Half a Brain is Enough.
A Case Study in Neuroeducation

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Summary

Neuroeducation is the modern attempt to bridge the gap between the sciences of education and the neurosciences (Battro, Cardinali, 1996). We are possibly reaching the threshold that will permit to look into the living cortex and identify new neural connections during learning and psychogenesis. This will be the new frontier of the "brain wide web" for education in the next century. The case of an hemispherectomized child (age 7) who is performing at the top of his class will be discussed as an example in neuroeducation.

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I. The Two Frontiers

The two great challenges in education, in my opinion, are, first, to expand the cultural external frontier of the "world wide web" of internet and videoconferences and, second, to explore our biological inner frontier, what I propose to call the "brain wide web".

As far as the first frontier is concerned educators are creating the expanding field of “digital education”, via computers and telecommunications. Distance education will become one of the most important educational tasks of the next century. The wealth of modern nations, I am convinced, will be based in their ability to “negotiate education” internationally. Individuals, institutions and nations will have to learn how to generate and distribute knowledge in the large scale of our global village. I have recently discussed these issues in a book I have written with Percival J. Denham (1997) about *Digital Education*, which is also distributed on Internet,(you can download it , free, from our site: www.byd.com.ar). This “dual book” (in print and in bits) is in itself an interesting experiment at the edge of the external www frontier.

I would like now to make explicit the fact that the use of the world wide web in education is strongly related to the way we can explore the intimacy of the brain wide web. Both are related to neuroeducation and what can be called the “intellectual prosthesis”.

II. The Intellectual Prostheses

Intellectual prostheses (IP) are computational devices that interface with human cognitive activities like speaking, writing, reading, drawing, etc. In particular, IP can “open” new cognitive paths in the brain, produce a significant amplification of cognitive performance and the functional substitution of impaired cortical areas (Battro, 1994)

Since the beginning of computation and robotics a great effort has been made to develop "friendly" human / machine interfaces: i.e. voice synthesizers, speech recognition devices, electro-mechanical switches, scanners, multimedia tools, virtual reality, tele-computing, etc. The remarkable growth in the power and speed of computers, and of the corresponding software, stimulate new uses of these machines in most human activities.

1. Human/machine interfaces

The idea of using the computer as a cognitive tool for the disabled was introduced by Seymour Papert at MIT in 1978. He coined the name of "information prosthetics" at a time when few could imagine any possible humanitarian use of computers. This technological and social breakthrough opened new ways to improve the quality of life of physically and mentally handicapped people by employing computers (Valente, 1979). I shall deal here with "intellectual prostheses" as a subset of the more general "informational prostheses". Indeed the latter include "physical prostheses" as well (cochlear implants for the deaf, limb computer stimulation for quadriplegic persons, array of electrodes in the visual cortex for the blind, etc). The "intellectual prosthesis" instead, does not imply any physical and direct contact between the nervous system and the computer. It is a pure "functional" prosthesis not a "physical" one. However it can be expected that both, "intellectual" and "physical" informational prostheses will interact in the future in ways that we hardly imagine today. A good introduction into this subject can be found in the fiction book *The Turing Option* , written by Marvin Minsky, one of the founders of the field of Artificial Intelligence, in collaboration with Harry Harrison (Harrison and Minsky, 1993).

Fig. 1 shows a communication network among humans H, machines M and environments E. This prism offers a global view about the specific links or interfaces: M / M, H / H, M / H, H /E, E /E. When one of these links is perturbed or abolished some new path in the network can be opened by means of specific technologies.

Fig. 1. Links and interfaces between humans H, machines M and environments E.

a) *H/H discommunications.* When "face to face" communication is impaired, as with deaf persons, the computers may bridge the gap. In 1982 we first introduced in Argentina computer networking in a primary school for deaf children (Battro, Denham, 1989). A BBS server allowed written communication (E-mail, conference, etc) among pupils, teachers and other users. We have since successfully experimented with radio-frequency communication (via radio-packet technology and radio low-orbit satellites , Fagundes, 1992). For a deaf person the use of a telephone or a radio equipment is a formidable cognitive and cultural acquisition that became available for the first time in the eighties thanks to improved computer technology. In a sense this "informational prosthesis" solves what we may call the *Graham Bell paradox*; Bell was also a dedicated teacher of the deaf but is remembered as the genial inventor of the telephone, unfortunately the telephone excluded the deaf user for almost a century! Communication among deaf people or users with speech impairments and a common audience, a tele-computing link

H / M / M / H can be established easily with the help of new informational devices that transform written text into voice and vice versa. This path "bypasses" the communication obstacles at the audio-speech H / H interface.

b) *M/H* obstacles can be classified essentially in two groups,
motor : for example a motor disabled person cannot easily type on the computer keyboard, and *sensory* : a blind person cannot read the messages on the computer screen. A great number of devices are now available at the market that overcome most of the M / H barriers of sensory or motor origin. (Borden, Fatherly,Ford, Vanderheiden, 1993).

M/H motor interfaces are being developed very rapidly. Among the most used in rehabilitation and special education are switches that replace the keyboard, touch screen devices, very large or miniature keyboards, "unicorns" that allow users to type with their head, devices that control the computer with gentle head movements or eye movements alone, voice recognition equipments that empowers speech to program and use a computer. *M/H sensory interfaces* include voice synthesizers that transform computer characters on the screen in artificial speech and produces a reasonable auditory information added to the standard visual format of written texts. Vision impaired people as well as young children during their learning process to read and write are frequent users of this friendly interface that can be coupled with any modern personal computer.

c) *M/M links.* The old personal computers or PCs, have been transformed nowadays into truly *inter-personal computers*. An isolated computer will become a rarity in the near future, every machine will be interconnected via Internet, or the like, and so millions of people. The M / M link of Fig. 1 includes channels of communication via modem, telephone lines, satellites, optic fibers, radio-frequency, etc. A direct consequence of this link is the building of a "24 hours-society" in planet earth. This fact sheds a light of hope for the education and work of our brothers and sisters that cannot move, speak, see, or learn at the proper pace required by modern living.

d) *H/E links.* When a man opens the door of his house, takes his car out of the garage, travels to his work, controls a huge machine with the help of levers and buttons, he is changing his environment, he is acting upon artificial or natural objects and systems. A common journey is a very complex path in the human environment. Unfortunately many physical objects become obstacles to people unable to use their hands, walk, hear, see, or are mentally disabled to process the complexity of our everyday world. Computers may help to overcome these barriers. Robots can do the work of humans, houses can be transformed into "intelligent homes", navigational devices can help our displacements. In our educational experience even disabled children may take advantage of the use of robots as instructional tools. For instance "Lego-Logo" interfaces provide micro-environments of great cognitive potential for them (Papert, 1980, 1996). Handicapped adults can move into intelligent houses with enough automation and control for independent living. This field is growing at an increasing speed and many kinds of *H/E interfaces* are now available or under study.

2. Amplification of cognitive performances

When using computers with the handicapped we may perceive several dramatic changes in mental activities and specific behaviors. Essentially the subject becomes more motivated, emotionally satisfied and shows significant improvement in his cognitive performance. I will give now two examples.

Learning to write. Mentally handicapped persons can dramatically improve their writing abilities with the use of computers. **Fig. 2** shows the learning curves of four mentally retarded subjects using a simple word-processor. After a latency period, that varies between 2 and 40 hours, the subject can manage to write 20 words (mostly as a copy of some printed text). Then a most remarkable "explosion" in the quality and quantity of writing takes place until a plateau is reached. The four subjects have different pathologies: S1. Age 18: mild mental retardation, S2. Age 20: borderline, spina bifida, quadriplegia, S3. Age 17: Down syndrome (trisomy 21) and S4. Age 16: autism with visceral and somatic malformations. All show a similar acceleration of their written output (a similar slope of the learning curves) after a specific delay. It must be emphasized that standard special education and rehabilitation practice might never show a comparable development in writing abilities. A significant learning acceleration is the rule when computers and word processors are used as intellectual prostheses for reading and writing. This implies a fairly long time of training, a condition that is not always fulfilled in common practice.

Fig. 2 . Learning curves using computers to write, by four mentally retarded adolescents.

A simple explanation of the permanent delays in the process of acquisition of new abilities by the mentally handicapped persons is that the brain needs a long period of activation to trigger a new way of doing things. For instance, standard learning offers poor intellectual feedback because of the very short span of attention of the mentally retarded. Therefore no long-term memory can be firmly established and learning of any intellectual valuable skill is impaired. Without the help of computers it seems that the training never reaches the threshold that opens new cognitive paths. But this remains to be proved with the help of the new non-invasive techniques like PET, nuclear magnetic resonance and the like.

Fifteen years of clinical observation with hundreds of disabled persons have shown us that perhaps a logarithmic scale should be used in order to measure the cognitive changes produced with the help of an intellectual prosthesis. As a matter of fact many psychophysical laws are intrinsically logarithmic, and our consistent observation in clinical practice could be related to deep changes in brain activation, that remain undetectable even with the most advanced technologies. The first changes are usually produced after 10 hours of practice (Figure 2 depicts the considerable delays to reach a meager 20 word per hour level!). After 100 hours a plateau can be attained. But a new scaling factor is triggered and a new explosion in the written output could be observed after 1000 hours of computer work, when many disabled students can attain a reliable rate (for those who think that this is too long please recall the 50 000 hours that a chess master needs to work on chess boards to excel in international competitions, but it seems now that even so he will not defeat a machine like Deep Blue!). Usually the first 100 hours of computer practice are quite difficult and cannot be compressed into few weeks. It takes almost 10 months for a mentally retarded student to assimilate the first 100 hours of computer work but the training can be accelerated after this first stage (mostly by home-work). This time consuming, and expensive training, requires a firm chain of solidarity and care in order to foster higher levels of performance. But the results are certainly worthy of this effort. Several of our mentally retarded students have been socially and economically integrated after two years work with computers and became good copyists and reliable data-entering clerks. Automatic translation, dictionaries and glossaries, improve the polishing of the written text, error correction and final editing. This acquired ability engages the disabled person in a truly competitive intellectual work, instead of being limited to do simple manual abilities that are badly paid or overprotected in special workshops. The worst possible attitude is to disengage a mentally disabled person from the intellectual work! The intellectual prosthesis, on the contrary, enables the subject to close the gap with his own cognitive capabilities and also with the intellectual world.

Some *threshold* needs to be reached after a training period of computer practice. The clinical difficulty is to keep the subject active during the long and boring latency period, that can be long enough to inhibit further learning - because of the lack of satisfactory feed-back - or even disappoint the instructor because of permanent poor results. We may interpret the accelerated segment of the written performance and the correlated decrease of errors as a behavioral sign of the opening in the brain of new cognitive paths for writing. Some day, it can be safely predicted that new non-invasive techniques for brain imaging should add reliable data at the neuronal or even molecular level.

Learning to draw.

The second example is related to the prosthetical applications of standard *Computer Assisted Design* (CAD) to students or professionals unable to use their hands to draw. The computer input can be given by speech using a voice recognition device with a microphone coupled with the CAD system. The remarkable feature in this case is that the informational system totally bypasses the area for motor control of arm, hand and fingers. The computer instructions to make a drawing can be vocally given and by this interface it has been possible, for instance, to train a quadriplegic architect to return to his professional practice after the outcome of a multiple sclerosis. The learning began with the voice control of a "screen turtle" using Papert's Logo language (Papert, 1980), first with simple instructions like *Forward* and *Right* to draw two dimensional pictures, then with the help of Reggini's few but powerful 3D Logo instructions (like *Pitch, Roll* and *Veer*) that can draw very complex figures in space (Reggini, 1985). Once this elementary stage with voice-controlled Logo was reached a systematic training with voice-controlled CAD produced in few months remarkable professional results (Battro, 1990).

3. Neuronal and cognitive paths

It is interesting to analyze from the neuro-cognitive point of view the differences between the prosthetic practice with speech recognition devices and the standard CAD drawings by instructions typed on the keyboard. It must be said that a good deal of training is always needed for an architect or to a painter to bypass, by way of CAD, the common gestures of drawing and sketching. The difference between both situations, typed or vocally produced instructions for computer drawing, remains in the cognitive paths having been activated in the brain. It is known that many different cortical areas are involved in saying a word. Even the cerebellum is active during a simple speech utterance (Posner, Reichl, 1994). Other cortical areas however are involved when moving the hand, as in the act of drawing.

The computer used as an intellectual prosthesis functions as a bridge to pass from one modality (hand-drawing) to the other ("speech-drawing").

Fig 3. shows this functional "cortical switch".

Fig. 3. The intellectual prosthesis can switch the brain from one cognitive mode (hand drawing) to the other (speech-drawing)

It is certain that the talents of draftsmen and painters are related to the cortical processing of spatial images (mostly in the right hemisphere) and to the motor control (by the left hemisphere) of our (right) hand (the inverse for pure left-handers). Therefore many "agencies" in both hemispheres in the sense of Minsky must be activated to produce the most simple drawing (Minsky, 1989). How many of them should then be active to produce the detailed layout and computerized images of a building! The finding reported here of an architect who made high quality 2D and 3D technical drawings "with his speech" encourages us to explore the detail of cognitive specific paths of the brain when intellectual prostheses are in use.

"Drawing by hand" is a typical "analogical" ability. "Drawing by speech", instead, is digital, in the sense that uttered sentences are chains of discrete elements like words, syllables or phonemes. Space cognition includes space perception, space memory, space images and 2D and 3D representations. When drawing by hand the cognitive paths must be opened to continuous motor control. This is not the case when the artist is drawing by speech with the aid of a computer, because of the digital nature of speech. There is perhaps a kind of a "navigational device" in these case too, but of a different nature. For instance, it would be difficult if not impossible for an aphasic artist to make a drawing by computer using only speech instructions because of his specific linguistic impairment. On the contrary, the analogical cognitive path used to make a drawing by hand may remain intact. It is recognized that right-handed draftsmen can produce the same pattern as left-handed ones, i.e. from the quality of the drawing it is quite impossible to distinguish among brain dominances. Moreover clinical practice shows that many right-handed hemiplegic aphasics can perfectly relearn to use the left hand to draw and paint, even with severe (written or spoken) language impairments.

One thing is certain, before the introduction of computers no human mind has ever produced a drawing by speech instructions alone! (although in ancient Peru the Inca architects were called "the men that give orders aloud"). We cannot imagine Michelangelo making the plans of Saint Peter by telling some assistants how to produce a detailed layout step by step, or painting the Sixtina shouting to his aids to "put a red there" or "trace a line here". Nowadays, however, this exploit is technically possible. When a human operator uses his speech in order to draw he activates a new neuronal network of his brain that was never before engaged in the act of drawing. Only a computer can make this brain-switching possible. *This switching to a new cognitive path is the essence of any intellectual prosthesis.* In other words, intellectual prostheses help the brain to perform some cognitive tasks that were normally processed by a quite different area of the cortex. Neuronal networks can be substituted or bypassed by new cognitive paths driven by computer instructions. This fact has very important consequences in clinical practice and special education.

The availability of non invasive techniques now in place in many institutions will certainly help to understand the incredible plasticity of our brain. The computer permits the neuro-imaging of cognitive paths at the same time it provides the tools for the opening of new ones when used as intellectual prosthesis. This impressive technological feat enhances our moral and scientific responsibility. We have already the means to improve the quality of life of the disabled persons in many fields. We will need a surplus of wisdom to do it correctly and certainly a definite ethical involvement with those who need all our solidarity and love.

III. Left and Right Brains.

A large litterature can be consulted nowadays in relation of left-right brain dominance. This is an essential problem in neuroeducation because it is related to the epigentical development of intellectual functions.

Some day non invasive techniques should show the different paths involved in cognitive growth too.

I would like to summarize some old experiments (Battro, 1981) related to our main subject today. Four classical Piagetian tests were submitted to right handed and left handed children to manipulate the objects of each test (clay, sticks, marbles, etc.) in a blind situation with only one hand at a time.

In **Figs. 4** and **5** we could show that for "concrete operations", like class-inclusion or conservation of substance and for "formal operations", like probabilities, the right-handed children performed at higher Piagetian level when using their left-hand! The inverse phenomenon occurred with spatial concrete operations as in the conservation of length of a rod. However no difference in performance among hands were found for the left handed group where a larger bilateral representation of some cognitive functions have been detected (Satz,1979).

Figs. 4 and 5. Piagetian concrete and formal operations performed by the left or the right hand in a blind task.

From the topology of the neural pathways we know that the information gathered from the left hand goes first to the right hemisphere and then via the corpus callosum reaches the left hemisphere in a second step. Thus the left hemisphere (related mainly to logical processing) “needs” the previous contribution of the right hemisphere (related to spatial processing) for the logical tasks. Conversely the right hemisphere needs the left one for the spatial processing and that was attributed to some cognitive specificity related to each hemisphere. In Marvin Minsky’s terms this route will encounter a larger number of “agents”, a good strategy for the mind (Minsky, 1986).

The neuronal paths taken by both types (logic and spatial) of operational thinking, were perfectly crossed:
a) For conservation of substance, class inclusion, probabilities:
Left hand-right hemisphere-left (logical) hemisphere
b) For conservation of length:
Right hand-left hemisphere-right (spatial) hemisphere.

These results suggested also a neurocognitive difference between the preoperational and the operational brain. Now, the remarkable advances of neurosurgery and clinical neurology have given new foundations to this kind of research. In particular the removal of a whole hemisphere as a treatment for some serious pathologies or injuries shows that we can proceed further in the study of the neuronal pathways involved in specific cognitive processes. Also the extended use of non invasive technologies such as PET, MRI, etc, provides new tools for the inspection of brain processes in cognition.

IV. Half a brain is enough

Functional hemispherectomy - an alternative to the classical complete anatomical resection- is a surgical intervention which is becoming more frequent as a treatment for children with intractable epilepsy. After surgery, even if half the cortex of the brain is removed or disconnected the basic brain functions remain intact, the diencephalon which regulates emotions and several body functions, the cerebellum which controls movement as well as the brain stem related to life-support systems.The expectation for a reasonable good life after surgery has increased and remarkable recoveries have been reported. It has been repeatedly shown that language and other motor and cognitive processes will develop normally, depending of the time of the surgical intervention, in the case of a right hemispherectomy and that even in left hemispherectomies language acquisition, which is strongly impaired, still improves with practice (Bach y Rita, 1990, Benecke et al., 1991, Muller et al., 1991, Varga-Khadem et al., 1991, Villemure, Rasmussen, 1993). The number of children being submitted to this kind of radical intervention is growing and accordingly the requirement for a better neuroeducation will increase.

We shall describe a child who has suffered a functional right hemispherectomy when he was 3 year old. As a result of this major surgery epileptic seizures completely disappeared and the child recovered amazingly well. He now shows 4 years after the intervention, only a mild limp and a limited use of his left arm and hand. He also has no left peripheral vision in either eye, but has developed a peculiar way of moving his head in order to center his sight. He types on the computer with his right hand, uses the mouse correctly, and is also learning to write and draw with a pencil, following the same steps as his class mates, now in his second grade of the elementary school. He is now a perfectly normal child with only some movement restraints that do not affect his will to play games outdoors and participate as far as he can in group sports. And what is more remarkable, he is a brilliant student at school, at the top of his class.

Figs. 6 , 7. MRI after a right functional hemispherectomy performed in a 3 year old child.

In the case described here we have started a strategy to help the child, the family and the school in the global process of education and also implemented some pedagogical actions toward the use of new technologies such as computers from the beginning of his schooling. But most important a team of teachers and psychologist has been organized to keep permanent track of how “half a brain develops into a full mind”. I understand this program as a model of what we may call “neuroeducation”. The following results will summarize some psychological findings about his cognitive capabilities (Battro, 1996).

Video (5’): A Piagetian session, classification and seriation. Play and laterality.

First of all it must be said that our pupil is a very nice child, full of enthusiasm, very active and deeply affectionate , well integrated at school and learning at a normal pace. He shows astonishing language proficiency for his age and has acquired literacy in a very short time. He reads and writes well above the average of his class, partly because he is favored by the use of a lap-top computer at home and at school, partly because he could be described as a typical “verbalizing” and “visualizing” child (Gardner, 1982).

Figs 8, 9,10, 11,12. Written comments with the help of a word processor.

Also he likes music and performs very actively in the musical events of his class. He has remarkable memory and curiosity in every field of his interest. He can be overactive, dispersed or tired during the long school hours, and this was felt as a real handicap at the beginning but he has significantly improved in this aspect. We have not detected a specific “attention deficit disorder”, which is so common at this age. He is only somewhat limited in the activities of design and drawing but he is continuously improving even in those fields which depend strongly on spatial processing, a cognitive function related to the right hemisphere (Franco, Sperry, 1977).

We are periodically submitting him to various classical Piagetian tests and can affirm that his mind develops in the normal way described by innumerable authors around the world (Piaget, Inhelder, 1963). We didn't find any sign of impairment or underdevelopment of his cognitive abilites. Moreover in some logical aspects he shows a faster pace than most of the children of his class. We have observed that he has reached the stage of the conservation of quantity in the 1-1 correspondence, using the computer as a tool, at age 5. This is an interesting point because only 50% of the children of his age reach this stage III (Piaget and Inhelder, 1963). In the test of seriation of rods of increasing length we adopted the computer to draw lines of different colors in order to improve his motivation. In that case we obtained a typical response of stage I, found in some 7% of children at age 6 and now at 7 he has proceed further in seriation with a correct intercalation of rods (Piaget and Inhelder, 1963). The conservation of substance was tested in the standard situation with two small and equal balls A and B made out of clay. The child confirms that they have the same amount of clay, even if B is transformed into a sausage B'. The arguments given were related to the conservation of "identity" under transformation. He has reached a full conservation of substance when tested at age 6;4, as do only 16% of children according to the classical Genevan studies (Piaget and Inhelder, 1963).

Instead at the same age he was a non conserver for the quantity of liquid. The conservation of liquid was tested using a simplified technique: two transparent glasses of identical shape and volume (A, B) have the same amount of water, when the child confirms the equality the water of one glass (A) is poured into a larger but shallower glass container(A'). The question is if there is the same amount of water in B and A'. Tested when he was 6;5 he gave non conservatory answers using arguments that were similar to those reported by 40% of children of the same age: "A' has less water because it's lower", etc. but tested 7 months later he has attained conservation (Piaget and Inhelder, 1963).

Concerning the representation of the horizontal level of a liquid inside a tilted glass with red liquid, at age 6 his drawings were already the most developed in relation to his whole class (N=29) ! This is quite striking because his spatial processing is entirely "forced" into his left brain, and most researchers agree that the right hemisphere is responsible for geometrical tasks (Franco, Sperry, 1977).

When he was tested at age 6 in logical thinking as class inclussion with a collection of small A and large beads A', he could answer correctly by counting them, but he couldn't properly quantify the subclasses in relation to the whole class B of “all” beads (A+A’=B). Only 13% of children at his age quantify class inclusion (Piaget and Inhelder, 1963).

These are only some partial results of a larger survey we have decided to make in order to construct a detailed cognitive map of his mental development. We think that the eventual identification of specific “décalages” will offer valuable information towards a better understanding of the cognitive specificities of a complete brain reorganization induced by a functional right hemispherectomy.

We can also try to summarize our findings using Howard Gardner’s framework of multiple intelligences (Gardner, 1985). Our young pupil excells in interpersonal skills (he is a leader) and intrapersonal insights (he makes astonishing comments about himself in every possible occasion), his linguistic performance (both written and verbalized) is really remarkable, he is also very able in music and logical-mathematical reasoning, but has a systematic deficit in his spatial abilities (in the drawing tasks) and, being hemiplegic, in his bodily-kinesthesic activities.

VI. Genetical and epigenetical models

The normal cognitive development of an hemispherectomized child, like our pupil, is for everybody a permanent source of wonder, at school and at home. Also from the theoretical point of view this remarkable case merits a closer epistemological consideration. In relation to this subject we shall briefly discuss the two different paradigms of Noam Chomsky and Jean Piaget, Both perspectives have yielded along the years a large collection of contradictory arguments, in particular since the celebrated Royamont debate (October 1975,) between both scientists (Piatelli- Palmarini, 1994). I would like to add some interesting comments from Marvin Minsky too.

As it is known Chomsky emphazises the need to study the cognitive structures (in particular language) as “mental organs”, in the same way we study any physical organ like the heart or the brain itself . He explicitly refuses the Piagetian constructivist approach of a sequence of cognitive stages developing from the sensory-motor schemes to the higher formal operations. He thinks that the mental organ of language has an ontogenetic as well as philogenetic history which unfolds the genetic program of the species. Piaget instead, affirms that “only the functioning of intelligence has an hereditary basis but the production of (cognitive) structures is given by the organization of successive actions upon the objects” (ibid, p.53).

Now we can add some impressive results from the neurocognitive sciences that were out of reach at the time of that debate. As we had reported Piagetian mental operations develop in the expected order when only half a brain is available. There is no such a thing as an “incomplete mental organ”, as might occur in several organic deficits and embriogenic pathologies where only a portion of the specific biological tissue has fully developed. Nor can we find an “incomplete logical reasoning” when the subject has been hemispherectomized. We observe instead a fully accomplished reasoning in a child with only one hemisphere, never a half reasoning with a half brain! It seems to me that the Chomskian hypothesis about a mental organ is not valid under these circumstances. Instead the Piagetian idea of cognitive equilibrium (Piaget, 1967) between assimilation and accommodation, between the subsystems of a system and inside a new global system (“équilibration majorante”) might offer some explanation for the reorganization of mental processes under the strain of a functional hemispherectomy, an extreme case of cognitive re-equilibration after a massive neuronal perturbation.

As a matter of fact, under medically favourable circumstances, a small child can loose half of his cortex but still will accomplish the same mental processes we attribute to the intact brain. Incidentally, I wish to remark that half a very great number of neurons is still a *very* great number of neurons! We are all submitted to a kind of “scale illusion” when dealing with power functions. I would like to propose to you the following mathematical test, that is somehow related to the set of “cognitive illusions” described by Amos Tversky and Daniel Kahneman (Piatelli-Palmarini, 1993). It has been calculated that the whole adult brain has approximately 10^{14} synapses, an incredible high number of elements indeed! The hemispherectomized individual has “only” half of these 10^{14} synapses, but this figure is also a very high number ¿Can you compute now this number? It is 5. 10^{13} and certainly not, as some perhaps might have guessed, 10^{7}.

It is well known that during embriogenesis and immediately after birth a significant destruction of neurons occurs physiologically, a process that has been described as “une hécatombe neuronale”, a neuronal devastation (Changeux, 1983). What should be then the term to express the elimination of thousands of millions of neurons and synapsis by hemispherectomy! It is hard to imagine any “mental organ” surviving such surgery. But the reconstruction of the whole cognitive processes in these children implies a radical reorganization of the neural paths in the surviving hemisphere. In the case reported here the right brain functions have been reconstructed into the left hemisphere. We would certainly need to know if the remaining hemisphere uses a larger number of neurons in order to compensate for the lost hemisphere (Adelson et al.,1995) as metabolic requirements put a limit to the number of neurons that can posssibly be active at the same time. Non-invasive brain images provided by PET and fMR can certainly give valuable information in these cases where removal of large sections of neural circuitry has been performed. But this implies a careful protocol submitted to ethical commitees before clinical research could be recommended.

Finally I would like to quote also some interesting comments from Marvin Minsky (1997) about this particular case. “I don’t deny that there are are important predispositions for specialization in brain - but my guess is that these are largely optional. My theory: after a certain point in development, when the child has acquired many different resources for thinking then (in accord with what I called “Papert’s Principle”) it becomes necessary to build higher level systems to manage those resources. Now, higher-level thinking requires deeper and more sequential operations. This is because a system that tries to do many things in parallel will therefore become more “fragmented” - in the sense that the different activities will have to compete for limited resources of various sorts. If this is permitted then each of the parallel process will become more stupid. It is a myth that it is good to use “parallel distributed” processes - because this leads not to cooperation but to mutual interference.

Accordingly, as a child developps higher systems, it becomes necesssary to “break” the right-left stmmetry! A deep intellectual process can serve only one master! So normally, one side of the brain becomes the master at deliberate sequential planning. What happens to the other side? My conjecture: in the end, it becomes largely wasted - because it remains childish while the other side matures! This is why, in split brain adults, the (usually) right side seems more romantic, less critical, more imagic, less symbolic,etc. It is because it has been left behind, because it has less well developed managers.
Now (more conjecture), the managers have simpler jobs, really, than the system that finally do the work; they use only a small proportion of the brain. In the case of your child, there is not much loss-because it only lacks a largely redundant “childish” copy”.

I must say that Minsky's interesting reflections about the loose of one hemisphere are inspiring and can suggest some cognitive experiments too.

Conclusions

The most significant result of this study is perhaps the striking autonomy of mental operations regarding the integrity of the brain tissue. With "half a brain" our child shows the same kind of argumentation and reasoning as has been reported in normal children of his age. An important finding is that his pre-operational thinking is evolving toward full concrete operations following the same steps that were described by Piaget. Now at 7 he is performing brilliantly at school where he has achieved remarkable literacy skills and is reaching concrete operational levels in several cognitive tasks.

The successful activation of alternative neurocognitive paths in this child reflects the amazing plasticity and redundancy of brain connectivity, the enormous power of the human brain wide web. Brain plasticity, redundancy and cognitive transfer from one hemisphere to the other certainly offer new insights into psychology and education. A senior journalist wrote about 8-year-old Matt, another hemispherectomized child: "I can imagine Matt telling his dates ten years from now -You won't believe this, but I have half a brain- " (Swerdlow,1995). I expect this intimate confidence to become the most natural comment in the near future of these hemispherectomized children. Under favorable circumstances we can say now that "half a brain is enough".

Neuroeducation is a new field of expertise and will become necessary not only in extreme cases like the one we have described, but in general. Our brain is the inner frontier of knowledge.

Aknowledgments

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