Understanding how learning takes place with neuroscience and applying the results to education

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Abstract. Human learning has been dramatically altered by the new situation that saw us climb down trees and out of the savanna to larger communities with great reliance on agriculture and more recently industry. Psychology appeared as a scientific discipline at a time that formal education for all was becoming accepted. From the very beginning psychology and education had a major influence on each other. Education is notoriously slow to change. As the ideas of developmental psychologists started influencing education policy, new paradigms for education emerge from a variety of disciplines including computer science, medicine and particularly neurosciences. Each of these disciplines has its own vocabulary and progress is often limited because there is no common framework to bring together specialists from different disciplines or to formulate common research. We provide such a framework through a generalization of key concepts of developmental psychology. In the new framework, these concepts are cloaked with what we might call the standard model of modern neuroscience. Here, we customize this framework for learning and education. Formal education is seen as a continuation of a process that begins with the mother and develops in pre-school play. The main goal of this process is to maintain and continually update an internal representation of the external world in the key brain networks while keeping intact the core representation of self. The first steps in a research program using this new framework are described with some results and conclusions about future actions.

Keywords: neural representation of self, self-evolution and education, midline self-representation core, (MSRC), sleep states, assimilation, accommodation, zone of proximal development (ZPD), mass screening of pupils

1 Introduction

Living is learning because learning is a prerequisite for survival. Our species was catapulted to the top of the evolutionary pyramid, primarily because of the changes in the anatomy and physiology of the brain that allowed an explosive increase in the capability of humans to learn. For millennia, human learning was perfected solely through the brutal laws of survival, which initially were confined to safe movement through space and fine control of body and its limbs [1]. The complexity of the new tricks to be learnt demanded a protracted childhood and the provision of guidance

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shielded from the life and death scenarios lurking beyond; this was provided by the family. In the beginning of life outside the womb, the newly born infant was helped primarily by the mother to grasp the connection between organized sequence of motor actions and achieving a distant goal. This assignment of meaning to motor sequences constitutes the "ontogenesis of narrative" [2] and hence the start of the long road to language. As the infant grew to childhood, play with other children had become the way to accumulate more knowledge often in semi-protected environment where danger was never far away. As agriculture allowed the growth of sizable communities, learning through play was diminished with work in the fields becoming a priority from a young age. As populations grew more, another aspect of learning grew in importance: harnessing the effort of each individual to serve team goals related to work, social order and the protection of the community against external threats. This form of learning required community-wide participation using rituals, music and language [3]. The emergence of rituals can be thought of as the beginning of formal learning "in the society" culminating in ancient times in festivals, theatre performances and other public events that reinforced the social bond between citizens and allegiance to the rulers. Formal education is a relatively new innovation in evolution, even if one counts the early and mainly privately organized form that arose in many cultures soon after they adopted writing as a way of keeping records and augmenting the information stored and transferred between generations. For the vast majority of children, progress did not mean improvement in their education but squashing the happy urge to learn through play into submission of the young to serve the rulers either as servants in homes and fields or later with the industrial revolution as factory laborers. The concept of public education for the general population grew slowly during renaissance as part of humanism's challenge of the church dogmas for a divine social order that fixed people in their proper strata of society. Humanists instead argued that through education human beings can change dramatically and documented these views in books and practiced them in the schools they created [4]. Attitudes towards education changed in the last two centuries with society largely accepting that mass education is not only beneficial for every child, but also it has an added value for society at large, in both monetary and social terms. However, the methods adopted for education were influenced by the recent history. The enlightened people that pushed for the provision of education to all children could only come from the same part of society that introduced and maintained so successfully the new ways of commerce and industry. In these circles the notion of learning through play have long been abandoned and replaced by methods designed to force children from young age to work in homes of aristocracy as servants, or as laborers in farms, mines and factories. Since the early days of mass education in the late 17th century, children were herded into classes and what the top tier of society considered important at the time was to be stamped into the children's mind through forced repetition and testing, aided by plentiful punishment for failure or dissent.

Psychology from its early beginnings, in the late nineteenth century to today has been pre-occupied with education and almost every one of its founders have something important and new to say about how children should be educated. Many of these people, notably Sigmund Freud and William James, completed degrees in medicine and/or what we now call neuroscience and neurophysiology. Although at these times the neuroscientific method had not matured enough to be a powerful instrument on its own, it seems that these pioneers of psychology had powerful and positive influence from their studies of the human body and especially the brain and of course training in the exact sciences. The effect was to transform psychology to a science of measurements turning to varied degree away from introspection to objective and measurable quantities. Some of them, notably Edward Thorndike and Samuel Skinner based their approach on the effect of reward on learning stimulus – response contingencies. The rather sterile and mechanistic view of learning did little to challenge the format that slowly became established, a format that can be summarized as teacher-in-front of a classroom model. Far from it, this format of education was actively promoted "*A complete science of psychology would tell every fact about every one's intellect and character and behavior, would tell the cause of every change in human nature, would tell the result which every educational force - every act of every person that changed any other or the agent himself -would have. It would aid us to use human beings for the world's welfare with the same surety of the result that we now have when we use falling bodies or chemical elements. In proportion as we get such a science we shall become masters of our own souls as we now are masters of heat and light. Progress toward such a science is being made.*" [5]. If such is the nature of man, it seems logical and appropriate to manipulate through coercion and a combination of reward and punishment each child until he/she adopted the expected "correct form". The teacher-in-front of a classroom format is highly appropriate for such an indoctrination.

Other psychology pioneers emphasized more the individual characteristics of the child in terms of chronology when cognitive tasks can be tackled (William James and Jean Piaget) and the importance of the social context within education takes place (Lev Vygotsky). These pioneers moved away from the coercive approach to a more humane one, allowing for the complexity of the growing organism and the individuality of each child as an agent with unique characteristics and preferences. The last two, Piaget and Vygotsky re-introduced play as an important component of learning and developed their ideas for learning in the context of play. The thesis I will promote in this paper is that the emphasis on play was forced upon these pioneers because through play the development of a child evolves in the natural ways that evolution has shaped humans to learn. In section 2, I will focus on key concepts introduced by Piaget and Vygotsky that seriously challenged the educational system and began to change it fundamentally in the second half of the 20th century. In section 3, I will briefly outline the more recent ideas about learning influenced greatly by information processing ideas, the tsunami of data collected by neuroimaging methods and how this new era of educational psychology is poised to influence education practice and especially education evaluation. In section 4, I will return to main concepts of psychology as these were introduced by the pioneers of developmental psychology, and adapt them and generalize them in the light of recent findings from studies of brain function during awake state and sleep. These studies identify the self as an evolutionary end-point with a corresponding neural representation. Education is then seen as the accommodation of the self within the wider social context, pointing out the importance of early mass screening to determine the maturity of neural networks at the very start of school. In section 5, I will introduce the practical considerations that follow and sketch the efforts to develop an effective early mass-screening system outlining both the successes and some problems that slowed down progress.

2 Core psychology related to learning and education

Piaget defined assimilation and accommodation as the two key polar tendencies driving cognitive development. As a child gets older, his/her cognitive capabilities grow through the evolution and consolidation of cognitive schemas, internal representations of the world that are linked to each other and adjusted by assimilation and accommodation. Through assimilation, new experiences are fitted into existing schemata as representations of objects, situations or skills. Accommodation “happens” as the accumulated new information demands a major change to take place in one or more of the existing schemata or the creation of a new one. The balance between assimilation and accommodation is achieved through what Piaget defined as equilibration. In Piaget’s framework, cognitive development follows a staircase course. Plateaus in cognitive development are characterized by assimilation-dominated periods when the child is in command of enough schemata to allow him/her to deal with new information through assimilation, with little need for drastic reorganization of existing schemata. As new information is accumulated however the equilibrium is upset because the existing schemata cannot cope any more. This creates a disagreeable state of affairs that drives the equilibration force through the generation of new schemata. Piaget defined four main stages of cognitive development, each one characterized by distinct qualitatively different kinds of learning. The driving force is an inner motivation to reach the equilibrium stages that is constrained by biological maturation and the exposure to different situations in the child’s environment.

Although Piaget was aware of the contribution of social influences in cognitive development, he paid little direct attention to them in his later work. In contrast Vygotsky emphasized the importance of social and cultural elements in the development of children. Like Piaget, Vygotsky focused on what is happening during play, stressing the fact that in a game situation a child performs ahead of its current capabilities, but within what he called the “zone of proximal development” (ZPD), which Vygotsky defined as the area from the current actual developmental level and what a child is able to do, if guided by adults or more capable peers. It therefore follows that what a child achieves does not only depend on maturity and exposure to an arbitrary environmental influence but also on the societal and cultural messages and rituals that he/she constantly encounters. According to Vygotsky, the most effective learning is possible when the child is guided and challenged through ZPD, by individuals (teachers and peers), society and culture.

Piaget and Vygotsky and their many followers belong to the constructivism strand of psychology. This brand of psychology emerged partly as a reaction to the blinkered empiricism that conceived the mind as a passive “camera” of the external world and has driven education into a sterile format until the middle of the 20th century. In the second half of the 20th century, the ideas of Piaget and his followers began to influence policy makers and eventually came to dominate not only the field of developmental psychology but also, in the 1960s and 1970s, started to greatly influence educational programs. In the following years the ideas of Vygotsky and his followers have become increasingly more effective, introducing socio-cultural elements in the curriculum.

3 Recent developments related to learning and education

Education is now at a crossroad. Major advances bring opportunities from three directions but there is great uncertainty about which of the many ways ahead can best realize the anticipated improvements in quality and effectiveness of education delivered, ensuring smooth transition within educational systems that are slow and conservative.

The first direction is how the progress in psychology beyond the pioneering work of Piaget and Vygotsky and their followers can be incorporated in the educational system. Neo-Piagetian theories adopted Piaget's idea and pushed them forward along the explanatory models that were prominent at the time. The computer era provided two concepts, processing power and memory capacity. Juan Pascual-Leone proposed a mathematical framework that used the processing power and memory content as contributors to the "set measure M", representing the "maximum number of discrete chunks of information or schemes that can be controlled in a single act" [6]. The M measure starts with the value of 1 increasing after the age of 3 by one unit every two years reaching the maximum value of 7 by the age of 15-16 years. As the M measure increases it becomes possible to accomplish more difficult tasks and hence traverse the developmental path that Piaget originally traced. This theme was elaborated by other theorist who replaced the mainly linear development in information processing capacity with more complex structures and processes.

Case and colleagues postulated a central conceptual structure (CCS) as a networks of semantic nodes and relations that support the full range of tasks that any given domain entails [7]: major transformations take place in the CCS as a child enters a new developmental stage, acting as frames for supporting and organizing the new knowledge to be accumulated. Key to our later discussion is the observation that the self can be seen as a specialized CCS implemented in the brain through the neuroanatomical structures that "support autobiographical self and extended consciousness" culminating achievement of ontogenesis [8] with a very precise neuroscientific definition of its key core neural elements [9]. Amongst the neo Piagetian theorists, Fischer integrated most effectively within the Piaget framework, not only the information processing elements but also paid due attention to the wider than the individual factors introduced by the environment and society. To achieve this he used the classic concepts of Vygotsky of internalization and ZPD and advocated the promotion of a new field of Mind, Brain and Education [10, 11].

While in psychology, theorizing was getting too detailed and finding applications in education was making slow progress, advances in in Information Communication Technology (ICT) and neuroscience were producing overwhelming volumes of new data and opportunities that specialists and educationalists alike have difficulty in following, let alone organize and use in the educational system. The progress appeared to be especially relevant in non-invasive neuroimaging [8, 12].

Progress in ICT has created a range of opportunities in education, at the level of classroom provision and supporting school-related work and individual unsupervised use of ICT resources by children. For example, the information volume now available in the internet surpasses what any school can provide in volume, breadth and quality. A child exposed early to ICT can use the internet effectively from the early years of elementary school. Depending how this knowledge is channeled by the middle and late years of the primary education the child can use the internet to enhance what the school provides or can have his/her brain addicted to computer games and pointless time wasting on trivialities. Serious Games (SG) are ideally suited to provide on demand specialized learning and training [13]. Intelligent Tutoring Systems (ITS) provide formal learning in a digital format. ITS have separate models for the learner and tutor. Modern Learner models describe cognitive and emotional states [14] to adapt learning strategies to suit learners' needs, objectives and interests. The use of neurophysiological measures during SG offers the possibility of evaluating other attributes of the learner and using them for improving ITS, as was done recently for gauging motivation levels [15]. Modern ICT provide the opportunity today to monitor individuals and entire classrooms; it is possible to record a huge amount of data about individual pupils, groups of pupils and entire classrooms (including teachers!) that can be very valuable for improving learning. However, such use of the technology is not likely to be acceptable because of objections for ethical reasons and personal privacy violation. It is technically feasible to collect such data in an automatic way, removing much of the personal data while retaining processed automated analysis that can be linked to performance (of individual pupils and classes) without revealing any information about individuals. Such technically challenging but yet perfectly feasible projects may be acceptable from the ethical point of view, given the impetus that it might give towards a better education provision.

The third direction is spearheaded by advances in neurosciences and specifically in different forms of non-invasive neuroimaging [16]. Neuroimaging has opened up numerous new windows on the working brain and scientists have been busy for the last few decades in collecting data, mainly for adults. For millennia, the working brain was an inaccessible territory only to be speculated upon. Just recently, in the last couple of centuries, the human brain could be studied after death or in animals with invasive electrodes, but with no parallel access to the linguistic communication channel that is only available with human subjects. All these changed in only a few decades; today, the working brain is accessible with non-invasive methods for human experiments. Using these methods we can study in detail how parts of the brain are activated in specific tasks and how the brain solves problems by combining the results of processing in individual areas into networks of transient character that adapt and learn to accomplish the goals set by the experiment design. It is beyond the scope of this paper to go through the enormous range of studies, ranging from responses to simple and complex stimuli, complex tasks probing different states of consciousness, including awake relaxed state (resting state), different types of attention, sleep and anesthesia. The explanatory framework for describing these results within neuroscience relies on brain anatomy to describe where in the brain activity takes place and how activity in different brain areas influences activity in other areas, what kind of activity takes place (unitary volley, or group of volleys of action potentials, oscillatory activity in the cell membrane potential and/or across wide parts of the brain). None of these concepts are directly relevant to educationalist and even many psychologists do not feel comfortable with the fundamentals of neuroscience yet. For most neuroimaging methods, it is easier (and takes less effort) to study right-handed adults for a variety of reasons that include control of movement, higher variability in performance for children, even within the same age range, availability and handling issues. Although studies of children are on the rise, these usually focus on special populations and generally use protocols developed for neuroimaging with little attention paid to developmental questions and other factors that are fundamental for drawing conclusions for education.

The problems mentioned above are addressed at many levels in an effort to formulate a more scientific basis for education, with some proposing the creation of a new science of Mind, Brain and Education [8]. At the level of neuroscience, a number of projects have been initiated for the systematic collection of neuroimaging databases across the developmentally interesting ranges with standardized protocols [17–19]. At the level of psychology studying how the brain functions is becoming more and more a necessity for new graduates of psychology; many prominent psychologists have embraced neuroscience and are key players in the neuroimaging community. The bridge established between psychology and education in the second half of the 20th century has helped ameliorate the sterile practices of early educational systems. The bridge between education and neuroscience seems to be a bridge too far at times, as educationalists find it difficult to relate to the neuroscience fundamentals, despite great efforts at the level of individual universities, national programs and international initiatives, with the Organization for Economic Co-operation and development (OECD) playing a leading role.

4 A wider and more neuroscientific definition of basic concepts

In this section we will adapt some basic concepts from developmental psychology as building blocks for a neuroscience-based framework for describing learning processes. The new framework that I propose here will allow neuroscientists, psychologists and educationalists to use the same concepts and exchange ideas in a shared language. Although the terms will carry slightly different connotations in the details of how they are used in the practices of each discipline, they will nevertheless convey the same central meaning that can be understood by all concerned specialists. The new framework has the additional advantage that it can produce automatically the stages of development as defined by Piaget, Vygotsky and their followers when details about how the anatomy of the brain and its function changes as different brain areas and their connections with the rest of the brain mature with age, in principle from birth to old age. I deal in separate subsections in turn with the key neuroscience background, how the neuroscience concepts introduced can cloak key basic concepts, specifically assimilation, accommodation and ZPD and how the resulting new framework provides an evolutionary perspective on education.

4.1 Neuroscientific concepts

The neuroscientific basis of our new framework is what we might call the standard model of neuroscience as this emerges by the voluminous results of neuroimaging in the last few decades. The brain structures can now be imaged using a variety of techniques with magnetic resonance imaging (MRI) providing a non-invasive view of amazing detail. The basic anatomical organization of the brain consists of a few hundreds of distinct cytoarchitectonic areas (CA), with neighboring center to center separation of a few millimeters [20]. CAs are connected to each other by bundles of white matter that allow electrical and chemical communication between them [21]. These white matter bundles can be mapped non-invasively using Diffusion Tensor Imaging (DTI) or traced using wet anatomy. Measurements with indirect and direct correlates of regional brain activity provide details about changes in activity within cytoarchitectonic areas as time advances or between conditions. The most widely used indirect methods are functional MRI (fMRI) and positron emission tomography (PET). Magnetoencephalography (MEG) and electroencephalography (EEG) are the most widely used direct correlates of mass electrical activity. Using these methods the activity within CAs can be mapped with temporal resolution from as small as a fraction of a millisecond or a few milliseconds (with EEG and MEG) to a few seconds (with fMRI) or minutes (with PET). Some of these techniques, especially EEG and to lesser extent fMRI, can be applied repeatedly so the time scale can be extended to weeks, months and years or the entire life of an individual. From these measurements one can construct correlational measures indicating linkage of activity from different areas; different methods exists to identify linked activity of varying types and complexity and therefore care must be taken when such results are interpreted [22]. High precision, real-time reconstructions can be used to compute causal descriptions of influences from one area to another with resolution in milliseconds [23, 24]. Using detailed modelling of the underlying neural basis of the interactions within and between areas, elaborate models of neural activity and connectivity can be tested using data from one or more neuroimaging modalities [25]. Graph theory provides a natural description of such an organization, both at the structural and functional level, with a hierarchy of networks relating structural and functional levels [26]. The notion of specialized areas that dominated neuroimaging for many years is now superseded by the concept of specialized networks that in healthy brains retain their individuality during awake resting state [27, 28] and sleep [29, 30]. The changes in activity from healthy canonical networks can then be documented within specific conditions and between conditions [31–33]. The evolution of networks can be also mapped as they change during a task and descriptive measures of network properties derived as time proceeds, e.g. relative to stimulus onset [34].

For the interest of brevity I will only discuss two networks that are the ones most relevant to our discussion: the default mode network (DMN) and the saliency network. The DMN comprises of a set of brain areas that were found to reduce their activity when a subject is awake and engages in a task that demands attention to external stimuli. The key networks of the brain can also be identified in studies of resting state, with the areas belonging to each network showing consistent correlated variation of activity over time. The DMN emerges as one of the networks and shows an anti-correlated pattern of variation with the other networks [28, 35], although some technical questions about these anti-correlations remain [36].

We have recently demonstrated [37] the only principled trend in large scale brain activity that one can recognize as a nearly monotonic change from awake state through light and deep sleep and eventually rapid eye movement (REM) sleep: a rise in the gamma band activity in two well-circumscribed areas in the left paramedial dorsal brain. For reasons that will become apparent soon we collectively label these two areas as the midline self-representation core (MSRC) of the brain. The first area, MSRC1 is on dorsal medial prefrontal cortex (dMPFC) with its center at Talairach Coordinates (TC) in mm (x=-5, y=42, z= 31). The second area, MSRC2, is in the precuneus in the midline posterior parietal cortex (center at TC: x=-5, y=-62, z= 51). If we group together the centers of these two areas and the centers of other areas assigned to the DMN in other studies, we will see that they separate into clusters with the two main clusters close to the midline sagittal cut, one in the frontal and the other in the caudal part of the brain. Now, if we view two-dimensional projections of each one of the two main clusters of DMN areas, it will appear that MSRC1 and MSRC2 are respectively at the center of the anterior and posterior clusters. A more careful examination reveals that MSRC1 and MSRC2 actually fill a void at the center of each cluster. With this perspective in mind, the anterior and posterior clusters of the DMN are revealed as an onion structure with at least three layers: each MSRC areas occupies the center of its cluster, surrounded in the next layer by areas identified in experiments with (awake state) tasks related to introspection autobiographical memories and the final outside layer identified in experiments with (awake state) tasks related to background and maintenance activities taking place where no attention needs to be allocated to specific tasks or the environment. Another clue about the nature of the representations of the MSRC is provided when we focus on the networks contributing to the mental operations relating to the self, as described for example by Uddin and colleagues. Imagining our own self activates areas close to the midline, called the cortical midline structures (CMS), while imagining others activates more lateral areas of the so called mirror neuron system (MNS) [38]. On the basis of these and many other related findings, I suggest that the MSRC areas carry the core neural representation of self, and hence the name.

The second network to consider is the saliency network that plays a critical role in monitoring the environment and accordingly recruiting other networks into action, either for introspection and rest, or to actively monitor the environment and objects just detected, or to initiate action to deal with some imminent perceived threat or opportunity [39]. The saliency network can be identified from resting state analysis of healthy subjects [28, 40] and its aberrant activation is associated with pathology [41]. Our latest analysis of sleep data showed that this network also plays a key role during sleep, and specifically during the second stage of (light) sleep, NREM2. In the analysis, we considered separately the periods around the large graphoelements from what we call "core periods" of NREM2, which correspond to the quiet, shorter lasting "B" periods of the cyclic alternating pattern in NREM [42, 43]. We then compared directly the activity of core periods of NREM1 and NREM2 and the periods before and during spindles and K-complexes (KC), the two characteristic graphoelements of NREM2 sleep stage [9]. The changes in activity that we identified, map a most interesting variation in environmental monitoring, most clearly expressed in the changes of activity in the rostral anterior cingulate cortex (rACC), the key node of the saliency network. These changes show that with sleep onset the loss of consciousness is accompanied by an active inhibition of environmental monitoring as seen by high low frequency (delta band) activity in the frontal lobe and reduction in high frequency (alpha and higher frequencies) activity in posterior parietal areas [9]. The transition from NREM1 to NREM2 is accompanied by a return of activity in rACC amidst the general increase in the inhibitory low frequency activity, which suggests opposing tendencies between sleep maintenance and the return of some vigilance mechanism. This conflict is present in the core periods well away in time from KCs and spindles that can be considered as the common baseline for these two characteristic graphoelements of NREM2. The periods in the last few seconds before spindles and KCs we see a clear differentiation: activity during KCs is seen in the same areas and largely in similar frequencies as in the periods before their occurrence; the activity during KCs simply grows in strength and spreads more widely. The KC activity is consistent with alerting influences in the frontal executive and environment monitoring areas gaining control just before KCs with the actual KC emerging as a final cognitive effort to decide whether or not sleep will continue.

In the case of spindles, the comparison between the activity during NREM2 core period and the two seconds before spindles shows increases in delta and theta bands: these increases were localized in the sub-genual anterior cingulate cortex (sgACC) and frontal pole in the delta band only, and in the rACC and dMPFC, sixth Broadman area (BA), BA6 in both delta and theta bands. These changes are consistent with a complete blockade of external inputs. During spindles we see only increases in activity in the alpha and sigma bands. The increases are in the frontal pole (low sigma only), dMPFC (alpha and low sigma) and precuneus (BA7, sigma only) medially (Figure 5B in [9]) and some other frontal areas of the left hemisphere (for details see [9]). All the changes identified before and during spindles are consistent with continuation of preparations starting at sleep onset and continuing all the way until spindles begin for some important process that must have no interference from the environment. This process requires cooperative activity between ventral structures and basal forebrain and linked sigma band activity between dMPFC and posterior parietal areas. These observations are consistent with the memory consolidation role assigned by many researchers to spindles [44].

In interpreting the results of our earlier studies [9, 37], we follow Menon's triple network model with an emphasis on the clear separation of roles in the key networks [41]. On the basis of our recent analysis of data from sleep [9, 37], it seems that the DMN separates into sub-systems with its central and least observed component (during awake state) the MSRC that carries the core neural representation of self [9]. The details of the activity of rACC, the key node of the saliency system, before and during spindles, has all the hallmarks of acting as a mechanism for blocking all external inputs and thus preventing interference with the operations to follow that involve MSRC. Adding to this the fact that the activity of the MSRC areas is reduced during awake state [37], it seems that evolution has invested a lot of effort on protecting the neural representation of self from interference in both awake state and sleep. The overall pattern of activity observed for this system begins to make sense from an evolutionary perspective and when they are viewed within a framework that borrows concepts from psychology with profound implications not only in pathology but also for education that I will explore a little later.

4.2 A wider definition and use for key concepts of developmental psychology

Before describing the basic concepts from psychology, we consider the sub-divisions of different states of awareness. The first major separation is in terms of states while we are awake and states while we sleep. We separate awake state into two parts. The first one allows free movement in the environment, which for this reason, makes it difficult to use in controlled experiments. The second one allows only limited or no movement and it is further divided into active states under a task or continuous interaction with the environment and resting state. The resting state is further divided into eyes closed or eyes open states, with further sub-divisions if desired. Sleep is divided into the sleep stages and rather than tasks the system is "exercised" by the large and/or highly rhythmic events that characterize each sleep stage. For all the states, except the first one, it is perfectly feasible today, to record EEG and MEG time-locked to additional recordings of the physiological state of the subject external stimuli and/or continually changing conditions in the environment (e.g. using virtual reality headsets) [45]. From such MEG measurements, it is possible to extract quantitative descriptions of brain activity at the levels of CAs, networks and whole brain. With a little more effort, this may also be possible using EEG data (with a sophisticated conductivity model for each subject). For the purposes of this article, I also assume that it will be possible in the not-too-distant future to extract similar information from wearable EEG devices after constructing a detailed model for each subject, using possibly a more extensive set of measurements with expensive (e.g. MEG) instrumentation for the model definition, but only once every few years. Given such a capability, it is a relatively short step to characterize each awake and sleep state and thus define physiological and non-physiological conditions for all the states of consciousness and whatever range of tasks one might wish to employ. A canonical set of measures can then be defined from measurements made across sufficiently large number of people. The canonical set will describe the range of basic neural network measures (including measures of network interactions) that are within the expected range for a given subset of the population, defined by categorical properties like gender, handedness etc. and ranges e.g. age range. By allowing an age range we acknowledge that there will be some variability especially in the early years of life, when the trajectory of neural network properties will be as important as the values that describe them. The goal is to define for any one healthy individual from infancy to old age a measure of his/her normal physiological range of brain activity (n-

PRoBA). It is important to stress that n-PRoBA can be quantified in terms of activity and organization of the basic brain networks during operations that the subject is doing routinely, e.g. at rest (i.e. the activity of the DMN while resting), or in a set of simple and complex tasks.

I now proceed to the selection of basic concepts that I want to use for the new framework. I selected as core concepts the ones that have established themselves in developmental psychology: assimilation, accommodation and ZPD. I redefine each one of them in terms of the neuroscientific terms introduced above so that these definitions are not restricted to children but they are applicable to any age. We also consider Piaget's schemata as the products of operations carried out by the interconnected neural networks in the brain identified by neuroimaging.

We define as assimilation any interaction with the environment that corresponds to effortless use of existing skill/knowledge that therefore corresponds to a (partial) fit of the experience into the current internal model of the world as this is represented by the activity of the neural networks of the individual's brain. In operational sense, we can define as assimilation any brain operation that help us navigate through the environment and social engagements that does not push the key networks, and especially the MSRC of the brain beyond their canonical performance in the sense defined above. During routine assimilation brain activity remains within n-PROBA.

We define as accommodation the process which involves controlled excursions away from n-PROBA that allow a re-adjustment of the internal model of the world that may lead to (mild) alterations of our own self-image. Accepting that the two left paramedial sides, MSRC1 and MSRC2 identified during our sleep studies [9, 37] are the core neural representations of self, we postulate that their activation during sleep are key elements of accommodation through memory consolidation mechanisms in light sleep [9]. Other memory consolidation mechanisms in slow wave sleep and during REM are also key contributors to accommodation, but their precise role requires further investigation. Whenever major accommodation takes place the input from the environment must be completely eliminated because only at these times the core representation of self is open to influences. This ensures that the inclusion of new experiences is integrated all the way to the core representations of self but without altering this representation more than it is absolutely necessary.

We define as ZPD the activities that are outside n-PROBA, but only because they have never, or rarely, been attempted so far. These activities are possible to undertake with the existing neural systems under guidance by teachers or advanced peers, especially during play. In essence ZPD is what the existing neural networks can do but have not done so yet, and as such they are likely to require no change in the basic networks and specifically no change in the MSRC. It is important to stress that ZPD, as defined here, does not require the existence of fixed developmental stages, it can be defined for any age. For example, a weak chess player may decide on retirement to play chess more regularly and does so with a coach and/or attending his/her local chess club; in doing so he/she enters regularly in his/her ZPD. A tempting speculation is that dreaming is an exercise in the new ZPD that accommodation creates through the incorporation of new memories. Dreams are our evening plays to prepare us for likely and demanding tasks of the next day.

In this framework assimilation takes place during the day and night when we are not asleep. Accommodation takes place all the time and during much of the day it involves alterations that do not require changes in the MSRC, generated by events operating within n-PROBA. Events and experiences that are beyond n-PROBA but are still within the ZPD, are stored temporarily in the hippocampus and the surrounding areas. The main accommodation process during sleep is simply the processing of the accumulated traces of salient experiences during the evening after all input from the environment is blocked. This is probably because during the day the influences from the environment cannot be blocked as this would be an unacceptable risk for survival. Thus storing them as they happen might change unacceptably the MSRC.

We propose under this framework that events so dramatic that can penetrate the protecting shield of MSRC during awake state and modify it, or they require too much change to be accommodated during sleep lead to pathological conditions and will not be examined here. Problems may also arise when the individual works within his n-PROBA but with conflicting pressures from its physical and social milieu for a long time, or within its ZPD but with insufficient guidance from adults or more competent peers, a situation that often arises when a child or adult changes the daily routine in a significant way. For a child, such a critical change can be at the start of formal schooling. We will return to the problems that often arises when children enter elementary school at the end of the next subsection. In the next section, we will discuss our research efforts and the practical solutions that we were driven to develop for effective work within the school environment.

4.3 Education from an evolutionary perspective

The self is an evolutionary end-point signifying that the complexity of the inner representation of the external world has grown sufficiently complex to include a self-representation. Early in ontogenesis, the infant has no sense of self. The sense of self, in its complete form that includes innate and social dimensions, is acquired with the help of adult carers and the society at large, but first and foremost by the mother. In terms of our earlier discussion, the newly born baby is for much of the time beyond his/her ZPD, simply because in the absence of a clear boundary of self, there is no clear cut boundary for ZPD either. It is the mother's interaction with the baby that allows the self to emerge through judicial selection of components that are "already present in spontaneous expression" [46]. The mother accomplishes an incredible triumph in guiding the infant through and beyond an ill-defined ZPD using fast decoding of each and every body movement, facial expression and voice intonation at recognition speeds that are only a few tens of milliseconds [24]. Through the reciprocal interaction with the mother, the infant is able to do the decoding too, setting off along a road to become an expert in recognizing the emotions and intentions of others in non-verbal interaction, the ticket for success in social life. Until EEG came to the scene, this decoding of the intentions of others as part of non-verbal communication was the closest we came to map (albeit sub-consciously) the networks of the brain. By the end of the first year the infant has some awareness of self. In the preschool years cognitive development and social interaction force the child's self-image to be influenced by how others describe his/her behavior. There remains some exaggeration of his/her abilities, as the preschool child cannot yet make a clear distinction between how the child observes his/her performance through the eyes of others and how he/she wishes his performance to be. The child enters formal education at this preoperational level of development, as Piaget described it, so there is inevitably a large variation in the self-image and cognitive development level.

Formal education should be thought of as an extension of what the mother and early play have started; ideally education adds more layers of knowledge and skills while nurturing the individuality and uniqueness of the person, which in our framework implies consistency of the new knowledge with the self-image, as this is maintained by the DMN and in particular the MSRC. When a new pupil arrives in school, there is little to inform the educator about the newcomer and any special abilities or needs can go unnoticed for years that affect specific sensory systems and general personality traits handled by specialized networks, e.g. for attention and emotions. In the last subsection, I outlined a framework for the neural representation of self and the other key brain networks. As I have already indicated, with such a generalized framework in place, it is possible to apply the neuroimaging technology available today for the evaluation of the maturity of the key neural networks of a child along one or more canonical classifications, derived from a central database of measurements. I hasten to add that collecting the data for such a database, thousands of children need to be scanned with MRI and detailed EEG and/or MEG data to be recorded in a series of experiments. Last but not least, sophisticated analysis must be performed on the recorded data. The database must have enough children of different ages, separating gender, handedness and other attributes like socioeconomic background, previous exposure to linguistic material and education. Given the magnitude of the task, what is needed is an initiative like the Research Domain Criteria (RDoC) [47], an attempt to base the classification of psychiatric diseases on brain systems that can be imaged and from which regional measurements of activity and quantitative descriptions of structural and functional networks can be objectively extracted for populations and individuals. Creating a canonical database using a framework like the one I propose in the last subsection could provide education a powerful tool for objective evaluation of the maturity level of networks dealing with cognition, attention and emotions.

In conclusion, not all children are ready for school when they enter elementary school. In terms of the framework developed above, some of the new activities a child is asked to do when he/she starts elementary school may simply be beyond his/her ZPD. In the next section I will describe a practical way for mass screening pupils at the first year of elementary school that was developed in the last decade and the ongoing efforts and problems to overcome the difficulties we have encountered. This effort is only the beginning in the long road towards a truly useful classification of each child's neural network maturity as he/she starts formal education.

5 Practical considerations for Education evaluation

If a child on entering elementary school is forced to work deep into, or beyond his/her ZPD without sufficient guidance, is like a recruit in the army thrown into battle without any basic training. More damage can be done if the child's failure is criticized continuously, directly or indirectly, as the result of laziness and/or stupidity. The usual reaction from an emotionally wounded child to such hostile new environment is to either become the class clown or keep quiet and just stay below the teacher's radar. The double tragedy is that in cases where learning difficulties are a real risk, like in developmental dyslexia (DD), the longer the real problem remains unrecognized the more difficult it becomes to take remedial action fast enough to enable the child to catch up with his peers. The situation is analogous to the child coming to the platform of education as the train is starting to move away. There is little precious time for the child to run and get on board, and the longer he stays behind, the more difficult it becomes to catch up the accelerating train. If the problem remains unresolved till the middle of elementary school, as is very often the case, then the train is already too far. The outcome of such a scenario is misery and performance well below the child's true ability throughout primary and secondary education, even when considerable resources are provided for remedial lessons. Statistics of the percentage of DD children that end up in low salary positions and criminality show clearly the disadvantage these children face. The success of many DD survivors of the educational system also show that this need not be the outcome.

We undertook a program of research aiming to characterize in an objective way and with as simple tools as possible, the maturity of key neural networks in the preschool and first years of elementary education. We were motivated by what we claimed above, namely that the technology for an objective evaluation of the maturity of key brain networks is possible today, but at a high cost. Initially, we targeted the diagnosis of DD. Our long term aim is to provide a mass screening capability with general evaluation for every child and eventually appropriate intervention designed individually for every child. The aim is optimal education for all children, helping children with special needs to overcome difficulties before these become a problem and helping children with special abilities to fulfill their potentials. Three projects were completed so far (see acknowledgements).

In the first project, *Personalized Advanced Cognitive Diagnosis for Children* (ΑΒΓΔΠ; December 2010 – February 2013) we assembled a set of non-linguistic visual tests to map basic neural networks using accuracy tests. Some of the tests were taken from the literature [48, 49], while others were developed especially for the project and they were based on results obtained in some of our earlier experiments [50–54]. These tests were tried with children in the age range from 4 to 8 years old in a longitudinal study with four measurements over a period of 3 years. The original test was part of a story-line woven in the lesson (e.g. in a mythology story). The children were asked to select the correct item from the ones shown on a screen as part of their effort to help the hero in the story (e.g. Hercules). The children indicated their response by marking the correct option on a multiple choice paper. The study showed clear differences, which correlated well with independent tests for each child using a subset of tests from the Wechsler Intelligence Scale for Children (WISC). The method was however deemed too cumbersome for the classroom environment and also limited as it only measured accuracy with no real measure for the speed of response. We therefore adapted the tests for use with personal computers (PC). This PC-based version of the tests used specialized software that allowed as to collect automatically the responses and the reaction time from each pupil. The results were promising, but using many PCs to do the tests in parallel, could only take place in schools with a dedicated ICT room. Even for these schools the occupation of the high demand ICT room for a few hours at a time made the approach unattractive.

These problems were addressed in the second project, *Prodromal Analysis of Noetic Difficulties with Individual Automated System*, (PANDIAS; September 2013 – May 2015). The main goal of PANDIAS was to develop a way for efficient testing an entire class to serve as the basis for a mass-screening program. The PANDIAS solution was a hand-held device that could be independently operated by each child [55]. With enough devices so that each child had one, it is possible to screen all the children in a classroom within one lesson period. The second project was completed in the spring of 2015 and the final prototype device was operating with four tests. The selection of the four tests was based on the results of the first project and it used the most informative collection of four tests for a complete session well within one lesson period. Responses for the set of four tests have been collected during the two projects from over three hundred children. The majority of data collected were from the excellent collaboration that we had with one private school (see acknowledgements). For most of the data collected, there are two and in some cases four measurements, with matched reports from the school teachers for each child, spread over a period of two to three years. The PANDIAS device can be interfaced with the EEG and combine behavioral data from PANDIAS and the EEG were recorded from a small number of children. In these measurements, the EEG was recorded in a protocol designed to probe specific neural networks, including sensory ones and the DMN. The EEG data analysis is ongoing using a newly developed method for tomographic analysis of EEG data developed under a third project by our team, *Dynamic Field Tomography* (DEFT; October 2012 – April 2015) and they will not be discussed further here.

The four tests provided in the final prototype device allow the collection of data with minimal disruption of the school program. The children respond well to these tests and they are happy to do them. The recording of reaction time provides significant and independent information to the accuracy results. The availability of data from all pupils in a classroom allows the data from each child to be contrasted with the data from his classmates, thus ensuring that the comparison is with peers with similar school experiences. Repeated tests can provide a particularly sensitive warning to changes in individual children. Indeed our preliminary longitudinal analysis of the data, collected from the projects ΑΒΓΔΠ and PANDIAS, suggests that while it is difficult to establish a level from the data of an individual child at any one point in time, the developmental trajectory one can trace when repeat data are available provides a much clearer picture of the progress achieved and where problems may exist. On the basis of the early results the minimum requirement is collection of data at the beginning and end of a school year, with some additional benefit obtained if one additional set is obtained half way through the academic year. We have also studied the evaluation of teachers with two independent evaluations per child. We found that the teacher evaluations from the middle years of the elementary school are more informative and confident and reasonably uniform across repeated periods and for different teachers in the same period. The evaluations of teachers in earlier years are less confident and judging from the divergence between teachers for the same child and same period, they are also less reliable.

I have presented a framework based on generalizations of key concepts of developmental psychology. This framework can serve as a common reference for neuroscience, psychology and education specialists. It can also support research programs by combining under one roof the knowledge about education accumulated over centuries with the latest neuroscience findings. Our limited efforts to start such a program of research has allowed us to adapt both the neuroscience knowledge and the approach to evaluation of entry level children to primary education. While teachers once engaged in the project were fascinated with the work and clearly saw its relevance to their work, the wheels of bureaucracy were often so slow to move and more often than not, made it difficult to exploit the results in the state schools. On the contrary the project colleagues from the private sector found it much easier to assimilate the knowledge and use it effectively in their school not only to help pupils but also to advance the careers and foster the enthusiasm of the teachers involved in the work.

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Abbreviations:

ΑΒΓΔΠ	*Personalized Advanced Cognitive Diagnosis for Children*
ACC	Anterior Cingulate Cortex
CA	cytoarchitectonic areas
CCS	central conceptual structure
CMS	cortical midline structures
DD	developmental dyslexia
DEFT	*Dynamic Field Tomography (project)*
DMN	default mode network
dMPFC	dorsal medial prefrontal cortex
DTI	Diffusion Tensor Imaging
EEG	electroencephalography
fMRI	functional MRI
ICT	Information Communication Technology
ITS	Intelligent Tutoring Systems

KC	K-complex
MEG	Magnetoencephalography
MRI	magnetic resonance imaging
MSRC	midline self-representation core MSRC
n-PRoBA	normal physiological range of brain activity
NREM	non-REM
OECD	Organization for Economic Co-operation and development
PANDIAS	*Prodromal Analysis of Noetic Difficulties with Individual Automated System*
PC	personal computer
PET	positron emission tomography
rACC	rostral ACC
RDoC	Research Domain Criteria
REM	rapid eye movement
SG	Serious Games
sgACC	sub-genual anterior cingulate cortex
TC	Talairach Coordinates
WISC	Wechsler Intelligence Scale for Children
ZPD	zone of proximal development

The three names in italics are completed research projects

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