

Intellectual Prostheses. Theory and Practice.

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Summary

1. Intellectual prostheses (IP) are computational devices that interface with human cognitive activities like speaking, writing, reading, drawing, etc.
2. IP open new cognitive paths in the brain, produce a significant amplification of cognitive performance and the functional substitution of impaired cortical areas.
3. Education and rehabilitation: IP are employed to improve human performance, in particular of physically or mentally disabled persons.

*Nec manus, nisi intellectus, sibi permissu, multam valent;
instrumentis et auxiliibus res perficitur.*

Francis Bacon, *Novum Organum*.

I would like to quote Sir Francis Bacon's *Novum Organum* to introduce the concept of intellectual prosthesis: *nec manus, nisi intellectus, sibi permissu, multam valent; instrumentis et auxiliibus res perficitur*. Bacon's *instrumentis et auxiliibus* are our "prosthetic devices". The psychologist Jerome Bruner rightly translated "neither the hand nor the mind alone, left to itself, would amount to much". And he asked: "what are these prosthetic devices that perfect them?" (Bruner, 1986).

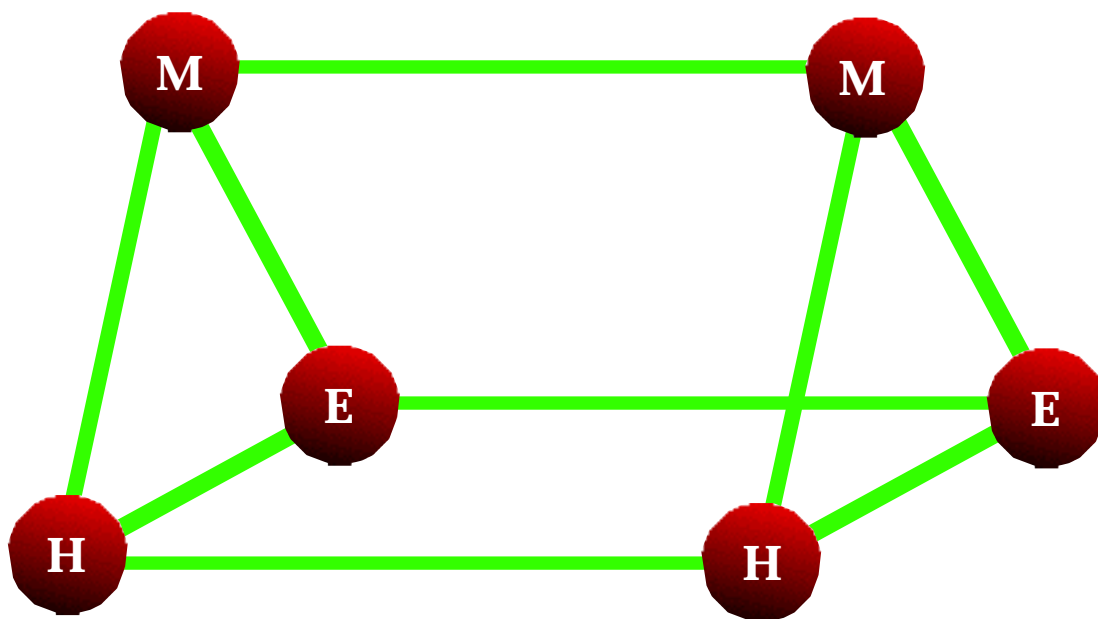
The answer may be: the computer. Since the beginning of computation and robotics a great effort has been made to develop "friendly" human/machine interfaces: i.e. voice synthesizers, speech recognition devices, electro-mechanical switches, scanners, multimedia tools, virtual reality, tele-computing, etc. The remarkable growth in the power and speed of computers, and of the corresponding software, stimulates new uses of these machines in most human activities. In this paper I shall deal with the application of computers in the field of neuro-cognitive sciences, in particular in the education and rehabilitation of the disabled person.

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 (Papert and Weir, 1978). 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). In

this report I shall deal 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 science-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. I shall summarize now our clinical and educational experience in this field.



H: Human
M: Machine
E: Environment

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 and Denham, 1989). A BBS server allowed written communication (E-mail, conference, etc) among pupils, teachers and other users.

After the first 10 months of training the number of electronic messages produced by the deaf children in this school increased from 30 to 600. Fig. 2 shows a picture of the relative significance of computer links and users in the network at a given time. We have since successfully experimented with radio-frequency communication (via radio-packet technology and radio low-orbit satellites) with the same deaf children. Radio-packet technology has the important advantage of free communication. Interesting experiences with radio-packet and the deaf are now in practice in Brazil (Fagundes, 1994). 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 a dedicated teacher of the deaf but is remembered as the genius who invented the telephone, unfortunately the telephone excluded the deaf user for almost a century! The new communication path thus established is H/M/M/H, via telephone lines, direct networking or radio coupled with computers. We should mention that a good example of a telephone/computer interface is given by *Minitel* in France, a public system that completely changed communication among disabled users on a very large social scale.

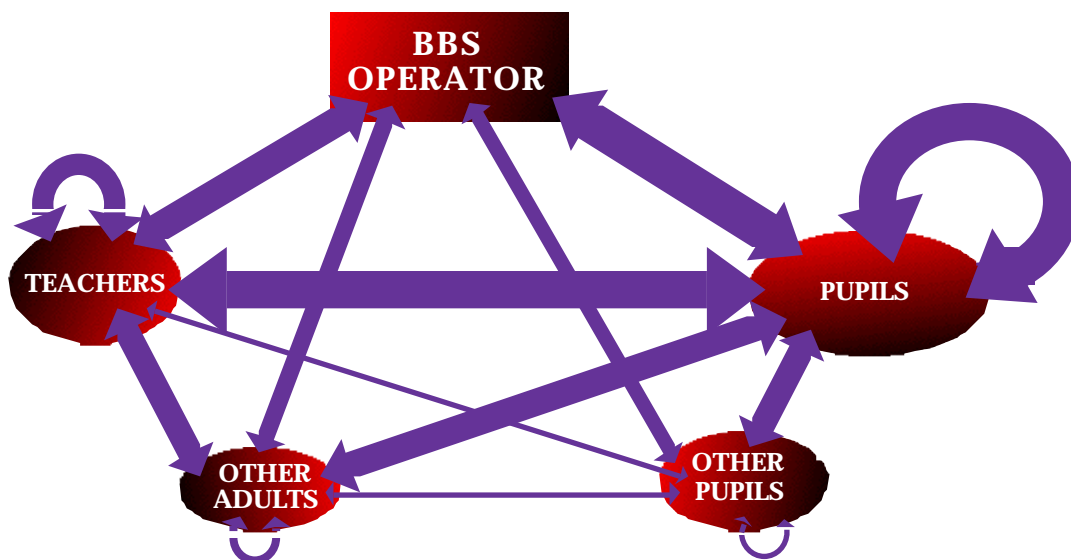


Fig. 2. Computer networking in a school for the deaf. The relative number of communications and users is represented by the size of the arrows and nodes.

Also for communication among deaf people or users with speech impairments and a common audience, a tele-computing link H/M/M/H can be established 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. Recently a remarkable catalogue in CD-

ROM with a detailed list of more than 17 000 assistive products, recordings of 50 different speech synthesizers and special software for the disabled has been published. In this particular case a blind person can even navigate through the CD-ROM and "hear" what he is actually browsing (Borden et al., 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 operate a computer. *M/H sensory interfaces* include voice synthesizers that transform computer characters on the screen into artificial speech and produce reasonable auditory information added to the standard visual format of written texts. Vision impaired people as well as young children during their learning process of reading and writing are frequent users of this friendly interface that can be connected to 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, 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 hour-society" on planet earth. This fact sheds a light of hope for the education and work of our brothers and sisters who are unable to 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 those people unable to use their hands, walk, hear, see, or who 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 movements. 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, 1993). 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 two examples now .

Learning to write. Mentally handicapped persons can dramatically improve their writing abilities with the use of computers. Fig. 3 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's 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.

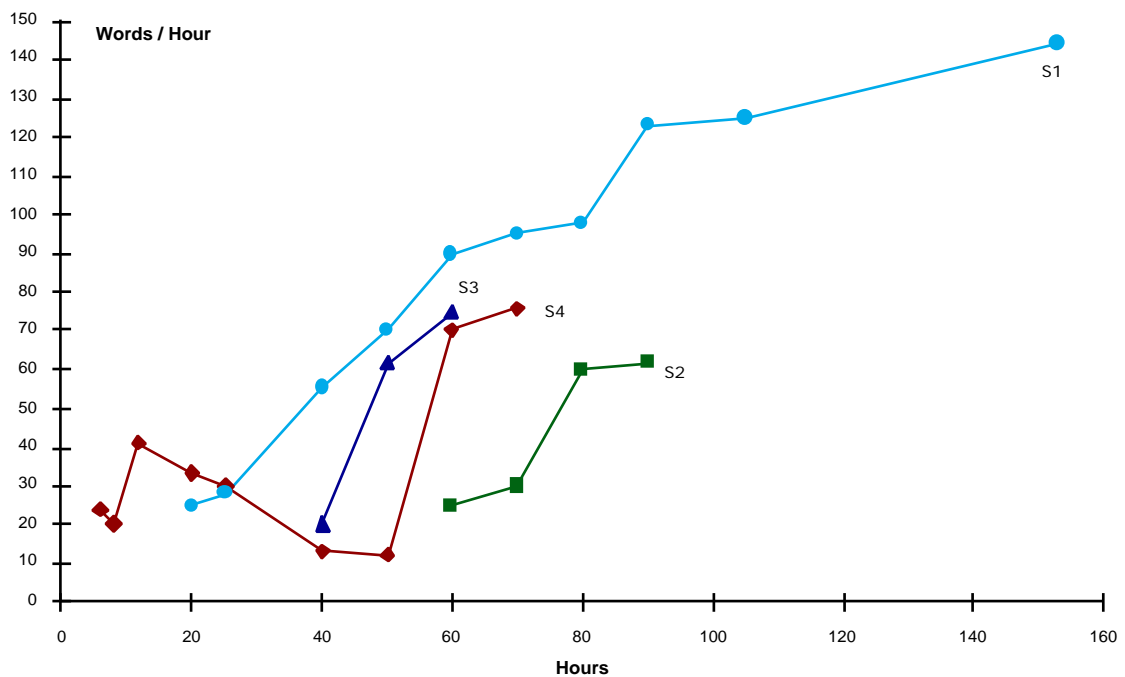


Fig. 3 Learning curves using computers to write, by four mentally retarded adolescents.

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 attention span 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 proven with the help of the new non-invasive techniques like PET, nuclear magnetic resonance and the like.

The phenomenon of cognitive amplification becomes evident also during telecommunication via computers in the rehabilitation of aphasic persons. It is necessary to create new habits of electronic mail and tele-conference between the user and the instructor. A great deal of patience and time is needed but the results are encouraging. This was the case with an aphasic patient with a permanent deficit in speech and very limited motor abilities with his right hand. His handwriting was severely impaired although he has managed to become a good painter with his left hand. With the prosthetic help of the computer he has shown a significant improvement of the length of the written messages (measured by the number of words per sentence). After 25 hours of training he improved from a poor average of 4 words per sentence to a maximum of 22. Also the number of one-word messages were reduced from 18 to 8. His impaired linguistic cortical networks were somehow "bypassed" with the help of the intellectual prosthesis at work. We assume that new cognitive paths became active in his brain.

Fifteen years of clinical observation of 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 3 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 can 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). 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, imply a firm chain of solidarity and care in order to foster higher levels of performance. But the results are certainly worth the 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 polish of the written text, error correction and final editing. This acquired ability engages the disabled person in a truly competitive intellectual activity, instead of being limited to do simple manual tasks that are underpaid or overprotected in special workshops. The worst possible attitude is to disengage a mentally disabled person from 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 feedback - or even discourage the instructor

because of continuing 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 multiple sclerosis. The learning began with the voice control of a "screen turtle" using Papert's Logo language (Papert, 1981), 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 remarkable professional results in a few months (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 required for an architect or 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 areas are involved in speaking: Broca and Wernicke areas, some bilateral areas of the motor cortex, the supplementary motor cortex, the insular cortex and even the middle cerebellum are active during a simple speech utterance (Posner and Raichle, 1994). Other cortical areas however are involved when moving the hand, as in the act of drawing. The computer used as an intellectual prosthesis works as a bridge to pass from one mode (hand-drawing) to the other ("speech-drawing"). Fig 4 shows a simplified representation of this functional "cortical switch".

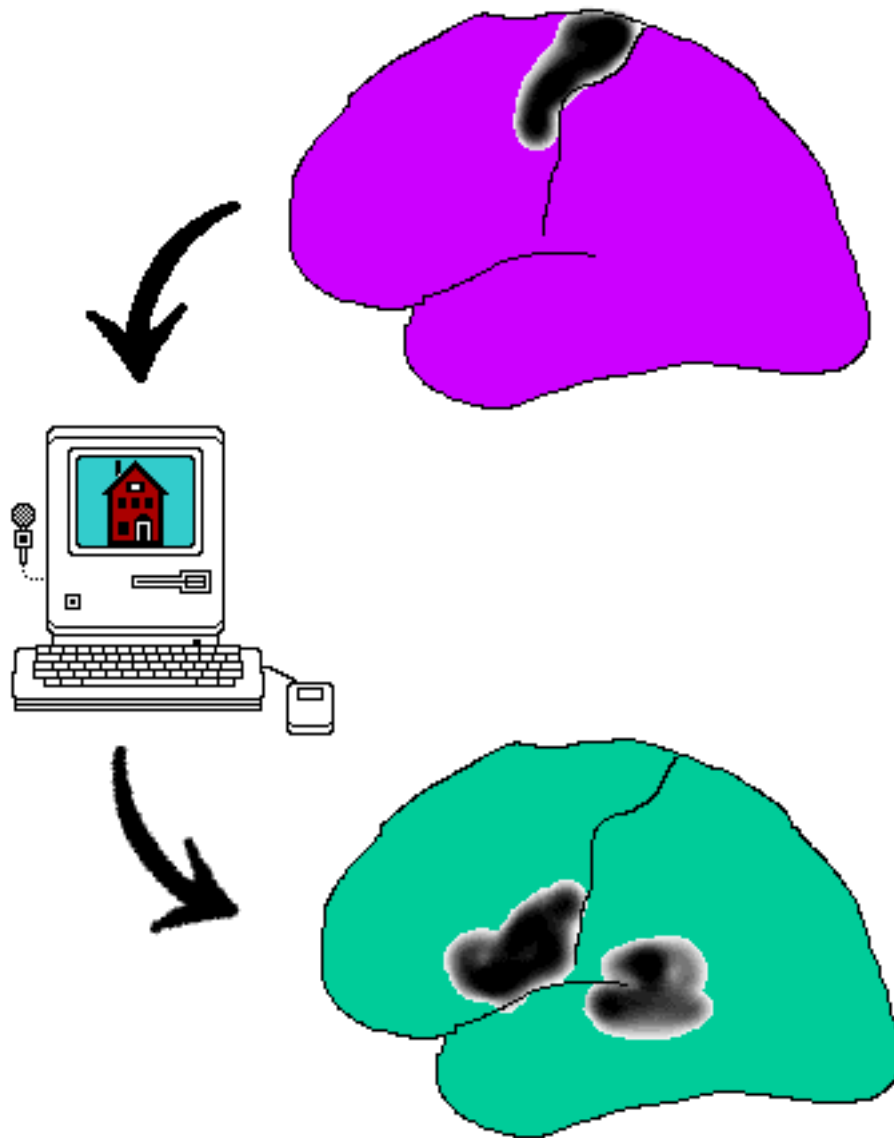


Fig. 4. The intellectual prosthesis can switch the brain from one cognitive mode (hand-drawing) to the other (speech-drawing)

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 Minsky's sense 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 makes 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 computer 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 San Pietro by telling some assistants how to produce a detailed layout step by step, or painting the Sixtina shouting to his aides to "put a red there" or "draw 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 on his brain that was never before engaged in the act of drawing. Only a computer can enable this brain-switching. *This switching to a new cognitive path is the essence of any intellectual prosthesis.* In other words, intellectual prosthesis 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.

Some day non invasive techniques should show the different paths involved in cognitive growth too. In our experiments four classical Piagetian tests were submitted to right handed and left handed children in a blind situation with only one hand at a time to manipulate the objects of each test (clay, sticks, marbles, etc.) (Battro, 1981). 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. The neuronal paths taken by both types 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.

This simple mapping of cognitive paths may inspire new experiments in neuro-cognition when the subject (young or old) is involved with computer prosthetic activities. 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.

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