

Preformation All the parts of an adult organism are contained in miniature in the germ cell. It is the opposite view of epigenesis and excludes innovation, also in the psychological sense.

Split brain The result of a section (or absence) of the fibers connecting one hemisphere to the other (corpus callosum and other commissures). In the split brain condition the individual may show a disconnection between the cognitive activities of the two hemispheres (Gazzaniga, 1970).

Skill A capacity to act in an organized way in a specific context (Fischer and Bidell, 1998).

Stage A state of stable equilibrium during mental development. The stages are necessary steps during the child's growth process and were described by Jean Piaget in four periods: sensory-motor, pre-operational (symbolic, representational), concrete operational and formal operational (Piaget & Inhelder, 1963).

Termites A name given to the gifted and talented subjects studied by Lewis M. Terman (1925-59).

Virtual reality A digital three-dimensional dynamic representation of any environment or object that allows exploration, interaction, and search.

Virtual brain A digital three-dimensional representation of a real brain, useful to study and simulate brain surgery on the computer.

The heart is in the brain

ubi enim est thesaurus tuus ibi est et cor tuum

For where your treasure is, there will your heart be also

MATTHEW, 6:21

This is a book about education and human nature. I would like to share a personal experience about our brains, mine and yours, so as to open up a debate about the brain, education and human development from a new perspective: that of brainpower and brain efficiency. In a sense, this book is an attempt to become aware of the treasure we have inside our skull, "for where your treasure is, there will your heart be also." And the heart is in the brain.

The expression "the heart is in the brain" is not simply a metaphor, it can be interpreted literally from the point of view of modern neurology, as described by Antonio R. Damasio (1994):

there is a region of the human brain, the ventromedial prefrontal cortices, whose damage consistently compromises, in as pure a fashion as one is likely to find, both reasoning/decision making, and emotion/feeling, especially in the personal and social domain. One might say, metaphorically, that reason and emotion "intersect" in the ventromedial prefrontal cortices, and they also intersect in the amygdala.

And the author continues,

there is a region of the human brain, the complex of somatosensory cortices in the right hemisphere, whose damage also compromises

reasoning/decision making and emotion/feeling, and in addition, disrupts the process of basic body signaling. (p.70)

But we shall see that when the right hemisphere is anatomically or functionally removed, as in the case we are going to discuss, the remaining hemisphere compensates actively for the loss and no major problems in cognition, sociability, and emotion appear.

New clues have emerged from this study of a child with congenital hemiplegia who was subjected to a right functional hemispherectomy because of intractable epilepsy at the age of three years and seven months. This child, Nico, has lost the use of an entire hemisphere but goes to school, where he has been closely studied from kindergarten to third grade. These three years in particular (five to eight), though only a short span of time, are so very important in a child's life. Moreover, I consider this research to be the start of a longitudinal study which should be continued until early adulthood. It will hopefully give me the opportunity to work on the foundations of a new field, to which I propose to give the name "neuroeducation," with the purpose of bridging the gap between the science of education and the neurosciences.¹ I shall also try to show how to empower the brain (or half of it) with the "pros-thetic" use of computers and how this might relate to the global distribution of knowledge in the new digital society. It is an ambitious program but I am certainly not alone in this voyage of discovery.

This book might also be used as a tentative guide to the education of a half-brained child. It would give me great satisfaction if it could help those families in which someone has undergone the ordeal of radical surgery, such as a hemispherectomy. But I must stress the fundamental point that Nico's remarkable rehabilitation is partly due to the fact that the hemispherectomy was performed on his minor right side at an early age. If the same operation were to be performed on the dominant left hemisphere at a later age, the overall result might be different, and certainly not always as satisfactory as in the case we shall discuss here at length. This book is therefore based on the fortunate case of a left half-brained child and should not be extrapolated to other cases without due distinction.

I shall try to show how the scientific study and tender care of a single half-brained child might shed new light on the understanding of the universals of

human nature. The opportunity to work with Nico has changed my intellectual life, and has certainly enriched my affective experience. This remarkable, intelligent, and affectionate boy has challenged most of my ideas concerning the brain, the mind and the computer, and may possibly also shake up some of yours. I can better understand now the profound impact that some pupils can make upon their teachers or some patients upon their doctors. Such unique cases produce a change in our views about man. Nico is certainly one of these privileged persons and I am deeply indebted to him.

Medicine is rich in studies of extraordinary neurological cases. The one-case style became popular in our time thanks to the writing talent of distinguished physicians such as Alexander R. Luria (1972, 1986, 1988), Oliver Sacks (1987, 1995, 1997), Norman Geschwind (1987), and Antonio R. Damasio (1994). Some patients have been monitored for decades, like "the man with a shattered world" reported by Luria after thirty years of observation. Psychology too has a long history of one-case reports. Jean Piaget was certainly a master of the detailed developmental analysis of individual children. He published his celebrated research on his children, Laurent, Jacqueline and Lucienne, in three complementary books: *La naissance de l'intelligence chez l'enfant*, Piaget (1936); *La construction du réel chez l'enfant*, Piaget (1937) and *La formation du symbole chez l'enfant*, Piaget (1945). I have a nice story to tell. The first time I had the pleasure of lunching with my "patron" at his house in Pinchat, near Geneva, Madame Piaget, née Valentine Chatenay, a psychologist by training, told me that she always wore a tiny notebook attached to her necklace so that she could record her observations of their children. These careful reports contributed substantially to her husband's research. To this maternal and paternal dedication I would add Luria's (1986, p. 147) comments: "romantics in science want neither to split living reality into its elementary components nor to represent the wealth of life's concrete events in abstract models that lose the properties of the phenomena themselves. It is of the utmost importance to romantics to preserve the wealth of living reality, and they aspire to a science that retains this richness."

A permanent record of our beloved Nico's works and deeds at school is also kept by his teachers. I do not keep an equivalent register at home, but his

parents regularly share the most significant developments with me. What I appreciate most is the loving care and commitment which support a long-term observation, an attitude that has more in common with "romantic" science than "classic" science, to use Luria's terms. In sympathy with the values of romantic science my friend Thierry Deonna, an expert child neurologist, wrote to me, "an accurate neurological, scientific description of deficits, compensatory strategies, etc. is perfectly compatible with a description of the 'roman de vie' in which such a unique experience unfolds and which gives it its proper existential dimension."²

As for the medical aspects of the surgery known as functional hemispherectomy, (I use the term hemispherectomy as a synonym for hemidecortectomy or hemidecortication), this clever technique was conceived and executed by the neurosurgeon Jean-Guy Villemure and his team at McGill University to solve the problem of intractable epilepsy. The essential details on functional hemispherectomy are given in Tinuper *et al.* (1988), Smith *et al.* (1991), Villemure and Rasmussen (1993), Villemure and Mascott (1995). They have devised a new way of removing the damaged brain hemisphere without risk of a neurological catastrophe. Instead of producing a whole and complete anatomical recession of the hemisphere, which might have devastating effects, they successfully tried a more physiological intervention. This functional surgery increases the chances of a successful rehabilitation following the removal of a significant part of the brain. In particular, it inhibits hemosiderosis (iron deposit in cells) and hydrocephalus, the most serious problems in anatomical hemispherectomies. Recent statistics show that most patients react very positively to this intervention, the seizures disappear and cognitive functions can even be enhanced.

Nico suffered a congenital left hemiplegia, but managed to walk before he was one year and seven months old and started to speak in sentences shortly before his second birthday. The first two epileptic seizures happened when he was a twenty-two months old, but they then completely disappeared during the following eight months, at which point they recommenced, with repeated convulsions and loss of consciousness. Medication proved useless and a dramatic increase in epileptogenicity was observed. An EEG confirmed an extended epileptic focus in his right cortex involving the right temporal, frontal and parietal area. Finally, when Nico was three-years-and-seven-months old

the family decided to try a neurosurgical treatment. The operation was originally to be restricted to a limited resection of the right temporal lobe and a disconnection of the right frontal lobe under corticographic control. However, after the first ablation and disconnection had been performed the corticography continued to show multiple spikes and discharges in the remaining right areas. The physicians discussed the options with Nico's parents and they agreed to a functional hemispherectomy being completed. The technique applied in this case consisted of the removal of the central cortical region, the parasagittal cortex and cingulate gyrus, plus a complete temporal lobectomy, including amygdala and hippocampus. The remaining portions of the frontal lobe and parieto-occipital lobes were also disconnected from the brain stem and the opposite hemisphere. The pathology found was polymicrogia of the right temporal and parietal lobes with mild chronic meningitis. Nico made a remarkable recovery. The seizures disappeared, he never lost his speech and in a few days he started to walk. He is now a healthy boy and a good pupil at school. The amazing fact is that nobody would imagine this impressive neuronal loss from his overt behavior. Indeed without seeing his brain images it is impossible to believe that Nico has only half a brain left! Figure 1.1 shows a dramatic view of this functional right hemispherectomy.

In order to take a further step inside Nico's remarkable left brain we could use other kinds of imaging technologies, such as functional magnetic resonance images (fMRI). But I still consider that some experimental research with non-invasive brain technologies is simply not justified, even with volunteers. I believe in the classic dictum: *primum non nocere*, even if the fMRI does not hurt. I am sure that these technologies will improve significantly in the near future, not only in image resolution but in friendliness, and the time will come to proceed further in our description of the function of this particular half-brain. To sum up, it is difficult to correlate the "catastrophic" reduction of his gray matter with Nico's normal cognitive, social and affective development. His only apparent problem is that he limps and cannot easily move his left arm. He also has a left hemianopia and has difficulty focusing on a visual target, for instance when reading, but in some tasks, such as spoken and written language, he is at the top of his class. How is this possible? How can half a brain sustain a full mind?

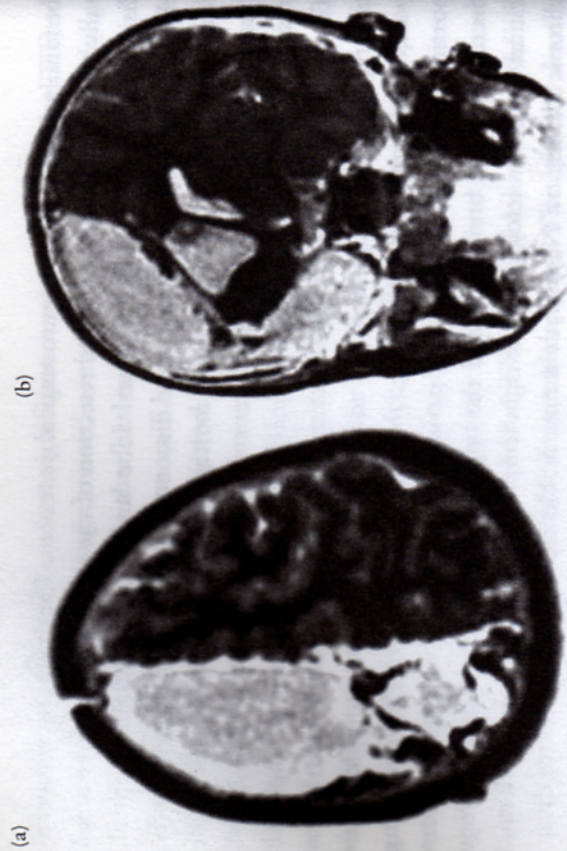


Figure 1.1 Two images of the functional right hemispherectomy. (Nico: three-years-and-seven-months): (a) horizontal (axial) view, (b) frontal (coronal) view. Only the left hemisphere is seen, most of the right hemisphere has been removed.

In order to answer this question it is important to take a general view of the problem. Hemispherectomy or hemidecortication are extreme surgical interventions in medical practice, and most of the publications on the subject are clinical reports, follow-ups and statistics from neurosurgeons or neurologists. I shall not deal here with the medical aspects because there are several good reviews which may be consulted.³

It is, however, interesting to note that hemispherectomy has not stimulated as much fundamental neuropsychological research as split brain surgery has. While the psychological literature on brain bisection is still growing, the study of the cognitive, affective and social consequences of the excision of a brain hemisphere is insufficient. This book is, in a sense, a modest attempt to enrich our psychological and educational knowledge of the consequences of hemispherectomy, but certainly much more should be done. In fact, neuro-psychologists are somehow late-arrivals in the field. Previously the central question concerned brain laterality and dominance. Now, and I think this is

progress, the problem is shifting to compensatory neural strategies and to the related questions of brain efficiency and capacity.

We can start with a landmark in the new philosophy of the brain. The philosopher Karl R. Popper and the neuroscientist John C. Eccles, in their classic book *The Self and Its Brain* (1977) have analyzed the left and right excision of the hemispheres. They reported that while the complete removal of the dominant (left) hemisphere gives somewhat enigmatic results, "the excision of the minor [right] hemisphere under local anesthesia gives rise to no loss of the patient's consciousness or self-awareness." And from that crude observation the authors reached the bold conclusion that a "minor hemispherectomy gives a result in complete agreement with the postulate that self-consciousness is derived only from neural activities in the dominant [left] hemisphere" (pp. 330-2). They concluded that the right hemisphere was a "minor brain." The clinical observations of Obrador (1964) and Austin, Hayward and Rouhe (1972) had already articulated this idea. Some years later, Michael C. Corballis (1983) analyzed the cognitive consequences of early and late surgical removal of the left or right hemispheres, the so-called Margaret Kennard doctrine: "the earlier the brain damage occurs the less the behavioral loss." The time at which a brain injury occurs is essential to the making of predictions and taking medical decisions. A detailed overview of the onset of the brain lesion and its impact on mental development can be found in Elizabeth Bates (*et al.* 1992). The issue being examined was the extent of brain plasticity in children and adults, in particular the recovery of linguistic skills in the absence of the dominant hemisphere. At that time the mortality rate was very high in this kind of neurosurgery, especially in adults, and it was difficult to make sound comparisons between left and right excisions. But, nevertheless, neurologists reported an amazing capacity for recovery of language after the removal of the left cortex. Thus the study of hemispherectomized subjects became an important issue in the debate on hemispheric equipotentiality and language acquisition.

The concept of "hemidecorticate syntax" was introduced. In a study of ten children subjected to left or right hemispherectomy because of infantile hemiplegia, Maureen Dennis (1980) discovered that left and right hemispheres "perform different encoding and decoding operations on a syntactically complex sentence in order to identify its meaning". In particular, left

hemispherectomized children were inferior to their right counterparts in both "ease and speed of syntactic discrimination, despite their similar verbal and non verbal intelligence." The results of Dennis and Kohn (1975) on nine cases of infantile hemiplegia who underwent left or right hemidecortication show that some syntactic skills, such as the comprehension of passive negative sentences of the kind "the truck was not hit by the car," were inferior in the left hemidecorticates compared to the right hemidecorticates. For example, Dennis and Whitaker (1976) have shown that one left hemidecorticated and two right children who underwent surgery prior to the age of five months, confirmed this linguistic asymmetry as "an organizational, analytical, syntactic problem, rather than a difficulty with the conceptual or semantic aspects of language." In research on written language acquisition after hemispherectomy Dennis (1981) has analyzed how the isolated hemisphere learns to read, write and spell in different ways. We shall discuss this most important topic later and also some new opportunities for using computers to enhance writing skills in the "atypical" brain – as Dennis called it – of a right hemispherectomized child. There were scarcely any computers at school twenty years ago and at that time the radical change which can be affected at the cortical level by computer word processing was unimaginable!

Research on speech and language in hemispherectomized children and young adults still continues to dominate the interest of neuroscientists. The work of R. E. Stark and associates (1995, 1997) provides a good example of the "left to right" transfer of language processes in left hemispherectomized subjects, but there are few studies about the inverse transfer of cognitive processes from the right to the left hemisphere. Perhaps the best analysis of the cognitive consequences of hemispherectomy is to be found in the review by Faraneh Vargha-Khadem and Charles E. Polkey (1992). The authors are aware of the lack of cross control of several variables in most studies (and they analyze fifty-one recent papers), such as age of initial disorder, age of hemidecortication, time elapsed since surgery, and psychological testing, left- or right-handedness before surgery, etc. They conclude that for those subjects with a left hemispherectomy

- a) the isolated right hemisphere has a basic visual and auditory lexicon consisting of concrete and high-frequency words; b) the isolated right hemisphere can recognize, comprehend, and produce words from this

lexicon through both speech and writing; c) in contrast with these domains of ability, the isolated right hemisphere has difficulty comprehending abstract, low-frequency and low-imagery words, manipulating subtleties of grammatical structure, and analyzing words according to their phonetic features. (p. 144)

Nothing particularly relevant is said of the right hemispherectomized subjects except that, "contrary to expectations, no gross deficits on many visual tasks sensitive to right hemisphere function, such as spatial orientation, visuospatial construction and face perception" were found (p. 146). Only one case of prosopagnosia – a cognitive deficit in human face recognition – was reported by Sergeant and Villemure (1989) in a thirty-three-year-old patient who had undergone a right hemispherectomy at the age of thirteen following seizure onset at the age of five.

It is interesting to note that there are no reports of serious language impairment in right half-brained children or adults. This makes sense if we accept that language has a left brain location in most right-handers but we also know that there is a significant percentage (70 per cent) of the population of left-handers that may have a bilateral cortical representation of language as reported by Satz (1979). Unfortunately, we lack statistics on the number of left-handers among the right hemispherectomized population to make a comparison. The question of the different cognitive outcomes of right and left hemispherectomy is still a matter of discussion. Our study is about a right-handed boy with a high linguistic performance, but in scientific literature the focus continues to be the loss of the left brain, not of the right one, as in our case study.

The core of the debate was again correctly identified by Corballis (1983):

at one extreme we have the notion of two hemispheres as fundamentally the same and as interchangeable, but each programmed differently by different rates of growth on the two sides. At the other extreme, we have the idea of the hemispheres as fundamentally different, each predestined to develop its own specialized functions. The one extreme emphasizes symmetry, continuity between humans and other species, and plasticity of function; the other stresses asymmetry, discontinuity, and rigid predetermination. Perhaps by keeping these extremes in mind, we shall be able in the future to arrive at a correct compromise. (p. 110)

I think we are closer now to reaching a new synthesis. The decisive factor might be the introduction of non-invasive dynamic brain image technologies, such as positron emission tomography (PET) and functional nuclear magnetic resonance images (fMRI). The impact of the new imaging techniques as a research and clinical tool is enormous. A good introduction to the non-invasive technologies is the splendid book *Images of Mind* by Michael I. Posner and Marchus E. Raichle (1994) and publications by Bigler (1996), Damasio (1995), and Salamon (*et al.*, 1990). It is important to note that the first dynamic brain images performed by Pawlick (*et al.*, 1990) on patients who had undergone hemispherectomies because of uncontrollable epilepsy show a remarkable involvement of association areas in both motor and speech activation. This new frontier of knowledge should be explored, but before proceeding any further, a careful and explicitly ethical approach is needed in case a conflict occurs between the interests of the patient and the advancement of science. The beginning of a promising new field of research often implies new moral dilemmas.

We may now return to our main question. How can half a brain sustain a full mind? And this in turn leads us to the brain/mind controversy – a very difficult epistemological problem that should be solved some day. New laboratories and research departments are being dedicated to the neurocognitive sciences and in several countries new journals contribute to the advancement of the field. We will rapidly globalize the findings through the Internet, where some leading scientists are now sharing interactive brain models on the Web. The number of scientists, publications, meetings, and grants in the neurocognitive sciences is rapidly increasing and I am convinced that only collaborative work on an international scale will succeed.⁴

Let us start with the most basic knowledge about the evolution of the nervous system. Evolutionary theories tell us that the mind and the brain evolve together, and as Harry Jerison (1979) affirms, “the size of the brain, its weight or volume is an extraordinarily useful measure in neurobiology.” But the problem is that nobody can explain why *Homo sapiens sapiens* have such a huge brain if it can be shown that, following surgery, half of this brain suffices! The once famous, encephalization quotient (EQ), and the ubiquitous intellectual quotient (IQ) are, in my opinion, two mismeasures of the

mental capabilities of man, in particular in the case of hemispherectomized individuals.

For a very well founded critique on the IQ, where intelligence quotient = actual intelligence/intelligence expected for an individual of the same age, I would recommend Gould (1981) and Gardner (1983, 1993). I share their opinion that IQ is not a good measure of intelligence and gives a limited and distorted view of the cognitive potential of an individual. However, I tested Nico's IQ to satisfy the curiosity of those who believe in it and to make a comparison with other clinical studies. In fact some authors have analyzed the IQ in hemispherectomized patients. In one of the best test studies available Peggy Gott (1973) has detected that in a child with a right hemispherectomy performed at the age of seven the IQ was just about half the one measured before illness. In our case, five years after the surgery Nico's IQ was 109 (verbal IQ 118, performance IQ 97). Certainly it has not halved! Besides Nico's IQ is also much higher than the IQs tested by Vargha-Khadem *et al.* (1991, table 2) on five right hemispherectomized children, where the highest IQ was 85 (verbal IQ 98, performance IQ 73).

We urgently need a different approach to the brain/mind correlation if we want to explain the behavior and cognitive abilities not only of these half-brained persons but of every one of us. Whales and elephants do have larger and heavier brains than ourselves but neither speak nor write. A half-brained child, on the other hand, with less than 700 grams of active neuronal encephalic tissue can speak and write perfectly well. Where does the difference lie? Do we really need so many neurons and so many synapses to be human? Science does not know – so far – how to count the number of neurons and synapses involved in “higher” mental activities, but can give a very detailed account of “motoric” neuro circuitry as has been shown by P. S. G. Stein and others (1998). Could we dream of a similar work on “thinking” neuro circuitry in the near future? I shall try to show that a hemispherectomized child can develop a normal mind although his brain has less active neurons than a microcephalic person. The difference with the latter, of course, is that Nico's left hemisphere has a normal neural architecture.

By the way, how much is half of the 10^{12} neurons of the human cortex? This is, incidentally, a good question to test the mathematical abilities of our friends or students; many will answer 10^6 . This is a typical “cognitive

illusion" of the type described by Amos Tversky and Daniel Kahneman (1982), and superbly summarized by Piatelli-Palmarini (1993) when our intuition contradicts our reason. The specific difficulty in dealing with power functions is also a hindrance when we deal with changes of scale, with the different orders of magnitude in the depths of the brain. We have had, all of us, a "linear" mathematical training in school and it is not easy to switch to the "power function" mode. We must learn, for instance, that half of a very great number is still a very great number! (the answer to our former question is 5×10^{11} neurons). When we say "he is brainy" or "she has brains" (in the plural) we are perhaps experiencing a neurocognitive illusion . . . But what is an objective measurement of human brainpower? And herein lies a subsidiary hypothesis: if the human cortex is so well-endowed a tissue as to be able to accomplish the same cognitive feats with only half of its neurons, then with the help of some external computational aids, would it not be possible for the brain to attain incredible levels of competence? This is the obvious inference to be drawn from our experience of the computer as an "intellectual prosthesis" in the education of a half-brained child, as we shall see later. I think that here we are at the leading edge of our capabilities as a species in a global society.

I shall finish with a practical question. What can we do to "put more brain" into education? Until now we have thought of a child's brain as a black box. But the neurocognitive sciences have opened that box and as a result some brain mechanisms have become clear, important cognitive processes have been identified and we have even been able to simulate how neural networks develop in the process of learning. All this is very distant from the demands of common classroom practice, but things are changing rapidly in education. It is no coincidence that the opening of the brain box is synchronous with the opening up of the world. We can now establish a relation between the World Wide Web and the brain wide web (Battro, 1997). The new domain of neuroeducation should deal with this complex dual network. The development of the brain wide web inside our heads and its connection to the World Wide Web around will perhaps become the new frontier of education in the twenty-first century. It reminds me of Kant's well known phrase in the *Kritik der praktischen Vernunft* about the two things that filled his mind with ever new and increasing wonder: "der bestirnte

Himmel über mir und das moralische Gesetz in mir," the starry heavens above me and the moral law within me. In a more modest way, what fills me with wonder now is the link between the two networks, the Internet and the brain.

to my rescue. They became interested in this case and at my request they kindly simulated on their *Dextroscope* the functional right hemispherectomy performed five years ago on Nico's brain, following the operative protocols of that surgery. I would like to acknowledge this technological prowess as a significant token of scientific solidarity from the Antipodes and I am deeply moved and grateful for their generous contribution.

Virtual surgery belongs to what is called *Computer Aided Surgery*. To quote W. L. Nowinski (1997) "the stereo virtual image of the brain is seen reflected in a mirror, allowing the user to reach into the virtual spaces. Physical and virtual spaces correspond, so that physical tools can manipulate virtual objects in a coordinated hand-eye manner". That means that

the user's left hand controls the entire displayed complex containing the actual patient's data, an individualized 3D atlas, and a stereotactic frame fixed to the patient's head. This complex can be turned and placed as one does an object held in the hand. The right hand performs detailed manipulation using 3D widgets to interact with the surgical planning tools and the actual patient's data. For example, the user can set the frame, pull out any cerebral structure for a closer look, or manipulate the stereotactic probe. All the interactions follow the principle of 'reach in for the object of interest and press the switch on the stylus to interact with it'. Whenever the stylus tip enters the volume of influence surrounding an object, the object signals interaction readiness by a color change or other highlighting.

A new kind of medicine and psychology is emerging. In the near future this digital interface will help us to analyze not only the anatomy but also the function of the living brain, in a virtual reality setting. It is impossible to describe the feeling of having a virtual brain in one's own hands with all the possibilities for planning surgery or studying anatomy and even neuro-psychology!

A VR simulation of the functional brain surgery is reproduced in figure 2.1 and is quite impressive. The virtual surgery shows that some frontal and parieto-occipital brain tissue remained intact, but during Nico's actual hemispherectomy these pieces were completely disconnected from the central nervous system and now they are no longer functional nor can they be re-activated.

2 Sculpting a new brain

*caro m'è il sonno, è più l'esser di sasso
mentre che il danno, e la vergogna dura
non veder, non sentir, m'è gran ventura
però non mi destar, deh, parla basso*

*Dear is sleep to me, but dearer still to be of stone
As long as the harm and shame endure
Not to see, not to hear, is great good fortune to me:
So do not awaken me, speak low.*

Epigraph by G. B. STROZZI TO LA NOTTE OF MICHELANGELO
(1534) TOMB OF GIULIANO, DUCA DI NEMOURS, SON OF LORENZO
IL MAGNIFICO, FLORENCE.

Look at the classic anatomical picture in any textbook, or take a solid cast of a brain hemisphere in your hands, or even better, if you are a student of medicine, handle a real brain in the human anatomy class and divide it into two parts through the corpus callosum leaving the cerebellum, the diencephalon, and the brain stem intact. Excise one hemisphere entirely and visualize the dramatic loss of brain substance that occurs to an hemispherectomized individual. I confess that I tried to model an anatomical hemispherectomy in clay but it was too difficult for me. My failure as a sculptor forced me to look elsewhere. I knew that the new technology of virtual reality (VR) was performing miracles in the field of virtual surgery, but it was inaccessible to me. The team of neuroscientists at the Kent Ridge Digital Labs (KRDL) of Singapore came

And last but not least, thanks to the new technology of virtual reality we can now share the experience of a powerful training tool for neuroeducation and a theoretical platform for philosophical reflection. I can even imagine a new way of looking at our own brains, after an MRI performed on ourselves, though not necessarily with Hamlet's grief as he holds Yorick's skull, "alas poor Yorick! I knew him, Horatio—a fellow of infinite jest, of most excellent fancy . . ." (Hamlet Act V Scene I). Now we can hold our own brain in our hands and still fancy! But there is a paradox in the way we analyze ourselves, namely that of being at once the observer and the observed, especially when dealing with actual brains. I agree with the mathematician Alain Connes (Changeux and Connes, 1992) that "in order to avoid the paradox of introspection we must introduce a hierarchy between analyzed brains (of type o) and analyzing brains (of type 1)." Stanislas Dehaene (1997) in a functional MRI study of his own brain during an arithmetic task has given us a good example of this. The virtual workbench will thus provide a new interface for "neuro introspection" so that one day not only my anatomical brain but also my functional virtual brain can be analyzed. Then perhaps new kinds of thinking skills will develop, so that whenever I manipulate my type o (virtual) brain on the VR workbench I will engage my type 1 (real) brain in a new kind of epistemological subject/object interaction. This now seems to be pure science fiction but I can imagine, in the near future, the impact of "virtual brain reality" upon neurocognition and neuroeducation.

Our simulation of brain sculpting as virtual surgeons might be useful also as a metaphor when comparing our images with that of a broken computer. It is obvious that chopping a PC or a Cray supercomputer in two is a rather costly and uninteresting action. A half-brain might work as a full-brain, a half-computer cannot. Modern hardware in no way corresponds to the architecture of the living brain. Only when the gap between computer hardware and brain architecture is bridged will machines behave like living organs. Perhaps that day is not very distant. Both computer scientists and neurocognitivists are very much concerned now with the "minimal architecture" needed to perform a specific mental function. Even the idea of "lesioning a network" has become operational. This notion may be traced back to John von Neumann and involves a very technical computational question, but a good summary related to neuropsychology has been given recently by

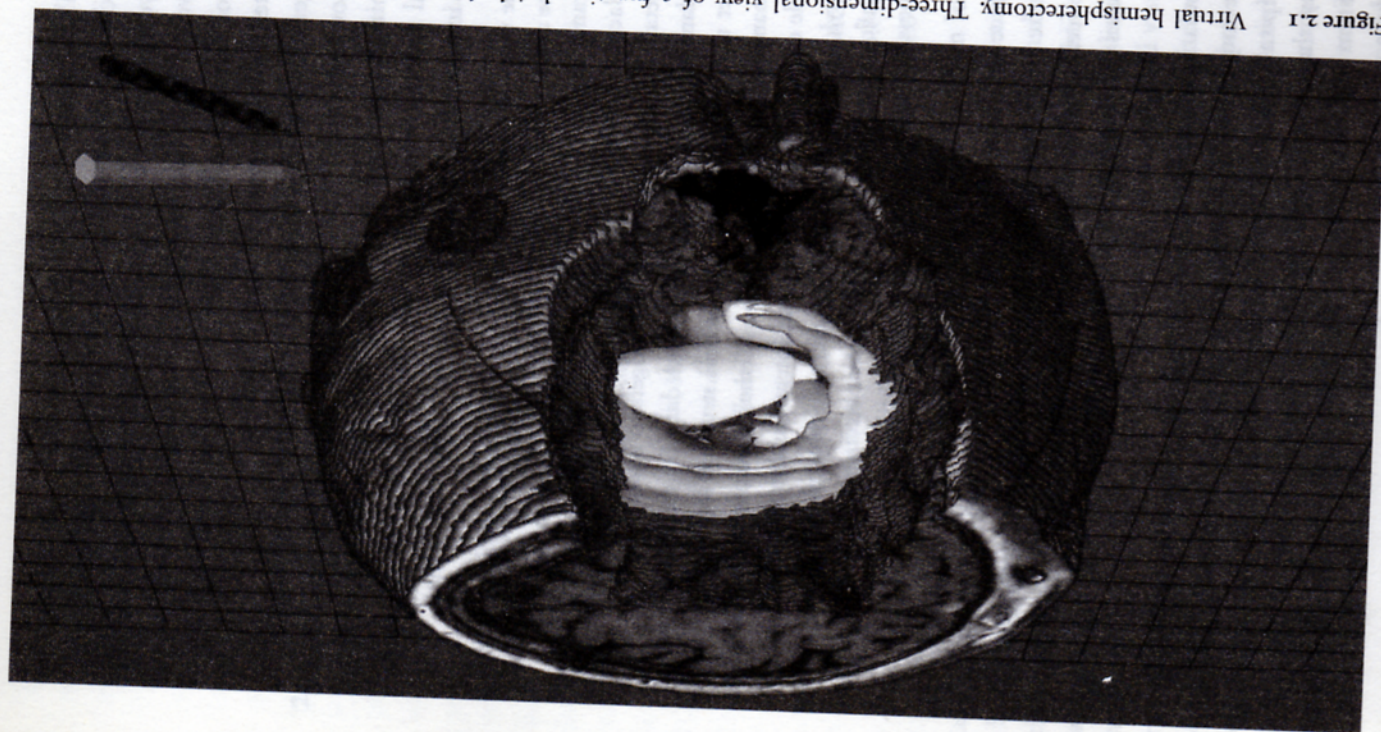


Figure 2.1

Virtual hemispherectomy. Three-dimensional view of a functional right hemispherectomy, simulated by Drs. Ralf Kockro and Yeo Tseeng Tsai on virtual reality. The surgeons have reproduced the procedure performed five years before on Nico's real brain. The basal ganglia are three-dimensional reconstructions of the digitalised Talairach-Tournoux Brain Atlas, co-registered with a standard MRI of a healthy brain (courtesy of the Kent Ridge Digital Labs KRDL, Singapore).

Table 2.1 Brain measurements (a power function scale)

K = 1 Kilo	$= 10^3$	Synapses per neuron,	Kilosynapse
M = 1 Mega	$= 10^6$	Neocortical columns,	Megacolumn
G = 1 Giga	$= 10^9$	Neocortical neurons,	Giganuron
T = 1 Tera	$= 10^{12}$	Total number of neurons,	Teraneuron
P = 1 Peta	$= 10^{15}$	Total number of synapses,	Petasynapse

synapse count alone, the amount of components that remains is still enormous. But a purely quantitative evaluation is clearly insufficient, we need a qualitative analysis as well. A hemispherectomized child may have an active brain which weighs only some 700 grams, the weight of a microcephalic brain! But these individuals are certainly not oligophenic, on the contrary, they can perform superbly in several domains, as in the case we are discussing. This is a great mystery because these children do not behave as if they had a "small" brain at all! Many of the questions that will arise from our investigation relate to problems such as this. We are prone to providing linear solutions to non-linear problems. But this intuitive bias is dangerous. We need careful metric and dimensional analysis to deal with questions concerning half-brained cases.

In the particular case we are now discussing, Nico underwent neurosurgery at the age of three-years-and-seven-months when the average brain weighs approximately 1100 grams. Around 300 grams of brain tissue was anatomically removed, but the functional surgery has disconnected a corresponding amount of matter from the central nervous system. According to the old clinical classification, a male brain under 1000 grams in weight should be considered microcephalic. But certainly removing a whole hemisphere does not produce a microcephalic mentally retarded person! Incidentally, it is worth noting that some microcephalic individuals may show some surprising mental capacities. Donaldson (1896) refers to the case of a microcephalic woman, with a stature of 1.32 metres, who "sang and spoke readily" with a brain weighing only 289 grams at the time of her death (age forty-one)! Some recent studies have shown more striking results, as in the case of trilingual

Plaut (1995). Plaut gives a connectionist and dynamical approach to the problem:

the connectionist framework should be viewed as a particularly privileged lens through which to explore and rethink development in terms of minimal architectural representability and/or computational predispositions.

What is really striking is the amazing brainpower that is left in humans who have undergone hemispherectomy – another reason not to trust those analogies between the brain and machines that have recently become so popular.

We can now analyze some facts about brain measurement that will help us to understand the quantitative consequences of hemispherectomy. The mean adult brain weight for men is about 1400 grams and for women 1200 grams. At birth the infant brain weighs circa 800 grams and will grow until early adulthood. It seems also that this growth is not as smooth as we had once believed but proceeds in stages. Also, when the brain reaches its maximum weight it starts to decrease and between age 30 and 80 a loss of 100 grams can be detected. At the same time, it is interesting to note that the surface area of the cortex and the weight of the brain are highly correlated. The implication is that convolutedness (the multiple folding of the cortex) and brain size are equivalent measures. This is most interesting because the functional relation of area to volume involves a parameter related to shape. Some authors consider the increase of convolutedness as an evolutionary solution to the problem of keeping the increasing amount of brain tissue inside the limits of the cranial volume. There is a whole province of neurological study dedicated to the measurement of the brain, but different authors give different figures for the calculation of the numbers of neurons, cortex surface, and brain volume.¹

Table 2.1 provides a (mnemonic) schema of the order of the magnitudes involved (the figures are rough estimates), and also proposes a new terminology.

Hemispherectomy or hemidecortication roughly halves most of the number of components, but as I mentioned previously half of a very large number is still a very large number! It is in this sense that "half a brain is enough" because if we measure brainpower quantitatively, by a neuron or

hyperlexia in a microcephalic girl (Lebrun et al, 1988). These and other extreme cases demonstrate the need for a better definition of human brainpower. It is also interesting to compare the development of the brain from childhood to adulthood in our species *Homo sapiens sapiens* with fossil brains (Saban, 1995). For example the *Homo paleojavanicus* had a brain capacity of 1000 ml (similar to a present day one year-old child), while *Homo habilis* had only 700 ml (similar to a baby of age forty days). The comparison of weight is only made here because of our search for a better understanding of what brainpower means. It is obvious that brainpower cannot be identified with a neuron count. As we shall see in Chapter 3 the fundamental aspect is "neural efficiency."

Nico's congenital left hemiplegia and the onset of severe epileptic seizures in the right hemisphere at the end of his first year, coupled with the right hemispherectomy performed at three-years-and-seven-months, have made it possible for a radical re-organization of the brain to take place, something which may even have started at birth. In a neurophysiological sense Nico had been forced anyway to develop a new brain, a new hemisphere, in his first three years of life. Many questions arise, for example, what kind of metabolic requirements ensue as a consequence of hemispherectomy? It is said that the brain accounts for approximately 2 per cent of total body weight but needs 20 per cent of body-at-rest energy! How much energy does an active half-brain need? Does the remaining cortex activate new areas in order to accomplish the specific processing of those functions that were embodied in the removed cortex? Will some extra energy be required to compensate for the loss of the other hemisphere? These are important questions that will demand a careful design in future neurocognitive studies of a half-brain.

To begin with, brain growth is non-linear. It seems to develop by definite steps, in "fits and starts," at different rates in time and space. For instance, H. T. Epstein (1974, 1978, 1979) was able to show a biennial increment in human head circumference. He was perhaps the first to put forward the bold proposition of a co-ordinated link between these brain stages and Piaget's cognitive stages. Epstein coined the term "phrenoblysis" to describe the brain spurts during growth and its correlation to mental stages: "human brain weight and head circumference manifest four growth stages at about 3-10 months, 2-4, 6-8, 10-12 and 14-16 years." He reached the conclusion that "since DNA

synthesis in the brain ceases around one and a half years, the last stages must be expressed mainly in elongation and branching of axons and dendrites, and in myelination of axons." Epstein also disseminated the highly controversial idea that many educational programs have failed because they focused on ages four to six, during a span of minimal brain growth. That the brain size grows in fits and starts is now widely accepted and was confirmed by different authors (Lampl and Emde, 1983, Lampl et al., 1992).

Of course, the measurement of head circumference is a very insufficient record of brain growth and can only be related to gross anatomical development (human brain weight is proportional to the cube of the head circumference). What is needed, as Robert W. Thatcher (1994) remarked, is to understand the functional neurophysiological changes at the microanatomical level during brain growth: axonal sprouting, synaptogenesis, myelination, expansion of existing synaptic terminals, pruning of synaptic connections, presynaptic changes in the amount of neurotransmitters, etc. A summary of the evidence concerning stages in brain growth, synaptogenesis and brain activity (EEG) is given by Kurt W. Fischer and Samuel P. Rose (1994). Coincidentally, Thatcher also uses the metaphor of "sculpting" the brain tissue. The cyclic brain growth spurts,

may reflect a convergence process that narrows the disparity between structure and function by slowly *sculpting* and shaping the brain's microanatomy to meet the eventual demands and requirements of the adult world. According to this notion, an individual's gross anatomical structure is established early in development, and the postnatal iterative *sculpting process* is used to fine-tune anatomical structure to meet the needs of diverse and unpredictable environments. (my emphasis, p. 257)

Also,

although the number of neurons decreases with age, the number of synapses per neuron does not necessarily decrease. This is because increased skull volume and decreased neuron number result in decreased packing density. However, decreased packing density is directly related to dendritic length. Since dendritic length is directly related to dendritic surface area, there is more space for synaptogenesis as neuron number declines. (p. 261-2)

Other scientists have studied this important issue too: Goldman-Rakic, 1987; Greenough, 1986; Hanlon, 1991; Hudspeth and Pribram, 1990, 1991; Rabinowicz, 1979.

Imperfect as they are, the current non-invasive technologies are constantly expanding our knowledge of how the brain and the mind grow together. Recent experiments provide some evidence of a stage-like growth of *both* brain and mind. Since Piaget's time and the Geneva school, several revisions of the notion of mental stage have been made. The notion of brain stages is more recent and it too will need further clarification and confirmation. The problem is how to relate the two stage-like phenomena. These considerations are vital to the study of a half-brained child. We can only infer some of these internal neural changes from his overt behavior. The idea of stage-like brain growth is founded experimentally on the data obtained from the new technologies in neurology, especially from the computerized electroencephalographic records in longitudinal studies and children's brain images. There is still a clear need to correlate brain growth and cognitive development. Later I shall discuss some intriguing results of the "brain-mind coupling" from the viewpoint of the developmental study of a half-brained child.

Using sophisticated techniques in EEG records taken from different points on the scalp it is possible to give a measure of the phase synchrony between spatially separated generators. This cross correlation is called the EEG coherence and represents the shared activity or coupling between neocortical neurons. Any increase in coherence reveals a corresponding increase in connectivity among neurons. Thatcher has discovered that "growth spurts" of cortical connectivity can be found during at least the first sixteen years of life. These spurts are measured by peaks in velocity in the coherent EEG records. What is interesting is that the growth spurts in connectivity are cyclic. He observed three cycles: I (from 1½ to 5 years), II (from 5 to 10 years), III (from 10 to 14 years).

The passage to the next cycle is always marked by phase transitions (or discontinuities) in the EEG records. This last fact provides a strong argument for a stage-like development in neuronal connectivity. Moreover, and this is central to our study of half-brained children, the growth spurts take place in different predominant locations during brain development. For instance, Thatcher observed six left and two right-hemisphere growth spurts between

ages 1½ and 2½ years, as the cycle moves from predominantly left to bilateral. The nesting of micro-cycles and sub-cycles in every major cycle can also be shown. According to the author the developmental sequence of the cortical neuronal networks of the left hemisphere "is from short-distance differentiation to long-distance integration," while "the right hemisphere begins with a long-distance integration of distributed subsystems and then progresses to short-distance differentiated or specialized subsystems" (p. 253). In his view, during neural development the right hemisphere integrates differentiation (short to long-distance neural connections) and the right one differentiates integration (long to short-distance). This can be related to an anterior-posterior anatomical *expansion* (left hemisphere) and *contraction* (right hemisphere) in the cortical system's connections. But also, approximately every four years, there is a lateral to medial *rotation*. The sequence "begins at left lateral cortex, then intrahemispherically expands to left dorso-medial cortex, then projects through the corpus callosum to the right dorsomedial cortex, and finally intrahemispherically contracts in the right cortex" (Thatcher, 1994, p. 244). The whole developmental picture of the growing brain can be synthesized as "two-year growth spurt cycles in the strength of intrahemispheric couplings, which are nested within four-year interhemispheric rotations."

If this is the growing neural pattern of connections in the normal brain, what will happen in the case of a half-brained child? The standard model should be challenged against the new situation, where the interhemispheric rotation of neuron connectivity is anatomically impossible (as is also the case in split brain patients). In our case Nico has undergone a right hemispherectomy in the middle of his first cycle (three years) at which time it is possible a bilateral growth spurt in neural connectivity was taking place. Nico, who at the time of this writing is eight years old, cannot iterate the spurt of bilateral connections, as a bilateral-brained child is expected to do. What sort of new connections are being established in his half-brain? We do not know. We should design an equivalent EEG experiment to test the neuronal growth in half-brained children on a rigorous physiological basis and look for differences from the standard pattern.

And what about the problem of cognitive stages and their relation to brain stages? Fischer has given an overall view of the correlated sequences of both.²

There also seem to be cyclic iteration of front-to-back power EEG spurts in the growing brain, which follow the construction of the cognitive developmental steps, called levels. Each level of skills presupposes the emergence of a new kind of neural network. Levels belong to larger cycles, called *tiers* by Fischer. He affirms that at the beginning of every tier (emergence of actions, representations or abstractions) a spurt of neuronal activity is detected by the power EEG technique in the frontal areas, followed by an occipital-parietal, then a temporal and finally by a central spurt, and restart again in the following tier with the same sequence. Like stages in Piagetian theory Fischer's tiers represent different levels of dynamic cognitive stability. This is an intriguing and important question to analyze.

The new assumption is that the frontal cortex plays a key role in the reorganization of all cognitive abilities at each developmental stage or tier. It would be interesting to discover whether the left half-brain will also show similar front-to-back spurt cycles in neural activity, irrespective of the neural effect of the right hemispherectomy. The fact is, as will be described in Chapter 4, that Nico displays no delay in the acquisition of mental skills, as assessed by the classic Piagetian tasks. To sum up, we are dealing with new and fascinating discoveries in the intimacies of the relation between postnatal cortical development and child cognition. The panorama is open to further research, in particular when a hemisphere has been anatomically or functionally removed. The new technologies might open an operational window to identify the way the half-brain reorganizes its neuronal circuitry and our quest for a measurement of brainpower should continue through the description of the many parameters involved in brain growth. It has been shown that purely quantitative analysis at the gross anatomical level (loss of neuronal tissue, etc.) is clearly insufficient. We need a detailed account of the architecture of the new neuronal networks in the half-brain. It is the hidden quality of this design that makes our brain powerful and efficient.

Compensatory analysis

Dos o tres veces había reconstruido un día entero; no había dudado nunca, pero cada reconstrucción había requerido un día entero.

Two or three times I had reconstructed an entire day; I had never hesitated, but each reconstruction took me an entire day.

JORGE LUIS BORGES, *FUNES THE MEMORIOUS*. 1944

In this book we are discussing a very extreme case of brain damage, hemispherectomy, an extensive lesion provoked by neurosurgery as a means to cure a disease, such as intractable epilepsy. I shall argue, however, that hemispherectomy is more than a neurological lesion. In my opinion it amounts to rebuilding a new brain, to inducing a new neuronal architecture in the remaining hemisphere following the removal of its counterpart. This half hemisphere is functionally transformed into a whole brain again. If half a brain is enough then half a brain amounts to a whole brain. Concepts such as brain efficiency, compensatory process, equipotentiality, self-reorganization, vicarious functioning, neural plasticity, prostheses, and the like, need to be carefully analyzed in this new context. Much of the actual progress in the neurosciences is based on "lesion analysis," a methodology employed by most experimentalists and clinicians but perhaps never so well described as by Hanna and Antonio Damasio (1989). Their definitions merit a detailed discussion if we want to sort out the identity of hemispherectomy. We will begin with lesion analysis first in order to get to compensatory analysis later.

First,

Lesion method is the establishment of a correlation between a circumscribed region of damaged brain and changes in some aspect of an experimentally controlled behavioral performance.

Hemispherectomy is the anatomical or functional removal of a complete hemisphere. As such, it is not a circumscribed region of damaged brain that will be correlated to certain behavioral performance but an intact hemisphere, a healthy half-brain, that might be experimentally tested. Thus, the lesion method cannot be applied, *stricto sensu*, in this case, because the active half-brain is, at face value, undamaged. The follow-up of some hemispherectomized patients can show functional troubles in the remaining hemisphere, as shown, for example, by EEG records (Smith *et al.*, 1991; Müller *et al.*, 1991). In Nico's case, no spikes or abnormal waves were detected in his left hemisphere, before or after surgery. The pre- and post-surgery MRIs also have shown a normal left hemisphere. We can infer that he has a healthy half-brain. Hemispherectomy amounts to a huge loss of components of the central nervous system, and a complete topological and topographical change in their connectivity. In this sense, as I said, it is the equivalent of sculpting a new brain.

Second,

Given a preexisting theory about the operation of the normal brain and how it would mediate the performance of an experimental task, the lesion (the area of brain damage) can be seen as a probe to test the validation of the theories, that is, a means to decide if the account of brain organization and operation provided by a given model is or not falsifiable.

This point is crucial, the method must be related to a theory. Philosophers of science have explored this relation in great detail. And, as often happens, they came out with incompatible theories about the validation of models. The theory invoked here is that a model cannot be proved as such, it can only be falsified or not (Popper, 1965). But how a model should be subjected to an empirical test in order to be validated is still a controversial theoretical issue. Philosophers and methodologists do not often agree about the required criteria but scientists continue to develop models and tests without much debate.

It seems that a standard agreement has already been reached in the practice of science, theories of science notwithstanding.

This way of thinking is a common methodological assumption among scientists today and operates in most cases. But, in my opinion, it is difficult to apply in the case of hemispherectomy. In fact there is not, as we have seen, an area of brain damage to be tested. The damaged hemisphere has been removed. The empirical behavioral testing should be performed on an intact half-brain. This is not a point of detail but a central one. For instance, as I will show, it is extremely difficult to predict a specific cognitive deficit from the lack of an entire hemisphere. Accurate inferences and detailed predictions, by contrast, are common in lesion analysis, in instances where the brain damage area is correctly identified. There are hundreds of papers and books on the neuropsychology of brain-damaged patients (including split brains), but few surveys of the developmental, cognitive, perceptual, moral or social aspects of hemispherectomized individuals. Compared with the massive neurosurgical intervention in such cases the deficits or troubles of behavior in these patients are relatively minor. For these cases we need an alternative methodology to lesion analysis, a positive approach to the half-brain.

Third,

As a consequence, the smaller the lesion probe capable of creating discriminatory effects . . . the more the lesion method will have to contribute.

Current neuropsychological assessment can evaluate very precise deficits and lesion analysis should provide the corresponding rationale of deficit measurement (Lezak, 1995). In extreme cases, lesion analysis could be applied to the experimental microscopical removal of a small group of neurons, as minute as a minicolumn of the cortex, for example. At this extreme minimal level of damage the theory can certainly be subjected to the rigorous scientific test of falsifiability. However, this is not always possible in clinical neurology where brain damage often implies the destruction of millions of neurons and connections. As Damasio (1994, p. 57) rightly says "neuropsychology is not, or should not be, about finding the brain 'localization' for a 'symptom' or 'syndrome'." In many cases, we must also deal *at the*

same time with the localizability of damage and the non-localizability of complex psychological functions! *A fortiori*, focused lesion analysis cannot be applied in hemispherectomy, where an entire galaxy of neuronal components has completely disappeared. Again, it is clear we need a positive approach in order to understand cases in which lesion analysis is inappropriate. Bach y Rita (1990), for example, describes how the brain self-generates "rehabilitation programs" to overcome damage. The alternative I am now proposing may be called "compensatory analysis."

Faraneh Vargha-Khadem and Charles E. Polkey (1992) produced a very thorough review spanning twenty years of publications on the cognitive effects of hemispherectomy or hemidecortication as a treatment for severe epilepsy. The results were encouraging. Not only did most children survive the drastic removal of a hemisphere but some of them, as in Nico's case, have shown such a remarkable readaptation in every activity that we cannot consider them to be living with a "damaged brain." They live with an intact brain. An intact half-brain. They enjoy life, friends and family, learning and playing. Their partial motoric (hemiplegia) and visual (hemianopia) loss makes them no more disabled than others who suffer from a peripheral neuromuscular trauma or disease. Nowhere is the coexistence of "broken brains and normal minds," as described by S. M. Kosslyn and M. van Kleeck (1990), more clearly expressed than in hemispherectomized persons. It is interesting to quote their main points:

- 1 Functional components cannot be identified with symptoms.
- 2 Functional components need not be neatly implemented within the brain.
- 3 It is difficult to determine the function-implementation mapping.
- 4 Behavior is determined by multiple components.
- 5 Quantitative deficits can produce qualitative effects.
- 6 Localization of the lesion does not necessarily localize the damage.
- 7 Descriptions of deficits are theory related.

The conclusion is that these children or youngsters should not be treated as having damaged brains! Parents, educators and physicians need to focus primarily on their motor rehabilitation (and on speech and linguistic training in cases where the left dominant hemisphere has been removed). In some cases, such as Nico, the degree of motor recovery can be astonishing. Immediately

after neurosurgery he could not walk at all. Now, five years later, he runs and plays, with only a slight limp. He gained motor control via the ipsilateral connections of the left brain. His left arm movements are limited, but when forced to use his left hand he can often reach the intended target. Sometimes, for instance, he uses a finger of his left hand in order to hold down a key to capitalize a letter on the computer. The most remarkable outcome, of course, is that, so far, no significant cognitive or affective disorder has been identified in this half-brained child. The question is: how will his potential develop in the future? The scientific literature is not very specific about long-term quality of life after hemispherectomy. We also lack sound statistical information about the cognitive abilities of a half-brained child beyond elementary school. Will Nico succeed in finishing high school and entering university? There is always a possibility that at some point in his psychological evolution there will be a breakdown and a failure at school as a consequence of a developmental arrest. We should be cautious and well-prepared to monitor his efforts to meet clearly defined objectives in his formal education. As I write this book many people are helping Nico to become a good student. At present there appear to be no obstacles to a successful completion of his elementary years, but it is difficult to make predictions.

In a sense we are leaving the neurological and educational domains now and moving into philosophy. Perhaps one of the most interesting examples of the philosophical use of brain-lesion analysis was given by Maurice Merleau-Ponty in his two books *La structure du comportement* (1942) and *La phénoménologie de la perception* (1944). He made an intensive study of the findings of the German neurologist and Gestalt psychologist Kurt Goldstein (1934) which relate mainly to the perceptive and cognitive effects of brain wounds. Some fifty years later the American thinkers Patricia Smith Churchland (1986) and Paul M. Churchland (1996) have developed a new discipline called "neurophilosophy" in which lesion analysis still plays a major role.¹ With the exception of the few pages Popper and Eccles (1977) have dedicated to the cognitive effects of hemispherectomy, no consistent reflection on half-brained patients has, to my knowledge, yet been undertaken by a philosopher. But, as I have said, we cannot explain the consequences of the removal of a complete brain hemisphere by classical lesion analysis. We would need a

different kind of analysis not only in neuropsychology but also in neuropsychology. I believe compensatory analysis could be a valid alternative.

The main requirements are as follows: first to focus on what is left, not on what has been removed, and second, to describe how the half hemisphere develops into a full and healthy mind. The first aspect relates to the fact that the remaining hemisphere is providing "substitutes" for many functions previously performed by the removed one, as we shall see. The second is an invitation for compensatory analysis to be performed over the entire life span of those individuals who have undergone hemispherectomy.

We expect these children will show a normal psychological development but also, in a very precise sense, the half-brained child can be considered an "exceptional child." He certainly develops a "high-ability-halfbrain": a half-brain that performs as a whole brain! This fact does not always imply giftedness, but does not exclude it either. The eventual spurt in neuronal efficiency in half-brained individuals can be tested by compensatory analysis. For example, we may compare the biopsychological cluster in the gifted described by Norman Geshwind and Albert Galaburda (1987) with the conditions exhibited by Nico.²

The Geshwind-Galaburda Syndrome (GGS) correlates five traits of very different type to giftedness: superior spatial skills, non right-handedness, bilateral cortical representation of language, language related problems and immune system disorders. This interesting mix of talents and handicaps, of gifts and deficits, shape a new kind of pathology: "the pathology of superiority" as it was called by Geschwind. An explanation for GGS is an altered brain organization due to an increase of testosterone in the fetal brain. Nico, a right hemispherectomized child, is the perfect mirror image of GGS: he performs poorly in some spatial tasks such as drawing, he is right-handed, he has a definite left cortical representation of language and no language related problems or immune system disorders. The altered brain organization in this "inverse GGS" case is primarily the result of two causes: first, of the congenital left hemiplegia and the functional effect of an early devastating epilepsy when the right cortex seizures interfered with his left non-epileptic cortex and, second, the anatomical effect of neurosurgery at age three. The combination of these successive injuries "forced" the left cortex to assume the functions of both hemispheres. It is in this sense that we may speak of

overcompensation. It is known, from animal research, that when some cerebral tissue is removed (in monkeys) the other brain compensates for the loss by an increase in growth (Goldman-Rakic and Rakic, 1984). Also, an intact left brain is necessary (in mice) in order to develop an intact immune system (Renou, 1988; Cardinali *et al.*, 1997). Both conditions seem to be fulfilled in Nico's case with the development of a new neural circuitry in the left brain. This might represent a kind of compensatory growth for the removal of the right brain and raises the important question of neural space and "neural crowding" in the remaining hemisphere.

If the left hemisphere can develop the skills of a whole brain, it follows that it has enhanced its efficiency. In fact, recent investigations of the way in which the human cortex consumes energy in the performance of different skills can provide valuable information. Non-invasive brain imaging techniques can be used to measure the consumption of glucose, the brain's fundamental source of energy, during clearly defined mental tasks. It seems, for example, that the high-ability brains of gifted persons are more efficient. That is to say they consume less glucose at the same time as performing better than the control ones (Haier *et al.* 1992; Posner and Raichle, 1994). Similar experiments should be conducted at some point on half-brained individuals in order to rigorously test their neuronal efficiency. This notion will help us to enrich and qualify the concept of brainpower.

In our subject the so-called right hemisphere skills — mathematics, visual arts, and music — have migrated to the left hemisphere. We must stress that Nico has no particular gift whatsoever in these skills but neither is he deficient in them. At school he performs like any other child of his age in arithmetic and music. Only his draftsmanship and his handwriting are poor for his age, but this does not involve a real loss of his cognitive spatial performance. Perhaps Nico has only shifted from an "analog" to a "digital" style in these abilities. In fact he can make good graphic designs with the help of a computer, and is mastering written language with the aid of a word processor. In the verbal domain, a left brain skill, Nico, performs well above average. A normal linguistic performance might be expected in his case but not as advanced as it actually seems to be. However, we cannot exclude the possibility that Nico might have had an exceptional verbal brain before surgery. It is impossible to test this assumption now but the point is that there

is no reason why a half-brained child should not also be a gifted child! As the number of half-brained children increases it is possible to imagine a longitudinal study of a cohort of children with high-ability half-brains. This program could take its inspiration from Lewis Terman's famous "study of genius", which started in 1921, but without its theoretical limitations (Terman and Oden, 1959). Nobody would deny the importance of a study that keeps track of hundreds of bright children (Terman's subjects were called the "termites") over the course of their entire life. Some of these children are now in their eighties! What will the life of a half-brained person be like at that age? Perhaps we might see the development of a new kind of giftedness in such high-ability half-brains. We need to keep track of them. They could turn out to be the termites of the twenty-first century!

We can now discuss some definitions for compensatory analysis. I would like to suggest the following three, in the hope that they might at least be of some use as heuristic tools:

First,

Compensatory analysis is the establishment of a correlation between the part and the whole, and in our case in particular, between the half-brain and the whole brain, by controlled experiments.

Thus the properties of a half-brain should be correlated to the properties of a whole brain, i.e. a double half-brain. This is not an easy task either for the experimental neurosciences or in terms of methodology.³ The compensatory analysis of the new circuitry in the half-brain will confront the strict logical problems of the extension of sets of neurons, with the inclusion of one subset in a set, and so on.

Second,

Given a preexisting theory about the operation of the whole normal brain and how it would mediate the performance of an experimental task, the half-brain can be seen as a probe to test the validation of the theories, that is, a means to decide if the account of brain organization and operation provided by a given model is or not falsifiable.

Instead of a damaged area we have here an intact brain hemisphere which acts as a probe to test the general theories of the mind and the brain. Until

now these theories have benefited enormously from lesion analysis but not so much from the study of hemispherectomy. In a sense, compensatory analysis sets out to validate a system from within the system, the whole from the part.

Let me give an example of compensatory analysis in vision. Because of his brain surgery Nico suffers a complete left hemianopia. He cannot see the left part of his visual field. He is constrained to move his head in order to focus on a visual target. The visual images that are formed in the left nasal and right temporal retinas cannot be transmitted because of the incomplete section of the corresponding pathways. In a normal brain the signals of the right hemiretinas travel through the optic nerve, optic tract, and optic radiations to the right primary visual cortex along the calcarine sulcus (the striate cortex or Brodman area 17 or V1) of the occipital lobe of the right hemisphere. Because of the hemispherectomy, Nico's right neocortical pathway (geniculate-cortical pathway) has been disconnected and his stereoscopic vision depends, exclusively, on his left occipital cortex. This is why the testing of the central processing of three-dimensional images can give us some vital information about hemispheric compensation. As far as I know there is no such information in the current literature on hemispherectomy. A good opportunity to apply compensatory analysis.

The interesting thing is that we can now perform a kind of "visual psycho-anatomy" with a half-brained child, and analyze his central process of vision for stereopsis. In fact three-dimensional vision is supported by retinal disparity (the left and right visual fields do not overlap completely). Stereograms are artificially produced with two slightly different views of the same object, which can be fused with the stereoscope. The fusion is produced at a central level, some four synapses at least past the receptors (rods and cones) of the retina: bipolar and ganglionar retina cells, lateral geniculate neurons (LGN), and cortical neurons of the primary visual cortex. There are no synaptic junctions of the right and left visual pathways at the LGN. The first contact is made at the visual cortex. Thus the information coming from the two retinas is not combined until the first cortical stage V1 and is reprocessed at the extrastriate cortex V2 (area 18). The main point is that the central nervous system can combine any stimulation pair and extract the information that is hidden to the peripheral process. Bela Julesz (1971) called this particular type



Figure 3.1 Random-dot stereogram. When monocularly viewed it appears as an aggregate of dots. When stereoscopically fused a diamond is perceived in the center hovering above the random-dot background. The corresponding anaglyph should be viewed with red and green eye filters (from Julesz, B., *Foundations of cyclopean perception*, Chicago University Press, 1971 © 1971 Bell Telephone Laboratories Inc.)

of central processing "cyclopean vision." He discovered a clever method of by-passing the peripheral process by means of random-dot stereograms which provide no familiar perceptual cues to the retina. When viewed monocularly, the random-dot patterns of figure 3.1 will provide the reader with an example of this. These patterns "do not tell" the retinas anything in particular. We can discern no shape in them. But when viewed through a stereoscope (or when green and red filters are used to view the corresponding anaglyphs) the reader should see a diamond shape that pops out from the background. This striking phenomenon is particular to the cyclopean vision of higher mammals, even a human infant can react to and stare at an elevated shape such as a central square hovering over the random-dot background. The use of random-dot patterns in this kind of experimental procedure introduces the observer directly into the visual cortex. This is a compelling reason to study the cyclopean vision of a half-brained child, particularly because stereopsis has been reported to be a right hemisphere-dominant process (Carmon and Bechtold, 1973).

In an experiment which Nico found most amusing, I tested him with the

colored anaglyph versions of five random-dot black and white stereograms provided in Julesz' text, inviting him to use a viewer with red and green filters, one color over each eye. In most individuals, though not all, the cyclopean view produces a strong depth effect which can be reversed by reversing the filters. This is a good test to control the subject's description of the visual three-dimensional image. Where is the "cyclopean-eye" located in a half-brained child? It is certainly not a geometrical construct midway between the two eyes. Compensatory analysis should help us to understand whether or not one visual area alone would suffice to produce a cyclopean visual image. From what we knew about Nico's abilities we were able to predict a perfect compensation. And this turned out to be the case. Nico performed with ease in all the tested visual tasks. He reported the appearance of a diamond, a square, a letter T, a saddle and a spiral shape, in the corresponding random-dot anaglyphs using the red-green goggles. His cyclopean eye is clearly supported by his left visual cortex alone! This fact corresponds to the prediction from the compensatory model of a "whole cyclopean brain" inside his left hemisphere.

Third,

As a consequence of that, the greater the loss of nervous tissue capable of creating compensatory effects in the remaining part of the brain the more the compensatory method will have to contribute.

In other words, what is the minimum brain architecture capable of acting as a sustainable probe in compensatory analysis? This is, I admit, a purely speculative problem in the context of contemporary neurology, but it could turn out to be a practical issue in the future, when an artificial neural prostheses could be connected to the brain. Perhaps the best exploration of this question is in a book of science fiction written by one of the founding fathers of Artificial Intelligence, Marvin Minsky, and the novelist, H. Harrison (1993). We can imagine, for instance a brain/computer physical interface that would create a new dual – organic/artificial – nervous system. At present, however, the minimum sustainable neural organization for compensatory analysis is the half-brain.