Part I

The mind, brain, and education triad

1 Introduction: Mind, brain, and education in theory and practice

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As the entomologist chasing butterflies of bright colors, my attention was seeking in the garden of gray matter, those cells of delicate and elegant forms, the mysterious butterflies of the soul, whose fluttering wings would someday – who knows? – enlighten the secret of mental life.

Santiago Ramón y Cajal (*Recuerdos de mi vida*, 1981)

Many scientists and educators feel that we are advancing toward new ways of connecting mind, brain, and education (MBE). This feeling arises, in part, because the disciplines related to the cognitive sciences, neurobiology, and education have made considerable advances during the last two decades, and scholars in the disciplines are beginning to seek interactions with each other (Fischer, Bernstein, & Immordino-Yang, 2006). Moreover, the increased connectivity among these disciplines has been enhanced by the growth of communication and information in the globalized world. The "digital environment" of our planet is a new phenomenon in evolution and in history (Battro, 2004), as Rita Levi-Montalcini describes in the preface to this book. We are lucky to live in a time when changes in education can rapidly reach and enrich the lives of millions. This opportunity invites us to foster the coordinated work of scientists, teachers, and students of many nations, races, and religions in the new transdisciplinary field of mind, brain, and education (Léna, 2002, and Koizumi, this volume).

One name for this effort is neuroeducation (Bruer, this volume), which emphasizes the educational focus of the transdisciplinary connection. Another is educational neuroscience, where the focus is on neuroscience, to which education connects. We use the name "mind, brain, and education" to encompass both of these focuses and others that bring together cognitive science, biology, and education. On one side, this emerging field touches on all levels of modern neuroscience: from molecules to genes, from synapses to artificial neural networks, from reflexes to behaviors, from animal studies to human brain imaging (Dawson & Fischer, 1994). On the other side, the term "education" is as vast as human culture itself. Because of the process of globalization, which intermingles so many different cultures, languages, and beliefs, the field of mind, brain, and education is becoming increasingly complex and necessarily diverse.

There is no doubt that education is much more than its neural aspects, but the brain and biological sciences can illuminate many of its processes and methods. New brain imaging and DNA-analysis techniques make increasingly visible hidden brain and genetic processes. In a few cases, scientists and educators seem to be on the verge of being able to observe the effects of educational interventions on brain processing and genetic expression. These important advances have stimulated great excitement and increasing expectations from society, which is enamored of biology because it has made so many impressive advances in recent decades. These great expectations, although sometimes unrealistic, reflect a genuine need for advances to improve education and deal with the complex new world of the twenty-first century, with its explosion of information and population and the shrinkage of the world through communication and globalization.

The need for major advances in education is urgent. In an earlier workshop entitled *The Challenges for Science – Education for the Twenty-First Century*, held at the Pontifical Academy of Sciences in Rome in November 2001, the issue of science in basic education was addressed: How can the world deal with the increasing gap, in almost every country, between the level of scientific knowledge and technology on the one hand and the scientific literacy of the population on the other, no matter what the stage of economic development? The remarkable success of the scientific and technological revolution in the twentieth century has created a major new problem for education. This earlier workshop and the questions it raised set the stage for the workshop on *Mind, Brain, and Education* in November 2003 that led to this book.

The issue of science education and the gap in knowledge is fundamentally important for justice and democracy and requires a revolution in educational practice. There is no magic recipe for success in such a venture, and a number of on-going, successful experiments are on their way in various countries, from the United States to Brazil, from Chile and Argentina to France, often introduced by the academies of sciences. All these programs try to restore the questioning role of the child, to open ways to his or her curiosity through active attitudes, language dialogue, and direct contact with nature through observation and experiments. These experiments have much to learn from a better knowledge of brain development, the role of stimulus and motivation, and the relation of learning and memory. Of special interest is early childhood, from ages two to six, where recent work in cognitive psychology shows the learning child acting as a "scientist" exploring and experimenting with the world at this early age (see Léna, 2002).

Progress in mind, brain, and education requires a genuine collaboration between researchers and practitioners, with both groups working together to contribute to investigation and knowledge. Research evidence can illuminate educational practice, and educational observations can provide important questions and insights for research. Our first book with Cambridge University Press, *Mind, Brain, and Education in Reading Disorders*, focuses on the connection of research with practice in children with learning problems. The current, second book emphasizes primarily the best scientific research that is relevant to connecting biology and cognitive science with education. We are preparing a third book, *Usable Knowledge in Mind, Brain, and Education*, which aims to promote an effective dialogue between scientists and educators that will create knowledge that can directly illuminate educational practice. That is the long-term challenge of this new field.

What we envision happening is not an all-encompassing new paradigm or a patchwork of unrelated research. Instead, we see the dynamic unfolding of many different scientific trends toward the formation of new networks of knowledge. One component will not swallow the other. Instead, we will expect a healthy growing organism of knowledge that will thrive with all kind of links and functions between the subcomponents in the system and outside the system. It will be the result of the efforts of many coordinated teams with clear aims and objectives, a realistic schedule, a great sense of adventure and a commitment to moral responsibility. This book is an attempt to express this growing international and transdisciplinary trend.

Plan of the book

The book is comprised of three sections. The first provides a historical, epistemological, and methodological framework for the new transdisciplinary field of mind, brain, and education. The second focuses on research that connects neuroscience research to learning and education, including dynamic, biologically based approaches to brain and cognitive development and especially the impact of brain imaging techniques on research and practice. The third section reviews research on brain processing of language and mathematics, areas where scientific advances have been substantial, with the promise of connections to educational practice in the not too distant future.

We are honored by a preface written by Rita Levi-Montalcini, honorary president of our conference on *Mind, Brain, and Education* at the

Pontifical Academy of Sciences, Nobel Prize winner for her discovery of the Nerve Growth Factor and a leading personality in the neurosciences of our time. She stresses the slow maturation of the human brain as well as the luxuriant development of the human neocortex, which relate to the protracted dependency of children on parents and teachers. This slow, lengthy period of development and learning leaves a permanent mark on the developing nervous structures of the child. Moreover, researchers have discovered that the cognitive capacities already functioning in infants' brains are greater than we thought in the past. From these findings, the importance of early education becomes ever more evident. In recent history information technologies became available to young children, and they started to use these technologies actively and productively, adapting to them easily. The amazing cognitive capacities of human beings and the relentless proliferation of new information together require a revolution in education. We certainly need, as Levi-Montalcini says, new generations "dressed as actors and not as spectators in the world arena of life."

Part I The mind, brain, and education triad

In this section the authors analyze important issues, assets, and obstacles in forming convergent paths toward the transdisciplinary field of mind, brain, and education. These involve historical frameworks for understanding human nature, epistemological analyses of knowledge of human brain and behavior, and methodological approaches to framing research and practice on development of mind, brain, and behavior.

In the chapter "Historical considerations on brain and self," Fernando Vidal, a distinguished historian of psychology at the Max Planck Institute in Berlin, describes the historical transition from considering the brain the "seat of the soul" to viewing it as the "organ of the self," a concept for which he coins the term "brainhood." The modern history of this significant conceptual change started in the eighteenth century when the brain began to be understood as the only organ essential to the self. Indeed, the recent development of biology and medicine, in particular of the neurosciences, has reinforced the idea of a "cerebral subject," a brain-based person. Many classical puzzles related to this conception (thought-experiments or philosophical brain-fictions like brain transplants, extra-bodily conservation, etc.) are still used in current debates about human identity, and the conception has pervasive practical and ethical implications, such as the notion of "brain-death" in medical practice. Vidal coined the new term "brainhood" to name the condition of being a brain – the "human being *as* brain" – which gives a wide anthropological and social picture and will certainly influence education in the future, in ways we cannot predict today. This idea of brainhood also inspires the work of some artists, as in the remarkable picture in this chapter of a "self-portrait" by Helen Chadwick – two caring hands holding a brain. Most important, the ethical impact of this conception in education is fundamental, requiring careful consideration of possible controversial observations, experiments, and even "non-invasive" interventions and assessments on students' brains. Groups such as the recent Committee on Neuroethics of the Ministry of Education of Japan will help human society to illuminate the implications of this conception of humanity (see Koizumi).

John Bruer, a philosopher by training and president of the James S. McDonnell Foundation, has been a key person in shaping early research in cognitive neuroscience and education in the United States and abroad. In "Building bridges in neuroeducation," he sharply criticizes how results of cognitive neuroscience are often used in educational practice and policy. One of the typical misuses is related to a very popular claim among educators that the critical periods shown in the visual system are the best model to explain cognitive development and life-long learning – a claim that Bruer demonstrates is fundamentally wrong. Moreover, the common idea that we need an elevated brain metabolism and synaptic density in order to learn new concepts and skills is not consistent with controlled experiments. As Bruer says, "over-reliance on developmental neurobiology generates pseudo-implications for teaching and learning." We should follow instead a broader approach to learning, where previous experience in a specific domain is more important than a presumed biological "window of opportunity" or critical period.

Bruer's analysis is that neurobiology can connect to education through its illumination of cognitive science research on learning and teaching. He argues that neurobiological research cannot connect directly to a better understanding of education. He uses the example of mathematics, in which programs like *RightStart* showed impressive results in teaching mathematics, especially to children at risk (Griffin, Case, & Siegler, 1994), and those cognitive results and concepts in turn relate to the neuroscientific work of Stanislas Dehaene and colleagues (Dehaene, this volume) on the multiple cortical representation of number concepts (number words, Arabic numerals, and analogue magnitudes). Together, the neuroscientific research and the cognitive research illuminate the educational pathways toward mathematical skill, but separately, he argues, the neuroscientific research does not connect to education. Similar connections from neuroscience to cognitive science to education seem to be happening in research on acquisition of language and reading (Dehaene, Goswami,

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Petitto, & Wolf, this volume). Bruer concludes that we need to refine our neuroeducation research strategy to connect neuroscience to cognitive science, and he asks for increasing "recursive interactions" between the fields involved in basic neurocognitive research and educational practice.

Self-consciousness and the brain are of central concern for contemporary philosophy, neuroscience, and education. Jürgen Mittelstrass, professor of philosophy and director of the Center of Philosophy and Theory of Science at the University of Konstanz, a recognized expert in the mind/brain problem, critically analyzes the different conceptual frameworks of monism and dualism. He proposes a constructivist mediation between "the overwhelmingly dualist research program of philosophy, and the overwhelmingly monistic research program of natural science (which includes scientifically oriented psychology)." He introduces the model of a "pragmatical dualism" in what he calls the "career of the mind-body problem." He defends independent psychological (cognitive) concepts on the grounds of their *explanatory value* and rejects the restricted view of neuro-reductionism. Perhaps this pragmatic model can help us to introduce to the practice of education the most advanced theoretical terms of modern neurocognitive science without making an ontological statement about what they refer to. We will always need the help of philosophical criticism in order to build a new field such as mind, brain, and education. Many blunders and simplications can be avoided through strict and rigorous philosophical analysis and synthesis. However, many concepts being introduced in neuroscience, cognitive science, and education are new to the history of philosophy and will need careful examination.

New concepts and new technologies imply the use of new research methodologies. The joining of mind, brain, and education into a coherent field requires a profound transformation of many habits of thinking, of many traditional standards in order to enrich the scope of psychological and educational research in the era of biology. The brain itself is a very complex organ that cannot be studied with only conventional intellectual tools. First, traditional linear analysis (which has dominated behavioral and cognitive research) cannot alone capture the brain's complexity, where the whole is so much more than the sum of its parts. The number of connections in the brain is astronomical, the number of interactions between parts in different time scales is overwhelming. Of all the tools in the scientific toolkit, only dynamic systems theory has the potential to capture how these parts form this remarkable organ. Second, mind/brain, body, and world are each complex systems in permanent interaction.

In this volume Paul van Geert, professor of psychology at Groningen University, and his colleague Henderien Steenbeek provide an overview of the complexity and dynamic system approach to neuropsychological development and how it can begin to be applied to analyzing educational processes. They define four features of complex systems: (1) non-linearity and self-organization, (2) superposition, (3) substance vs. process, and (4) the multi-layered and multi-scaled nature of causality. The first describes the increase of order and structure during development, including the emergence of new organization. The second means that a phenomenon can be characterized by two (apparently) incompatible properties at the same time, such as genes and environment in learning. System dynamics routinely include contradictory or "incompatible" processes. The third refers to how different levels of analysis for a phenomenon relate to its apparent nature as a stable substance or a variable process. For example, an individual skill such as kicking a ball can be treated as substance to the degree that it is stable over long time periods, and simultaneously it involves process because it varies intrinsically over shorter time periods as a function of factors such as practice, fatigue, the nature of the ball, the context of the frame, etc. Fourth, the layers that go from the individual to the species in the human being are organized in different strata such as person, group, society, and culture. The layering also occurs in time scales such as microdevelopmental, ontogenetic (macrodevelopmental), historical, and evolutionary. They all interact in "mutual or reciprocal causality," as the authors say.

One practical implication of this conceptualization of complex systems is that measurements need to capture the intrinsic richness of a system as it changes over time. Inadequate measurements misrepresent the system and make it seem static. For instance, if we can identify a brain region for a certain mental activity, such as reading, we still cannot say that we know what reading is. In the author's words "knowledge of the brain adds another piece to the complexity puzzle and will thus contribute to solving the puzzle, [but] it does not replace the puzzle by the real picture."

Van Geert and Steenbeek provide a good example of the predictive power of these models in a research study of the way children of different leadership status interact. There are many other examples where complexity analysis can predict diverse phenomena, including sudden emergence of new concepts such as conservation of quantity (in the sense of Piaget), stable stages, fluctuating skills, inverted U curves of learning or development, regressions, etc. These methodological considerations are of great importance for education and should be stressed by the educators of the twenty-first century.

Part II Brain development, cognition, and education

One of the great challenges in science is to make links between fundamental or basic research and everyday life. The success of modern societies is related to this enterprise, and the success of education too. Such great changes have been introduced at all levels of learning and teaching by the computer and the communication technologies, and of course the changes include the brain (Battro, 2002). We expect the next frontier in education to come from technologies deriving from the cognitive and brain sciences.

Along with the societal changes created by technology come epistemological changes created by "opening" and making known the brain mechanisms involved in the process of knowing. Wolf Singer states this point from the viewpoint of a brain scientist: "Search for the sources of knowledge is equivalent with the search for processes that specify and modify the functional architecture of the brain." The scientific enterprises of explaining the neurobiology and genetics of learning and thinking are building radical conceptual change, something that only a few educators could imagine several decades ago. Scientists today are tracking the sources of knowledge with the multiple and powerful tools of neurobiology and analyzing the relations between genetics and epigenetics, between phylogeny and ontogeny, and among the different levels of learning and memory across the whole of the human life span.

This is basic research, performed by thousands of talented scientists around the world, and right now its relevance to the field of education is not yet clear. For instance, one of the most important handbooks in the new cognitive neurosciences (Gazzaniga, 2003) does not even mention the term "education" in its index, while the term "learning" has multiple entries. This omission probably does not indicate a lack of personal interest in education by the many prominent authors, but it tells us that there is a scientific gap to be filled, a new field to explore. The space for working to fill this gap is *beyond* the laboratory and its strict, traditional models of learning. The new "learning space" for the neuroscientist is the classroom! In the rich learning and teaching environment of the school the cognitive neurosciences can grow to ask deeper, more useful, more meaningful questions.

In the first chapter in this section, Wolf Singer, leader of the Max Planck Institute for Brain Research at Frankfurt, proposes two specific topics where scholars and practitioners can bridge the gap from basic neuroscience to educational practice: critical periods in vision, and sleep time in day-care centers for babies. (The latter is relevant also to the chapter on chronoeducation by Daniel Cardinali in this volume.) He discusses research with animals and babies which shows the complex sequences of sleep and wakefulness and their importance in developmental processes, memory consolidation, and learning improvement. Regarding critical periods Singer relies on his vast experience with animal models, in particular in the visual system, where he has analyzed the principle that "neurons wire together if they fire together." In this model of neuronal synchrony, circuits undergo a test of functionality, in which connections are either consolidated or removed for the rest of life. When the window of development closes, it seems that neurons stop producing new synapses and existing connections can no longer be removed. The extreme case is "sensory deprivation" of visual input: Babies who have suffered from infections of their eyes and have not developed proper visual circuitry at the cortical level in early development can remain functionally blind even if their retinas come to function normally later.

At the same time, there is often enough plasticity in the brain to undo apparent irreversibility, as Bruer discusses in his chapter and elsewhere (Neville & Bruer, 2001). Even adult brains can produce new neurons and connections in the hippocampus and the olfactory bulb, and perhaps in other areas of the cortex as well (Gage, 2003), a promising phenomenon mentioned by Singer. Of course these facts do not translate directly into educational programs, but relations to education are likely to be discovered as the number of scientists engaged in basic research with a focus in education increases. What we still need are teachers and neuroscientists engaging together to grapple with crucial features of education that have not yet been explored in laboratories. We hope the next generation will build a dynamic cycle of connection from neuroscience to education and from education to neuroscience, which will dramatically affect views and findings relating to education.

A topic for which such a positive cycle already exists is chronoeducation. Daniel Cardinali, director of the Department of Physiology of the Medical School of the University of Buenos Aires, is a world leader in this field and explains in his chapter how the biological clock influences the learning process and affects education. First he describes the circadian rhythms of about 24 hours in all the cells of the body, which respond to signals generated by a pacemaker, a biological clock that is written in the gene-protein-gene feedback loops. In mammals a major circadian oscillator is located in the suprachiasmatic nuclei (SCN) of the hypothalamus and acts as a timer. An entraining agent (Zeitgeber) can reset or phase-shift (advance or delay) the internal clock. For instance, light exposure during the first part of the night delays the phase, but in the second part it advances the phase. In the opposite direction, melatonin, the "endogenous code of the night" (a hormone produced by the pineal gland),