Educational Neurosciences – More problems than promise?

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Introduction

In recent years, new research methods have led to amazing progress in our understanding of the biological basis of human cognition and learning. In year 2011, on average more than two scientific articles that used results from functional magnetic resonance imaging (fMRI) on human brain were published every day. There are now over 100 000 fMRI brain studies available in the US PubMed database. Functional MRI and other imaging techniques have allowed researchers to look inside the living brain, creating fascinating and colorful images that locate regions of activity associated with specific cognitive tasks, as well as reveal structural differences among individual brains. Detailed understanding of the biochemistry of brain develops at rapid pace and new tools such as DNA microarrays that can reveal the expression of millions of genes in parallel will lead to new important insights about normal and abnormal functioning of the brain. At the same time, single-neuron studies using intra-cellular recording, pharmacological interventions, and, for example, laser scanning microscopy, have provided detailed information about the nature and functions of neurons, both in test tubes and in living organisms. Combined with behavioral research, these studies have greatly improved our understanding of the basic processes that underlie capabilities such as numeracy, literacy, attention, memory, and social interaction.

Partly because of this abundant flow of new research results, there has been great interest in the possibility to improve learning and education using brain research. As we are moving towards a knowledge-intensive network society and innovation-based economy, life-long learning is becoming a basic requirement for employability and social participation. Consultants are now promoting "brain-based education," and also policy-makers have been attracted to the idea that education could be science-based, with the understanding that much of the relevant science would be natural science.

According to the proponents of brain-based education, the brain is intimately involved in and connected with everything educators and students do at school. For example, Jensen (2008) and others (e.g.,Pasquinelli, 2011) argue that educators should ask whether their educational strategies and approaches are based on "solid research from brain-related disciplines," or based on myths, a well-meaning mentor teaching, or 'junk science'. For Jensen the brain is involved with everything, and sociology and psychology, among other disciplines, are brain-based. According to Jensen, to argue differently would be "absurd, because if you remove the brain's role from any of those disciplines, there would be no discipline."

A brief review of sociological literature would, of course, reveal that sociologists have extensively theorized about knowledge, memory, cognition and learning during the last two centuries. In general, sociologists, however, have managed quite well without explicit references to neurons and brains. Many sociologists have explicitly argued that sociological phenomena, including the accumulation and creation of knowledge, cannot be reduced to individual behavior. Although individuals provide a substrate for social phenomena to exist, and brains are a part of this substrate, many sociologists would find naïve the idea that social phenomena could be reduced to individual behavior, brains, neurons, or their constituent atoms. In a similar fashion, the history of psychology is also marked with frequent and intense debates about the possibility of linking behavior and biology, and some of the most influential theories of human learning, indeed, are based on the claim that this is not possible.

It is clear that brain-based models are often interesting, important and useful, and we will discuss such cases below. The conclusion will be that there are good reasons to move towards “brain-informed” theories of learning that eventually can be used to develop new teaching and educational practices. Brain-informed theories of learning, however, do not equal “brain-based” theories, where neuroscience would provide a “foundation” for theory. There are good reasons why reductionistic models do not work in sociology, psychology or biology, as Robert Rosen (e.g. 1991) argued throughout his career. As highlighted below, one of the most important empirical results of recent brain studies has been the observation that the fundamental requirement that underlies computational models of human information processing, the separation between hardware and software, breaks down. This observation has profound consequences that will shape theories of cognition in the decades to come. The human brain is not a computational system, and it can not be modeled as an information processing machine. “Brain-based” theory of cognition thus may well be a contradiction in terms, at least if the brain is understood as a network of elementary logical units that shift bits from one pile to another.

Educational neuroscience and the broader brain-based Mind, Brain and Education (MBE) movements have struggled in the last decade with the challenge of bridging the very different epistemic and pragmatic concerns of neuroscience and education. It has often been claimed that educational neuroscience needs to evolve to a transdisciplinary field and find new ways to communicate across disciplinary boundaries (e.g., Ansari & Coch, 2006; Della Chiesa, Christoph, & Hinton, 2009; Fischer, 2009; Gardner, 2009; Perkins, 2009; Samuels, 2009). Sometimes the proponents contrast learning science, speculation and traditional beliefs in a somewhat Anglo-American perspective, where natural sciences provide the basic research and “scientific evidence” (e.g., National Research Council, 2000), and where the empirical facts of neuroscience provide the foundation for education in a similar way as biochemistry provides the foundation for medicine (Fischer et al., 2007). In this context, it may sometimes appear that educationalists are inadequately aware of science and too deeply embedded in their current practices, and that this explains their resistance to change and new knowledge. On the other hand, there seems to be too little resistance, and the proponents of educational neuroscience worry about exaggerated claims and hasty interpretations of research outcomes. Brain research has its own substantial collection of popular "neuromyths," and laboratory results are often quickly extended to educational contexts (Bruer, 2006; Lindell & Kidd, 2011; Pasquinelli, 2012).

OECD's influential "Brain and Learning" project, which run from 1999 to 2006, dispelled several of these neuromyths, at the same time arguing that it is essential for educators and everyone concerned with education to gain an understanding of the scientific basis of learning processes. The authors of the OECD report interpreted the scientific basis as the neural base, and asked whether "it is acceptable, in any reflection about education, not to take into consideration what is known about the learning brain." (OECD, 2007, p. 28)

This is actually a very complex question, both in theory and in practice. Whereas OECD asked whether it would be ethical to ignore the results of neuroscience, apparently adopting a rather straightforward linear model of scientific progress, and a theory of ethics that would require omniscience, a more pragmatic approach has been suggested by researchers who highlight the necessity of interdisciplinary research. As Varma et al. (2008, p. 148) point out:

> "Neuroscientists are unlikely to plow through hundreds of education articles. So, without collaboration, neuroscientists are at risk of running naïve experiments informed by their personal experiences of how children come to learn content area skills and knowledge."

Bruer, a long-time critic of brain-based education, has pointed out that many key outcomes of neurocognitive studies simply corroborate earlier psychological research, and make sense only in a context provided by cognitive theories (Bruer, 2006). Several recent popular books and an increasing number of brain-based education consultants have promoted the application of neuroscience to educational context in somewhat uncritical way. On the other hand, there is, indeed, a large trove of new experimental results that could have important implications for research on learning. In some cases they generate new research questions and provide starting points for new theories. In others, they invite us to reconsider old theories and instructional approaches. In yet other cases, they allow us to ask fundamental questions about theoretical foundations that underlie neuroscience and neurocognitive research. We shall discuss all these below.

The brain is involved in everything we do and think. This paper explores the question about how this involvement should be conceptualized and how we could understand the neural basis of learning. Below we review some key results from research on neural and cognitive studies that have potential relevance for education and learning. The paper then puts these results in broader historical and theoretical perspectives.

This is a “think piece” that aims at provoking some fundamental questions about the potential and prospects of educational neuroscience and future of learning sciences. The main conclusion is that educational neuroscientists need to reconsider some of their key assumptions, but there are already important advances that should to be taken into account in educational practice, in particular in supporting children that have difficulties in learning.

The promise of educational neurosciences

Educational neurosciences span a wide array of evolving conceptual frameworks. Many of the scientific claims that underlie it make most sense in a historical context where cognitivistic ideas dominate. It is therefore useful to briefly lay out this context.

In 1943, inspired by the mechanization of logic by Turing, Warren McCulloch and Walter Pitts proposed to model neurons as simple interconnected logical elements, suggesting that the brain is a mechanism that computes logical inferences. Hebb's associationistic learning model, where learning was interpreted as enforcement of synaptic connections between neurons that fire simultaneously, was appropriated by Rosenblatt, who in 1957 produced the Perceptron neural network model, which gained wide interest in the emerging artificial intelligence community. This interest waned when Minsky and Papert showed in 1969 that single-layer perceptrons cannot compute the logical XOR function, and therefore cannot be the universal logical machines described by Turing. Partly through Papert's influence, the Piagetian constructivist ideas then became dominant in research on artificial intelligence, leading to a tight interaction between the emerging cognitive science and computer-based studies of mind and brain.

The resulting “classical” cognitive science is characterized by two key ideas. First, the neural system is understood to be an information processing mechanism. Second, the processing operates on structures that “represent” the inner and outer world. In artificial intelligence research, this was accompanied by a move away from models that tried to program universal algorithms of problem solving and learning towards models that were based on explicit representation of knowledge structures.

Towards the end of the 1980s, the relatively modest successes of implementing cognitive capabilities using computers and the increasing availability of computer processing power led to a resurgence of research on artificial neural networks. It was shown that multi-layer perceptrons can avoid the problems highlighted by Minsky and Papert, and several alternative models of neural networks gained visibility. Beyond the old framework of logical machines, these included distributed, adaptive, and self-organizing networks, as well as physical and statistical models of biological neural networks.

These developments have been closely associated with advances in computing technologies and they have contributed to the idea that cognitive functions and representations are implemented with neural networks. Although it is understood that neurons cannot in any simple way be reduced to binary logical elements, the idea that the brain is an information processing mechanism that consists of specialized functional units is now so widely spread that it is often assumed to be trivially true.

In this framework, cognitive differences are expressed through structural differences in network connectivity. In this context, the scientific study of human thinking, perception, and action, therefore, to a large extent equals the study of neural structures. At the most macro-level, the studies focus on regional localization of the functions of the brain, the connections between functional regions, and the processing tasks accomplished. At the micro-level, the studies focus on connections between neurons and the factors that influence connectivity, including synaptic structures and biochemical and genetic factors that influence neural signaling and cellular growth.

In recent years, the rapidly increasing processing power of computers has been combined with new research instruments, leading to a veritable explosion of brain-related research, both at the macro and micro levels. In particular, functional magnetic resonance imaging has been used extensively to study the functions and representations in the human brain. The number of fMRI related studies on human brain is shown in Figure 1. In fMRI, changes in neural activity can be detected by observing changes in the blood flow of oxygen, assumed to be correlated with the energy use of the cells. The spatial resolution in typical fMRI studies can be as small as one cubic millimeter, and the changes in oxygen consumption can be measured at about 1 second intervals. fMRI aggregates data over many neurons and does not differentiate between inhibitory and excitatory activity. Due to the relatively slow response time of changes in oxygen consumption, fMRI is not able to detect rapid changes and is therefore sometimes complemented with EEG measurements.

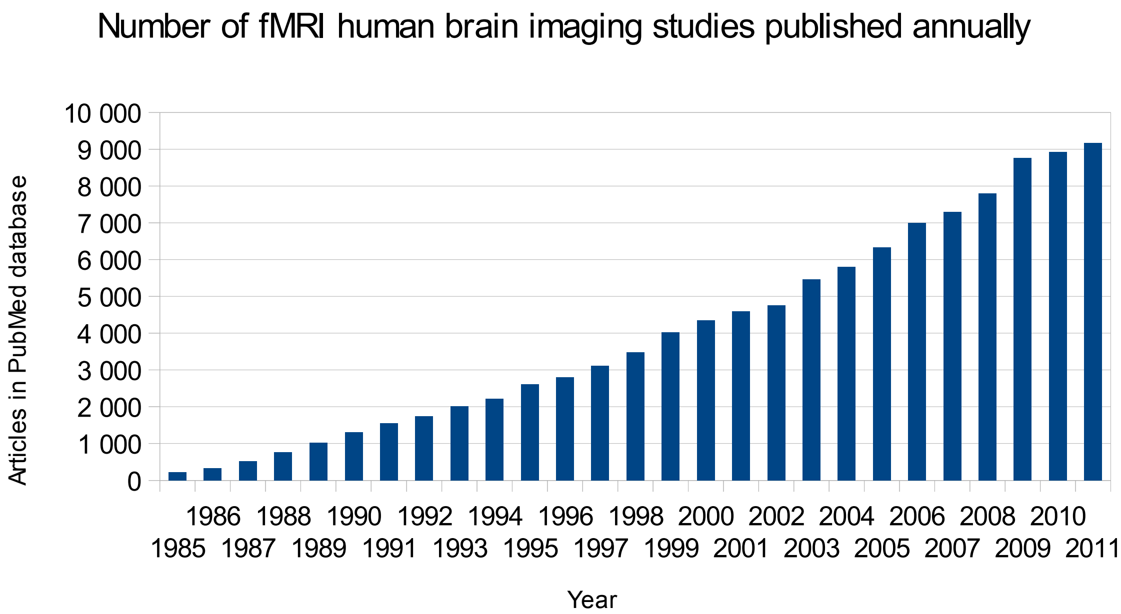

Figure 1: Functional magnetic resonance imaging studies on human brain, 1985-2011.

Indeed, much has been learned about neural structures and the dynamics of neural activity and change in the last two decades. As was pointed out above, one of the main results may well be that we need to rethink some basic assumptions of neuroscience and cognitive sciences, including concepts such as localization, computation and cognitive representations. For the time being, however, a large majority of research and writing on educational neuroscience operates under the theoretical frameworks of classical cognitive science. Empirical brain research, however, can also be read to tell a story in which something much more interesting is emerging, with a potential to change our views on both brains and learning.

Below we briefly review some major observations that have been claimed to be of importance for education and learning.

Synaptogenesis and neural plasticity

The brain is an incredibly complex organ with probably over 80 billion ($80x10^9$) neurons[1], each with on average maybe 7 000 synapses. Already the pioneer of neuroscience, Ramón y Cajal, suggested that learning and memory may result from changes in synaptic connections between neurons, and that memories may be formed by strengthening the connections between neurons. This idea underlies the Hebbian theory of learning. Since the 1970s it has been known that there are long-lasting activity-dependent changes in synaptic strength, known as long-term potentiation (LTP) and long-term depression (LTD), and other forms of synaptic plasticity, which now are commonly believed to provide an important basis for memory and learning.

Synaptic plasticity is now known to be only one form of neural plasticity. Until the 1980s, the general consensus was that no new neurons are generated in the human brain, although the brain may rewire its neuronal connections and relocate its functions. Today it is known that new neurons, new connections, and also new synapses are continuously being created in the human brain.

Experience-dependent plasticity is most clearly visible in the early phases of development, during critical periods. Well-known classical studies showed that the alteration and deprivation of sensory input, for example by rearing kittens in a restricted sensory environment, had clear effects on the neural structures, but only if this occurred in a specific stage of development. Critical periods of neural development have been shown to exist in virtually all species. In the visual system, the effects of monocular deprivation and the existence of critical periods has been characterized in the monkey, cat, rat, mouse, ferret and human. In the auditory system, the most studied critical period is associated with the calibration of the auditory space map by visual input. There have also been some studies on the effects of increased sensory experience. For example, it has been shown that musical training in infancy leads to an expanded auditory cortical representation, but only if practicing begins before the age of 9 (Pantev et al., 1998). It has also been shown that already brief access to sensory experience may have major effects in development. For example, in dark rearing experiments with cats, even a brief exposure to light can trigger the process of visual development (cf. Lewis & Maurer, 2005).

The classical studies on critical periods of experience-dependent plasticity focused on early postnatal development. For example, the critical period for stereoscopic vision seems to extend to about 60-80 months in humans, although it is also known that lack of sensory input can lead to the extension of critical periods. As it is now known that critical periods do not have sharp time windows, they are also called sensitive periods. Studies have also shown, for example, that there are multiple sensitive periods in the development of vision during which sensory input is required, and that there can be multiple mechanisms

1 Recent studies have reduced the the total number of neurons in the human brain below the somewhat apocryphal 100 billion frequently mentioned in literature. Also the number of glia cells is now estimated to be about 85 billion, less than ten times the commonly used figure of one trillion that apparently originated from Hubel's Nobel lecture. Most interestingly, it seems that the human cerebral cortex has only about 16 billion neurons, whereas the cerebellum seems to have 69 billion neurons (Lent, Azevedo, Andrade-Moraes, & Pinto, 2012).

underlying these. Whereas the classical studies focused on the period where normal development occurs, abnormal input can have a permanent deleterious effect also after the period of normal development is over. Lewis and Maurer (2005) called these the ”sensitive periods for damage,” and showed that visual deprivation up to 10 years of age leads to a permanent deficit in visual acuity. Research has also indicated that it may be possible to control and extend the timing of sensitive periods, for example, by genetic manipulation of a single molecule known as BDNF or the brain-derived neurotrophic factor (Berardi, Pizzorusso, & Maffei, 2000; Hooks & Chen, 2007).

More recently, it has been noted that experience-dependent plasticity occurs also in adults. For example, studies on asymmetric vision and functional blindness in the abnormal eye have shown that the visual system has plasticity beyond the critical period. In a widely popularized study that used structural MRI to measure the differences between brains of London taxi-drivers and a control group, it was shown that the size of hippocampus correlated with the amount of time spent as a taxi driver (Maguire et al., 2000). The posterior hippocampus, commonly associated with spatial navigation, was enlarged, whereas the anterior hippocampus was smaller than in the control group. The researchers concluded that there is a capacity for local plastic change in the structure of the healthy adult human brain in response to environmental demands.

The shape and size of the brain thus depends on its use. A recent study of the structure of Einstein's brain showed, for example, an unusually large “knob” in the right hemisphere, in an area known as the “sign of omega” that represents motor representation of the left hand (Falk, Lepore, & Noe, 2012). This feature has been seen also in the brains of other long-time right-handed violinists.

It is now known that adult brains continuously create new neurons (Gage, 2002), and there is substantial research on the “critical periods” during which these newly generated neurons can become functional parts of the neural system (Ge, Yang, Hsu, Ming, & Song, 2007). It has been proposed that these newly generated neurons play an important role in memory (Aasebø, Blankvoort, & Tashiro, 2011; Kempermann, 2002). Neurogenesis may also be important for continuous adaptation and renewal in adult brains. Castrén ((2005), for example, has suggested that the delayed effects of antidepressants and recent studies that show that antidepressants induce neurogenesis indicate that they may function by increasing the generation of new neurons that rewire the brain. The “chemical hypothesis” of depression should therefore be replaced by a structural information processing model, where neural plasticity has a central role.

The problem of mouse-based education

The research on neural plasticity has shown that the brain changes both its physical structures and functionality as a result of its use. The brain is not simply a repository for knowledge; instead, learning shapes both the brain and its cognitive capabilities, thus changing the possibilities for further learning. It may eventually be possible to influence the conditions for learning and memory by intervening with the basic neuronal and chemical processes in the brain.

For example, recent research on human subjects indicate that orally administered D-cycloserine (DCS), an antibiotic effective against *Mycobacterium tuberculosis*, may enhance procedural, declarative, and emotional learning (Kuriyama, Honma, Koyama, & Kim, 2011; Onur et al., 2010).

Such research, then, rises the question to what extent this research is about the scientific basis of learning. A quick answer is that, of course, the neural foundations for learning are important. On a closer look, however, the answer is more complicated and important for understanding the potential of educational neuroscience. We can illustrate this by comparing, for example, the experimental setup used by Onur et al. (2010) with Vygotsky's model of conceptual development (1998, 1999; Vygotsky, 1986).

Onur et al. found in their randomized controlled trial with forty healthy volunteers that DCS facilitates declarative learning and increases activity in hippocampus. In their item-categorization task, the subjects had to make push-button responses to judge the category membership A or B of three-digit numerical items presented repeatedly on screen. Subjects were informed that there was no underlying rule defining which item belonged to which category, and the categories were generated by a random algorithm. Once assigned, category membership remained constant over six presentations. At each presentation, a gray dot visible to the subject changed to red if the category guess was wrong, and green if the guess was right. Functional MRI was used to detect changes in oxygen-dependent activity in different areas of brain.

A somewhat similar categorization task underlies Vygotsky's theory of conceptual development. This experimental arrangement was originally described by Lev Sakharov, a student of Vygotsky, in 1928 (Sakharov, 1994). Vygotsky used it to explain cognitive development, and it also underlies his theories about the nature of advanced forms of human cognition, which today provide the foundation for many influential learning theories. A brief description on this experiment highlights a fundamental challenge for educational neuroscience.

The Sakharov test uses 22 wooden blocks varying in color, shape, height, and size. On the underside of each figure, which is not seen by the subject, is written one of the four nonsense words: lag, bik, mur, cev.[2] Regardless of color or shape, lag is written on all tall large figures, bik on all flat large figures, mur on the tall small ones, and cev on the flat small ones. The examiner turns up a sample, shows and reads its name to the subject, and asks the subject to pick out all the blocks which the subject thinks might belong to the same kind. After the subject has done so, the examiner turns up one of the “wrongly” selected blocks, shows that this block has a different word written at its bottom, and encourages the subject to make a new try. After some trial and error the subject learns to group all the blocks according to the name on their bottom.

Vygotsky used this setup to study the forms of conceptual thinking in the different stages of child development. He observed that a young child first puts blocks in “heaps” based on their closeness in the visual field. In later developmental stages, the basis for categorizing

2 The original version of Sakharov experiment differs in detail from this description based on Hanfmann & Kasanin (1942).

the blocks changes, in a complex process where the continually evolving forms of abstraction and generalization interact. A schematic picture of this process of conceptual development is depicted in Figure 2.

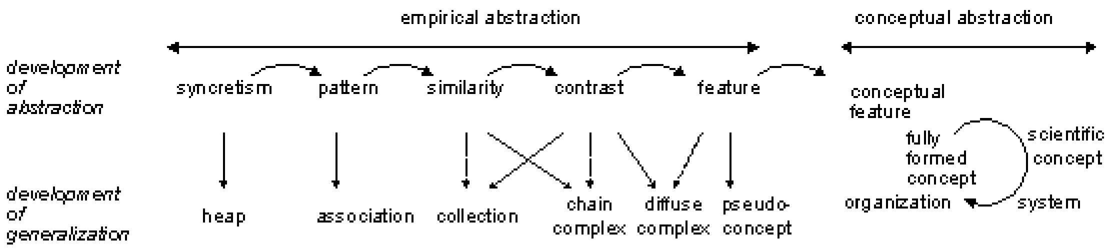

Figure 2: A model of Vygotskian theory on development of conceptual thinking (Tuomi, 1998).

Vygotsky's main claim was that fully developed adults use categories and concepts that are products of cultural and historical development, and that children develop their cognitive capabilities with the support of adults who already use these cultural-historical concepts in their thinking. Thus, whereas the early phases of cognitive development are similar in, for example, apes and humans, the more advanced forms of human thinking are unique to humans, who are able to use language and historically accumulated conceptual systems in their cognitive processes (Luria & Vygotsky, 1992).

A basic question for educational neuroscience is then to what extent it can inform us about human learning. Whereas the neural basis for plasticity and non-plasticity may be the same in mice, cats, apes and men, in the Vygotskian framework perfect knowledge about this neural basis would say very little about the uniquely human forms of learning and memory.

Vygotsky developed his basic insights on human cognition as a response to what he saw as a “crisis in psychology.” In contrast to Pavlovian and other forms of reflexology that dominated the Soviet psychological scene in the 1920s, Vygotsky pointed out the “semiotic” character of advanced forms of human cognition. Human cognition does not react to externally observable stimuli. Instead, it “reacts” to the meaning of signals. A crucial point, missed by reflexology and behaviorism, is that there is no causal link between an observable stimulus and its meaning. Perception is mediated by concepts that are accumulated products of historical and cultural evolution. In the Vygotskian framework, cognition is oriented towards action and it is mediated by tools and cognitive artifacts. Meaning is thus an essentially social and cultural phenomenon, and the uniquely human forms of advanced cognition need to be studied in a developmental, historical, and social context.

To the extent that the biochemical, genetic and structural principles of neural functioning are “universal” and the same with mice and men, studies on these principles can therefore only reveal similarities between mice and men. For example, the experimental study by Onur et al. could relatively easily be repeated by mice, as it remains somewhere around the first two stages of conceptual development shown in Figure 2. It may therefore capture similarities in the learning and decision-making processes among men and mice, but it does not necessarily address learning processes that are more characteristic for humans.

This problem could be called “the challenge of antireduction.” Vygotsky's claim was that you cannot explain advanced mental functions in humans by starting from “more basic” principles that are sufficient for understanding apes or cats. Those mental functions that we call “higher mental functions” are exactly those mental functions that mice do not possess. The “scientific foundation” of psychology thus cannot in any straightforward way be found from the neural basis of cognition, or revealed through experiments with rats. The “learning” that is the object of study in low-level neural studies is a different phenomenon from the “learning” that most educationalists understand as their object of study.

Chemical cognitive enhancers such as DCS are easily popularized as “memory pills” that students should digest while preparing for final examinations. Their consumption could be more limited if they were marketed as “mouse-learning pills.” Whether and when “mouse-learning” is useful for humans cannot be answered without putting these low-level processes in a higher-level context. Here fMRI studies have provided important new insights. These are discussed in the next section.

Dyslexia, mathematics, and mirrors in the brain

In general, a “science-based” study of human forms of learning requires rather sophisticated methodological frameworks and theoretical approaches. It is, however, possible to avoid many of these theoretical challenges when the object of study, in fact, is on a level that is shared by mice and men. Even when we assume that the advanced forms of human cognition cannot be reduced to those forms that are shared by animals and humans, it is clear that problems in the neuronal basis of cognition are reflected also in the advanced forms of cognition. In several important cases, neuroscience is able to show how learning can go wrong. Perhaps among the most influential lines of research for brain-based education have therefore been studies on learning disabilities and disorders, including dyslexia and dyscalculia.

Although large bodies of behavioral research on the nature of dyslexia have existed for several decades, recent brain-based studies have provided some important novel insights. The practical implications of these studies are large also for education, as it is estimated that up to every tenth person may suffer from dyslexia.[3]

Recent imaging studies have corroborated the earlier suggestions from behavioral studies that dyslexic persons have structural and functional differences in their brains, compared to persons with normal reading skills. These studies have promoted the idea that dyslexia has neurological origins. Shaywitz et al.(2006), for example, found that good readers show a consistent pattern of strong activation in the back of the brain with weaker activation in the front of the brain during reading tasks. Dyslexics, in contrast, showed the opposite pattern. An important observation, supported by brain imaging studies, has been that reading

3 As pointed out by the EU High Level Group of Experts on Literacy (September 2012) there are very many different definitions of dyslexia and partly because of this the estimates of its vary between 4-10 percent.

depends on auditory processing, and that languages with different ortographic characteristics produce different difficulties for dyslexics.

As the understanding of text seems to depend on translating written text to speech, and in some languages this translation is simpler than in others, it has been assumed that the prevalence of dyslexia varies between languages. Languages with “shallow” alphabetic ortography, such as Spanish, Italian and Finnish, have relatively simple mappings from the alphabetic representation of words to their auditory representation. In Finnish, for example, each letter maps to a single phoneme, and words are read in the same way as they are written. Languages with “deep” ortography, such as French and English, in contrast, have complex mappings. Modern English, for example, blends Old English, French and German, each with different rules, and the way in which the words are transliterated is also influenced by the errors made by early Dutch printers. As Cathy Davidson has pointed out, the child who learns to read English “phonetically” has to filter out a lot of irregularity and even more dissonance between the written and the spoken language:

> “Sound it out!” the teacher says. Right. Think about it. Look at this short paragraph and think about consistent rules for sounding out just about anything here.”[4]

English, indeed, is a deviant among alphabetic writing systems. The most transparent writing systems have about 20-40 letter-sound connections. In English, the number of consistent connections between written and spoken language units is close to 2000, and there are a large number of exception words which cannot be pronounced by relating letters to sounds (Lyytinen, Erskine, Kujala, Ojanen, & Richardson, 2009).

The realization that dyslexia may be linked to the peculiarities of alphabetic languages that have deep ortography has led to the question whether dyslexia is predominantly a problem in English-speaking countries. This does not seem to be the case. Paulescu et al. (2001) used positron emission tomography scans to show that Italian dyslexics performed better than English and French dyslexics. However, all dyslexics performed worse than their control groups in reading and phonological tasks. As a result, they concluded that there is a common neurocognitive basis for dyslexia. More recently, fMRI studies of Chinese and English dyslexics have shown similar results (e.g., Hu et al., 2010). Although reading Chinese and English activates very different areas of brain in fluent readers, these cultural differences were not observed in Chinese and English dyslexics. Dyslexics apparently use similar ineffective strategies for reading.

At the same time these studies show that, indeed, reading requires very different cognitive functions in different cultures. Earlier studies have also shown that literate and non-literate people have different brain structures. It is therefore quite clear that the structures and functioning of brain depends on both cultural influences and the use of brains. Education thus not only transfers knowledge into the receiving minds; it actually changes the capabilities of brains.

Developmental dyslexia has been shown to have genetic markers and it can be detected in the event-related responses newborn infants. Most importantly, it has been shown that

4 Davidson, C. (2008) Dyslexia differs by language: Think again! http://hastac.org/node/1294

dyslexia can be mitigated by early educational interventions and training. Lyytinen and his colleagues at the Jyväskylä Longitudinal study of Dyslexia have been pioneers in this area since the 1990s, and their computer-based Ekapeli, also known as Graphogame and Literate (e.g., Lyytinen, Ronimus, Alanko, Poikkeus, & Taanila, 2007), is now widely used for preventive training with children who are at risk of failing to acquire reading skill at a normal rate.

Learning mathematics

Towards the end of the 1990s, Dehaene (1999) popularized the idea that mathematical thinking has a neural basis and that spatial and mathematical processing are closely related in the human brain. A large number of studies have researched the ways in which numbers and magnitudes are represented and processed in the brain. It is now generally accepted that numerical understanding is not limited to numerate adults and that also infants and animals are able to process non-symbolic numerical magnitudes. Butterworth (2000) argued that the brain has non-symbolic core numeric representations that provide the foundation for mathematical processing, and studies with monkeys have, indeed, revealed that there are specific neurons that respond to specific numbers (Nieder & Miller, 2004). Dehaene and his colleagues (Dehaene, Izard, Spelke, & Pica, 2008) have also shown that education seems to change the spatial representation of quantities. For young children and Mundurucu, an indigenous Amazon group with little formal education, the spatial mapping of quantities is logarithmic, whereas for educated adults smaller quantities are mapped to a linear space. Furthermore, Dehaene and others have argued that there is a single representational system for magnitudes that is independent of the modality and format of the magnitude, so that, for example, Arabic numbers, collections of visual dots, and sequences of auditory clicks are mapped to the same underlying number system.

The idea that a single mechanism underlies numerical cognition has also led to education and rehabilitation programs and interventions that, for example, aim at helping children with dyscalculia. It has been assumed that training on non-symbolic numerosity will improve the number computation with digits. This idea, however, has recently been questioned by Cohen Kadosh et al. (2011), who used fMRI to test whether numeric magnitudes, indeed, are represented independent of their format. Their study indicates that this is not the case, suggesting that developmental dyscalculia may need interventions that are specific to the format, for example, Arabic digits.

It has also been shown that native Chinese speakers and native English speakers use different parts of their brain when doing mental calculations. This is interesting because, in mathematics, Chinese and English speakers use Arabic numbers in a system that is shared across cultures. Using fMRI to study native Chinese and English speakers engaged in mental computations, Tang et al. (2006) showed that arithmetic tasks seem to require language processing, whereas comparison tasks less so. Language, culture, and education can, thus, influence the ways in which people process numbers.

Chinese characters are composed of strokes and subcharacters, and native Chinese speakers learn to write by copying samples of characters, establishing linkages among orthographic, phonological and semantic content. Recent studies have shown that humans parse mathematical expressions in a highly non-linear way, where the "syntax" of mathematical expressions is extracted by focusing on mathematically meaningful clusters of symbols (Schneider, Maruyama, Dehaene, & Sigman, 2012). The system of Chinese writing may thus develop skills that are also useful for mathematical understanding, and the brevity of Chinese language for numbers may also facilitate better use of short-term memory in mathematical processing (Tang et al., 2006). In general, Chinese speakers seem to benefit from good visual capabilities for mathematical processing, and this may partly be reflected in the wide use of abacus in many Asian schools.

The basic claim of Dehaene has been that "the mapping of numbers onto space plays and essential role in mathematics, from measurement and geometry to the study of irrational numbers, Cartesian coordinates, the real number line, and the complex plane" (Dehaene et al., 2008, p. 1217). This claim suggests that spatial skills could be important for mathematics. It might, for example, be possible to improve mathematical processing by learning to dance or by playing football.

The idea that we have basic non-symbolic numeric capabilities that map quantities onto space and provide the foundation for mathematical thinking can, however, be questioned on at least two accounts. First, it is not clear that non-symbolic numeric skills are related to mathematics. Numbers gain meaning in a cultural system that facilitates interpersonal communication of quantities. Second, biologically space and relative magnitudes are primary categories grounded in an organism's capability to move and act in its environment. Historically, Cartesian coordinates have been used to map space into numbers, and not vice versa. The concept of number may thus be a high-level abstraction that has little relevance for elementary neural and cognitive processes.

In fact, one of the early pioneers of neuroscience, Warren McCulloch gave in 1960 an insightful talk entitled "What Is a Number, that a Man May Know It, and a Man, that He May Know a Number?" In it, and long before brain imaging was known, he pointed out that numbers 1 to 6 are natural numbers, shared with the beasts (McCulloch, 1988). McCulloch had shown with Walter Pitts that a combination of spiking and not-spiking neurons can form networks that are equal to any possible logical machine, and that, due to equivalence of mathematics and logic, the human brain is, indeed, able to understand mathematics. McCulloch and Pitts extended this argument in a paper published in 1947, entitled "How We Know Universals." The argument was purely logical, but one may loosely extrapolate it to claim that it is possible to use fMRI to highlight areas in the brain that become active when people process problems that deal with, for example, eternity, infinity, immortality, and space, itself. This, of course, does not necessarily imply that we would have located the representations of these concepts in the studied brain; more probably, these concepts represent the way in which the researcher and his or her brain views the world. I will return to the relevance of this possibility for educational neuroscience towards the end of this paper.

The idea that the brain maps and represents universals, including non-symbolic numbers, may be wrong for many reasons. This, of course, does not mean that neuroscientific studies on mathematical processing would be irrelevant for education. For example, it would be educationally important if neuroimaging studies would indicate that specific types of mathematical problems require spatial, musical, linguistic, emotional or premotor processing. In fact, the importance of emotional capabilities has been well illustrated by Immordino-Yang in her studies on two high-performing hemispherectomized boys and in her subsequent analysis of these cases (Immordino-Yang & Damasio, 2007; Immordino-Yang, 2007, 2008). Humans are able to compensate massive damage in their brains, but they do this to a large extent by mobilizing capabilities that are available to them. For a person with only the right side of the brain remaining, a mathematical challenge or text understanding may be a problem of syntax, whereas for a person with the right side of brain remaining it may be an emotional and social problem. Yet both may solve the problem with closely similar outcomes. For people who still have both sides of their brains remaining, both the way the learner constructs the problem and the way in which she goes on solving it may involve many interacting functional capabilities. Brain imaging studies, for example, show that there are cognitively many different languages and probably many different mathematics withing the totality of the current system of mathematics. Finger counting is a different thing from algebra. We can keep on counting fingers as long as we want, but that will not move us to the world of mathematics.

Mirror neurons and social capabilities

One of the most conceptually intriguing lines of research in neuroscience in recent years has focused on mirror neurons. It was first shown that monkeys have neurons in the premotor areas that become active not only when the monkey performs a motor act, but also when it perceives others performing a similar act. These “mirror neurons” fire when the monkey observes another monkey to perform the act, for example, grasping, or tearing a piece of paper, or when it observes a human to perform the same act. Furthermore, it has been shown that mirror neurons seem to respond to action at high-levels of abstraction. For example, they respond regardless of the whether grasping is done using right or left hand or the mouth, and also when grasping is done using tools (cf. Bonini & Ferrari, 2011). These studies have suggested that the human brain mirrors the observed actions of others using their own motor knowledge, and that this mirroring occurs at the level of goals of action. This, indeed, is a radical suggestion, as it implies that our neuronal system mirrors the behavior of others at levels that are not observable, but which already include the meaning of action.

Mirror neurons have been suggested to provide the foundation for social interaction. We can make sense of the behavior of others because our brain recognizes different types of actions of others as meaningful goal-oriented actions, enhancing the perceived acts with our personal knowledge about the meaning of similar acts. Recent studies have also shown that mirror neurons in monkeys respond differently if the observed action occurs in the proximity of the monkey or in distance, and that some mirror neurons seem to encode the possibility for interaction. This suggests that the meaning of the actions of others can also depend on the possibility for social interaction. The discovery of neurons that mirror the attention of others, in turn, suggests a critical mechanism for social learning. In addition to goals, mirror neurons can also respond to specific motoric patterns, enabling high-fidelity imitation of the movements by others. Research has shown, for example, that sparrows have individual mirror neurons that respond to specific learned song sequences, and that the strength of the response depends on the closeness of the sequence to the dialect of the sparrow population in question (J. F. Prather, Nowicki, Anderson, Peters, & Mooney, 2009).

One of the fascinating studies in this area was conducted by Iacoboni et al. (2005). Using fMRI, they showed that mirror neuron areas in humans do not only track the behavior of others, but also the intentions of others. Iacoboni and his colleagues compared brain activations generated by a set of video clips that enabled them to differentiate between different intentions, one about grasping a cup of tea for drinking and another for cleaning the table. They found that there are mirror neurons that react specifically to the predicted intentions of others. Similar results have also been observed with monkeys. Mirror neurons, therefore, seem to predict the future.

Furthermore, EMG studies have shown that when a child performs a grasp-to-eat action, the activity of muscles responsible for mouth opening starts to rise at the beginning of the arm reach-to-grasp phase, while no activation occurs when the child grasps the object to place it into a container located near the mouth, and that similar results are found when a non-autistic child observes an experimenter doing the same actions (Cattaneo et al., 2007). It has also been shown that mirror neurons keep on firing also when the action continues behind an occluding wall, and when the actual action is unobservable. Furthermore, mirror neuron areas seem to be activated independent of sensory modality, and seeing someone to tear a paper and hearing it activates the same neurons.

The importance of mirroring seem to be supported by studies on apraxic patients. They show that people who have problems with moving hands are also specifically impaired with the recognition of hand-related sounds and people with difficulties in moving their mouth area have difficulties in recognizing mouth-action related sounds (Pazzaglia, Pizzamiglio, Pes, & Aglioti, 2008).

In general, one of the main conclusions from studies on mirror neurons is that action is important in learning. One intriguing result from the studies on bird-song learning is that when juvenile sparrows are exposed to different tutor songs, they seem to retain neurons that specifically detect these songs also when the birds are adult. Juvenile sparrows learn and practice many songs, but they retain only some of these in their repertoire when they become adult. Prather et al. (2010) have shown that there are neurons that recognize also those tutor songs that are not retained, as well as tutor songs that have never been performed. Tutoring, thus, seems to have quite permanent effects in the sparrow brain.

The realization that motor action is important for perception, communication and interaction is important for educational practice, as it highlights the point that learning does not happen only by transferring knowledge from teachers and books to a students mind. Highly abstract cognitive skills may have a motor component. In effect, the prevalence of mirroring supports pedagogical approaches that emphasize learning by doing and social constructivist models. Somewhat paradoxically, also rather mechanical retrieval practice can, however, be an effective form of learning by doing (Karpicke & Blunt, 2011).

On a more theoretical level, the discovery of mirroring is both extremely interesting and also problematic. Hickok (2009), for example, has questioned the empirical and conceptual justification of almost all the main claims related to mirror neurons. Although many of the empirical results gained in studies on mirror neurons seem to be robust, the causal story remains highly ambiguous. For example, it is unclear whether there actually are “mirror neurons” in humans that encode goals of actions of others, or whether the activation of the neurons can be explained in other ways.

On a conceptual level, the extrapolations from mirror neuron systems observed in monkeys to humans have so far inadequately explicated the underlying theories of action. The idea that unexpressed motor behavior is important for speech, communication, and thought is not new. Both the Russian reflexologists and the American pioneer of behaviorism J. B. Watson argued at the beginning of the 19th century that though is unarticulated speech. Hickok has pointed out that motor theories of cognition have been extremely popular long before mirror neurons were detected in the laboratory at the beginning of the 1990s. Indeed, Vygotsky and the subsequent cultural-historical and sociocultural traditions of psychology and education were to a large extent based on the critical observation that a more advanced model of action is needed. Leont'ev's activity theory (1978) explicitly addressed this challenge by separating the levels of activity, goal-oriented acts, and operations.

Immordino-Yang has suggested that the term “mirroring” may be misleading for both educators and neuroscientists, as the internalization of another's goals and actions happens in a culturally modulated dynamic interaction. According to Immordino-Yang, “mirroring” suggests a passive internalization of other's actions, emotions and goals. In practice, the representation of another's situation is constructed and experienced on one's own self “in accordance with cognitive and emotional preferences, memory, cultural knowledge, and neuropsychological predispositions” (Immordino-Yang, 2008, p. 70). This suggestion is well aligned with the cultural-historical tradition in psychology and education. In humans, mirror neurons cannot just mirror goals of others. Goals, such as grasp-to-clean-up-a-table-after-a-nice-cup-of-five-o'clock-tea, are meaningful only in a cultural context. Their interpretation requires extensive bodies of knowledge, and also some tacit knowledge about how cups can store liquid in normal gravitational fields. The interpretation of such acts cannot be built bottom up, from elementary meaningful actions, without relying on an extensive network of background knowledge.

From a purely conceptual point of view, it is therefore probable that, to the extent that mirror neurons respond to meaningful human action, they represent a tip of an iceberg; neurons that are visible in laboratory experiments, but only because they are the most visible parts of much broader networks. If that is the case, causal explanations that use mirror neurons as their starting points may look attractive “evidence-based” incarnations of the old motor theories of cognition, but simply miss the point that neural systems are networks.

Functional localization on the Sukhumvit road

At this point, we may try and summarize some main conclusions from this brief review and discussion of research that underlies educational neurosciences today. First, it is clear that neuroscience is producing very thought-provoking results at a very rapid rate, as new experimental methods open new possibilities to study brains from the levels of individual neurons and their biochemical processes to their functional organization. At times, the results are radical. It seems that, for example, it is possible to scan for genetic markers for many learning disorders, and that early interventions can mitigate these disorders. Recent research has discovered, for example, that a variation in the dopamine receptor gene modifies the impact of parental educational level on a student's academic achievement in adolescence (Keltikangas-Järvinen et al., 2008). The individual's genetic constitution, in other words, may partially determine the extent to which socio-economic status influences learning outcomes.

On the other hand, the realization that environmental factors can rapidly influence the expression of genes, has revealed that the traditional debates on inherited capabilities and the role of education and upbringing in development need substantial revision. What we eat, what we do, and what we learn, in effect, changes our genetic inheritance. One conclusion of the accumulated studies, therefore, is that learning is a much more central and generic characteristic of human beings than we ever realized before. In learning, we do not only move explicit knowledge from one mind to another; instead, we change the brain, our body, our neurons, and also our genetic makeup.

Second, much of the intriguing neuroscience research has been conducted at a level that can be characterized as fundamental research. We are still in the process of finding out what would constitute those neuroscientific "facts" that would be relevant for education. The high-profile flagging of educational neuroscience as a "fact-based" approach to education is clearly premature, and appears rather ignorant of the need to first establish theoretical frameworks where different types of facts make sense. An unproblematic focus on "facts" indicates that the proponents of educational neuroscience and brain-based education often operate in a specific theoretical perspective, inside which facts and evidence look theory-neutral. Often this theoretical perspective seems to be based on a fusion of behavioristic and computationally-oriented cognitivist ideas.

The Vygotskian observation that apes, children and adult humans have qualitatively different cognitive processes, thus clarifies also more generally the claim that the infant brain arrives into the world endowed with four or five "core knowledge systems" (Spelke & Kinzler, 2007). The core knowledge has been claimed to include systems for representing objects, actions, number and space, and perhaps a fifth system that represents social partners. According to Spelke and Kinzler, although educated human children and adults are the only organisms that engage in symbolic mathematics, the process by which we add symbolic numbers draws crucially on a nonsymbolic ability, shared by monkeys, pigeons, and newly hatched chicks. Spelke and Kinzler (2009) argue that "the finding that uniquely human numerical reasoning depends on cognitive systems that we share with other animals allows for a breakthrough in studies of the origins of knowledge."

In a Vygotskian perspective, this breakthrough appears more trivial. All human forms of science and activity, including mathematics, rely on some basic mental capabilities. From a biological point of view, apes and children use their brains to differentiate between quantities and magnitudes, and there may well be good reasons why similar areas of their brains are activated while doing this. What we normally call mathematics, however, is an integrated conceptual system, where the basic elements are non-observable theoretical constructs. The spontaneous empirical concepts that apes, pigeons and newly born infants generate, belong to a different "knowledge system" than more advanced culturally and historically developed forms of mathematics. Indeed, as McCulloch argued, this specific knowledge system may consist of numbers 1 to 6, shared by men and the beasts.

This is the reason why the Vygotskian theory led Davydov and his collaborators to develop pedagogical practices where children learn mathematics by first inventing the basic theoretical abstractions and only subsequently applying these in concrete contexts (Davydov, 1982, 1990; Schmittau & Morris, 2004). In the Davydovian curriculum, children are guided from basic empirical observations on relations and magnitudes towards developing basic symbolic systems of mathematics. This process leads children in a classroom to construct their own numbering systems and syntaxes based on empirical problems for which mathematics can provide solutions. After the children understand the importance of numbering systems and syntaxes, they are gradually guided to replace the notations they have invented with the standard mathematical notations. In the Davydovian curriculum, children, for example, first learn real numbers and only subsequently invent integers as a special case of real numbers. A practical consequence of this approach is that children in this curriculum cannot have difficulties in "moving from integers to fractions." In effect, they are moving from fractions to integers, in a developmental process that reverses the one proposed by Dehaene, Spelke, Kinzler, and others as the foundation for mathematical thinking.

It has been difficult for many educational practitioners to understand the Davydovian approach because we commonly assume that basic counting forms the foundation for mathematics and mathematical thinking. From the Vygotskian and Davydovian point of view, the "core knowledge systems" are, however, exactly those systems that are, in general, irrelevant for normal pedagogy. The number system that educational neuroscientists talk about is a knowledge system that is shared by pigeons and people, not the sociocultural system of mathematics that educators are talking about. According the Vygotsky, the development of advanced mental functions occurs when the child unlearns the pigeon numbering system and learns the system used by educated adults.

Third, perhaps the main outcome of brain studies in the last decades has been the overwhelming evidence that almost all of the key assumptions of modern computational and information processing theories of human thinking have been are wrong. This is probably an extremely radical conclusion for people who have been well-educated in cognitive sciences in the last decades. The human brain is not a computer, and the analogy probably misses the most interesting characteristics of biological cognition. As discussed above, the physical and functional characteristics of brain change in use. A key characteristic of the "hardware" of the brain is its plasticity. There is no hardware and no software in the brain, and the distinction between these has always been without empirical foundation.

The reason why the computer analogue has been so influential in brain research and cognitive science can be found from the historical fact that computers were thought to be logical mechanisms, and that the early blueprints of computer designs were also used to make sense of the brain. Although there have been many different types of computer designs during the years, including systems based on reconfigurable hardware, almost all computers are still based on a separation between memory storage, a logic processing unit, and an abstract algorithmic description of how information is processed. Indeed, von Neumann's major insight in the 1940s was that both data and the algorithms that process it can be stored in the same physical memory. A specific characteristic of these computers is that they can deterministically process data. In simple terms, computer is a machine that can do purely syntactic manipulations (Rosen, 1987). Such purely syntactic operations are sufficient for solving the two key problems that computers originally tried to address: iterative solution of differential equations and management of strings in databases required for census. Computers have been designed to be able to do this without understanding what they do; at the same time and somewhat paradoxically, they have become the dominant model for human brains. This is reflected both, for example, in the common localization of "executive functions" in the frontal regions of the brain and also, at a deeper level, in the widely accepted idea that the nervous system is an information processor.

In practice, data have to be represented in a computer in a way where the location of data in the memory structure completely determines its meaning. In computers, location equals meaning. It is rarely recognized that complex social processes define how program designers become able to fix the mapping between meaning of data and its location in the data structures. Without communication and shared conceptualizations, computer programmers and computers users could not reconstruct the meaning encoded in computer memory (Tuomi, 2000). This, of course, requires complex processes of social learning. Somewhat paradoxically, we therefore need theories of learning before we can explain computers. The idea that computational information processing models could provide a solid fact-based ground for learning, therefore, puts the cart before the horse.

A biological neural system is very different from a computer. It is essentially a network. This means that brain imaging and functional localization studies would benefit from a reflection on their conceptual starting points. The concept of localization becomes highly problematic when we give up simple computer analogies of the brain. After thousands of studies on functional localization, it still remains unclear what is the epistemic and methodological role of localization, if any. This is a complex issue, but we can provide a simple illustration of it by taking a taxi in Bangkok.

Sukhumvit road, one of the main traffic arteries in Bangkok, has frequent traffic congestion. It is part of a larger network of streets, and people use it to get to places that are in various distances from it. Without complex road networks that extend to every corner of Bangkok and beyond, there would, however, be no traffic congestion on the Sukhumvit road.

The localization of traffic jams, therefore, to a large extent depends on our explanatory strategy that implicitly associate local effects with local causes. In practice, however, traffic congestion often disappears when the road network is changed far from the place where the congestion looks worst.

When a neuron spikes and sparks, is it then the network, or the neuron? If we throw a stone in water, is the wave in the trough, or in the cap of a wave? Indeed, it could be argued that the idea of localization of brain activity is a deeply Western idea, fundamentally based on the Aristotelian distinction between objects and subjects, or subjects and their environments.

Alternative explanatory models can perhaps most easily be articulated in other cultural contexts. Indeed, the inadequacy of the Aristotelian approach in explaining human cognition was analyzed in great sophistication by Nishida, the founder of the Kyoto School of philosophy, at the beginning of the 20th century (e.g., Nishida, 1987). Nishida worked throughout his life—without final breakthrough—to find a logic that could describe worlds where subjects and objects are part of the same process. Rosen (1985, 1991) to a large extent succeeded in doing this, extending Nicolas Rashevsky's relational biology with sophisticated mathematical tools such as category theory. At present, Rosen's work, indeed, provides perhaps the best starting points for the next paradigm of neuroscience.

Localization can be very dynamic and also static. Some empirical phenomena are essentially distributed as waves on water, and others are more like the cliffs of the shore, shaped by thousands of waves. In biological systems, both static and dynamic structures are important. Bergson argued over a hundred years ago that living beings have instinctive knowledge that embeds outcomes of evolutionary adjustment in complex behavioral and structural forms. An example of instinctive knowledge can be found in the paralyzing instinct of certain wasps. As Bergson described:

> "The yellow-winged Sphex, which has chosen the cricket for its victim, knows that the cricket has three nerve-centres which serve its three pairs of legs—or at least it acts as if it knew this. It stings the insect first under the neck, then behind the prothorax, and then where the thorax joins the abdomen. The Ammophila Hirsuta gives nine successive strokes of its sting upon nine nerve-centres of its caterpillar, and then seizes the head and squeezes it in its mandibles, enough to cause paralysis without death. The general theme is 'the necessity of paralyzing without killing': the variations are subordinated to the structure of the victim on which they are played." (1983, p. 172)

Bergson pointed out that when we try to explain the "knowledge" of a yellow-winged Sphex, we view the insect as an entomologist, who knows the caterpillar as he knows everything else—as an observer, from the outside. We have difficulty in understanding the development of instinct as we think that the insect has to learn, like the entomologist, one by one, the positions of the nerve-centers of its object. But if we view this development as coupling of two living beings in a process of simultaneous development, instinctive knowledge would express, in a concrete form, a relation of one being to another. Instinct emerges as a result of a history of continuous change, and therefore it remains unexplainable to intelligence, which, according to Bergson, is an organ of reduction and analysis.

A similar evolutionary starting point underlies also the Vygotskian theory of cognitive development, as well as one of the best known alternatives for information processing and computational models of human brain. This is the autopoietic theory of living systems, developed by Maturana and Varela (cf. Mingers, 1995; Tuomi, 1999; Varela, Thompson, &

Rosch, 1991). In their famous introduction to autopoietic theory, *The Tree of Knowledge*, Maturana and Varela (1988) link evolutionary processes from the cellular level all the way up to social phenomena. At the same time, they explicitly reject the basic ideas of cognitive information processing and provide an alternative model of human cognition, based on theoretical biology and neuroscience, instead of computer models of mind.

For those educational neuroscientists who claim that we need to get rid of tradition and old beliefs and move to fact-based learning sciences, it may look unattractive to bring up philosophers and theorists, many of who have been dead for almost a century now. Another way of viewing the discussion above is that learning sciences can benefit from conceptually and theoretically sophisticated frameworks that enable right questions to be asked. For example, the nature of the “core knowledges” related to objects, actions, space, and number have been discussed in great detail and sophistication by some of the leading thinkers of the 20th century. Leont'ev's cultural-historical theory of action (Leont’ev, 1978, 1995) includes an explicit model of the hierarchy of activity, and it also underlies, for example, Engeström's (Engeström, Miettinen, & Punamäki, 1999; 1987) more recent models of expansive learning. Perhaps educational neuroscience could also benefit from testing its theoretical assumptions in the contexts of extended, distributed, and ecological cognition (e.g., Hutchins, 1995; Mace, 1977; Salomon, 1993). If nothing else, philosophers such as Bergson (1983, 1988), Nishida (Carter, 1997; Nishida, 2012) and Whitehead (1978), and theoretical biologists such as Rosen show that real progress in brain-based education will probably require additional conceptual work before laboratory evidence can be put into productive contexts.

Conclusion

In this paper, we have briefly reviewed some recent studies on neuroscience that are of interest for educators. These studies are interesting, and they are often highly thought-provoking. In this “think piece,” I have argued that the field of educational neuroscience has great potential, but the realization of this potential also requires that we reconsider some of the core assumptions of cognitive science, educational neuroscience, and brain-based approaches to education. Indeed, the most interesting possibility is that through studies on neuroscience we become able not only to refine the currently dominant conceptual frameworks that provide the foundation for majority of neuroscience research, but also establish alternative frameworks that fully benefit from earlier research on learning and human cognition.

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