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HOMO EDUCABILIS: A NEUROCOGNITIVE APPROACH

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The butterflies of the soul

> *As the entomologist chasing butterflies of bright colors, my attention was seeking in the garden of gray matter, those cells of delicate and elegant forms, the mysterious butterflies of the soul, whose fluttering winds would some day – who knows? – enlighten the secret of mental life.*
>
> Santiago Ramón y Cajal (1923)

The Greek name for mind or soul is *psyché*, which is also the name of a species of butterfly. Moreover, Psyche was the name of the charming girl engaged to Cupid, the god of love, who gave her the gift of immortality. Iconography pictures Psyche with butterfly wings, which is an exception to the bird wings of so many spiritual creatures in the art of different cultures. Metaphors are bridges between worlds but, today, the language of science has shifted to 'models' as the only acceptable metaphors able to describe and predict many kinds of phenomena, our mental life, among them. Therefore we should try to go beyond the beautiful myth of Psyche and the prophetic vision of Cajal. In his work the great neuroanatomist was opening the way to a systematic analysis of neuronal growth and plasticity. As a matter of fact the growth cone at the tip of an axon moving in search for a synapse reminds us of the flight of a butterfly. I opened the workshop co-chaired by Kurt W. Fischer and Pierre Léna on *Mind, Brain and Education* at the Pontifical Academy of Sciences in 2003 where we celebrated the 400th anniversary of the foundation of the famous Accademia dei Lincei, origin of our Pontifical Academy, with a short video produced by a young high school student based on Cajal's metaphor where butterflies and neurons were entangled in a fascinating dance.[1]

[1] www.rossinstitute.org/default.asp?nav=publications&content=butterfliesCD

This poetic vision also inspired the work of the International Mind, Brain and Education Society, IMBES,[2] launched at that meeting, and the first summer school (2005) on *The Educated Brain* at the Ettore Majorana Center for Scientific Culture at Erice.[3]

Educability and Human Nature

Human nature has many dimensions and the contemporary sciences have several ways to identify, understand, explain and even predict some of them. One of the unique properties of human nature belongs to the 'educability' of the human being. This is why the expression *Homo Educabilis* reveals a substantial aspect of humanity and, following the classical terminology, 'educability' is a 'proprium' of our species, not a mere 'accident'. Other expressions such as *Homo Ludens*[4] have been analyzed in depth. Perhaps a constellation of human properties may continue to expand, so great is the richness of the *Homo Sapiens*. My thesis is that 'educability', i.e. the remarkable capability to learn and to teach, is based in the extraordinary plasticity of the human brain. As a corollary to that we can assume that the practical outcomes of education, the enormous expansion of schools around the world, the incredible feats of many students and teachers, the sad failures of others, are related to this potential for neuronal change, to the ever changing neural networks in our brains. In this sense we can predict that future interventions in the process of education would take in due account the neurobiological foundations of teaching and learning. As a result of this change of perspective we can understand education as a 'neuronal recycling' process of the brain, in the sense of Stanislas Dehaene.[5] In fact, human brain has not evolved in our species since the inception of formal education in human societies (some 5000 years ago) and to explain the fast growth of learning and teaching in society we need to rely on specific functional changes in the neuronal endowment of individuals. We can draw the conclusion that education unfolds a second nature in the human being because culture can change our brains.

[2] www.imbes.org
[3] www.ccsem.infn.it
[4] Huinziga, 2000.
[5] 2005, in print.

Learning and Teaching Brains. Human and Animal Models

An increasing amount of research has discovered the intimacy of these changes, in particular of synaptic changes during learning.[6] What we lack is a similar insight into the 'teaching brain'. As a matter of fact it is difficult to find brain images of the teaching brain while the study of functional images of the human 'learning brain' is growing at a geometric rate. The human brain is educable in a strong sense, because it can be transformed by education. Educability has two properties, one is related to learning the other to teaching. Most studies in animal and men related to the brain are focused in the learning aspect but we do not have comparable studies in the teaching brain. This is due to the scarce interest in the (neuro)cognitive aspects of teaching in most current psychological and pedagogical research, as has been clearly shown by Sidney Strauss.[7] But teaching is a natural neurocognitive ability, a natural skill in all humans. We teach at all ages. Children as young as 3 years old spontaneously teach other children when they play a new game, first by demonstration later by explanation. At age 5 they have already a well developed 'theory of mind' that allows them to perceive cognitive and emotional changes in the partner, predict and avoid errors during teaching, stop when the apprentice has understood, change the teaching approach when there is an obstacle, etc. With all this knowledge available it is certainly odd that still we do not have images of the teaching brain! Of course we need both sources of the educational cycle, teacher and student, in order to understand the whole process of education. However, the evidence that most, if not all, of our knowledge of brain processes in the course of education comes from the studies of learning and not from teaching is a warning, a signal of a serious bias. Perhaps the reason is that animal models used in many laboratories can tell us a lot about some common learning skills but nothing about human teaching skills. Animals cannot teach in the way humans do, but of course they can learn many things, and this is why animal studies are helping us to understand many human learning processes and about the neuronal plasticity involved.[8] For instance Albert Galaburda (2002) has investigated some specific brains lesions in rats that are similar to human lesions in severe dyslexias.

[6] Huttenlocher, 2002.
[7] 2002, 2005.
[8] Hauser, 2000; Premack & Premack, 1996; Tomasello & Call, 1997.

Certainly rats are not dyslexic but they can show us some intimacies of the mechanisms of dyslexia. Perhaps one of the most radical proofs of 'neuronal recycling' in animals has been offered by the work of Mriganka Sur and his team at MIT. They reoriented by surgery the visual paths to the auditory cortex of ferrets at birth with the result of producing a radical cortical rearrangement.[9] The retinal axons were routed to the medial geniculate nucleus (MGN) and the visual input was relayed from the retina through the MGN to the primary auditory cortex. As a result of these new connections visually responsive neurons in the rewired auditory cortex show orientation modules similar to those groups of visual cells that share a preferred stimulus orientation in the visual area. This is an extreme case of anatomical-induced neuronal recycling in animals, but we can also see in the clinical human practice several good examples related to a cortical functional substitution or 'cortical shift'.

One example is the effect on the cortical visual cortex during the Braille training of blind people.[10] This occipital portion of the brain is normally the site of the primary processing of visual stimuli, letters, for instance, but the blind person is unable to have any access to it. However, the tactile information given by the Braille code is still processed in these visual areas, an unexpected and fascinating discovery indeed. And what is even more important, a systematic training in Braille reading produces significant stable changes in the amount of the visual areas involved in decoding the tactile information given into embossed letters or dots. Moreover the cortical motor area representing the 'reading' finger, increases during the week of intensive training and decreases during the weekends and vacations. This result is one of the first controlled experiments of neuronal recycling in an educational setting. We can imagine in the future many other experiments on brain plasticity related to the educational schedule.

As a complement to this study, physicians use magnetic stimulating devices (Transcranial Magnetic Stimulation, TMS) on the skull to test those cortical areas under the magnet that can be excited or inhibited. A very short pulse can inhibit the cortical functioning under the magnet for a short time and allows the surgeon to localize a lesion, for instance. Alvaro Pascual-Leone and his colleagues have used this technology to investigate the effect of magnetic stimulation of the visual cortex of blind students of

[9] Sharma, Angelucci & Sur, 2000.
[10] Pascual-Leone *et al.*, 1999.

Braille. They discovered that the reading tactile skills can be specifically inhibited or excited by repetitive TMS of different frequencies, clearly proving the involvement of the primary visual area in blind persons. It seems that the visual cortex is recycled into the tactile mode and it is not necessary for the brain to create a brand new neural network for reading Braille. In other words, education is quite conservative at the brain level: we use what we already have, but in different ways. The questions are how do we shift neural circuits? What are the synaptic mechanisms involved in that particular recycling dynamics? How is the recruitment of the visual cortex to interpret a tactile skill as Braille produced? These questions go deep into the nature of 'educability' and brain plasticity.

In the same vein we can interpret as 'neuronal recycling' the use of the same cortical areas for processing sign language and oral language as Laura-Ann Petitto has clearly shown. Deaf babies 'babble' with their hands: 'by hand or by tongue ... there is a common brain activation in sign and spoken language'.[11] This is another example of the remarkable plasticity and parsimony of human brain learning mechanisms. Distance communication, of course, is a main obstacle in the deaf community but the expanding use of networked computers will help to overcome this issue. Incidentally, the deaf pupils formed, in many places, the first cohort of students with access to computer networks, local area networks in the eighties, internet in the nineties, even before mainstream primary school students became connected to the web. In the near future we will have schools extensively connected where all students and teachers alike will enjoy the use of portable and powerful computers, as in the 'One Laptop Per Child' program developed at MIT by Nicholas Negroponte and his team,[12] a program that will involve disabled students as well. Adding to that we should refer to the increasing use of computer prostheses for the disabled, in particular the cochlear implants for the deaf, which is the first brain-computer interface tested with great success in the educational practice. Nowadays many special schools for the deaf have a large proportion of implanted children and we can affirm that the whole practice of deaf education has been radically changed because of that. The deaf child must 'learn to hear' from the very beginning, some of them are now implanted in the first year of life and the teacher wears a microphone

[12] laptop.org

[11] Petitto 1991, Petitto *et al.*, 1998.

which is tuned to the frequency of the hearing aids in order to enhance the quality of the audition. At the same time cochlear implants become more sophisticated and better adapted to everyday life while experts analyze the functional plasticity of language related areas in implanted brains.[13] Again, because of the plasticity of the nervous system the impaired auditory paths can be supplanted by digital artifacts that bring hope and education to thousands of deaf persons around the world. In other words, the 'educability' of a deaf person is enhanced and his inclusion in society is growing, a society which is increasingly globalized.

The 'click option' is a universal asset[14] and plays a decisive role in the case of the disabled persons. When somebody interfaces with a computer into the web a whole world of possibilities is opened. Today we can even 'train our brain' to control a cursor on the computer without any voluntary muscular movement, just 'thinking' to go to the right or to the left and click. This has been experimented in extreme cases with implanted electrodes in the cortex of some patients suffering from a complete locked-in syndrome and who are unable to perform any voluntary movement.[15] Non-invasive techniques arrive at similar feats, by controlling a cursor via eye movements,[16] by biofeedback of EEG records or by voiced commands, as was the case of the talented quadriplegic architect we trained 'to draw with his voice' and produce professional architectural work with a voice recognizer system.[17] These examples dramatically show how much we can stretch our learning capability beyond severe neurological limitations with the help of special digital devices. We verify, once again, in those extreme cases, the remarkable 'educability' of our species. We can always trust in the marvelous plasticity of our nervous system and in our creativity to produce effective prostheses to enhance our cognitive capacities. It is our responsibility to provide this kind of assistance to those who need it.

[13] Guiraud, 2001.
[14] Battro, 2004.
[15] Kennedy *et al.*, 2000.
[16] Farid and Murtagh, 2002.
[17] Battro, 1991.

The Educated Brain

> *The great thing in all our education is to make our nervous system our ally instead of our enemy.*
>
> William James, *The principles of psychology* (1890)

Today we can have a glimpse in the organization of the neuronal nets during the educational process via the powerful imaging techniques available in our laboratories. However the enormous amount of information given about the living human brain should be carefully analyzed if we don't want to fall into a new kind of sophisticated phrenology. It is important to note that many components at different levels interact in a working brain: cerebral blood flow and metabolism, neuronal activity and neurotransmitter dynamics interact with behavior in a closely related manner.[18] We must be cautious to interpret our findings, in particular when we display them in the press without the necessary caveats. Despite the immense effort and the remarkable accomplishments of the neurocognitive sciences we must recognize that we are still exploring the fringes of the mental universe in our quest without end about our human nature. It is impossible to review all the fields of knowledge and culture already explored by the neurocognitive scientists. The arts and sciences, the ethics and virtues, all are under close scrutiny with the help of the most advanced brain techniques. In the following I will summarize only some findings that are relevant to the study of neural plasticity in the process of education. They will shed, I hope, some new light on our knowledge of human nature.

One of the most spectacular effects of culture on the brain function is detected in bilingualism.[19] It has been shown that early bilingualism showing comparable proficiency in both languages is represented in the same areas of the temporal cortex while in late bilingualism the cortical representation is more distributed in different cortical areas. As bilingualism is becoming more and more an asset in the globalized world many educators and policy makers are proposing different strategies but it is plain that some of them, as banning bilingualism in public schools, contradict basic neurocognitive findings. Another case is the prevention and remediation of the troubles in reading and writing so common in dyslexic children around the world. The impressive results of the brain sciences in the understanding of

[18] Kéri and Gulyás, 2003.

[19] Paulesu *et al.*, 2000.

the basic mechanisms of ortography, phonology, grammar, semantic memory, etc, are now helping thousand of dyslexic students to overcome their troubles.[20] On top of that languages differ in many ways and one important aspect is how ortography maps into phonetics, some languages being more 'transparent' than others. Monolingual readers of Italian and English, for example, show different distributions of cortical language activities. In other words different cultures shape differently the linguistic brain. We cannot underestimate the impact of culture on the human brain.

Reading, writing and arithmetic define the common ground of education for all students around the world. While a great variety of languages are investigated by hundreds of neurocognitive scientists in different cultures, arithmetic, instead, has the privilege to be unique, it has the same content and form in every culture: 2+2 = 4 everywhere and always. This universality is an epistemological issue from the point of view of the brain studies. However our mathematical brain can be shaped differently by training and mathematical prodigies show clear particularities in functional brain images.[21] Stanislas Dehaene (1999) and his team in Paris have shown the remarkable differences between the reading of letters and the detection of Arabic symbols at the cortical level. A common parieto-precentral network for elementary calculations has been observed in adults belonging to different cultures and languages. Moreover, the 'numerosity' of small sets of objects is found also in animals and babies and it has been discovered that some individual neurons in the parietal area of monkeys are tuned to some preferred numerosity. This specific area, the same in all individuals, is not the result of training but is the prerequisite of learning arithmetic in humans. A confirmation of this innate capability is that a specific lesion in this region disables the brain and the person will show dyscalculia or acalculia. Quantity representation at the cortical level is one of the most striking features of the mathematical brain and the task now is how to proceed from this quasi-automatic level of detection of numerosity to the most advanced mathematical representations. It will be a long time before scientists arrive to conclusions but the exploration of this path is under way. Mathematics is, without doubt, a touch stone for the study of the *Homo educabilis*.[22]

[20] Wolf, Goswami, in press.
[21] Butterworth, 1999, 2001.
[22] Changeux and Connes, 1989.

It seems that we can also detect in the cortex the traces of a 'conceptual change' such as the shift from Aristotelian to Newtonian physics. Andy di Sessa (1982) some decades ago showed with the aid of computers the amazing difficulty of students to interact in a Newtonian world where forces correlate to velocity and not to position as in Aristotelian mechanics. Most students have a naïve theory, a preferred set of concepts (called phenomenological primitives by di Sessa) that are in contradiction with what they have learned in the physics class but they still use them, for instance the 'impetus' idea or that objects move in the direction you push them. J. Fugelsang and Kevin Dunbar[23] have shown changes in the brain representation of 'Newtonian' and 'naive' movies where balls of different sizes fall at equal or different rates, respectively. They have tested two groups of subjects, physics students and non-physics students looking at these films. The fMRI records an increased activation in the Supplementary Motor Area and in the Anterior Cingulate that may 'inhibit' the naïve theory in the physics students and 'inhibit' the Newtonian theory in the non-physics students. This kind of research opens a completely new field in neuroeducation and will enormously enrich our knowledge of the mechanisms of human educability.

Half a Brain is Enough

Human nature is marked by the most complex system of the world, the human brain. In his remarkable book on *Finite and infinite machines* (1967) Marvin Minsky expressed a profound intuition: 'the human brain is probably too large already to use in an effective manner all the facilities which seem to be anatomically present!'. In fact we are gathering more and more evidence that it is not sheer encephalic volume or gray mass that expresses the overwhelming superiority of our species over other animals with larger brains than ours. Norbert Wiener (1948) half a century ago gave us a provocative view: 'In man, the gain achieved by the increase in the size and complication of the brain, is partially nullified by the fact that less of the organ can be used effectively at one time'. And he gave the example of Pasteur who suffered a cerebral hemorrhage on his right side when he was 46 years old. 'It has been said that after his injury "he had only half a brain". Nevertheless, after this injury, he did some of his best work'.[24]

[23] In press.

[24] See also Valéry Radot, 1922.

The question now, in the context of *Homo educabilis* can be the following: how much brain do we need to learn? My answer is: half a brain is enough. This is the title of my book[25] which relates the story of Nico, a right hemispherectomized child I have studied for ten years, and who is still a source of marvel for all of us. Perhaps he may even become a teacher someday in some specific discipline. In that case he will prove that half a brain is also sufficient to teach. I am convinced that the 'half-brain' studies will become a necessary complement to the well established 'split-brain' studies lead by Roger Sperry and Gazzaniga.[26] They will show us some of the incredible tricks human beings use to learn from the environment in the most extreme situations. The importance of these longitudinal studies should be evident for neuroeducation.

Nico, now 16 years old, cannot do everything with the left part of his body, however he plays tennis, swims, rides a bike and is good at fencing. But he can learn many things in high school in the arts and in the sciences. His right hemisphere was removed when he was 3 years and 7 months old, because of intractable epilepsy produced by polimicrogyria. How can he manage to perform so well with only his left hemisphere? We can compare his performance with another exceptional case, Brooke, a young man, now 22, who had his left hemisphere removed when he was 10 years and 10 months old and was diagnosed with a Rasmussen syndrome with severe seizures at age 9 and 7 months. Brooke is now going to college. Nico never lost his speech after surgery but Brooke became mute and took about 18 months to regain his language. In both cases the basal ganglia and the cerebellum remained intact. A comparative study of the cognitive and emotional strategies of both was done by Mary-Helen Immordino-Yang at the Harvard Graduate School of Education (2005) and can help us to better understand the relations between educability and plasticity. Brooke and Nico were tested in controlled tasks concerning prosody (tone discrimination for sarcasm or sincerity) and emotions (categorizing positive and negative relations and identifying pictures of faces evoking sadness, joy, fear, etc). We know that each hemisphere contributes in specific ways to process emotions and prosody in the intact brain. Both reveal outstanding performances in prosody, for example, but they use different strategies. The strategy for Nico was to rely more on

[25] Battro, 2000.
[26] Gazzaniga, 1970.

categorization (a mostly left hemisphere skill) and for Brooke to rely more on emotions and pitch recognition (a mostly right hemisphere skill). 'Nico was relatively efficient at categorizing based on tone and emotion, but quite poor at making connections between his judgment and the broader social and emotional contexts that would normally inform them'. Brooke, on the contrary, 'brought either emotional or intonational explicity to bear, even on basic discriminatory tasks requiring only categorical judgments'. In other words, 'both boys appear to be compensating so successfully because, instead of changing themselves to suit the problem, they have used their remaining strengths to reinterpret the processing problem itself into something they know how to do'. Immordino-Yang concludes that learners approach new problems differently not simply by 'bringing different strengths to bear on the same problem but may actually be transforming the intended problem in something new'. The author said that 'rather than compensating for their extensive brain damage by painstakingly adapting their remaining hemisphere to take over functions normally associated to the missing hemisphere, both Nico and Brooke appear to have instead transformed the nature of the processing itself to suit the existing strengths of their remaining hemisphere'. I think this is a good way to capture the essence of 'educability' as a proprium of human nature. We can shift cognitive and emotional strategies because the brain has an incredible degree of plasticity, and even half of our brain power is sufficient to cope with most stituations, old and new.

The NeuroLab in the School

As I said before, we should bridge the 'brain gap' between learning and teaching. We need to study the teaching brain with the same interest we are studying the learning brain. We have done practically nothing until now in favor of a neurocognitive approach towards teaching although we know a lot about teaching from many other perspectives. It seems to me that we need to create a new mind set, a corporate task, a teamwork with teachers and neurocognitive scientists. The best place for this encounter of the two cultures, teaching and research, is certainly the school, not the standard laboratory far away from the school and alien to most educational questions. We can imagine a NeuroLab inside a school. The time is ripe for this endeavour, we need to bridge the gap between the laboratory and the school. Of course it is a challenge for both communities of scientists and educators but we have discovered that a small interdisciplinary team can make a difference. We have recently started a Neurolab in Argentina with Daniel P. Cardinali in the Colegio Marín, a traditional school of Beccar, Buenos Aires. In our NeuroLab we have focused on the effects of chronobiology in school performance[27] as a first step towards neuroeducation. We call this Chronoeducation.[28] We are now using low-tech equipment as electrocardiograms to measure the variability of the autonomic nervous system, online questionnaires about sleep habits, etc., but we hope to introduce high-tech devices in the near future. We think that the Near Infrared Spectroscopy NIRS would provide us with relevant data from the functional cortex in the classroom setting.[29] We can imagine, for instance, a class with the students and the teacher wearing head caps with the necessary computer interfaces for the online recording of the activities of their brains during a particular lesson. New portable brain technologies will come to make this dream possible. In all cases we should use our creativity to bring the brain into the classroom.

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[27] www.marin.edu.ar/neurolab

[28] Cardinali, in press.

[29] Koizumi, in press; Petitto, in press.

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