single words, in children with dyslexia [14–16]. Perhaps most relevant for education are studies that have investigated the effects of structured reading remediation programs on brain function for students with dyslexia. There are a growing number of functional neuroimaging studies that have compared the brain activation of students before and after they have undergone behavioral interventions aimed to remediate the poor reading performance in dyslexia [17–19]. Broadly speaking, these studies show that such remediation programs lead to changes in the functional brain activation patterns associated with reading. More specifically, the comparison of brain activation patterns pre- and post-intervention revealed normalization of brain regions that were found to be under-activated in individuals with dyslexia relative to typical readers as well as additional activation in brain regions not typically associated with reading that were thought to reflect compensatory brain activation. The finding of compensatory activation following reading intervention is a nice example of how cognitive neuroscience complements and extends the existing knowledge of relevant cognitive processes that has been solely obtained on the basis of behavioral data so far [20]. Specifically, these findings suggest that instruction and specific interventions lead to the establishment of novel reading strategies in individuals with dyslexia and thus encourages greater investigations into the precise ways in which these individuals compensate for their difficulties. Such research may eventually lead to training protocols that facilitate the use of compensatory strategies if they turn out to be beneficial for the learning progress.

Perhaps the most striking potential of cognitive neuroscience lies in its possibility for early identification of children with reading difficulties [3]. If at-risk children can be identified before or at the very beginning of formal reading instruction, it might be possible to minimize or even eliminate their difficulties in reading at a very early stage. For example, longitudinal data by Molfese [21] have demonstrated that event-related potentials (ERP), collected in infants and young children (i.e. in the absence of dyslexia symptoms), predict future language and reading development. This all demonstrates that neuroimaging measures may have important diagnostic value as neuroimaging methods become more widely available.

Compelling evidence in support of the notion that neuroimaging measurements provide a novel level of explanation is demonstrated in a study by Hoeft et al. [15] in which both behavioral and neuroimaging data were used to predict individual differences in children's reading skills. Their analyses indicated that functional and structural neuroimaging methods can predict individual differences in reading achievement but, most importantly, that models that combine both behavioral and neuroimaging measures predicted reading measures better than models that comprised only one of each type of measure.

Neuroimaging of reading has also provided evidence to constrain educational expectations. In this vein, a recent study by Froyen, Bonte, van Atteveldt and Blomert [22] is particularly noteworthy. Educational policy in the Netherlands states that students should have acquired letter-speech sound association by the end of the first grade, suggesting that these associations are more or less fully developed (and should not be fostered anymore) by this stage. Dutch is a transparent language and, therefore, it makes intuitive sense that letter-sound correspondences should be acquired rapidly, an observation that is confirmed by behavioral evidence based on accuracy data. However, using ERP, Froyen et al. were able to show that even after 4 years of reading, the brain responses associated with letter-speech sound integration were not fully 'adult-like'. Thus, these brain imaging data indicate that children do not have fully integrated speech-letter sound representations after 1 year of schooling. Such neuroimaging evidence might help educational policy makers in setting the expectations for the achievement of educational milestones.

On a more basic level, recent research has provided direct evidence that learning to read changes brain activation patterns. Specifically, through a comparison of literate and illiterate participants, Dehaene, Pegado, Braga, Ventura, Nunes, Filho, Jobert, et al. [23] were able to demonstrate that learning how to read not only changes brain activation in areas typically associated with reading, but also alters activation in brain circuits associated with speech perception. Furthermore, brain responses to visually presented words in occipito-temporal brain regions, frequently referred to as the 'Visual Word Form Area', expanded to adjacent brain regions coding for the processing of faces. These findings demonstrate that learning how to read changes, not only brain circuits typically associated with reading, but also leads to changes in the brain circuitry that is used in other domains. These findings provide novel insights into the consequences of reading acquisition on brain function and, provocatively, suggest that learning to read does not simply lead to brain changes in regions found to subserve reading in literate subjects but also affects other domains. Moreover, Dehaene et al. have found that learning how to read changes brain mechanisms regardless of whether literacy skills were acquired in childhood or adulthood, indicating that plastic brain changes when learning to read can occur at different levels of development.

Neuroimaging methods have also provided findings that are entirely different to those obtained from behavioral measures. For example, in an ERP study of the development of rhyming, Coch, Grossi, Coffey-Corina, Holcomb and Neville [24] found that while reaction times and accuracy during rhyming change over developmental time, brain responses that are sensitive to the difference between rhyming and non-rhyming pairs of words were found to be similar across different age groups. These data provide examples of the value added by neuroimaging methods in exploring the development of educationally relevant processes, such as learning how to read.

Numeracy and Arithmetic

Research on the brain circuits underlying numeracy and arithmetic lags significantly behind equivalent work on reading. Notwithstanding, convergent research [25] from work with neuropsychological patients, functional neuroimaging as well as single-cell recordings in awake, behaving primates has identified a set of brain regions that are critical to the representation and processing of numerical magnitude (the total number of items in a set). The bilateral regions of the intraparietal sulcus have been found to be particularly important for the processing and representation of numerical magnitude. Furthermore, brain responses during numerical magnitude processing appear to be qualitatively similar across species and over the course of human development [26, 27].

This has led to a focus on the role played by the processing of numerical magnitude in the learning of arithmetic and, particularly, the breakdown of calculation skills in children with dyscalculia. Individuals with dyscalculia have been found to have difficulties in processing numerical magnitude in behavioral experiments [28, 29, 30] and exhibit atypical patterns of brain activation during numerical magnitude processing [31, 32]. More broadly, it has been demonstrated that individual differences in the ability to discriminate numerical magnitudes (presented symbolically as Arabic numerals or non-symbolically as sets of items) is related to and even predicts variability in children's mathematical achievement [33–36].

The research on numeracy and arithmetic provides a clear demonstration of the indirect effect that neuroscientific research can have on education. Specifically, by revealing brain circuits involved in numerical magnitude processing that are similar across species and over the course of human development, neuroscience research has helped researchers to gain a greater understanding of the role of such basic processes in the typical and atypical development of mathematical skills. Applied research is now being conducted on how basic numerical magnitude processing might be taught to enhance children's learning of higher-level skills such as mental arithmetic [37, 38] and, furthermore, on how measures of basic numerical magnitude processing may be used as individual differences measures in diagnostic contexts [39].

Neuroscientific research has also started to reveal how brain mechanisms underlying calculation change as a function of learning and development. Cross-sectional, developmental neuroimaging studies of mental arithmetic have shown that the brain areas activated during mental arithmetic change in fundamental ways with chronological age [40]. Specifically, while younger children recruit areas of the frontal cortex as well as subcortical areas including the hippocampus (associated with encoding memories), relatively older children recruit regions of the left inferior and superior parietal cortex, including the intraparietal sulcus (IPS) and the angular and supramarginal gyri. Interestingly, training studies with adults reveal similar, training-related, shifts in brain activation [41]. Specifically, studies in which adults were trained on sets of arithmetic problems and subsequently tested using both trained and untrained problems, reveal greater activation for trained compared to untrained problems in the left angular gyrus, while the reverse contrast reveals greater activation in frontal brain areas as well as other areas of the parietal areas (including the IPS). These findings suggest that development and learning leads to specialization of the left inferior parietal cortex, in particular the angular gyrus, for mental arithmetic.

A recent fMRI study [42] provides a further constraint on these findings by revealing that the left angular gyrus exhibits higher activation for arithmetic problems for which adult participants indicated use of a retrieval strategy (e.g., "I knew the answer" or "the solution just popped into my head") versus problems for which subjects reported using a procedural strategy (e.g., "I broke the problem down into multiple steps"). In contrast, greater fronto-parietal activation was observed when evaluating which brain regions were more activated for problems solved using a procedural compared to using a retrieval strategy. These findings suggest that both age and learning-related change in brain activation during arithmetic may, at least partially, be reflective of the increasing use of retrieval strategies and the gradual decline in the use of non-retrieval, procedural strategies. This work on arithmetic strategies is particularly relevant, given that difficulties in arithmetic strategy use, more specifically a failure to rely on arithmetic fact retrieval, constitute one of the most consistent features of children with dyscalculia. Interestingly, recent work by De Smedt, Holloway, and Ansari [43] provided a neural correlate of the fact retrieval difficulties in children with low mathematics achievement aged 10–12 years. These children continued to rely, to a greater extent than their typically achieving peers, on brain circuits in the intraparietal sulcus during the solution of very easy problems, which their peers probably retrieved from memory, suggesting that children with low mathematics achievement continued to rely on quantity-based procedural strategies.

In the context of research of arithmetic strategy use, neuroimaging data have very recently been used to validate behavioral methods of strategy assessment. The applied problem-solving strategy (retrieval or procedural) can either be inferred from the size of the presented problem (e.g., small problems are more frequently solved by fact retrieval than large problems) or can be assessed by means of trial-by-trial verbal strategy reports. Against the background of studies questioning the validity of these verbal strategy reports [44] Grabner & De Smedt [45] used EEG data to compare the brain correlates of both approaches. They observed a stronger association of the EEG data with the verbal strategy reports than with problem size, suggesting that the verbal strategy reports are indeed a valid means to capture strategy use in mental arithmetic. This provides a nice example of how neuroscientific data might, through methodological triangulation, complement knowledge that is obtained on the basis of behavioral data.

Even more compelling are studies where neuroscientific data produce findings that are difficult to generate by behavioral data. For example, Lee et al. [46] compared the symbolic and schematic method for solving algebraic problems. Findings revealed that despite equal behavioral performance, neuroimaging data revealed that the symbolic method was more effortful and required higher attentional demands. This type of evidence might be particularly relevant for evaluating the effects of educational interventions as neuroimaging data might reveal effects of interventions that are not (yet) detectable by means of behavioral data; a possibility that needs to be verified empirically.

It is important to note that most of the existing neuroimaging studies in this domain have been carried out with adult participants. What we are currently lacking from the study of the neuroscience of numeracy and arithmetic are studies that investigate brain activity in children who are in the process of learning mathematics and how this activity is affected by different instructional conditions. In addition, there is a great need for studies that evaluate the effects of structured remedial interventions on brain function for students with mathematical difficulties. These represent important domains for future research.

Brain Training

An obvious question emerging against the background of neuroscientific research that is revealing plastic changes in the brain following learning is whether training specific cognitive functions can lead to improvements in overall brain function. One neurocognitive function that has received much attention in this regard is working memory. Working memory refers to the limited capacity mechanism that allows us to hold and manipulate information during ongoing task performance. This capacity is critical to successful performance in a large number of educationally-relevant domains, such as learning arithmetic, reading and language acquisition [47], and therefore, it has been contended that training working memory may enhance performance in these academic domains. Indeed, it has been shown that the training of working memory leads to increases in brain activation in fronto-parietal regions [48] and changes in performance not only on the tasks that participants were trained to perform but also on untrained working memory tasks [49]. However, what has been more difficult to establish are so-called 'far transfer effects' in which the training of working memory leads to improvements in the academic domains such as arithmetic, reading and language acquisition. Commercially advertised 'brain training' programs, which focus on the training of working memory, have either not been scientifically evaluated or were found to lack such transfer effects in healthy adults. Owen and colleagues [50], for instance, tested over 11,000 participants using an online method on various programs purported to be 'brain training' games. While the authors found that the training improved task performance in the games themselves, there were no findings suggesting that training on one set of activities leads to improvement in other domains. On the other hand, there is first evidence that specific working memory training protocols may have far transfer effects. Jaeggi et al. [51] administered a highly demanding working memory training over 8 to 19 days to young adults and observed improvements in fluid intelligence tasks, which were higher for longer training durations. The authors argued that the transfer effects are due to the overlap of brain regions engaged in the training and transfer tasks—in other words, training of a neural circuit that is critical for many higher-order cognitive tasks was proposed to enhance the performance in these tasks.

At present, the evidence for general cognitive benefits through 'brain training' is scarce and mixed but the idea of such training protocols should not be entirely discarded. These programs are very much in their infancy and many of the current studies have not investigated the long-term effects of training, have not employed a wide range of transfer tasks, have lacked adequate control groups, or have not addressed whether training affects different populations and/or age groups in differentiated ways. Furthermore, so-called 'brain training' programs, in our view, very often lack the input of educational researchers and experts in instructional design. Experimental psychologists and cognitive neuroscientists are frequently tempted to simply convert an experimental task that captures meaningful individual differences (such as a measure of working memory) into an intervention tool. This approach overlooks the possibility that the tool used to measure a given competence may not itself represent a candidate for training. There need to be greater efforts to design educational interventions to train skills that are reflected in performance on an experimental measure. However, these competences may not be trainable by simply repeatedly administrating the measure itself. The current state of research into the effects of 'brain training' illustrates the importance of 'neuroeducation' becoming a truly interdisciplinary endeavor that involves neuroscientists and educational researchers as equal partners.

What Are Some of the Challenges Facing the Field of Neuroeducation?

Clearly much progress has been made in understanding the neuronal mechanisms underlying competencies that are key components of formal education, such as reading and math. The studies cited here are just a few examples of the available empirical evidence that feeds the growth of neuroeducation. In this vein, it is important to note that significant advances have also been made in other domains that are relevant to education, such as the effects of physical exercise on brain function [52], adolescent brain development [53, 54] as well as how variability in socio-economic status affects neurocognitive capacities [55]. Furthermore, exciting evidence is revealing that teaching students about brain development can influence their attitudes towards learning and consequently, lead to improvements in learning [56]. Mangels et al.'s study is especially interesting since it provides a novel line of research in neuroeducation: instead of asking how neuroscience can inform education, these researchers explore how knowing about the learning brain can change students' approaches to learning.

While all this progress in research is positive, there are many challenges facing the emerging field of 'neuroeducation'. Here we discuss four ethical issues that people in the field of neuroeducation should be aware of: interdisciplinary communication, the status of biological explanations of behavior, managing expectations between disciplines and methodological limitations.

Before we turn to these issues in more detail, it is important to highlight the crucial mechanism for dealing with these issues appropriately, which is the interdisciplinary training of researchers and practitioners [57]. Clearly, we must create opportunities for neuroscientists to be trained in educational research and pedagogy and for educational researchers and educators to receive instruction about neuroscientific findings, theories and methods. For neuroscientists and educational researchers, this requires a more widespread establishment of interdisciplinary training programs like the Master's program in 'Mind, Brain and Education' at Harvard that was mentioned at the outset of this article. To equip educators with a basic understanding of neuroscience, a review of brain development, functional and structural neuroimaging evidence should be part of their training [57]. It has been articulated before [58] that one of the key ways in which the field of neuroeducation is going to progress is by using training to level the playing field for educational researchers, educators and neuroscientists to interact as equals. Through such interdisciplinary training, neuroscientists will ask more educationally relevant questions and educators will be able to use knowledge gained through exposure to neuroscience in their educational practice.

Communication

One of the greatest obstacles to real progress in neuroeducation is represented by differences in levels of understanding possessed by educational researchers, teachers and neuroscientists about each other's disciplines and traditions, practices and methodological approaches. While neuroscientists have an in-depth understanding of how the brain changes as a function of learning, only a few neuroscientists have a good insight into educational research methods or indeed, into what is known from a long-standing history of educational research about learning processes. Unfortunately, in our experience, neuroscientists are frequently ignorant about progress that has been made in educational research and, consequently, will misrepresent or underestimate current research on learning and instruction, which can, justifiably, lead to negative attitudes amongst such researchers towards neuroeducation [59]. Furthermore, neuroscientists frequently are largely unaware of the current pedagogical approaches used in schools and, therefore, lack an actual overview of what is being taught in school, how this is taught, and what expectations are being set by curricula etc.

In turn, educational researchers lack insights into neuroscientific theories and methodological approaches. There is a frequent skepticism leveled at highly controlled experimental research by educational researchers, who are typically steeped in traditions that focus on rich natural environments that include many variables that cannot be controlled for. On the other hand, these rich environments are the context in which classroom learning takes place and, therefore, it will be important for future studies to investigate how data obtained in highly controlled neuroimaging studies relate to classroom learning.

Such lack of understanding can lead to fundamental misrepresentations on both sides. One prominent example of this are so-called 'Neuromyths'. These are commonly held and articulated assumptions about brain function that directly contradict or are largely unsubstantiated by available evidence. For example, it is often thought that some people are 'right-brained' while others are 'left-brained' and that this has implications for the kinds of abilities that they can acquire. This assumption is directly contradicted by a vast amount of evidence showing that the brain activation during most cognitive processes involves both hemispheres and that communication between the cerebral hemispheres is a key component of neuronal processing. This neuromyth is often linked to another faulty assumption: the existence of learning styles or the notion that some individuals are better auditory learners, while others may excel if material is presented visually or kinesthetically. A recent, systematic literature review suggests that there is currently no evidence to support the notion of learning styles [60].

Another neuromyth that is pervasive is that individuals only use a fraction (10% is frequently cited) of their brain function in ongoing cognitive functions. Again, there is an enormous body of peer-reviewed evidence (too large to be adequately cited here) to show that in even the simplest tasks, multiple brain areas are involved. There are many more such neuromyths [61] that educators are being exposed to through books, newspapers and other resources (such as online materials). Without an adequate understanding of neuroscience, educators cannot be expected to arbitrate between empirically proven evidence and neuromyth.

Biological Explanations of Behavior

There may be a trend, in the general public as in science, that is rooted in the assumption that a biological understanding of behavior is more informative or reliable than a non-biological explanation. Here again, we believe that training, more specifically of future educators and teachers, is important to wipe out this particular prejudice [57, 58, 62]. This training should also be clear on the scope of a biological explanation: such an explanation does not indicate that a behavior is innate, hardwired or unchangeable. On the contrary, the human brain shows remarkable plasticity and is shaped by experience, as we also have outlined in the above sections on the neuroscience of academic skills.

Methodological Limitations

Another obstacle is represented by the constraints placed on educationally relevant research by the available neuroscientific methods. Most of the available neuroimaging methods available require participants to sit still and to respond to tightly controlled stimuli via button presses. Such experimental environments hardly resemble the complex environments in which both children and adults learn. Thus, a major challenge for neuroeducation is to develop methods that allow for ecologically valid measurements of brain activation of educationally relevant processes and to examine how and to what degree neuroimaging data relate to learning in the classroom [20]. Take, for example, the study of the brain circuits underlying calculation. Since fMRI measurements are confounded by head motion and verbal articulation induces head motion, researchers have studied calculation by asking individuals to verify whether the result of a calculation problem is correct or incorrect (e.g., $3 + 5 = 9$) instead of asking participants to generate the answer to a calculation problem. Since the verification of a correct or incorrect solution is rather uncommon in most classrooms, such tasks may be measuring the neural correlates of processes that are only tangentially related to those that are being expressed in educational contexts.

Another methodological challenge is represented by current sample sizes used in neuroscientific research as compared to educational research. Most neuroimaging studies have relatively small sample sizes. A sample of 20 participants in an fMRI study is considered to be a large sample size. Such small sample sizes are justified by the enormous number of data collected during one imaging session and by the costs involved in conducting functional neuroimaging research. This, of course, poses a number of problems for the representativeness of neuroscientific findings. First of all, small sample sizes compromise the degree to which results can be generalized. Often, samples are drawn from populations that are not representative of variability in socio-economic status and, moreover, do not reflect international differences in education opportunities [63]. Currently, cognitive neuroscience is far from being a science that has produced evidence that can be generalized across cultures while, at the same time, the effects of culture on brain function are being revealed [26].

Furthermore, in research on the effects of interventions on brain function, such sample sizes do not allow for random assignment to conditions in a way that would be considered acceptable in the evaluation of the efficacy of educational interventions. This point illustrates the current gulf that exists between what educational researchers consider representative and reflective of educational settings and what cognitive neuroscientists deem to be generalizable. It is unclear to what extent this difference in methodological approaches can be resolved and whether, indeed, this is necessary. A more constructive approach may be to take these methodological limitations and differences as a point of departure and to seek new ways to creatively combine the power of large-scale, randomized controlled, ecologically valid, educational research methods with neuroscientific methods that employ relatively small sample sizes and controlled environments and, therefore, ecologically less valid approaches. Such hybrid research methodologies require, as discussed in the sections on the challenges pertaining to communication and training, greater interdisciplinary dialogues between educational researchers and neuroscientists.

Managing Expectations

The application of scientific research to education has had a long and complicated history [64]. There is often an expectation that research, be it neuroscientific or otherwise, will provide a 'quick fix'. Put crudely, there is (and we have encountered this expectation frequently in interactions with educators) an expectation that researchers will go into their laboratories and generate research findings that provide a recipe for better teaching. These expectations that research will lead to direct application are shortsighted and not consistent with models for the translation of research findings into applications in other fields [58]. While many of the above-discussed research findings are certainly interesting, the most obvious question a teacher may ask is, "How will I be able to apply this knowledge?" There is, in our view, no reason to expect that neuroimaging research, will determine directly how teaching should take place. This is considered by many "a bridge too far" [1]. Rather, this work enhances our understanding of the learning process and should be reconciled, in a next step, with principles from instructional design. This should then result in learning environments, which should be evaluated in various phases of empirical research starting with small-scale intervention studies followed by larger randomized controlled trials, before they can be implemented in the classroom. Importantly, understanding the learning process represents only one aspect of education and there are various other contextual factors that need to be considered.

So how do we manage the expectations that research should generate immediate, practical answers? Again, we believe that the solution lies in training and through the generation of researcher-practitioners or 'translators', who are versed in educational practice as well as instructional design and have a firm grasp of neuroscientific evidence, similar to those that have been part of the medical establishment for decades. We would also like to suggest, if somewhat provocatively, that teachers, as well as educational theorists, start to view themselves as active participants in the process of translating research into practice. In other words, instead of expecting research to come up with concrete and directly applicable tools for instructors, teachers need to be ready to serve as part of the bridge between research and its application. Such a reconceptualization, however, requires that teachers do not only receive a profound training in educational research, but also have the opportunity to acquire a fundamental knowledge about cognitive neuroscience.

The process of understanding how to apply insights about brain function to the classroom will be a gradual one and much patience is required. It should be noted that the effects by which neuroscience will impact on educational practice may often be very indirect. At the same time, it is clear from the above review that neuroscience is already impacting on diagnostic tools and is guiding researchers towards potential targets of remediation. Patience, but also mutual respect between neuroscientists and educators, will be key to the survival of neuroeducation. Whether policy makers and funding agencies will be able adjust their expectations remains to be seen.

Summary and Conclusions

Incredible progress has been made in neuroscience. The availability of non-invasive tools to image the human brain have allowed researchers to investigate how the brain changes over the course of development and learning and to investigate the brain circuits involved in key academic skills, such as reading and arithmetic, as well as more general cognitive skills, such as working memory. This unprecedented level of progress has spurred efforts to forge greater links between neuroscientists and educators in an effort to improve learning. As the review of three subfields (Reading, Mathematics and 'Brain Training') illustrates, there is much reason to be enthused by the novel insights that have come from within neuroscience. In particular, cognitive neuroscience studies are making great strides towards enhancing our understanding of how the brain and cognition change as a function of learning.

Notwithstanding, there are many open questions and challenges that face the emerging field of neuroeducation. Providing answers to these will be of utmost importance to the full development of the field. One of the crucial mechanisms for addressing these challenges will be the development of interdisciplinary training programs in which, on the one hand, neuroscientists become knowledgeable with regards to educational research and pedagogy and, on the other hand, educators and educational research are exposed to the latest neuroscientific findings, theories and methods, including their limitations. There should be bi-directional and reciprocal interactions between both disciplines of neuroscience and education and research originating for each of these traditions is considered to be compelling in its own right.

This will add to a greater communication between neuroscientists, educators and educational researchers, of which the aim must be to achieve a common language to generate future research questions and translate research into concrete educational applications. For neuroeducation to survive, much patience is required. The translation from research to practice will not be straightforward and will require many intervening steps and professionals capable of facilitating those.

Despite these limitations, we feel that there is now a critical mass of researchers from around the world who are dedicated to pushing this field forward. Furthermore, there is now a clear 'buy-in' from international educational and neuroscientific societies as well as funding agencies and governmental agencies. The groundwork is most certainly laid; now it is time to do the hard work in an effort to find new, creative and scientifically-based ways to improve education.

References

1. Bruer, J.T. 1997. Education and the brain: A bridge too far. *Educational Researcher* 26: 4–16.
2. OECD. 2002. *Understanding the brain: Towards a new learning science*. Paris: OECD Publishing.
3. Gabrieli, J.D.E. 2009. Dyslexia: A new synergy between education and cognitive neuroscience. *Science* 325(5938): 280–283.
4. Meltzoff, A.N., Kuhl, P.K., Movellan, J., and Sejnowski, T.J. 2009. Foundations of a new science of learning. *Science* 325(5938): 284–288.
5. Carew, T.J., and S.H. Magsamen. 2010. Neuroscience and education: An ideal partnership for producing evidence-based solutions to Guide 21(st) Century Learning. *Neuron* 67(5), 685–688.
6. Shonkoff, J.P., and P. Levitt. 2010. Neuroscience and the future of early childhood policy: moving from why to what and how. *Neuron* 67(5): 689–691.
7. Keller, T.A., and M.A. Just. 2009. Altering cortical connectivity: Remediation-induced changes in the white matter of poor readers. *Neuron* 64(5): 624–631.
8. Bennett, C.M., and A.A. Baird. 2006. Anatomical changes in the emerging adult brain: a voxel-based morphometry study. *Human Brain Mapping* 27(9): 766–777.
9. Lenroot, R.K., and J.N. Giedd. 2006. Brain development in children and adolescents: insights from anatomical magnetic resonance imaging. *Neuroscience and Biobehavioral Reviews* 30(6): 718–729.
10. Draganski, B., and A. May. 2008. Training-induced structural changes in the adult human brain. *Behavioural Brain Research* 192(1): 137–142.
11. Grabner, R.H., and D. Ansari. 2010. Promises and potential pitfalls of a 'cognitive neuroscience of mathematics learning'. *ZDM The International Journal on Mathematics Education* 42(6): 655–660.
12. Gazzaniga, M.S. (ed.). 2000. *Cognitive neuroscience: A reader*. Oxford: Blackwell.
13. Stern, E., R.H. Grabner, and R. Schumacher. 2005. *Lehr-Lern-Forschung und Neurowissenschaften: Erwartungen, Befunde und Forschungsperspektiven. Vol. 13*. Berlin: Bundesministerium für Bildung und Forschung (BMBF).
14. Hoeft, F., A. Hernandez, G. McMillon, H. Taylor-Hill, J.L. Martindale, A. Meyler, et al. 2006. Neural basis of dyslexia: a comparison between dyslexic and nondyslexic children equated for reading ability. *The Journal of Neuroscience* 26(42): 10700–10708.
15. Hoeft, F., A. Meyler, A. Hernandez, C. Juel, H. Taylor-Hill, J.L. Martindale, et al. 2007. Functional and morphometric brain dissociation between dyslexia and reading ability. *Proceedings of the National Academy of Sciences of the United States of America* 104(10): 4234–4239.
16. Shaywitz, B.A., S.E. Shaywitz, K.R. Pugh, W.E. Mencl, R.K. Fulbright, P. Skudlarski, et al. 2002. Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry* 52(2): 101–110.
17. Eden, G.F., K.M. Jones, K. Cappell, L. Gareau, F.B. Wood, T.A. Zeffiro, et al. 2004. Neural changes following remediation in adult developmental dyslexia. *Neuron* 44 (3): 411–422.
18. Shaywitz, B.A., S.E. Shaywitz, B.A. Blachman, K.R. Pugh, R.K. Fulbright, P. Skudlarski, et al. 2004. Development of left occipitotemporal systems for skilled reading in children after a phonologically- based intervention. *Biological Psychiatry* 55(9): 926–933.
19. Temple, E., G.K. Deutsch, R.A. Poldrack, S.L. Miller, P. Tallal, M.M. Merzenich, et al. 2003. Neural deficits in children with dyslexia ameliorated by behavioral remediation: evidence from functional MRI. *Proceedings of the National Academy of Sciences of the United States of America* 100(5): 2860–2865.
20. De Smedt, B., and L. Verschaffel. 2010. Travelling down the road from cognitive neuroscience to education.... and back. *ZDM The International Journal on Mathematics Education* 42: 49–65.

21. Molfese, D.L. 2000. Predicting dyslexia at 8 years of age using neonatal brain responses. *Brain and Language* 72(3): 238–245.
22. Froyen, D.J., M.L. Bonte, N. van Atteveldt, and L. Blomert. 2009. The long road to automation: neurocognitive development of letter-speech sound processing. *Journal of Cognitive Neuroscience* 21(3): 567–580.
23. Dehaene, S., Pegado, F., Braga, L.W., Ventura, P., Nunes Filho, G., Jobert, A., et al. How learning to read changes the cortical networks for vision and language. *Science* 330 (6009): 1359–1364.
24. Coch, D., G. Grossi, S. Coffey-Corina, P.J. Holcomb, and H.J. Neville. 2002. A developmental investigation of ERP auditory rhyming effects. *Developmental Science* 5(4): 467–489.
25. Nieder, A., and S. Dehaene. 2009. Representation of number in the brain. *Annual Review of Neuroscience* 32: 185–208.
26. Ansari, D. 2008. Effects of development and enculturation on number representation in the brain. *Nature Reviews. Neuroscience* 9(4): 278–291.
27. Brannon, E. 2006. The representation of numerical magnitude. *Current Opinion in Neurobiology* 16: 222–229.
28. Ashkenazi, S., N. Mark-Zigdon, and A. Henik. 2009. Numerical distance effect in developmental dyscalculia. *Cognitive Development* 24(4): 387–400.
29. Landerl, K., A. Bevan, and B. Butterworth. 2004. Developmental dyscalculia and basic numerical capacities: a study of 8-9-year-old students. *Cognition* 93(2): 99–125.
30. Mussolin, C., Mejias, S., and M. P. Noel. 2010. Symbolic and nonsymbolic number comparison in children with and without dyscalculia. *Cognition* 115(1): 10–25.
31. Mussolin, C., De Volder, A., Grandin, C., Schlogel, X., Nassogne, M.C., and M.P. Noel. 2009. Neural correlates of symbolic number comparison in developmental dyscalculia. *Journal of Cognitive Neuroscience.*
32. Price, G.R., I. Holloway, P. Rasanen, M. Vesterinen, and D. Ansari. 2007. Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology* 17(24): R1042–R1043.
33. De Smedt, B., L. Verschaffel, and P. Ghesquiere. 2009. The predictive value of numerical magnitude comparison for individual differences in mathematics achievement. *Journal of Experimental Child Psychology* 103(4): 469–479.
34. Halberda, J., M.M. Mazzocco, and L. Feigenson. 2008. Individual differences in non-verbal number acuity correlate with maths achievement. *Nature* 455(7213): 665–668.
35. Holloway, I.D., and D. Ansari. 2009. Mapping numerical magnitudes onto symbols: the numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology* 103(1): 17–29.
36. Mundy, E., and C.K. Gilmore. 2009. Children's mapping between symbolic and nonsymbolic representations of number. *Journal of Experimental Child Psychology* 103 (4): 490–502.
37. Wilson, A.J., S. Dehaene, P. Pinel, S.K. Revkin, L. Cohen, and D. Cohen. 2006. Principles underlying the design of "The Number Race", an adaptive computer game for remediation of dyscalculia. *Behavioral and Brain Functions* 2: 19.
38. Wilson, A.J., S.K. Revkin, D. Cohen, L. Cohen, and S. Dehaene. 2006. An open trial assessment of "The Number Race", an adaptive computer game for remediation of dyscalculia. *Behavioral and Brain Functions* 2(1): 20.
39. Butterworth, B. 2003. *Dyscalculia screener*. London: NFER Nelson Publishing Company Ltd.
40. Rivera, S.M., A.L. Reiss, M.A. Eckert, and V. Menon. 2005. Developmental changes in mental arithmetic: evidence for increased functional specialization in the left inferior parietal cortex. *Cerebral Cortex* 15(11): 1779–1790.
41. Zamarian, L., A. Ischebeck, and M. Delazer. 2009. Neuroscience of learning arithmetic-evidence from brain imaging studies. *Neuroscience and Biobehavioral Reviews* 33(6): 909–925.
42. Grabner, R.H., D. Ansari, K. Koschutnig, G. Reishofer, F. Ebner, and C. Neuper. 2009. To retrieve or to calculate? Left angular gyrus mediates the retrieval of arithmetic facts during problem solving. *Neuropsychologia* 47(2): 604–608.
43. De Smedt, B., Holloway, I. D., & D. Ansari. (in press) Effects of problem size and arithmetic operation on brain activation during calculation in children with varying levels of arithmetical fluency. *Neuroimage*. doi:10.1016/j.neuroimage.2010.12.037
44. Kirk, E.P., and M.H. Ashcraft. 2001. Telling stories: the perils and promise of using verbal reports to study math strategies. *Journal of Experimental Psychology. Learning, Memory, and Cognition* 27(1): 157–175.
45. Grabner, R.H., and B. De Smedt. 2011. Neurophysiological evidence for the validity of verbal strategy reports in mental arithmetic. *Biological Psychology* 87 (1): 128–136.
46. Lee, K., Z.Y. Lim, S.H. Yeong, S.F. Ng, V. Venkatraman, and M.W. Chee. 2007. Strategic differences in algebraic problem solving: neuroanatomical correlates. *Brain Research* 1155: 163–171.
47. Klingberg, T. 2010. Training and plasticity of working memory. *Trends in Cognitive Sciences* 14(7), 317–324.
48. Olesen, P.J., H. Westerberg, and T. Klingberg. 2004. Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience* 7(1): 75–79.
49. Holmes, J., S.E. Gathercole, and D.L. Dunning. 2009. Adaptive training leads to sustained enhancement of poor working memory in children. *Developmental Science* 12(4): F9–F15.
50. Owen, A.M., A. Hampshire, J. Grahn, R. Stenton, S. Dajani, A.S. Burns, R.J. Howard, and C.G. Ballard. 2010. Putting brain training to the test. *Nature* 465: 775–778.
51. Jaeggi, S.M., M. Buschkuehl, J. Jonides, and W.J. Perrig. 2008. Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences* 105: 6829–6833.
52. Hillman, C.H., K.I. Erickson, and A.F. Kramer. 2008. Be smart, exercise your heart: exercise effects on brain and cognition. *Nature Reviews. Neuroscience* 9(1): 58–65.
53. Casey, B.J., Duhoux, S., and M. Malter Cohen. 2010. Adolescence: what do transmission, transition, and translation have to do with it? *Neuron* 67(5): 749–760.
54. Steinberg, L. 2009. Should the science of adolescent brain development inform public policy? *The American Psychologist* 64(8): 739–750.
55. Hackman, D.A., Farah, M.J., and M.J. Meaney. 2010. Socioeconomic status and the brain: mechanistic insights

from human and animal research. *Nature Reviews. Neuroscience* 11(9): 651–659.

56. Mangels, J.A., B. Butterfield, J. Lamb, C. Good, and C. S. Dweck. 2006. Why do beliefs about intelligence influence learning success? A social cognitive neuroscience model. *Social Cognitive and Affective Neuroscience* 1(2): 75–86.
57. Ansari, D. 2005. Time to use neuroscience findings in teacher training. *Nature* 437(7055): 26.
58. Ansari, D., and D. Coch. 2006. Bridges over troubled waters: education and cognitive neuroscience. *Trends in Cognitive Sciences* 10(4): 146–151.
59. Stern, E. 2005. Pedagogy meets neuroscience. *Science* 310: 745.
60. Pashler, H., M. McDaniel, D. Rohrer, and R. Bjork. 2008. Learning styles: Concepts and evidence. *Psychological Science in the Public Interest* 9(3): 105–119.
61. Goswami, U. 2006. Neuroscience and education: from research to practice? *Nature Reviews. Neuroscience* 7(5): 406–411.
62. Szucs, D., and U. Goswami. 2007. Educational neuroscience: Defining a new discipline for the study of mental representations. *Mind, Brain and Education* 1(3): 114–127.
63. Habadzi, H. 2006. *Efficient learning for the poor: insights from the frontier of cognitive neuroscience*. Washington: The World Bank.
64. Condliffe Lagemann, E. 2000. *An elusive science: the troubling history of education research*. Chicago: University of Chicago Press.