6 The double brain

> What we can put on our shelves
> we should not put into our brains
>
> AUGUSTE FOREL

Rudyard Kipling (1927) wrote a poem that deserves a reading and a moment's thought, in the light of what we have been describing:

The Two Sided Man

Much I owe to the lands that grew –
More to the lives that fed –
But most to Allah who gave me two
Separate sides to my head.

Much I reflect on the Good and the True
In the faith beneath the sun
But most upon Allah who gave me two
Sides to my head, not one.

I would go without shirt or shoe
Friends tobacco or read,
Sooner than lose for a minute the two
Separate sides of my head.

The bilateral symmetry we have in common with all other human beings is unquestionably a marvelous gift. Conversely, a broken symmetry seems to disrupt the biological harmony of the whole.

The poet's eulogy of the two-sided head is in marked contrast with the reality of a half-brained person who has lost one side. It is true to say we do not give much thought to our remarkable double brained status. It requires an explicit mental effort or a poet's spark of inspiration to become conscious of it. We do not feel our brains. But how would an hemispherectomized person react to the the poem's theme? Personally I think he should be proud of his exceptional situation. A respected journalist wrote in the same vein about another eight year old right hemispherectomized child: "I can imagine Matt telling his dates ten years from now – You won't believe this, but I have half a brain –" (Swerdlow, 1995). I must confess that in the course of writing this book I became so involved in the problem of the half-brain that at times I experienced a strange mixture of awe and delight about the "wet web" inside my own skull. The terms *wet web* or *wet computer* have a deep impact on our ego; they somehow undermine our supposed robust neurobiological foundations and expose a more fluid inner state. A similar sense of fluidity came to me as a young physician after analyzing mountains of EEG records; when I closed my eyes before falling asleep I sometimes saw a disturbing sea of endless electric waves (see also the essay about the *wet mind* by Kosslyn and Koenig, 1992). The dictionary definition of awe is "a wondering reverence tinged with fear inspired by the sublime" (Webster, 1991). I kept repeating to myself that the wonder is inside our heads. And I tried to imagine what it would mean, as the poet said, to lose for a minute one side of my brain. The real wonder is that some human beings are endowed with only one side of a double brain.

The notion of a broken right-left symmetry in the brain comes from Marvin Minsky. I think it is important to quote it in full as it is insightful comment from one of the creators of the concept of artificial intelligence and relates to the consequences of a right hemispherectomy.[1]

> I do not deny that there are important predispositions for specialization in the brain – but my guess is that these are largely optional. My theory: after a certain point in development, when the child has acquired many different resources for thinking, then (in harmony with what I called Papert's Principle) it becomes necessary to build higher level systems to manage those resources. Now, higher-level thinking requires deeper and more sequential operations. This is because a system that tries to do many things in parallel will therefore become

> more fragmented – in the sense that the different activities will have to compete for limited resources of various sorts. If this is permitted then each of the parallel processes will become more stupid. It is a myth that it is good to use parallel distributed processes – because this leads not to cooperation but to mutual interference. Accordingly, as a child develops higher systems, it becomes necessary to break the right-left symmetry! *A deep intellectual process can serve only one master!* So normally, one side of the brain becomes the master at deliberate sequential planning. What happens to the other side? My conjecture: in the end, it becomes largely wasted – because it remains childish while the other side matures! This is why, in split brain adults, the (usually) right side seems more romantic, less critical, more imagic, less symbolic, etc. It is because it has been left behind, because it has less well developed managers. Now (more conjecture), the managers have simpler jobs, really, than the systems that finally do the work; they use only a small proportion of the brain. In this case there is not much loss – because it only lacks a largely redundant childish copy.

Minsky is not alone in this view about the redundant nature of the right brain. The great zoologist J. Z. Young wondered whether the right hemisphere might be "merely a vestige" and the late neurophysiologist Sir John Eccles dismissed the right hemisphere as a "mere computer" (an epithet which is in itself a vestige of the old brain/computer controversy). However, there is enough evidence of the role played by the right hemisphere in the normal and damaged brain. The point is not to deny it but to understand the way it may be substituted by the left brain.

I would now like to summarize some experiments, both old and new, involving a large team of collaborators, in the hope that they may add some neurological evidence to Minsky's theory of the agents or managers in the "society of the mind" as it relates to the half-brain. Over 1000 children and adolescents (4 to 18 years old) were tested for hand, eye and foot dominance (Battro, 1981, 1996, see note 2).

Conservation of length

Two 14 cms rods were mounted on two parallel rails and could be moved in either direction by one hand. The experiment began with the two rods A and B facing each other. The child introduced one hand through a hole in the screen which hid the rods from view and explored the length of A and B. The experimenter asked whether they were the same length; if the answer was yes one of the rods was slightly displaced to the right and the same question was repeated. The displaced rod was then returned to the first position and the same question was repeated. Finally, the other rod was displaced to the left and the experimenter asked the same question again. The answers were classified according to Piaget, Inhelder and Szeminska (1948): pre-operational children said that the displaced rod became longer, operational children affirmed the conservation of length, i.e. that both rods were the same length and that only the position had changed. The conservation of length was significantly increased ($p = 0.015$) in the RH group of children (4 to 8 years old, $N=256$) using the right hand. In LH children by contrast, no statistically significant difference was found between the right and the left hand groups ($N=92$) although a mirror inversion of the performances appeared.

Conservation of substance

The child was told to put one hand through a hole in a screen and touch two small balls of clay A and B of equal size. The experimenter asked whether A had the same amount of clay as B. The child was then invited to transform one of the balls (B) into a sausage (B'). The question was then repeated for A and B'. The answers were classified according to the criteria established by Piaget and Inhelder (1941). Conservation of substance is established when the child affirms that A=B' because while the shape may have changed, the amount of clay is unchanged, or because the objects are equal, nobody having added or subtracted a piece, etc. These answers imply concrete operations. Figure 6.1 shows the results of 152 RH (4 to 12 years old) and 80 LH (4 to 8 years old). The RH group performed significantly better with the left hand ($p = 0.0042$). There was no significant difference between hands in the LH group.

Class-inclusion

Using one hand, the child manipulated a bracelet (B) made of eight wooden beads consisting of five big beads (A) and three small beads (A'). The bracelet was hidden behind a screen. The first questions related to the form, material, number and size of the beads. The experimenter then asked about the inclusion (A<B): "Are all the small beads made of wood? Are all the big beads made of wood? If you make a bracelet with all the wooden beads (B) and another with all the big beads (A) which will be the larger? Are there more wooden beads or more big beads in the bracelet?", etc. Children were classified according to the criteria established by Piaget and Szeminska (1941) to justify class-inclusion as a concrete operation. Again, the RH group (4 to 12 years old, N = 62) performed better with the left hand (p = 0.0027) but in the LH group this difference was not significant (4 to 8 years old, N = 92).

Probabilities

Thinking about probabilities implies a formal balance between favorable cases vs possible cases. A tactile test for the quantification of probabilities was adapted from Piaget and Inhelder (1956). Using only one hand in a blind situation as before, a set of smooth wooden cubes S was compared with a set of rough cubes R. For instance: one S and four R were compared with two S and four R. In which set is there a higher probability of picking up a rough cube R at the first attempt? A correct answer implies the comparison of pairs in the example above (4/5) > (4/6) where the higher probability of picking up an R is in the first set. A large number of different probabilities was presented to 224 RH adolescents (12 to 18 years old). No LH subjects were submitted to this test. In the RH group we detected a higher performance in formal operations in those using the left hand (p=0.045). As in the other logical tasks (conservation of substance and class-inclusion), the right hemisphere seems to play a key role as a relay of the information which will be fully processed by the left hemisphere. I am now entitled to ask what happens in the case of the right hemisphere being removed?

In the first place, it could be shown that for "concrete operations" such as class-inclusion or conservation of substance, and for "formal operations" such as probabilities, the right-handed children who used their left hands, thus activating their right hemispheres, performed at a significantly higher level than the group using their right hands and left hemispheres! The inverse phenomenon occurred in concrete spatial operations such as the conservation of length of a rod; the group who used their right hands, thus activating

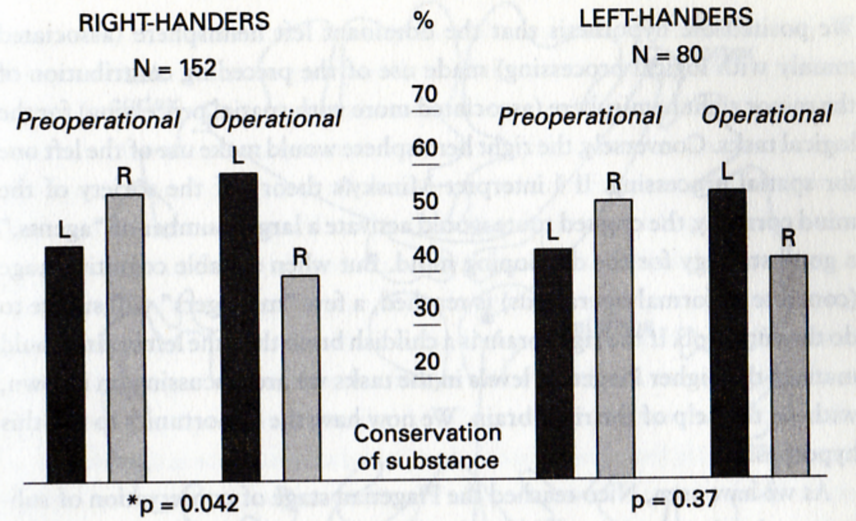

Figure 6.1 Distribution of pre-operational and operational performances on the Piagetian task of conservation of substance with different hands L: left, R: right, in right-handers and left-handers.

their left hemispheres, attained a more advanced level of spatial reasoning. However, no significant difference in cognitive performance was found in the left-handed group, irrespective of which hand and therefore, which brain hemisphere was used. The reason for this may be that they have a larger bilateral cortical representation (Satz, 1979). What is the explanation for this intriguing result? We know that the information gathered by the left hand goes first to the right hemisphere and then reaches the left hemisphere in a second step via the corpus callosum, and vice versa. The amazing conclusion was that different neuronal paths favor different (logical or spatial) kinds of operational thinking and were perfectly crossed in the right-handed group. For instance,

(a) in the logical tests of conservation of substance, class inclusion and probabilities, the subjects attained concrete thinking at higher operative levels with the sequence: left hand > right hemisphere > left hemisphere.

(b) in the spatial test of conservation of length, by contrast, the subjects attained the best cognitive performance with the sequence: right hand > left hemisphere > right hemisphere.

We posited the hypothesis that the dominant left hemisphere (associated mainly with logical processing) made use of the preceding contribution of the minor right hemisphere (associated more with spatial processing) for the logical tasks. Conversely, the right hemisphere would make use of the left one for spatial processing. If I interpret Minsky's theory of the society of the mind correctly, the crossed route would activate a larger number of "agents," a good strategy for the developing mind. But when a stable cognitive stage (concrete or formal operations) is reached, a few "managers" will suffice to do the entire job. If the right brain is a childish brain then the left brain should manage the higher Piagetian levels in the tasks we are discussing on its own, without the help of the right brain. We now have the opportunity to test this hypothesis.

As we have seen, Nico reached the Piagetian stage of conservation of substance when he was six years old. What happens if we repeat the test two years later, but this time in a blind situation? The change from vision to touch is crucial here: instead of seeing the transformation of the ball into a sausage with his own eyes, he will be forced to rely solely on the tactile and proprioceptive feedback from his hands. The right hand is not disabled and connects normally to the left hemisphere. Following the right hemispherectomy, however, no crossed paths exist from the left hand, only some relatively minor ipsilateral connections to the left brain remain (Benecke *et al.*, 1991, Adelson *et al.*, 1995). As previously mentioned, Nico still has some restricted movement in his left hand but his stereognosia is impaired. When asked to identify some familiar solid objects (a key, a spoon, a fork) behind a screen with his left hand, he had great difficulty and gave no correct answers. However, with his right hand he immediately identified the objects correctly. What is your conjecture about the result of this tactile version of the Piagetian test? Let us try to apply our compensatory analysis. First, if the left hemisphere fully compensates for the loss of the right one, then no deviation from the cognitive norm will be observed. The half-brained child who acquired the concept of conservation of substance two years earlier would thus have no difficulty in replicating the same reasoning in the new blind setting as when the tactile information passed from the right hand to the left hemisphere. The main contralateral connections to the left hemisphere would suffice to give reliable information on the transformation of the ball of clay. But would the minor ipsilateral

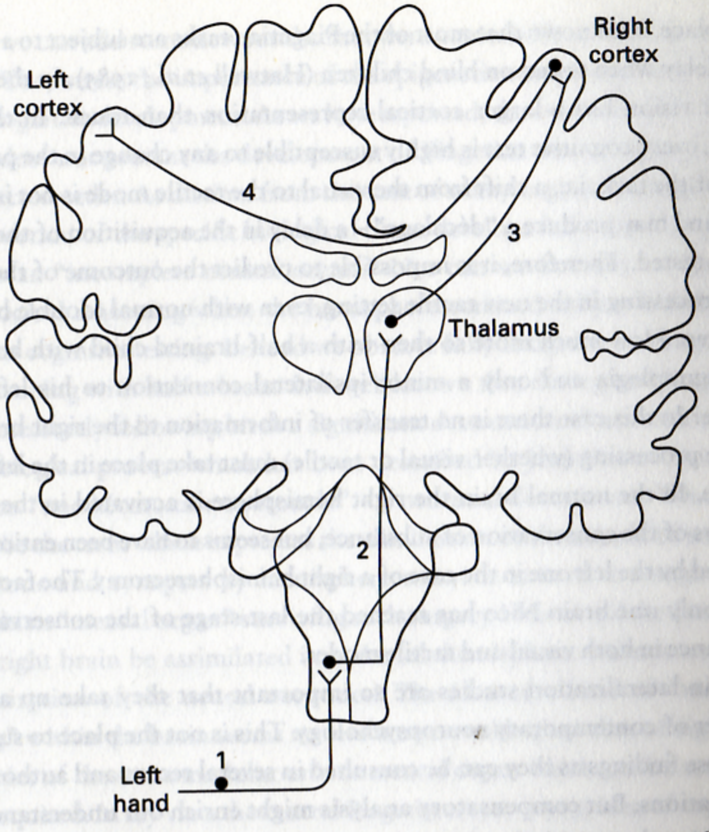

Figure 6.2 Crossed pathways. 1 Dorsal funiculus, 2 Crossing lemniscal fibers, ventral thalamic nucleus. 3 Somesthesic projection system. 4 Interhemispheric fibers, callosum.

pathways from the left hand to the left hemisphere convey the same kind of information? The prediction from compensatory analysis would say no. In effect, Nico gave a perfect response to the Piagetian task of conservation of substance using his right hand, but not with his left hand! This is exactly the inverse situation to the group of normal children who showed a higher cognitive performance with their left hands. In other words, cortical compensation is fully developed for concrete tasks which reach the left brain via a crossed main path but not via the ipsilateral connection.

For the moment this example suffices for our purpose. In fact, the standard visual situation is not equivalent to the blind tests for many reasons. In the first place, it is known that most of the Piagetian tasks are subject to a systematic delay when tested on blind children (Hatwell *et al.*, 1985). In the second place, vision has a larger cortical representation than touch. In the third place, every cognitive test is highly susceptible to any change in the presentation of the task, i.e. a shift from the visual to the tactile mode is not insignificant and may produce a "décalage" – a delay in the acquisition of the notion being tested. Therefore, it is impossible to predict the outcome of the cognitive processing in the new tactile setting, even with normal (double brained) children. How much more so then with a half-brained child with hemianopia, hemiplegia and only a minor ipsilateral connection to his left hemisphere? In this case there is no transfer of information to the right brain and all the processing (whether visual or tactile) must take place in the left hemisphere. In the normal brain the right hemisphere is activated in the logical process of the conservation of substance, but seems to have been entirely substituted by the left one in the case of a right hemispherectomy. The fact is that with only one brain Nico has reached the last stage of the conservation of substance in both visual and tactile modes.

Brain lateralization studies are so important that they take up a whole chapter of contemporary neuropsychology. This is not the place to summarize these findings as they can be consulted in several recent and authoritative publications. But compensatory analysis might enrich our understanding of the subject,[3] particularly when we consider the opposing views of cognitive modularity and constructivism, the paradigms of Noam Chomsky and Jean Piaget as expressed in the celebrated 1975 Royaumont debate between the two scientists (Piatelli-Palmarini, 1979, 1994). Chomsky emphasizes the need to study cognitive structures (particularly language) as "mental organs" in the same way that we study any physical organ such as the heart or the brain itself. He explicitly refutes the Piagetian constructivist approach of a sequence of cognitive stages developing in complexity from the sensory-motor schemes to the higher formal operations. He thinks, for instance, that the mental organ of language has an ontogenetic as well as philogenetic history which follows the genetic program of the species. Piaget on the other hand, affirms that "only the functioning of intelligence has a hereditary basis but the production of (cognitive) structures is given by the organization of successive actions upon the objects".

Now we can add some new results that were unavailable at the time of that debate. They stress the importance of the epigenetic component in the brain and of cognitive development. As we have reported, the existence of only half a brain does not prevent the development of Piagetian mental operations in the expected order. As distinct from the case of many organic deficits, where only a portion of the specific biological tissue develops fully, there is no such thing as an "incomplete mental organ." Nor can we find any evidence of faulty logical reasoning when the hemispherectomized subject is duly submitted to cognitive testing. Instead we observe fully fledged reasoning, never half reasoning with half a brain! It is well known that during embriogenesis and immediately following birth a significant destruction of neurons occurs, a physiological process which has been described by Jean-Pierre Changeux (1983) as "une hécatombe neuronale" – a neuronal devastation. What then should be the term which expresses the elimination of thousands of millions of neurons and synapses by hemispherectomy! It is hard to imagine any Chomskian "mental organ" surviving such surgery. How could the functions of the right brain be assimilated into the left hemisphere without a radical reorganization of the neural networks? The idea of a kind of "modular cloning" within the brain seems no less unreasonable than that of right and left copies of the same modular unit or mental organ which can be activated when required. In my view the central Piagetian (1967, 1975) idea of cognitive equilibrium offers a better explanation for the radical reorganization of mental processes following a functional hemispherectomy. This is the idea of an equilibrium between assimilation and accommodation, between the subsystems of a system within a new global system ("équilibration majorante"). In Nico we have an extreme case of cognitive re-equilibration following a massive neuronal perturbation. Moreover, there is some recent physiological evidence to suggest that Piagetian cognitive cycles of accommodation and assimilation can be related to cyclic cortical activity (Thatcher, 1998, Fischer, 1997).

New dynamic models of cognitive and cortical growth can now be tested following the removal of a hemisphere. We would certainly need to know if, as in the case of hemispherectomized animals, the remaining hemisphere uses a greater number of neurons in order to compensate for the lost hemisphere (Adelson *et al.*,1995). But metabolic constraints will certainly limit the number of neurons that can be simultaneously active. We can conclude that the successful activation of alternative neurocognitive networks as a result of hemispherectomy reflects the amazing plasticity and redundancy of cerebral connectivity. It reflects the enormous power of the human brain wide web. Our double brain is undoubtedly the inner frontier of knowledge.

7 Brain, education, and development

Fabricando fabricemur

DIDACTICA MAGNA, 1640

JAN AMOS COMENIUS

This chapter has a distant source in one of the founding fathers of modern pedagogy, the Czech theologian Jan Amos Comenius (1592–1670). His proposition was "to learn to write in writing, to sing in singing, to think in thinking." He also introduced an interesting correspondence between mind, brain, and thinking (mens, cerebrum, ratio) on the one hand, and hands, activity, and artistic skill (manus, operatio, artes) on the other. Three centuries later Jean Piaget (1957) reinterpreted this outdated concept in the modern "act and construct" framework of developmental psychology and progressive education: "understanding of the rule derives from the retroactive organization of examples already utilized in spontaneous practice." Today the way forward for the education of future generations is two-fold – the digital web which connects people and institutions across the planet, and the brain web of new synaptic connections made inside our heads in the process of learning. We are talking here about an extremely large scale of interactions, both internal and external, a very complex system which is still difficult to imagine, compute or manage for current educational purposes. Consequently, this final chapter should be interpreted as a preliminary sketch of that delicate process of amazing complexity I call neuroeducation.[1]

I will try to describe briefly how brain, education and development are

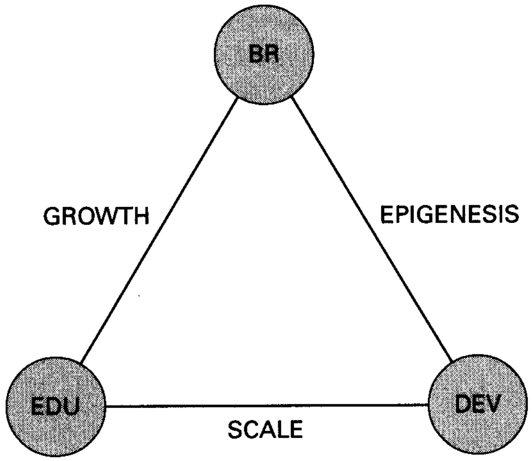

Figure 7.1 BRED. Brain, education, and development

linked in a triad I call BRED. A half-brained child gave me the unique opportunity to reflect on this topic and to monitor some precise pedagogical interventions in this new field. But BRED should also be treated as an area of knowledge in itself and as a wider program of action that can hopefully lead to the enrichment of many lives in our global society.

Figure 7.1 may help to understand the new concept of BRED: BRain, Education and Development. The nodes BR, EDU, DEV are represented as the points of a triangle and the sides represent the links: BR-EDU, EDU-DEV, DEV-BR. To each link I propose to "paste" the observed neurocognitive phenomena and the main concepts involved. For the sake of brevity I have chosen six links (from a larger collection) which I have studied extensively in other contexts, and which were selected to fit our study of a half-brained mind.

I firmly believe that the education of an hemispherectomized child can open new perspectives on the way we understand human nature and the nature of education itself.

Transitions and the link between education and the brain

Education is a widely inclusive cultural phenomenon which accepts all categories of individuals and seeks to overcome all kinds of obstacles, especially those which relate to physical and mental disabilities. Those teachers who are dedicated to so-called "special education" know well how much pedagogical

Table 7.1 *BRED links*

BRED	*phenomena*	*concepts*
EDU-BR	learning curves	transitions
EDU-DEV	micro/macro	change of scale
DEV-BR	compensation	epigenetic growth

effort is dedicated to the training of precise, controlled skills. Over a period of more than fifteen years I have worked thousands of hours endeavouring to help such children (and their families) to deal with their disabilities. Nico the first hemispherectomized child I met in my whole career, was a new challenge for everybody. To help him we put together an interdisciplinary team of teachers, psychologists, and technicians. We met regularly at school in a monthly seminar to assess Nico's schooling in every possible field of activity. In addition I had regular conversations with Nico's parents and, of course, many opportunities to work with him either in a group situation, or individually, both at school and at home. From the outset we have kept a detailed record of his school work and have videotaped some of his activities. These records allow me to affirm today that his early epileptic trouble and his right hemispherectomy have not – so far – given rise to any specific impediment to Nico's learning process. On the contrary, he learns at the same pace as his schoolmates and he follows a normal developmental trend. But of course Nico's education needs careful and responsible supervision in order to detect any sign of trouble as soon as possible. We cannot take for granted that he will continue to learn and develop without major problems. He attends a large, busy school with hundreds of pupils and a great diversity of requirements and we are ready to implement new educational strategies if at any stage he should begin to show signs of stress under the ever increasing institutional strain, or fall behind his classmates. All the signs, however, indicate that Nico is performing up to his own and our expectations.

We can now explore the first cell of Table 7.1, the learning process, and for this purpose we can take the example of Nico's written language. As I have stated, his written output does not differ from the norm for his age. It might

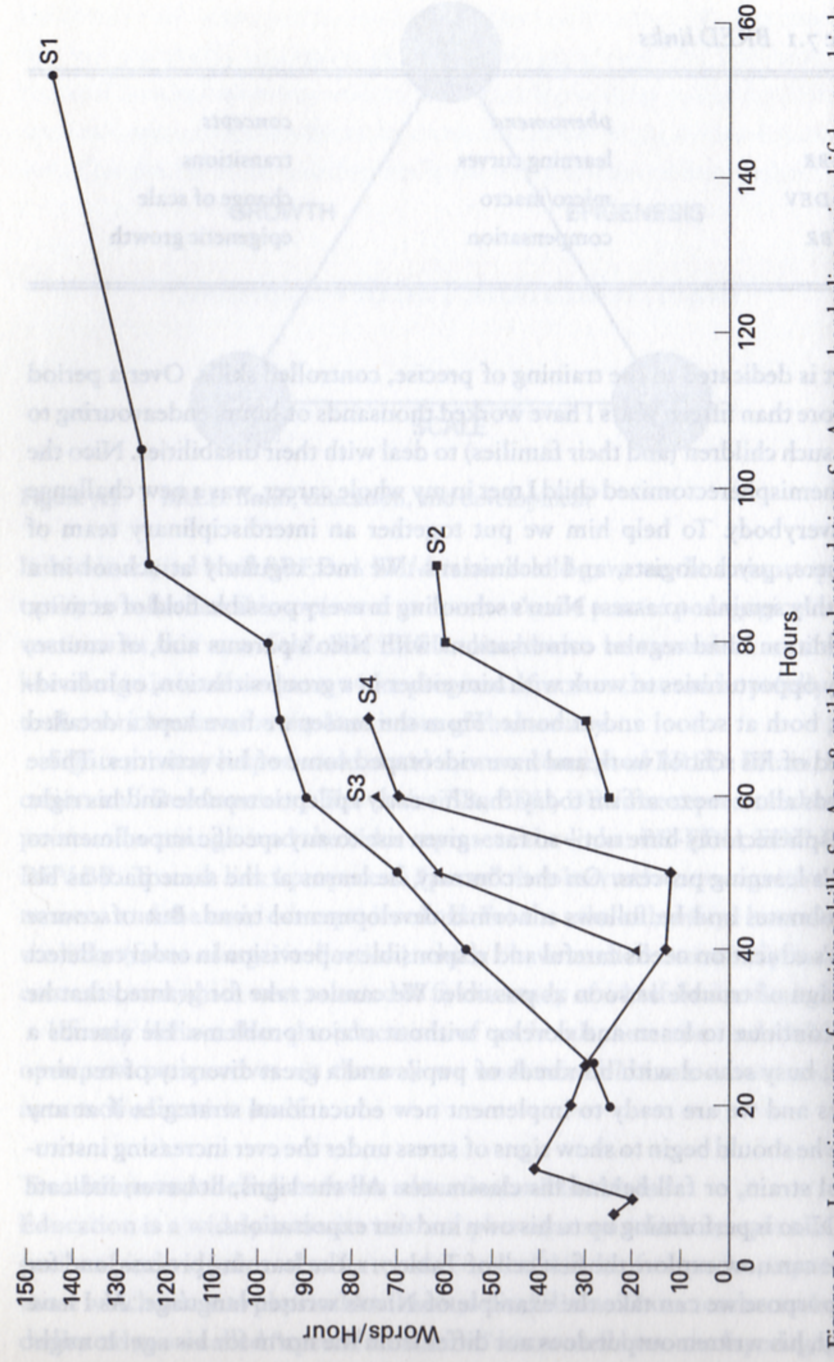

Figure 7.2 Learning curves for writing skills. S1. Age 18: mild mental retardation, S2. Age 20: borderline, spina bifida, quadriplegia, S3. Age 17: Down's syndrome (trisomy 21) and S4. Age 16: autism with visceral and somatic malformations.

be useful however, to compare his computer writing skills with those of some other brain disabled subjects. For them the writing process develops very slowly, a feature that will allow us to make a more precise analysis of the respective learning curves with a word processor in general. Figure 7.2 shows the learning curves with a word processor of four handicapped youths. After a latent period which varies from two to forty hours of weekly training, the disabled student is capable of at most twenty written words in a one hour session (mostly as a copy of some printed text). We can take this as a turning point. Then a most remarkable "explosion" in the quality (decrease in the number of errors) and quantity of writing (increase in the number of words per hour) takes place until a plateau is reached. All the subjects show a comparable acceleration in their written output (similar slopes in the learning curves) after a specific time-delay. To sum up, these sigmoidal learning curves are composed of three segments: first, a latency period which may extend to dozens of hours of practice, second, a clear transition with a very steep segment of improved performance, third, a plateau is reached showing a stabilized skill. This kind of non-linear development of a simple skill is very common, as has been described in detail (Fischer and Rose, 1994, 1998; Thatcher *et al.*,1997). What is important here is the rapidity of the change in the transitional phase, where we observe a similar slope in all four cases. This abrupt increase in output is accompanied by a simultaneous dramatic decrease in the number of errors (misspelt words), which in some cases drops to under 10 per cent after initially representing over 80 per cent of the total written production! This abrupt increase in efficiency seems to be a general neurocognitive phenomenon during the acquisition of many skills. My conjecture is that this leap forward can be linked to the opening of new neural pathways in the brain.

A simple explanation for the exceptionally long time it takes for these handicapped persons to acquire new abilities is that their brains need a longer period of activation to trigger a new way of doing things. The clinical difficulty is to keep the subject active during the protracted and tedious latency period, the duration of which can inhibit further learning, either because of lack of motivation and positive feedback, or even because the subject's consistently poor results cause the demotivation of the instructor. It can often seem as if the training never reaches the threshold capable of "opening" new cognitive paths in the brain and building new neural networks. We can say that the first changes take place after approximately ten hours of practice and that a plateau can be attained at around 100 hours. But a new scaling factor can be triggered and a new explosion in written output observed after about 1,000 hours of computer work. This final spurt enables some disabled students to look for jobs as clerks, but few subjects stay long enough to reach this second threshold. We may interpret the accelerated segment of written performance – and the correlated decrease in errors – as a behavioral sign of the "opening" in the brain of new cognitive paths for writing. Logarithmic scales are known to represent psychophysical phenomena. At this point they help us to establish a functional link between the brain and learning. The concept that sheds the most light on the whole learning situation is that of "transition" – the abrupt change in the underlying dynamic of the learning process from one stable stage (few words, many errors) to another stable stage (many words, few errors). There is a whole branch of mathematics known as catastrophe theory, developed by René Thom (1972) which might be applied to model this kind of bi-stable behavior. The abrupt transition from one level of written performance to the other can be interpreted as a "cusp" in the mathematical sense of the theory of catastrophes, but we need more experiments to test the model in greater detail. The catastrophe theory became fashionable at the end of the 1970s when I became engaged in that topic too (Battro,1976; Rozestraten, Battro and Santos Andrade, 1976). Now, with the new angle on dynamics and bifurcations of neural networks it is surfacing again with some interesting results in experimental psychology (Wang and Blum,1995).

We never subjected Nico to an exhausting one hour session on a word processor. But from his day-to-day records at school (over a period of three years) we observed a steady increase in the quantity and quality of his writing; a very low number of errors (less than 10 per cent) from the outset (copy) and a format of short messages of about forty words (free production, letters, comments, etc.). This would represent an estimated output of more than 300 words per hour, double that of the best 18-year-old pupil from our former study. We can infer from these data that Nico's latency period was very brief and that the transition to a plateau was abrupt. He has now attained a satisfactory written output but his typing is comparatively slower than the actual

(hand-written) production of many of his classmates. This quantitative difference could become greater in the future and might have some detrimental educational consequences. However, things may improve now because of Nico's growing use of email, which in itself merits comment.

For a child, the fact of communicating via the Internet signifies a qualitative cognitive change (as it is for every one of us). I am convinced that the rehabilitation process of a handicapped person can be enriched by regular email contact. I must say that this is a new kind of professional (medical or psychological) tool, which for some reason is underestimated by my colleagues. For instance, most computers in hospital are operated by healthy adults. Very few patients have access to them, fewer still if those patients are children. However, when this technology becomes accessible, it can change the quality of life of the disabled user. I began to explore the beneficial effects of email with deaf children when computers were first introduced in schools in the early 1980s and I extended the idea of networking to many other disabled students as well. Via the network we were able to communicate easily with a deaf adolescent who designed all the computer graphics for our book about "discommunications," an essay on the use of computers with the deaf (Battro and Denham, 1987). Its social impact aside, email offered all of them the unique opportunity to combine the syntactic, semantic and pragmatic dimensions of language in one single act of communication through the Web. And this is essential for education. I always try to maintain a regular email exchange with my former students with disabilities and I certainly recommend this professional practice. Some of them are still sending emails after more than ten years. It is a very gratifying experience indeed for the teacher and the student!

Formal education has traditionally been confined to the communication which takes place within the school walls. Today circumstances have changed and students and teachers can enjoy and benefit from a wider horizon of communication through the Web. We have also empowered Nico's communication capabilities by means of a sustained digital link. With these resources we have opened up a new world to him and his whole class. Initial results have been very exciting, although it is too early to predict the scope of this email activity in the long term. But in a year's time I fully expect the whole class to have established a regular digital habit, as is frequently the case when the school provides "email for all" at an early age. The next step will be to develop the necessary skills to surf the Web. I must confess my great joy when I receive a message from Nico, an event which I await daily with a mixture of admiration and expectation. We have established some ground rules for send/reply operations and we respect a commitment to keep up regular exchanges. We have so many things to share! At this point in time it is hard to imagine the life of a half-brained child as a young man, but I believe this digital habit will grow as he does.

The change of scale and the link between education and development

This is a more general topic and I shall follow a different route – from concepts to facts. Education can be described as an intervention in the course of mental development. Both are closely linked and modern theory and practice provide a vast amount of evidence for their strong correlation over a person's entire life span. Jean Piaget was one of the most prominent advocates of establishing a progressive education based on the different stages of human development. He recognized Comenius as the founding father of the idea, but progressive education seems to be as beset with difficulties today as it was in the seventeenth century. Some optimists, and I belong to this category, believe that we are on the verge of a sea change in the old educational paradigm because of the massive impact of computers and communications on society. In fact we are about to see a radical change in the "scale" of education. And this lies at the core of our discussion.

I know that the question of scale, of the change of magnitude in a system, is extremely complex. In education we must face this question from the outset. As a matter of fact education is very sensitive to quantitative changes, and every teacher, administrator or minister of education knows this. In the first place, a mere increase in the amount of equipment or human resources does not ensure a qualitative leap forward in learning. In the second place, education seems to be "scale dependent." This explains why it is impossible to apply a possible success in a restricted learning environment to a broader one. In other words pedagogical intervention is valid only in the specific scale in which it has been tested. Unlike engineers who can simulate the behavior of a river in a scale model of a dam, educators cannot predict the outcome of a national program from a well monitored model in a few experimental

schools. Education is not scalable in the sense that hydrodynamics is. In this context we have performed a wide variety of experiments with children concerning some Piagetian cognitive invariants using different scales. We discovered, for instance, that the psychogenetic construction of the 1–1 correspondence and of the projective lines were scale-dependent, the conservation of surfaces and the axiom of distance, on the contrary, were scale-independent (Battro *et al.*, 1976, 1977). For example, the acquisition of the concept of 1–1 correspondence between large objects (such as real cars and real trees) is delayed in time compared with the ordinary tests using small objects (eggs and egg-cups). A systematic study of this kind of significant cognitive scale-shifts should be reconsidered in the era of globalization. Scale too, therefore, should be a matter of pedagogical concern.

Micro education and macro education seem to be altogether different disciplines. Each node in the BRED system has specific internal scales. There is a micro-EDU in the short learning process of a simple skill (eg. click and drag a computer mouse) and a macro-EDU in the long learning process of a domain (eg. musical composition). There is a micro-DEV in problem solving (eg. recursion in the Tower of Hanoi task) and a macro-DEV in geometric concepts (eg. from simple topological to elaborate Euclidean thinking). Each of these levels corresponds to a specific space and time scale and they can be mixed in a very complex manner. A similar imbrication of levels has been reported in Chapter 2 in relation to the BR node (microcycles of brain growth within macrocycles or tiers of cortical reorganization). The change of scale may modify the way we teach a half-brained child. Nico is being educated in a private school equipped with a wealth of computers and digital networks, a television production studio, online videoconferencing facilities, and the like. He is totally immersed in a digital environment. We have observed that this rich informational milieu is providing a crucial prosthetic support, especially for his writing skills. In years to come he will be using many other digital school facilities to develop a larger array of skills. We have already described the nature of a "digital education" (Battro and Denham, 1997) and it will suffice for our purpose to reflect briefly on the impact of these technologies on the education of a half-brained child. We are dealing here with the new frontiers of knowledge in the digital world of the future.

First, we know that one of the principal properties of digital systems is their astonishing "scalability," we can add more and more computers and optic fibers to a network without altering its nature. The digital world has no frontiers and is expanding smoothly in a seamless network that will soon cover the whole planet. At school the profound changes from a simple local network to the World Wide Web, from intranet to Internet, from a BBS to a home page, are akin to the growth of a living system. Let me recount my experience at a school where everybody made very intensive use of the local digital network. One day the number of students and teachers using the Internet reached 1,000. They were exchanging the same kind of messages as before but on a global scale! This abrupt and impressive change of scale of many degrees of magnitude was clear to all of them. The same digital behavior pattern is being repeated in an increasing number of schools around the world. Nico is extremely fortunate to have been born at the end of the twentieth century, when a well trained half-brained person will certainly receive his fair share of the formidable expansion of knowledge which the growing digital world has to offer.

Second, I would like to emphasize some of the invariant properties of many of the functional changes which link a change of scale in education with individual mental development. For a half-brained child such as Nico, as for any "double-brained" child, it is important to feel at home when facing tasks of increasing difficulty, even when some of these imply a change of scale. A pedagogically well designed task will convey some functional anchors as well as some structural analogies which may be recognized as invariants, despite the increasing complexity of the whole problem. Let me give an example from a different domain, that of urban design. For many years I have been working on the cognition and perception of urban space by children and adults and I had the good fortune to work with the late Kevin Lynch (1960,1979), a pioneer in the field. With a large team of psychologists and architects in several towns we established the developmental trends in the psychological representation of the urban features that make up the general pattern of a place: borders (i.e. a river), zones (a park), paths (a street), landmarks (a church), nodes (a road crossing). The children were asked to go round a large part of their own town and then build a maquette, a scale model of the place, and also to make some drawings. We discovered that the representation of the urban plan was made in stages; the paths were

established first, the landmarks last. And most interestingly, when we asked them to visit and reproduce a small public park instead of a large urban space, we discovered that the same pattern from paths to landmarks was repeated. In this particular instance, a part of the town, a public place, was itself composed of borders, zones, paths, landmarks, and nodes, just as in the town as a whole! These five features act as invariants or cognitive anchors in the change of scale (Battro and Ellis, 1989). We interpreted this cognitive phenomenon as an example of "self-similarity," a central concept of Benoit Mandelbrot's (1997) mathematical theory of fractals. These mathematical objects can be self-similar, i.e. a part of an object conserves some of the properties of the whole object. For instance, when we inspect a coast in detail we can observe bays and capes, but if we proceed further, with a finer measurement, we find other similar (but smaller) bays and capes in a shorter section of the same coast. We can continue at smaller and smaller scales and the complexity will continue to grow (bays inside bays inside bays . . .). This is a restricted geographical example of recursion but if properly extended to a mathematical curve the complexity and length of the coast line will grow endlessly. There are many interesting models of this sort of recursive self-similar curves (Koch curves, for example). I believe that fractals may help to analyze some theoretical questions in our BRED model too. In particular those questions related to the micro and macro levels. For instance, how do we manage to go from an individual micro-development to a collective macro-education? or from macro-development to a micro-learning process? We must recognize that we are still in trouble when dealing with changes of scale and self-similarity problems in education and psychology, but there are some new developments in the most advanced neurosciences, as is the case with fractal strategies for neural networking scaling (Lister, 1995).

This notion of spatial invariance can be taken as a metaphor for many kinds of cognitive changes of scale during learning. The same invariants frequently crop up at both the macro and micro levels. For instance, when children transfer their writing skills from simple word processing for homework to higher levels of communication, such as sending messages on the Internet, an important cognitive change of scale takes place but the basic digital skill (writing sentences on a computer) remains invariant. The scale shift, however, is considerable. The first task is at the level of a micro-development, the second can open the door to long-distance education, a macro-educational level. Shifting from one level to the other, changing cognitive scales, is an essential activity in education. Nico is now engaged in this ever empowering practice through email, thanks to the fortunate choice of a school in which digital education is bringing about the spread of new global links to develop the potential of each student.

Epigenetic growth and the links between the brain and mental development

Epigenesis is the opposite of preformation. It can be studied in the development of an organism interacting with the environment. There is a developmental path to be followed, a "chreod" in Conrad H. Waddington's (1974) terminology. But this dynamic process can suffer all kinds of disturbances, both natural and artificial. Experimental embryology is based on the ability to provoke and monitor these disturbances. Waddington proposed a dynamic theory according to which some disturbances in the system can be corrected by a procedure known as homeo-rhesis. This is defined as a regulated flow through the basins of an "epigenetic landscape," with hills and valleys, the unstable repulsors and stable attractors of the dynamic system. These dynamic notions are also very useful in the study of neural development, where hereditary and acquired factors are closely interwoven. Jean-Pierre Changeux has defined the notion of a "genetic envelope" as the frontier between the invariant characteristics submitted to the strict determinism of genes and the characteristics submitted to phenotypic variability (in Piatelli-Palmarini, 1979). There is a huge amount of evidence relating to epigenetic phenomena in the nervous system. For example, at the molecular level the synapses are constantly renewed in the neuromuscular juncture of the embryo (every twenty hours) and also in the adult (every eleven days). The whole brain is submitted to an important epigenetic regulation by nervous activity (Arbib *et al.*, 1998).

The BR-DEV link is essentially an epigenetic link. Jean Piaget was perhaps the first psychologist to have made the transfer of the epigenetic model from biological evolution to cognitive development in a systematic way. His example has been followed by others, and it can be said that the study of epigenetic mechanisms is at the cutting edge of one of the most advanced areas of neurocognition. Hemispherectomy studies may also

profit from these advances. The surgical removal of the right cortex in particular, as in Nico's case, represents a key test for the epigenetic reorganization of the left cortex. And this in turn implies a revision of our theories about the neural processes involved in the acquisition and growth of human knowledge. Piaget called genetic epistemology the study "of the mechanisms of the growth of knowledge" and he made a distinction between restricted and generalized genetic epistemology. The former includes "all psychogenetic research or historico-critical research about the methods of the growth of knowledge, to the extent that it is based on a system of reference constituted by the state of knowledge existing at the moment of observation." In the latter "the reference system is itself included in the genetic or in the historical process which has to be studied" (Piaget, 1950). In this sense, perhaps the study of the epigenetic mechanisms of the developing brain will lead to a new "epigenetic epistemology."

I am convinced that any progress in the theory of knowledge will profit in a fundamental manner from the epigenetic study of brain development. We saw a reconstruction of the hemispherectomy performed on Nico some five years ago on a virtual reality workbench. Using similar technology we can imagine a digital brain atlas which will be able to simulate the continuous growth of the different structures of the nervous system – fibers, nuclei, gyri, cortices. This description will illustrate the neural developmental curve from birth (or before) to full brain growth (and its subsequent regression), in short, the complete arc of life, particularly the segment which spans the school years when a significant proportion of the brain's growth takes place. I must say that in the course of my research I became increasingly aware of the amazing changes in the shape and size of a child's head which we usually take for granted because of the overall growth of the body. Pediatricians and anthropologists have studied this fact for decades but few educators have assimilated the profound consequences of this phenomenon from the point of view of the growing neural web inside the skull during schooling. Should we wait for a twenty-first century D'Arcy Wentworth Thompson (1952) striving to describe the "growth and form" of neural structures? Neuro-education certainly needs a good map of the schooled brain in different scales of anatomical detail. It is worth noting that as yet the field of current brain imaging has provided little information on the developing brain. And we can even imagine a corresponding dynamic atlas of the growing brain in which the location of the most important cognitive processes will be shown as they evolve. We certainly need to map this new "epigenetic landscape" but this is no easy task and should be included in a far reaching BRED program.

My thesis that "the half-brain is a new brain" will also need rigorous epigenetic study, at all possible levels, from the micro-architecture of synaptogenesis to the macro-connectivity of emergent neural networks. I am aware that in this book I have only drawn a rough sketch of the epigenetic neurocognitive landscape of a half-brained person, but I hope many others will go more deeply into what I have explored superficially. With the help of team work we should begin to unravel the marvels of the amazing reconstruction of the brain which I have been so fortunate to study.

Notes

1 The heart is in the brain

1 The book *Education and the brain*, edited by Jeanne S. Chall and Allan F. Mirsky (1978), is one of the rare publications in recent times that deals explicitly with the subject I now call "neuroeducation." At that time *The National Society for the Study of Education NSSE*, founded a commission on *Education and the Brain* with such distinguished scholars in both fields as Jeanne S. Chall, Allan F. Mirsky, Richard Held, Jerome Kagan, Horace W. Magoun, Richard L. Thompson, Sheldon H. White and Merlin C. Wittrock. We can also find some remarkable insights in the same vein in the last century. A professor of neurology of the University of Chicago, Henry Herbert Donaldson, wrote a very interesting book *The growth of the brain: A study of the nervous system in relation to education* (1896). He began his study, a century ago, with the following words "we are told that this age is one of nervous strain . . ."

I think it would be fruitful today to continue the work these pioneers have started. The new master concentration directed by Kurt W. Fischer at Harvard Graduate School of Education: *Mind, Brain and Education, MBE* is an answer to that challenge.

2 The study of the damaged brain has been for many scientists a platform for philosophical reflexion. The eminent German neurologist, Kurt Goldstein (1878–1965), delivered the 1938–39 William James Lecture at Harvard with the title *Human nature in the light of psychopathology* (1940). It must be said that Goldstein's classical text *Der Aufbau des Organismus* (1934) was very influential on European phenomenology, in particular on the work of Maurice Merleau Ponty. I had the chance to audit his teaching at the Collège de France when I was at