Half a Brain is Enough is the moving and extraordinary story of Nico, a little boy who at the age of three was given a right hemispherectomy to control intractable epilepsy. Antonio Battro, a distinguished neuroscientist and educationalist, charts what he calls Nico's 'neuroeducation' with humor and compassion in an intriguing book which is part case history, part meditation on the nature of consciousness and the brain, and part manifesto. Throughout the book Battro combines the highest standards of scientific scholarship with a warmth and humanity that guide the reader through the intricacies of brain surgery, neuronal architecture and the application of the latest information technology in education, in a way that is accessible and engaging as well as making a significant contribution to the current scientific literature.

Half a Brain is Enough will be compulsory reading for anyone who is interested in the ways we think and learn.

Born in Argentina, ANTONIO M. BATTRO is a physician and a cognitive psychologist graduated from the Universities of Buenos Aires and Paris. He was a fellow of the International Center of Genetic Epistemology at the University of Geneva and an associate director at the Ecole Pratique des Hautes Etudes in Paris. He received the Guggenheim, Fulbright and Eisenhower fellowships and was a visiting scholar at the graduate school of education at Harvard University. He has been honored with the Argentine National Science award and was an invited lecturer at the Pontifical Academy of Sciences. He is the author of several books, among them *Piaget: dictionary of terms*. He is a member of the Argentine Academy of Education.

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Half a Brain is Enough

The Story of Nico

ANTONIO M. BATTRO

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011-4211, USA www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain

First published 2000

Printed in the United Kingdom at the University Press, Cambridge

Typeface Monotype Sabon 10.5/14.5pt. *System* QuarkXPress™ [SE]

A catalogue record for this book is available from the British Library

ISBN 0 521 78307 0 hardback

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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 "prosthetic" 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 hemidecorticectomy 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 epileptogenecity 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 hipoccampus. 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 polymicrogiria 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?

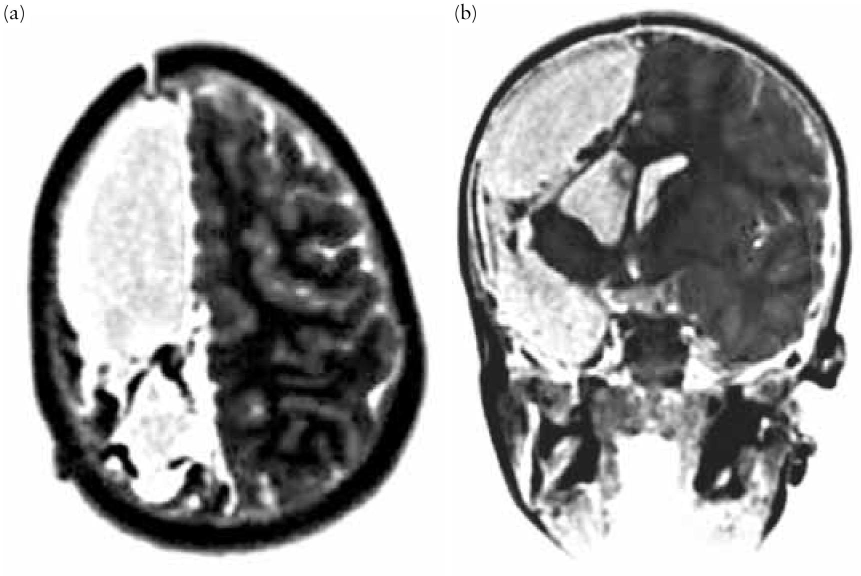

Figure 1.1 Two images of the functional right hemispherectomy. (Nico: three-years-and-seven-months): (a) horizontal (axial) view, (b) frontal (coronal) view. Only the left hemisphere is seen, most of the right hemisphere has been removed.

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, neuropsychologists 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 hemidercorticates 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 Sergent 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 differentially 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 recommed 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.