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Understanding the Brain: The Birth of a Learning Science
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Executive Summary

> Education is like a double-edged sword. It may be turned to dangerous uses if it is not properly handled.
>
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After two decades of pioneering work in brain research, the education community has started to realise that "understanding the brain" can help to open new pathways to improve educational research, policies and practice. This report synthesises progress on the brain-informed approach to learning, and uses this to address key issues for the education community. It offers no glib solutions nor does it claim that brain-based learning is a panacea. It *does* provide an objective assessment of the current state of the research at the intersection of cognitive neuroscience and learning, and maps research and policy implications for the next decade.

Part I "The Learning Brain" is the main report, which is the distillation from all the analyses and events over the past seven years of the OECD/CERI "Learning Sciences and Brain Research" project. Part II "Collaborative Articles" contains three articles devoted to the "learning brain" in early childhood, adolescence and adulthood, respectively. These have been written, in each case, by three experts who have combined their experience and knowledge in synergy of the different perspectives of neuroscience and education. Annex A reproduces some insights and dialogue that have emerged from the project's interactive website, open to civil society and including notably a teachers' forum. Annex B updates the reader with developments in neuroimaging technology which have proved so fundamental to the advances discussed in this report.

The first chapter offers a novel "ABC" of the contents of the report by listing and discussing keywords in alphabetical order. This serves both to give short summaries of complex concepts and to steer the reader towards the relevant chapter(s) providing the more in-depth coverage. This is followed in the first half of the following chapter by a short but essential overview of the brain's architecture and functioning.

How the brain learns throughout life

Neuroscientists have well established that the brain has a highly robust and well-developed capacity to change in response to environmental demands, a process called *plasticity*. This involves creating and strengthening some neuronal connections and weakening or eliminating others. The degree of modification depends on the *type* of learning that takes place, with long-term learning leading to more profound modification. It also depends on the *period* of learning, with infants experiencing extraordinary growth of new synapses. But a profound message is that plasticity is a core feature of the brain throughout life.

There are optimal or "sensitive periods" during which particular types of learning are most effective, despite this lifetime plasticity. For sensory stimuli such as speech sounds, and for certain emotional and cognitive experiences such as language exposure, there are relatively tight and early sensitive periods. Other skills, such as vocabulary acquisition, do not pass through tight sensitive periods and can be learned equally well at any time over the lifespan.

Neuroimaging of adolescents now shows us that the adolescent brain is far from mature, and undergoes extensive structural changes well past puberty. Adolescence is an extremely important period in terms of emotional development partly due to a surge of hormones in the brain; the still under-developed pre-frontal cortex among teenagers may be one explanation for their unstable behaviour. We have captured this combination of emotional immaturity and high cognitive potential in the phrase "high horsepower, poor steering".

In older adults, fluency or experience with a task can reduce brain activity levels – in one sense this is greater processing efficiency. But the brain also declines the more we stop using it and with age. Studies have shown that learning can be an effective way to counteract the reduced functioning of the brain: the more there are opportunities for older and elderly people to continue learning (whether through adult education, work or social activities), the higher the chances of deferring the onset or delaying the acceleration of neurodegenerative diseases.

The importance of environment

Findings from brain research indicate how nurturing is crucial to the learning process, and are beginning to provide indication of appropriate learning environments. Many of the environmental factors conducive to improved brain functioning are everyday matters – the quality of social environment and interactions, nutrition, physical exercise, and sleep – which may seem too obvious and so easily overlooked in their impact on education. By conditioning our minds and bodies correctly, it is possible to take advantage of the brain's potential for plasticity and to facilitate the learning process. This calls for holistic approaches which recognise the close interdependence of physical and intellectual well-being and the close interplay of the emotional and cognitive.

In the centre of the brain is the set of structures known as the limbic system, historically called the "emotional brain". Evidence is now accumulating that our emotions do re-sculpt neural tissue. In situations of excessive stress or intense fear, social judgment and cognitive performance suffer through compromise to the neural processes of emotional regulation. Some stress is essential to meet challenges and can lead to better cognition and learning, but beyond a certain level it has the opposite effect. Concerning positive emotions, one of most powerful triggers that motivates people to learn is the illumination that comes with the grasp of new concepts – the brain responds very well to this. A primary goal of early education should be to ensure that children have this experience of "enlightenment" as early as possible and become aware of just how pleasurable learning can be.

Managing one's emotions is one of the key skills of being an effective learner; self-regulation is one of the most important behavioural and emotional skills that children and older people need in their social environments. Emotions direct (or disrupt) psychological processes, such as the ability to focus attention, solve problems, and support relationships. Neuroscience, drawing on cognitive psychology and child development research, starts to identify critical brain regions whose activity and development are directly related to self-control.

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Language, literacy and the brain

The brain is biologically primed to acquire language right from the very start of life; the process of language acquisition needs the catalyst of experience. There is an inverse relationship between age and the effectiveness of learning many aspects of language – in general, the younger the age of exposure, the more successful the learning – and neuroscience has started to identify how the brain processes language differently among young children compared with more mature people. This understanding is relevant to education policies especially regarding foreign language instruction which often does not begin until adolescence. Adolescents and adults, of course, can also learn a language anew, but it presents greater difficulties.

The dual importance in the brain of sounds (phonetics) and of the direct processing of meaning (semantics) can inform the classic debate in teaching reading between the development of specific phonetic skills, sometimes referered to as "syllabic instruction", and "whole language" text immersion. Understanding how both processes are at work argues for a balanced approach to literacy instruction that may target more phonetics or more "whole language" learning, depending on the morphology of the language concerned.

Much of the brain circuitry involved in reading is shared across languages but there are some differences, where specific aspects of a language call on distinct functions, such as different decoding or word recognition strategies. Within alphabetical languages, the main difference discussed in this report is the importance of the "depth" of a language's orthography: a "deep" language (which maps sounds onto letters with a wide range of variability) such as English or French contrasts with "shallow", much more "consistent" languages such as Finnish or Turkish. In these cases, particular brain structures get brought into play to support aspects of reading which are distinctive to these particular languages.

Dyslexia is widespread and occurs across cultural and socioeconomic boundaries. Atypical cortical features which have been localised in the left hemisphere in regions to the rear of the brain are commonly associated with dyslexia, which results in impairment in processing the sound elements of language. While the *linguistic* consequences of these difficulties are relatively minor (*e.g.* confusing words which sound alike), the impairment can be much more significant for *literacy* as mapping phonetic sounds to orthographic symbols is the crux of reading in alphabetic languages. Neuroscience is opening new avenues of identification and intervention.

Numeracy and the brain

Numeracy, like literacy, is created in the brain through the synergy of biology and experience. Just as certain brain structures are designed through evolution for language, there are analogous structures for the quantitative sense. And, also as with language, genetically-defined brain structures alone cannot support mathematics as they need to be co-ordinated with those supplementary neural circuits not specifically destined for this task but shaped by experience to do so. Hence, the important role of education – whether in schools, at home, or in play; and hence, the valuable role for neuroscience in helping address this educational challenge.

Although the neuroscientific research on numeracy is still in its infancy, the field has already made significant progress in the past decade. It shows that even very simple numerical operations are distributed in different parts of the brain and require the co-ordination of

multiple structures. The mere representation of numbers involves a complex circuit that brings together sense of magnitude, and visual and verbal representations. Calculation calls on other complex distributed networks, varying according to the operation in question: subtraction is critically dependent on the inferior parietal circuit, while addition and multiplication engage yet others. Research on advanced mathematics is currently sparse, but it seems that it calls on at least partially distinct circuitry.

Understanding the underlying developmental pathways to mathematics from a brain perspective can help shape the design of teaching strategies. Different instructional methods lead to the creation of neural pathways that vary in effectiveness: drill learning, for instance, develops neural pathways that are less effective than those developed through strategy learning. Support is growing from neuroscience for teaching strategies which involve learning in rich detail rather than the identification of correct/incorrect responses. This is broadly consistent with formative assessment.

Though the neural underpinnings of dyscalculia – the numerical equivalent of dyslexia – are still under-researched, the discovery of biological characteristics associated with specific mathematics impairments suggests that mathematics is far from a purely cultural construction: it requires the full functioning and integrity of specific brain structures. It is likely that the deficient neural circuitry underlying dyscalculia can be addressed through targeted intervention because of the "plasticity" – the flexibility – of the neural circuitries involved in mathematics.

Dispelling "neuromyths"

Over the past few years, there has been a growing number of misconceptions circulating about the brain – "neuromyths". They are relevant to education as many have been developed as ideas about, or approaches to, how we learn. These misconceptions often have their origins in some element of sound science, which makes identifying and refuting them the more difficult. As they are incomplete, extrapolated beyond the evidence, or plain false, they need to be dispelled in order to prevent education running into a series of dead-ends.

Each "myth" or set of myths is discussed in terms of how they have emerged into popular discourse, and of why they are not sustained by neuroscientific evidence. They are grouped as follows:

- "There is no time to lose as everything important about the brain is decided by the age of three."
- "There are critical periods when certain matters *must* be taught and learnt."
- "But I read somewhere that we only use 10% of our brain anyway."
- "I'm a 'left-brain', she's a 'right-brain' person."
- "Let's face it – men and boys just have different brains from women and girls."
- "A young child's brain can only manage to learn one language at a time."
- "Improve your memory!"
- "Learn while you sleep!"

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The ethics and organisation of educational neuroscience

The importance and promise of this new field are not the reason to duck fundamental ethical questions which now arise.

For which purposes and for whom? It is already important to re-think the use and possible abuse of brain imaging. How to ensure, for example, that the medical information it gives is kept confidential, and not handed over to commercial organisations or indeed educational institutions? The more accurately that brain imaging allows the identification of specific, formerly "hidden", aspects of individuals, the more it needs to be asked how this should be used in education.

The use of products affecting the brain: The boundary between medical and non-medical use is not always clear, and questions arise especially about healthy individuals consuming substances that affect the brain. Should parents, for instance, have the right to give their children substances to stimulate their scholarly achievements, with inherent risks and parallels to doping in sport?

Brain meets machine: Advances are constantly being made in combining living organs with technology. The advantages of such developments are obvious for those with disabilities who are thus enabled, say, to control machines from a distance. That the same technology could be applied to control individuals' behaviour equally obviously raises profound concerns.

An overly scientific approach to education? Neurosciences can importantly inform education but if, say, "good" teachers were to be identified by verifying their impact on students' brains, this would be an entirely different scenario. It is one which runs the risk of creating an education system which is excessively scientific and highly conformist.

Though educational neuroscience is still in its early days, it will develop strategically if it is trans-disciplinary, serving both the scientific and educational communities, and international in reach. Creating a common lexicon is one critical step; another is establishing shared methodology. A reciprocal relationship should be established between educational practice and research on learning which is analogous to the relationship between medicine and biology, co-creating and sustaining a continuous, bi-directional flow to support brain-informed educational practice.

A number of institutions, networks and initiatives have already been established to show the way ahead. Vignette descriptions of several leading examples are available in this report. They include the JST-RISTEX, Japan Science and Technology's Research Institute of Science and Technology for Society; Transfer Centre for Neuroscience and Learning, Ulm, Germany; Learning Lab, Denmark; Centre for Neuroscience in Education: University of Cambridge, United Kingdom; and "Mind, Brain, and Education", Harvard Graduate School of Education, United States.

Key messages and themes for the future

Educational neuroscience is generating valuable new knowledge to inform educational policy and practice: On many questions, neuroscience builds on the conclusions of existing knowledge and everyday observation but its important contribution is in enabling the move from correlation to causation – understanding the mechanisms behind familiar patterns – to help identify effective solutions. On other questions, neuroscience is generating new knowledge, thereby opening up new avenues.

Brain research provides important neuroscientific evidence to support the broad aim of lifelong learning: Far from supporting ageist notions that education is the province only of the young – the powerful learning capacity of young people notwithstanding – neuroscience confirms that learning is a lifelong activity and that the more it continues the more effective it is.

Neuroscience buttresses support for education's wider benefits, especially for ageing populations: Neuroscience provides powerful additional arguments on the "wider benefits" of education (beyond the purely economic that counts so highly in policy-making) as it is identifying learning interventions as a valuable part of the strategy to address the enormous and costly problems of ageing dementia in our societies.

The need for holistic approaches based on the interdependence of body and mind, the emotional and the cognitive: Far from the focus on the brain reinforcing an exclusively cognitive, performance-driven bias, it suggests the need for holistic approaches which recognise the close inter-dependence of physical and intellectual well-being, and the close interplay of the emotional and cognitive, the analytical and the creative arts.

Understanding adolescence – high horsepower, poor steering: The insights on adolescence are especially important as this is when so much takes place in an individual's educational career, with long-lasting consequences. At this time, young people have well-developed cognitive capacity (high horsepower) but emotional immaturity (poor steering). This cannot imply that important choices should simply be delayed until adulthood, but it does suggest that these choices should not definitively close doors.

Better informing the curriculum and education's phases and levels with neuroscientific insights: The message is a nuanced one: there are no "critical periods" when learning *must* take place but there are "sensitive periods" when the individual is particularly primed to engage in specific learning activities (language learning is discussed in detail). The report's message of an early strong foundation for lifetimes of learning reinforces the key role of early childhood education and basic schooling.

Ensuring neuroscience's contribution to major learning challenges, including the "3Ds": dyslexia, dyscalculia, and dementia. On dyslexia, for instance, its causes were unknown until recently. Now it is understood to result primarily from atypical features of the auditory cortex (and possibly, in some cases, of the visual cortex) and it is possible to identify these features at a very young age. Early interventions are usually more successful than later interventions, but both are possible.

More personalised assessment to improve learning, not to select and exclude: Neuroimaging potentially offers a powerful additional mechanism on which to identify individuals learning characteristics and base personalisation; but, at the same time, it may also lead to even more powerful devices for selection and exclusion than are currently available.

Key areas are identified as priorities for further educational neuroscientific research, not as an exhaustive agenda but as deriving directly from the report. This agenda for further research – covering the better scientific understanding of such matters as the optimal timing for different forms of learning, emotional development and regulation, how specific materials and environments shape learning, and the continued analysis of language and mathematics in the brain – would, if realised, be well on the way to the birth to a trans-disciplinary learning science.

This is the aspiration which concludes this report and gives it its title. It is also the report's aspiration that it will be possible to harness the burgeoning knowledge on learning to create an educational system that is both personalised to the individual and universally relevant to all.

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Glossary

Acalculia. See dyscaculia.

Accumbens area. See nucleus accumbens.

Action potential. This occurs when a neuron is activated and temporarily reverses the electrical state of its interior membrane from negative to positive. This electrical charge travels along the axon to the neuron's terminal where it triggers the release of an excitatory or inhibatory neurotransmitter.

Activation study. Study performed with imaging techniques (see also PET and fMRI).

ADHD (Attention Deficit Hyperactivity Disorder). A syndrome of learning and behavioural problems characterised by difficulty sustaining attention, impulsive behaviour (as in speaking out of turn), and hyperactivity.

Alzheimer's disease. A progressive degenerative disease of the brain associated with ageing, characterised by diffuse atrophy throughout the brain with distinctive lesions called senile plaques and clumps of fibrils called neurofibrillary tangles. Cognitive processes of memory and attention are affected (see also neurodegenerative diseases).

Amygdala. A part of the brain involved in emotions and memory. Each hemisphere contains an amygdale ("shaped like an almond") and located deep in the brain, near the inner surface of each temporal lobe.

Angular gyrus. An area of the cortex in the parietal lobe involved in processing the sound structure of language and in reading.

Anhedonia. Recognised as one of the key symptoms of the mood disorder depression. Patients with anhedonia are unable to experience pleasure from normally pleasurable life events such as eating, exercise, and social/sexual interactions.

Anterior cingulated cortex. Frontal part of the cingulate cortex. It plays a role in a wide variety of autonomic functions, such as regulating heart rate and blood pressure, and is vital to cognitive functions, such as reward anticipation, decision-making, empathy, and emotions.

Aphasia. Disturbance in language comprehension or production.

Apolipoprotein E (or "apoE"). Has been studied for many years for its involvement in cardiovascular diseases. It has only recently been found that one allele (gene factor) of the aopE gene (E4) is a risk factor for Alzheimer's disease.

Artificial intelligence (AI). A field of computer science which attempts to develop machines that behave "intelligently".

Attention. Attention is the cognitive process of selectively concentrating on one task while ignoring other tasks. Imaging studies have been able to show the distinct networks of neural areas which carry out the various functions of attention such as maintaining the alert state, orienting to sensory information and resolving conflict among competing thoughts or feelings.

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Auditory cortex. The region of the brain that is responsible for processing of auditory (sound) information.

Auditory nerve. A bundle of nerve fibers extending from the cochlea of the ear to the brain, which contains two branches: the cochlear nerve that transmits sound information and the vestibular nerve that relays information related to balance.

Autism/autistic spectrum disorders. A spectrum of neurodevelopmental conditions, characterised by difficulties in the development of social relationships, communication skills, repetitive behaviour, and learning difficulties.

Axon. The fiberlike extension of a neuron by which the cell sends information to target cells.

Basal ganglia. Clusters of neurons, which include the caudate nucleus, putamen, globus pallidus and substantia nigra, that are located deep in the brain and play an important role in movement. Cell death in the substantia nigra contributes to Parkinsonian signs.

Bipolar disorder. Otherwise known as manic depression. Bipolar disorder involves extreme swings of mood from mania (a form of euphoria) to deep depression. There is no simple cause, although there is strong evidence that it is associated with internal chemical changes to various natural transmitters of mood to the brain, but the precise way in which this happens is not yet known. The disorder can be triggered by the stresses and strains of everyday life, or a traumatic event or, in rare cases, physical trauma such as a head injury.

Brainstem. The major route by which the forebrain sends information to and receives information from the spinal cord and peripheral nerves. It controls, among other things, respiration and regulation of heart rhythms.

Broca's area. The brain region located in the frontal lobe of the left hemisphere, involved in the production of speech.

Caudate or caudale nucleus. A telencephalic nucleus located within the basal ganglia in the brain. The caudate is an important part of the brain's learning and memory system.

Cerebellum. A part of the brain located at the back and below the principal hemispheres, involved in the regulation of movement.

Cerebral hemispheres. The two specialised halves of the brain. The left hemisphere is specialised for speech, writing, language and calculation; the right hemisphere is specialised for spatial abilities, face recognition in vision and some aspects of music perception and production.

Cerebrospinal fluid. A liquid found within the ventricles of the brain and the central canal of the spinal cord.

Cerebrum. Otherwise known by more technical term telencephalon. Refers to cerebral hemispheres and other, smaller structures within the brain, and is composed of the following sub-regions: limbic system, cerebral cortex, basal ganglia, and olfactory bulb.

Circadian clock/rhythm. A cycle of behavior or physiological change lasting approximately 24 hours.

Classical conditioning. Learning in which a stimulus that naturally produces a specific response (unconditioned stimulus) is repeatedly paired with a neutral stimulus (conditioned stimulus). As a result, the conditioned stimulus can become able to evoke a response similar to that of the unconditioned stimulus.

Cochlea. A snail-shaped, fluid-filled organ of the inner ear responsible for transducing motion into neurotransmission to produce an auditory sensation.

Cognition. Set of operations of the mind which includes all aspects of perceiving, thinking, learning, and remembering.

Cognitive maps. Mental representations of objects and places as located in the environment.

Cognitive networks. Networks in the brain involved in processes such as memory, attention, perception, action, problem solving and mental imagery. This term is also used for artificial networks as in artificial intelligence.

Cognitive neuroscience. Study and development of mind and brain research aimed at investigating the psychological, computational, and neuroscientific bases of cognition.

Cognitive science. Study of the mind. An interdisciplinary science that draws upon many fields including neuroscience, psychology, philosophy, computer science, artificial intelligence, and linguistics. The purpose of cognitive science is to develop models that help explain human cognition – perception, thinking, and learning.

Cognitive training. Teaching methods and training to remediate cognitive deficits.

Cohort study. A type of longitudinal study used in medicine and social sciences that compares a cohort, or group of people who share a common characteristic or experience, to an outside group.

Competences. Referring to student ability. The mental capacity to perform particular tasks.

Constructivism. A learning theory whereby individuals actively construct understanding from their experiences.

Corpus callosum. The large bundle of nerve fibers linking the left and right cerebral hemispheres.

(cerebral) Cortex. Outer layer of the brain.

Cortisol. A hormone manufactured by the adrenal cortex. In humans, it is secreted in greatest quantities before dawn, readying the body for the activities of the coming day.

Critical period. Concept referring to certain periods when the brain's capacity for adjustment in response to experience is substantially greater than during other periods. In humans, critical periods only exist during prenatal development. Sensitive periods, however, are known to occur in childhood (see sensitive period).

Cross-sectional study. A type of descriptive study that measures the frequency and characteristics of a population at a particular point in time.

CT (Computed Tomography). Originally known as computed axial tomography (CAT or CT scan) and body section roentgenography. A medical imaging method employing tomography where digital geometry processing is used to generate a three-dimensional image of the internals of an object from a large series of two-dimensional X-ray images taken around a single axis of rotation.

Decoding. An elementary process in learning to read alphabetic writing systems (for example, English, Spanish, German or Italian) in which unfamiliar words are deciphered by associating the letters of words with corresponding speech sounds.

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(senile) Dementia. A condition of deteriorated mentality that is characterised by marked decline from the individual's former intellectual level and often by emotional apathy. Alzheimer's disease is one form of dementia.

Dendrite. A tree-like extension of the neuron cell body. It receives information from other neurons.

Depression. A lowering of vitality of functional activity: the state of being below normal in physical or mental vitality. Senile depression refers to depression in later life which may be dominated by agitation and hypochondria. Whether this form of depression is distinct from depression during earlier life is not clear.

Development. Progressive change that occurs in human beings as they age. Biological inclinations interact with experience to guide development throughout life.

DNA (Deoxyribonucleic acid). DNA is a long polymer of nucleotides (a polynucleotide) that encodes the sequence of amino acid residues in proteins, using the genetic code.

Dopamine. A catecholamine neurotransmitter known to have multiple functions depending on where it acts. Dopamine-containing neurons in the substantia nigra of the brainstem project to the caudate nucleus and are destroyed in Parkinson's victims. Dopamine is thought to regulate emotional responses, and play a role in schizophrenia and cocaine abuse.

DTI (Diffusion Tensor Imaging). A magnetic resonance imaging (MRI) technique that enables the measurement of the restricted diffusion of water in tissue. It allows the observation of molecular diffusion in tissues in vivo and therefore the molecular organisation in tissues.

Dyscalculia. Impairment of the ability to perform simple arithmetical computations, despite conventional instruction, adequate intelligence and socio-cultural opportunity.

Dyslexia. A disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence, and socio-cultural opportunity.

Dyspraxia. Motor co-ordination difficulties in carrying out any complex sequence.

ECG (Electrocardiogram). A recording of the electrical voltage in the heart in the form of a continuous strip graph.

EEG (Electroencephalogram). A measurement of the brain's electrical activity via electrodes. EEG is derived from sensors placed in various spots on the scalp, which are sensitive to the summed activity of populations of neurons in a particular region of the brain.

Electrochemical signals. These signals are the means by which neurons communicate with one another.

Emotional intelligence. Sometimes referred to as emotional quotient ("EQ"). Individuals with emotional intelligence are able to relate to others with compassion and empathy, have well-developed social skills, and use this emotional awareness to direct their actions and behaviour. The term was coined in 1990.

Emotional regulation. Ability to regulate and appropriately temper emotions.

Emotions. There is no single universally accepted definition. The neurobiological explanation of human emotion is that emotion is a pleasant or unpleasant mental state organised mostly in the limbic system of the mammalian brain.

Endocrine organ. An organ that secretes a hormone directly into the bloodstream to regulate cellular activity of certain other organs.

Endorphins. Neurotransmitters produced in the brain that generate cellular and behavioral effects similar to those of morphine.

Epigenetic. Changes in gene function, often elicited by environmental factors.

Epilepsy. A chronic nervous disorder in humans which produces convulsions of greater or lesser severity with clouding of consciousness; it involves changes in the state of consciousness and of motion due to either an inborn defect of a lesion of the brain produced by tumour, injury, toxic agents, or glandular disturbances.

ERP (Event-related potentials). Electric signals are first recorded with an EEG. Data from this technology is then time locked to the repeated presentation of a stimulus to the subject, in order to see the brain in action. The resulting brain activation (or event-related potentials) can then be related to the stimulus event.

Evoked potentials. A measure of the brain's electrical activity in response to sensory stimuli. This is obtained by placing electrodes on the surface of the scalp (or more rarely, inside the head), repeatedly administering a stimulus, and then using a computer to average the results.

Excitation. A change in the electrical state of a neuron that is associated with an enhanced probability of action potentials.

Excitatory synapses. Synapses where neurotransmitters decrease the potential difference across neuron membranes.

Experience-dependent. A property of a functional neural system in which variations in experience lead to variations in function, a property that might persist throughout the life-span.

Experience-expectant. A property of a functional neural system in which the development of the system has evolved to critically depend on stable environmental inputs that are roughly the same for all members of species (*i.e.* stimulation of both eyes in new-borns during development of ocular dominance columns). This property is thought to operate early in life.

Explicit memory. Memories that can be retrieved by a conscious act, as in recall, and can be verbalised, in contrast to implicit or procedural memories, which are less verbally explicit.

Fatty acids. The human body can produce all but two (linoleic acid and alpha-linolenic acid) of the fatty acids it needs which the brain is made up of. Since they cannot be made in the body from other substrates and must be supplied in food (namely in plant and fish oils) they are called essential fatty acids. (See also Omega and HUFA).

Fear/fear conditioning. Fear conditioning is a form of classical conditioning (a type of associative learning pioneered on animals by Ivan Pavlov in the 1920s) involving the repeated pairing of a harmless stimulus such as a light, called the conditioned stimulus, with a noxious stimulus such as a mild shock, called the unconditioned stimulus, until the animal shows a fear response not just to the shock but to the light alone, called a conditioned response. Fear conditioning is thought to depend upon the amygdala. Blocking the amygdala can prevent the expression of fear.

fMRI (Functional Magnetic Resonance Imaging). Use of an MRI scanner to view neural activity indirectly through changes in blood chemistry (such as the level of oxygen) and investigate increases in activity within brain areas that are associated with various forms of stimuli and mental tasks (see MRI).

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Forebrain. The largest division of the brain, which includes the cerebral cortex and basal ganglia. It is credited with the highest intellectual functions.

Frontal lobe. One of the four divisions (parietal, temporal, occipital) of each hemisphere of the cerebral cortex. It has a role in controlling movement and associating the functions of other cortical areas, believed to be involved in planning and higher order thinking.

Functional imaging. Represents a range of measurement techniques in which the aim is to extract quantitative information about physiological function.

Fusiform gyrus. A cortical region running along the ventral (bottom) surface of the occipital-temporal lobes associated with visual processes. Functional activity suggests that this area is specialised for visual face processing and visual word forms.

Gene. A gene is the unit of heredity in living organisms. Genes influence the physical development and behaviour of the organism. See also genetics.

Genetics. The science of genes, heredity, and the variation of organisms. **Classical genetics** consists of the techniques and methodologies of genetics predating molecular biology. **Molecular genetics** builds upon the foundation of classical genetics but focuses on the structure and function of genes at a molecular level. **Behavioral genetics** studies the influence of varying genetics on animal behaviour, and the causes and effects of human disorders.

Glia/glial cells. Specialised cells that nourish and support neurons.

Graphemes. The smallest unit of written language, including letters, Chinese characters, numerals, and punctuation marks.

Grey matter/gray matter. Gray matter consists of neurons' cell bodies and dendrites.

Gyrus/gyri. The circular convolutions of the cortex of which each has been given an identifying name: middle frontal gyrus, superior frontal gyrus, inferior frontal gyrus, left interior frontal gyrus, posterior middle gyrus, postcentral gyrus, supermaginal gyrus, angular gyrus, left angular gyrus, left fusiform gyrus, cingulated gyrus.

Hard-wired. Meaning "not changeable". In contrast to concept of plasticity in which brain is malleable to change.

(cerebral) Hemisphere. One of two sides of the brain classified as "left" and "right".

Hippocampus. A seahorse-shaped structure located within the brain and considered an important part of the limbic system. It functions in learning, memory and emotions.

Hormones. Chemical messengers secreted by endocrine glands to regulate the activity of target cells. They play a role in sexual development, calcium and bone metabolism, growth and many other activities.

HUFA (Highly unsaturated fatty acids).

Hypothalamus. A complex brain structure composed of many nuclei with various functions. These include regulating the activities of internal organs, monitoring information from the autonomic nervous system and controlling the pituitary gland.

Immune system. The combination of cells, organs and tissues which work together to protect the body from infection.

Implicit memory/learning. Memories that cannot be retrieved consciously but are activated as part of particular skills or action, and reflect learning a procedure of a pattern, which might be difficult to explicitly verbalise or consciously reflect upon (*i.e.* memory that allows you to engage in a procedure faster the second time, such as tying a shoe).

Information-processing. An analysis of human cognition into a set of steps whereby abstract information is processed.

Inhibition. In reference to neurons, this is a synaptic message that prevents the recipient cell from firing.

Insomnia. Inability to remain asleep for a reasonable period.

Intelligence. Characeristic of the mind lacking a scientific definition. Can be fluid or crystallised intelligence (see also multiple intelligences, IQ).

Interference theory. A theory of forgetting in which other memories interfere with the retention of the target memory.

Ions. Electrically charged atoms.

IQ. A number held to express the relative intelligence of a person originally determined by dividing mental by chronological age and multiplying by 100.

Left-brained thinking. A lay term based on the misconception that higher level thought processes are strictly divided into roles that occur independently in different halves of the brain. Thought to be based on exaggerations of specific findings of left hemisphere speclialisations, such as the neural systems that control speaking.

Limbic system. Also known as the "emotional brain". It borders the thalamus and hyphothalamus and is made up of many of the deep brain structures – including the amygdala, hippocampus, septum and basal ganglia – that work to help regulate emotion, memory and certain aspects of movement.

Lobe. Gross areas of the brain sectioned by function (see also occipital, temporal, parietal and frontal).

Long-term memory. The final phase of memory in which information storage may last from hours to a lifetime.

Longitudinal study. Studies that track the development of individuals over an extended period of time.

Long-term potentiation (LTP). The increase in neuron responsiveness as a function of past stimulation.

MEG (Magnetoencephalography). A non-invasive functional brain imaging technique sensitive to rapid changes in brain activity. Recording devices ("SQUIDs" for *Superconducting Quantum Interference Devices*) placed near the head are sensitive to small magnetic fluctuations associated with neural activity in the cortex. Responses to events can be traced out on a millisecond time scale with good spatial resolution for those generators to which the technique is sensitive.

Melatonin. Produced from serotonin, melatonin is released by the pineal gland into the bloodstream. It affects physiological changes related to time and lighting cycles.

Memory. Working memory/or short-term memory refers to structures and processes used for temporarily storing and manipulating information. **Long-term memory** stores memory as meaning. Short-term memory can become long-term memory through the process of rehearsal and meaningful association.

Memory consolidation. The physical and psychological changes that take place as the brain organises and restructures information in order to make it a part of memory.

Memory span. The amount of information that can be perfectly remembered in an immediate test of memory.

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Mental imagery. Also known as visualisation. Mental images are created by the brain from memories, imagination, or a combination of both. It is hypothesised that brain areas responsible for perception are also implicated during mental imagery.

Mental images. Internal representations consisting of visual and spatial information.

Metabolism. The sum of all physical and chemical changes that take place within an organism and all energy transformations that occur within living cells.

Meta-cognition. Conscious awareness of one's own cognitive and learning processes. In short, "thinking about thinking".

Micro-array. A tool for analysing gene expression that consists of a glass slide or other solid support with the sequences of many different genes attached at fixed locations. By using an array containing many DNA samples, scientists can determine the expression levels of hundreds or thousands of genes within a cell in a single experiment.

Micro-genetics. A method of tracking change during development. The micro–genetic method stresses that change is continual and occurs at many different points aside from the major stage changes. Tracking these ongoing changes can help researchers understand how children learn.

Mind. The mind is what the brain does, it includes intellect and consciousness.

Mirror neurons. A neuron which fires both when a human performs an action and when a human observes the same action performed by another. Mirror neurons therefore "mirror" behaviours as if the observer himself was performing the action.

Mnemonic technique. A technique which enhances memory performance.

Morphology. In linguistics, morphology is the study of word structure.

Motivation. Can be defined as whatever causes to act. Motivation reflects states in which the organism is prepared to act physically and mentally in a focussed manner, that is, in states characterised by raised levels of arousal. Accordingly, motivation is intimately related to emotions as emotions constitute the brain's way of evaluating whether things should be acted upon. **Intrinsic motivation** is evident when people engage in an activity for its own sake, without some obvious external incentive present, as opposed to **external/ extrinsic motivation** which is reward-driven.

Motor cortex. Regions of the cerebral cortex involved in the planning, control, and execution of voluntary motor functions.

Motor neuron. A neuron that carries information from the central nervous system to the muscle.

MRI (Magnetic Resonance Imaging). A non-invasive technique used to create images of the structures within a living human brain, through the combination of a strong magnetic field and radio frequency impulses.

Multiple intelligences. Theory that each individual has multiple, partially distinct, intelligences, including: linguistic, logical-mathematical, spatial, bodily-kinesthetic, musical, interpersonal, and intrapersonal.

Multiple sclerosis/MS. A chronic, inflammatory disease affecting the central nervous system.

Multi-tasking. Simultaneous performance of two or more tasks.

Myelin/myelination. Compact fatty material that surrounds and insulates axons of some neurons. Process by which nerves are covered by a protective fatty substance. The sheath (myelin) around the nerve fibres acts electrically as a conduit in an electrical system, increasing the speed at which messages can be sent.

Myth of three. Also known as the "Myth of the Early Years". This assumption states that only the first three years really matter in altering brain activity and after that the brain is insensitive to change. This extreme "critical period" viewpoint is not accurate. In fact, the brain is responsive to change throughout the lifespan.

Neurobiology. The study of cells and systems of the nervous system.

Neurodegenerative diseases. Disorders of the brain and nervous system leading to brain dysfunction and degeneration including Alzheimer's diseases, Parkinson's disease and other neurodegenerative disorders that frequently occur with advancing age.

Neurogenesis. The birth of new neurons.

Neuromyth. Misconception generated by a misunderstanding, a misreading or misquoting of facts scientifically established (by brain research) to make a case for use of brain research, in education and other contexts.

Neuron. Nerve cell. It is specialised for the transmission of information and characterised by long fibrous projections called axons, and shorter, branch-like projections called dendrites. Basic building block of the nervous system; specialised cell for integration and transmission of information.

Neurotransmitter. A chemical released by neurons at a synapse for the purpose of relaying information via receptors.

NIRS (Near Infrared Spectroscopy). Non-invasive imaging method which allows measures of the concentrations of deoxygenated haemoglobin in the brain by near-infrared absorption (near-infrared light at a wavelength between 700 nm and 900 nm can partially penetrate through human tissues).

Nucleus accumbens. The nucleus accumbens (also known as the accumbens nucleus or nucleus accumbens septi) is a collection of neurons located where the head of the caudate and the anterior portion of the putamen meet just lateral to the septum pellucidum. The nucleus accumbens, the ventral olfactory tubercle, and ventral caudate and putamen collectively form the ventral striatum. This nucleus is thought to play an important role in reward, pleasure, and addiction.

Nurture. The process of caring for and teaching a child as the child grows.

Occipital lobe. Posterior region of the cerebral cortex receiving visual information.

Occipito-temporal cortex. Also known as Brodman's area is part of the temporal cortex in the human brain.

Omega fatty acids. Polyunsaturated fatty acids which cannot be synthesised in the body.

Ontogenesis. The developmental history of an individual.

Orthography. The set of rules about how to write correctly in the writing system of a language.

OT (Optical Topography). Non-invasive trans-cranial imaging method for higher-order brain functions. This method, based on near-infrared spectroscopy, is robust to motion, so that a subject can be tested under natural conditions.

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Oxytocin. Also known as the "love hormone". Oxytocin is involved in social recognition and bonding, and might be involved in the formation of trust between people.

Pallidum/globus pallidus. A sub-cortical structure of the brain.

Parasympathetic nervous system. A branch of the autonomic nervous system concerned with the conservation of the body's energy and resources during relaxed states.

Parietal lobe. One of the four subdivisions of the cerebral cortex. It plays a role in sensory processes, attention and language. Involved in many functions such as processing spatial information, body image, orienting to locations, etc. Can be subdivided into superior parietal lobule and inferior parietal lobule. The precuneus, postcentral gyrus, supramaginal gyrus and angular gyrus make up the parietal lobe.

Parkinson's disease. A degenerative disorder of the central nervous system that affects the control of muscles, and so may affect movement, speech and posture (see also neurodegenarative disorders).

Peripheral nervous system. A division of the nervous system consisting of all nerves which are not part of the brain or spinal cord.

Perisylvian areas. Cortical regions that are adjacent to the sylvian fissure – major fissure on the lateral surface of the brain running along the temporal lobe.

PET (Positron Emission Tomography). A variety of techniques that use positron emitting radionucleides to create an image of brain activity; often blood flow or metabolic activity. PET produces three-dimensional, coloured images of chemicals or substances functioning within the brain.

Phonemes. Basic units of oral speech that make up words.

Phylogenic development. The process of evolution which favors those genetic behavioural traits in both genders that best assure survival of the species.

Pineal gland. An endocrine organ found in the brain. In some animals, it seems to serve as a light-influenced biological clock.

Pituitary gland. An endocrine organ closely linked with the hypothalamus. In humans, it is composed of two lobes and secretes a number of hormones that regulate the activity of other endocrine organs in the body.

Plasticity. Also "brain plasticity". The phenomenon of how the brain changes and learns in response to experience. See also experience-expectant/experience-dependent plasticity.

Precuneus. Structure in the brain positioned above the cuneus and located in the parietal lobe.

Prefrontal cortex. The region in front of the frontal cortex which is involved in planning and other higher-level cognition.

Primary motor cortex. Works in association with pre-motor areas to plan and execute movements.

Primary visual cortex. The region of the occipital cortex where most visual information first arrives.

Pruning/synaptic pruning. The natural process of eliminating weak synaptic contacts.

Putamen. A component of the limbic system. This part is responsible for familiar motor skills.

Qualia. A term for subjective sensations. In "Phantoms In The Brain", Professor Ramachandran describes the riddle of qualia like this. How can the flux of ions and electrical currents in little specks of jelly, which are the neurons in my brain, generate the whole subjective world of sensations like red, warmth, cold or pain? By what magic is matter transmuted into the invisible fabric of feelings and sensations?

Reasoning. The act of using reason to derive a conclusion from certain premises using a given methodology. Two most commonly used explicit methods to reach a conclusion are **deductive reasoning** in which the conclusion derived from previously known facts, and **inductive reasoning**, in which the premises of an argument are believed to support the conclusion but do not ensure it.

REM (Rapid eye movement sleep). The stage of sleep characterised by rapid movements of the eyes, when the activity of the brain's neurons is quite similar to that during waking hours.

"Reptilian" brain (so-called). Refers to the brain stem which is the oldest region in the evolving human brain.

Right-brained thinking. A lay term based on the misconception that higher level thought processes are strictly divided into roles that occur independently in different halves of the brain. Thought to be based in exaggerations of specific findings of right hemisphere specialisation in some limited domains.

Schizophrenia. A mental disorder characterised by impairments in the perception or expression of reality and/or by significant social or occupational dysfunction.

Science of learning. Term that attempts to provide a label for the type of research possible when cognitive neuroscience and other relevant disciplines research joins with educational research and practice.

Second messengers. Recently recognised substances that trigger communications between different parts of a neuron. These chemicals are thought to play a role in the manufacture and release of neurotransmitters, intracellular movements, carbohydrate metabolism and, possibly, even processes of growth and development. Their direct effects on the genetic material of cells may lead to long-term alterations of behavior, such as memory.

Sensitive period. Time frame in which a particular biological event is likely to occur best. Scientists have documented sensitive periods for certain types of sensory stimuli (such as vision and speech sounds), and for certain emotional and cognitive experiences (such as attachment and language exposure). However, there are many mental skills, such as reading, vocabulary size, and the ability to see colour, which to do not appear to pass through tight sensitive periods in the development.

Serotonin. A monoamine neurotransmitter believed to play many roles including, but not limited to, temperature regulation, sensory perception and the onset of sleep. Neurons using serotonin as a transmitter are found in the brain and in the gut. A number of antidepressant drugs are targeted to brain serotonin systems.

Short-term memory. A phase of memory in which a limited amount of information may be held for several seconds to minutes.

SPECT. Functional imaging using single photon emission computerised tomography.

Stimulus. An environmental event capable of being detected by sensory receptors.

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Stress. The physical and mental responses to anything that causes a real or imagined experiences and changes in life. Persistent and/or excessive stress may lead to depressive (withdrawal) behaviour.

Striatum. A subcortical part of the telencephalon, best known for its role in the planning and modulation of movement pathways but is also involved in a variety of other cognitive processes involving executive function.

Stroop task. A psychological test for mental vitality and flexibility. *E.g.* If a word is printed or displayed in a color different from the color it actually names; for example, if the word "green" is written in blue ink , a delay occurs in the processing of the word's color, leading to slower test reaction times and an increase in mistakes.

Sulcus/sulci. A furrow of convuluted brain surface. While gyri protrude from the surface, sulci recede, forming valleys between gyri.

Sympathetic nervous system. A branch of the autonomic nervous system responsible for mobilising the body's energy and resources during times of stress and arousal.

Synapse. A gap between two neurons that functions as the site of information transfer from one neuron to another (called "target cell" or "postsynaptic neuron").

Synaptic density. Refers to the number of synapses associated with one neuron. More synapses per neuron are thought to indicate a richer ability of representation and adaption.

Synaptic pruning. Process in brain development whereby unused synapses (connections among neurons) are shed. Experience determines which synapses will be shed and which will be preserved.

Synaptogenesis. Formation of a synapse.

Temporal lobe. One of the four major subdivisions of each hemisphere of the cerebral cortex. It functions in auditory perception, speech and complex visual perceptions.

Terminal/Axon terminal. A specialised structure at the end of the axon that is used to release neurotransmitter chemicals and communicate with target neurons.

Thalamus. A structure consisting of two egg-shaped masses of nerve tissue, each about the size of a walnut, deep within the brain. It is the key relay station for sensory information flowing into the brain, filtering out only information of particular importance from the mass of signals entering the brain.

TMS (Transcranial magnetic stimulation). A procedure in which electrical activity in the brain is influenced by a pulsed magnetic field. Recently, TMS has been used to investigate aspects of cortical processing, including sensory and cognitive functions.

Trans-disciplinarity. Term used to explain the concept of fusing completely different disciplines resulting in a new discipline with its own conceptual structure, known to extend the borders of the original sciences and disciplines included in its formation.

Ventricles. Of the four ventricles, comparatively large spaces filled with cerebrospinal fluid, three are located in the brain and one in the brainstem. The lateral ventricles, the two largest, are symmetrically placed above the brainstem, one in each hemisphere.

Visual cortex. Located in the occipital lobe; involved in detection of visual stimuli.

Wernicke's area. A brain region involved in the comprehension of language and the production of meaningful speech.

White matter. White matter consists of myelinated axons that connect various grey matter areas of the brain.

Table of Contents

Executive Summary 13

Part I
The Learning Brain

Introduction 21

Chapter 1. **An "ABC" of the Brain** 23

Acquisition of knowledge 24
Brain 24
Cognitive functions 24
Development 25
Emotions 25
Functionality, neural base of learning 25
Genetics 26
"Hands on" and Holistic – learning by doing 26
Intelligence 27
Joy of learning 27
Kafka 28
Language 28
Memory 29
Neuron 29
Opportunity windows for learning 30
Plasticity 30
Quality existence and healthy living 30
Representations 31
Skills 31
Team and social interactions 31
Universality 32
Variability 32
Work 33
... XYZ 33

Chapter 2. **How the Brain Learns throughout Life** 35

Basic principles of the brain's architecture 36
Functional organisation 38
The structure of the brain 39

How the brain learns over the lifetime . . . 41
Plasticity and sensitive periods . . . 42
Childhood (approximately 3-10 years) . . . 43
Adolescence (approximately 10-20 years) . . . 45
Adulthood and the elderly . . . 49
Learning to delay age-related cognitive decline . . . 50
Combating declining cognitive function . . . 50
Combating damaged brain function . . . 51
Conclusions . . . 55
References . . . 56

Chapter 3. **The Impact of Environment on the Learning Brain** . . . 59
Social interactions . . . 62
The regulation of emotions . . . 63
Motivation . . . 70
Sleep and learning . . . 73
Conclusions . . . 76
References . . . 77

Chapter 4. **Literacy and the Brain** . . . 83
Language and developmental sensitivities . . . 85
Literacy in the brain . . . 86
Linguistically-mediated literacy development . . . 88
Developmental dyslexia . . . 90
Conclusions . . . 93
References . . . 94

Chapter 5. **Numeracy and the Brain** . . . 97
Creating numeracy . . . 98
Babies calculate . . . 99
Numeracy in the brain . . . 99
Number and space . . . 102
The role of instruction . . . 102
Gender and mathematics . . . 103
Barriers to learning mathematics . . . 104
Conclusions . . . 105
References . . . 106

Chapter 6. **Dispelling "Neuromyths"** . . . 107
What is a "neuromyth"? . . . 108
"There is no time to lose as everything important about the brain is decided by the age of three" . . . 109
"There are critical periods when certain matters must be taught and learnt" . . . 110
"But I read somewhere that we only use 10% of our brain anyway" . . . 113
"I'm a 'left-brain', she's a 'right-brain' person" . . . 114
"Let's face it – men and boys just have different brains from women and girls" . . . 117
"A young child's brain can only manage to learn one language at a time" . . . 118
"Improve your memory!" . . . 120
"Learn while you sleep!" . . . 121

UNDERSTANDING THE BRAIN: THE BIRTH OF A LEARNING SCIENCE – ISBN 978-92-64-02912-5 – © OECD 2007

Conclusions 124
References 125

Chapter 7. **The Ethics and Organisation of Educational Neuroscience** 127
The ethical challenges facing educational neuroscience 128
For which purposes and for whom? 129
Ethical issues regarding the use of products affecting the brain 130
Brain meets machine – the meaning of being human? 131
The risk of an excessively scientific approach to education? 131
Creating a new trans-disciplinary approach to understanding learning 132
Trans-disciplinarity 132
Reciprocal inputs from both sides – bi-directional progress 140
Moving beyond national boundaries through international initiatives 144
Cautions and limitations 148
References 149

Conclusions and Future Prospects 151
Key messages and conclusions 152
Key areas for further educational neuroscientific research 157
Birth of a learning science 158
References 158

Part II

Collaborative Articles

Article A. **The Brain, Development and Learning in Early Childhood** 161
A.1. Introduction 162
A.2. What do we know about brain development in neonates, infants and young children? 162
A.2.1. The onset and process of brain development 162
A.2.2. The part played by experience 164
A.2.3. Timing and sequencing – important factors in brain development 164
A.2.4. Plasticity – a key feature of the infant brain 165
A.2.5. Critical or sensitive periods in neural development? 166
A.2.6. Sensitive periods and brain plasticity 167
A.2.7. Learning in and beyond early childhood 168
A.3. How important are the early years of development and learning? 168
A.3.1. The case for early intervention and education programmes 169
A.3.2. Children's learning dominates early childhood 171
A.3.3. Negative contexts for learning 171
A.3.4. Early childhood education and care – important but no "magic bullet" 172
A.4. What do we know about learning environments to facilitate early childhood development? 172
A.4.1. The subtleties of play and learning in this period 172
A.4.2. Curriculum and pedagogical focus and young children's development 173
A.4.3. Learning environments that support language development 174

A.4.4. Strategies used by educators to support learning in early childhood . . . 175
A.5. What challenges exist in synthesising research in neuroscience and early education? . . . 176
A.6. Practitioner's response . . . 177
References . . . 180

Article B. **The Brain and Learning in Adolescence** . . . 185
B.1. Introduction . . . 186
B.2. Understanding brain development – what are we looking at? . . . 186
B.2.1. Brain development at the microscopic level . . . 186
B.2.2. Brain development at the macroscopic level . . . 187
B.2.3. Brain development can be examined at multiple levels . . . 188
B.2.4. Imaging techniques . . . 189
B.2.5. It is difficult to tell to what extent development is caused by nature or/and by nurture . . . 190
B.3. The brain is a sculpture carved by experience . . . 191
B.3.1. Brain activity seen over time . . . 191
B.3.2. Brain structure seen over time . . . 192
B.3.3. Relationships between brain and behaviour are often indirectly derived . . . 192
B.3.4. Children and adults do not use the brain in the same way . . . 193
B.3.5. The adolescent brain and changes in adolescent behaviour . . . 193
B.3.6. Summary and general implications . . . 194
B.4. Theories of learning in adolescence and the life course . . . 195
B.4.1. Implications for teaching and learning in the adolescent years . . . 199
B.5. Challenges and future directions: towards a new synthesis? . . . 201
B.6. Practitioner's response: I have a dream . . . 203
B.6.1. Re-considering teaching . . . 203
B.6.2. Should we define new goals for schools and new missions for teachers? . . . 206
References . . . 208

Article C. **Brain, Cognition and Learning in Adulthood** . . . 211
C.1. Introduction . . . 212
C.1.1. What is learning? . . . 212
C.1.2. The human brain in adulthood . . . 213
C.1.3. Overview of paper . . . 213
C.2. Adult age-related changes in cognition and learning . . . 214
C.2.1. Cognitive aging . . . 214
C.2.2. Lifelong learning: a perspective from adult education . . . 215
C.3. Aging and brain function: structural neuroimaging . . . 217
C.4. Aging and brain function: functional neuroimaging . . . 217
C.5. Individual differences in age-related brain and cognitive changes . . . 219
C.6. Genetics and individual differences in cognition . . . 220
C.7. Training and aging . . . 222
C.7.1. Cognitive training . . . 222
C.7.2. Training – the developmental perspective . . . 222

UNDERSTANDING THE BRAIN: THE BIRTH OF A LEARNING SCIENCE – ISBN 978-92-64-02912-5 – © OECD 2007

C.8. Creating positive learning environments for adults 225
C.8.1. Competence-based learning: prepare for solving problems 225
C.8.2. Constructivist learning: making use of subjective experiences 226
C.8.3. Situated learning: organising learning environments 227
C.9. Future agenda 228
C.10. Practitioner's response 228
References 233

Annex A. Fora 239

Annex B. Brain Imaging Technologies 245

Glossary 250

Also Available in the CERI Collection 263

Boxes

2.1. Learning Therapy (Japan) 54
3.1. Nutrition 61
3.2. Attention as seen through the neuroscientific lens as an organ system 65
3.3. Physical exercise 67
3.4. Music 70
3.5. Play 71
3.6. Video games 72
3.7. Sound pressure level 75
7.1. Mind, Brain, and Education (MBE) 137
7.2. Centre for Neuroscience in Education: University of Cambridge, United Kingdom 138
7.3. Learning Lab Denmark 139
7.4. Harvard Graduate School of Education 140
7.5. Educators' views of the role of neuroscience in education 142
7.6. Technology and a world wide education perspective 143
7.7. Transfer Centre for Neuroscience and Learning, Ulm, Germany 144
7.8. JST-RISTEX, Japan Science and Technology-Research Institute of Science and Technology for Society, Japan 145
7.9. Educational Neuroscience Initiatives in the Netherlands 147
A.1. Emotions and memory (learning) 163
A.2. Initial language development 167
A.3. Mirror neurons 169
B.1. The principle behind MRI 189
B.2. The principle behind PET and fMRI 189
A. What is fMRI? 246
B. Near-infrared optical topography (NIR-OT) for learning sciences and brain research 247

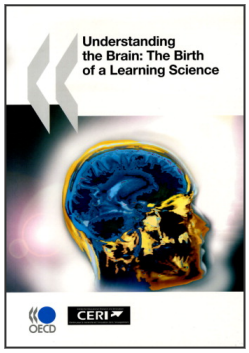
Tables

2.1. Summary of how the brain learns 48
2.2. Declining or damaged brain functioning and possible response 55

Figures

2.1. A synaptic connection between two neurons 37
2.2. The major subdivisions of the cerebral cortex 40
2.3. The frontal lobe 40
2.4. The adolescent brain 46
3.1. Inner structure of the human brain, including the limbic system 63
5.1. Cerebral areas 101
7.1. The evolution of trans-disciplinarity 134
7.2. Bi-directional exchange between research and practice 140
A. Functional magnetic resonance imaging 246

UNDERSTANDING THE BRAIN: THE BIRTH OF A LEARNING SCIENCE – ISBN 978-92-64-02912-5 – © OECD 2007



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