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Understanding the Brain: The Birth of a Learning Science
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PART I

Conclusions and Future Prospects

It is no good to try to stop knowledge from going forward. Ignorance is never better than knowledge.

Enrico Fermi

This chapter concludes Part I of this report by bringing together the key messages and potential policy implications, which show how neuroscientific research is already contributing to education and learning policy and practice. The themes include discussion of lifelong learning; ageing; holistic approaches to education; the nature of adolescence; ages for particular forms of learning and the curriculum; addressing the "3 Ds" (dyslexia, dyscalculia, and dementia); and assessment and selection issues in which neuroscience might increasingly be involved. The chapter also points to areas needing further educational neuroscientific research that have emerged from the different chapters of the report.

After seven years of a pioneering activity on learning sciences, it would be tempting on the one hand to exaggerate the claims that can be made, but also easy to hide behind the plea that further research is needed before we can reach any conclusions. On the latter, it is certainly true that more research is needed, and some key lines for further research are suggested below. On the former, this concluding chapter largely abstains from specific recommendations. The field is still too young, and the connections between neuroscience and education too complex, for this to be justified. There are few instances where neuroscientific findings, however rich intellectually and promising for the future, can be used categorically to justify specific recommendations for policy or practice. Indeed, one of the messages from this activity, made already in the 2002 *Understanding the Brain – Towards a New Learning Science* report, is that we should beware of simplistic or reductionist approaches, which may grab headlines or offer lucrative opportunities but which are a distortion of the knowledge base.

This chapter brings together the main themes and conclusions from the preceding analysis. It is possible to put forward some broad propositions or challenges which can open up and refresh the debate on the future shape and character of our education systems. If we witness the birth of a science of learning, new ideas and evidence will rapidly arise and transform the current landscape. We do not need to wait for that research; part of CERI's mission has always been to help OECD countries think through their future agendas. The conclusions are at quite a high level of generality, precisely in order to give the necessary impetus to carry the discussion across the very broad terrain mapped out in the preceding chapters.

Key messages and conclusions

> The most important scientific revolutions all include, as their only common feature, the dethronement of human arrogance from one pedestal after another of previous convictions about our centrality in the cosmos.
>
> *Stephen Jay Gould*

Educational neuroscience is generating valuable new knowledge to inform educational policy and practice

The sweep of this volume – from the learning that takes place in the earliest years of infancy through to that of the elderly, from knowledge related to specific subject areas through to that concerned with emotions and motivation, from the remedial to the more general understanding of learning – shows how wide-ranging is the contribution that neuroscience can make to educational policy and practice. It has shown that the contribution of neuroscience to education takes different forms.

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On many questions, neuroscience *builds on the conclusions of existing knowledge* from other sources, such as psychological study, classroom observation or achievement surveys. Examples discussed in this volume – such as the role of diet to improve educational performance, the turbulence of puberty, or that confidence and motivation can be critical to educational success – are not new. But the neuroscientific contribution is important even for results already known because:

- it is opening up understanding of "*causation*" *not just* "*correlation*"; and moving important questions from the realm of the intuitive or ideological into that of evidence;
- by revealing the mechanisms through which effects are produced, it can *help identify effective interventions and solutions*.

On other questions, neuroscience is *generating new knowledge, opening up new avenues*. Without understanding the brain, for instance, it would not be possible to know the different patterns of brain activities associated with expert performers compared with novices (as a means to understanding comprehension and mastery), or how learning can be an effective response to the decline of ageing, or why certain learning difficulties are apparent in particular students even when they seem to be coping well with other educational demands.

To these two key contributions can be added a third – that of *dispelling neuromyths*. Such distortions, discussed in detail in Chapter 6, risk to distract serious educational practice with the faddish, off-the-shelf solutions of the airport lounge bookshop.

Another key set of distinct contributions by neuroscience to education is:

- Research which is *deepening the knowledge base of what constitutes learning* as a central aspect of human and social life, and in ways which cut across the different institutional arrangements called "education".
- Neuroscience is developing the means *for revealing hitherto hidden characteristics in individuals*, which may be used for remedial purposes – to overcome reading problems or dyscalculia for instance. Eventually, they may also be used to select or improve performance or exclude, raising a raft of thorny ethical issues as discussed in Chapter 7.
- It is, along with other disciplines, able *to inform how best to design and arrange different educational practices*, especially as regards the match between findings on how best learning takes place and when, on the one hand, and how education is conventionally organised, on the other. It is another question whether that knowledge is being sufficiently acted upon at present.

Brain research provides important neurological evidence to support the broad aim of lifelong learning and confirms the wider benefits of learning, especially for ageing populations

One of the most powerful set of findings concerned with learning concerns the brain's remarkable properties of "plasticity" – to adapt, to grow in relation to experienced needs and practice, and to prune itself when parts become unnecessary – which continues throughout the lifespan, including far further into old age than had previously been imagined. The demands made on the individual and on his or her learning are key to the plasticity – the more you learn, the more you can learn. Far from supporting ageist notions that education is best concentrated on the young – the powerful learning capacity of young people notwithstanding – neuroscience has shown that *learning is a lifelong activity and that the more that it continues the more effective it is*.

As the demands for having an evidence-base on which to ground policy and practice grow, so has it become even more important to broaden the understanding of the "wider benefits" of education beyond the economic criteria which so often dominate policy cost-benefit analyses. There is growing evidence to show for instance that educational participation can have powerful benefits in terms of health or civic participation (see also CERI work on the "Social Outcomes of Learning"). This report has underpinned the arguments about the wider benefits of learning: the enormous and costly problems represented by senile dementia in ever-ageing populations can be addressed through the learning interventions being identified through neuroscience.

Combinations of improved diagnostics, opportunities to exercise, appropriate and validated pharmacological treatment, and good educational intervention can do much to maintain positive well-being and to prevent deterioration.

We need holistic approaches based on the interdependence of body and mind, the emotional and the cognitive

With such a strong focus on cognitive performance – in countries and internationally – there is the risk of developing a narrow understanding of what education is for. Far from the focus on the brain reinforcing an exclusively cognitive, performance-driven bias, it actually suggests the need for holistic approaches which recognise the close interdependence of physical and intellectual well-being, and the close interplay of the emotional and cognitive, the analytical and the creative arts.

The ways in which the benefits of good diet, exercise, and sleep impact on learning are increasingly understood through their effects in the brain. For older people, cognitive engagement (such as playing chess or doing crossword puzzles), regular physical exercise, and an active social life promote learning and can delay degeneration of the ageing brain (see Chapter 2).

The analysis of this report shows not only how emotions play a key part in the functioning of the brain, but the processes whereby the emotions affect all the others. Especially important for educational purposes is the analysis of fear and stress, which shows how they, for instance, reduce analytical capacity, and *vice versa* how positive emotions open doors within the brain.

This is just as relevant for the adult student confronted by an uncomfortable return to education as it does for the young person confronted by the unfamiliar demands of secondary or higher education. It has an equity dimension, for fear of failure, lack of confidence, and such problems as "maths anxiety" (Chapters 3 and 5) are likely to be found in significantly greater measure among those from less privileged backgrounds.

We need to understand better what adolescence is (high horsepower, poor steering)

This report is particularly revealing about the nature of adolescence in terms of the stage of brain development in the teenage years and particularly in terms of emotional maturation.

The insights provided by neuroscience on adolescence and the changes which take place during the teenage years are especially important as this is the period when so much takes place in an individual's educational career. The secondary phase of education is conventionally covered by this phase, with key decisions to be made with long-lasting consequences regarding personal, educational, and career options. At this time, young people are in the midst of adolescence, with well-developed cognitive capacity (high horsepower) but emotional immaturity (poor steering).

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Clearly, this cannot imply that important choices should simply be delayed until adulthood. It does suggest, with the additional powerful weight of neurological evidence, that the options taken should not take the form of definitively closing doors. There needs to be stronger differentiation of further learning opportunities (formal and informal) and greater recognition of the trajectories of adolescent maturation.

Neuroscience also has developed the key concept "emotional regulation". Managing emotions is one of the key skills of being an effective learner. Emotional regulation affects complex factors such as the ability to focus attention, solve problems, and support relationships. Given the "poor steering" of adolescence and the value of fostering emotional maturity in young people at this key stage, it may well be fruitful to consider how this might be introduced into the curriculum and to develop programmes to do this.

We need to consider timing and periodicity when dealing with curriculum issues

The work of psychologists like Piaget has long influenced our understanding of learning linked to individual development. Educational neuroscience is now permitting the qualification of the Piagetian models (including demonstration of the capacities already possessed by young infants), while broadening the understanding of timing and optimal learning through the study of "sensitive" periods.

The message emerging from this report is a nuanced one: there are no "critical periods" when learning *must* take place, and indeed the neuroscientific understanding of lifetime "plasticity" shows that people are always open to new learning. On the other hand, it has given precision to the notion of "sensitive periods" – the ages when the individual is particularly primed to engage in specific learning activities.

The example of language learning has featured prominently in this report, and is a key subject in an increasingly global world. In general, the earlier foreign language instruction begins, the more efficient and effective it can be. Such learning shows distinct patterns of brain activity in infants compared with school-age children compared with adults: at older ages more areas of the brain are activated and learning is less efficient. Even so, adults are perfectly capable of learning a new language.

This report has also dispelled myths about the dangers of multilingual learning interfering with native language competence; indeed, children learning another language reinforce the competences in their mother tongue.

These are important questions for education. These findings deepen the basis on which to pose questions about when in the lifespan certain types of learning should best be undertaken, grounded on evidence rather than tradition. They support the importance of laying a very strong foundation for lifelong learning, hence further emphasise the key role of early childhood education and basic schooling, not as ends in themselves but as giving the best possible start.

At the same time, the report (Chapter 6) has warned against *over-emphasising* the determining importance of the ages birth to three years on later learning.

Neuroscience can make a key contribution to major learning challenges

The contribution that neuroscience is already making to the diagnosis and identification of effective interventions is most clear in what might be termed the "3-Ds": dyslexia, dyscalculia, and dementia.

Dyslexia: Until recently, the causes of dyslexia were unknown, but now it is understood that it results primarily from atypical features of the auditory cortex (and maybe, sometimes, of the visual cortex). Only recently has it been possible to identify these features at a very young age. Early interventions are usually more successful than later interventions, but both are possible.

Dyscalculia is now understood to have comparable causes as dyslexia, though early identification and hence interventions are well less developed.

Dementia: The very significant findings about learning and dementia have been mentioned above, and education is being identified as an effective, desirable source of "prevention" to among other things delay the onset of Alzheimer's symptoms and reduce their gravity.

On the more general understanding of literacy (Chapter 4), the dual importance of phonological and direct semantic processing in the brain during reading in English suggests that a balanced approach to literacy instruction may be most effective for non-shallow alphabetic languages. As for shallow orthographies, neuroscience seems to confirm the appropriateness of "syllabic methods" to learn reading, and there is interesting potential to be explored in comparisons between alphabetic and non-alphabetic languages on reading acquisition.

On numeracy (Chapter 5), since humans are born with a biological inclination to understand the world numerically, formal mathematics instruction should build upon existing informal numerical understandings. Because number and space are tightly linked in the brain, instructional methods that link number with space are powerful teaching tools.

More personalised assessment to improve learning, not to select and exclude

The potential of brain imaging could have very far-reaching consequences for education, as well as raising critical ethical issues. Knowledge about how the brain functions, and about how competence and mastery are reflected in brain structures and processes, can be applied at a *system-wide level*, interrogating conventional educational arrangements and practices to ask whether we organise them for optimal learning. Many conventional forms of assessment, where success can be boosted by cramming, have been shown to be "brain-unfriendly" with low retained comprehension.

But beyond these general findings, the results of neuroscience may eventually also be applied *on individual learners* to find out such matters as whether they really comprehend certain material, or about their levels of motivation or anxiety. Used properly, this individual focus may add fundamentally powerful diagnostic tools to the process of formative assessment (OECD, 2005) and personalised learning.

This relates to the pursuit in a number of countries of greater "personalisation" of curricula and educational practices (OECD, 2006). Neuroimaging potentially offers a powerful additional mechanism on which to base personalisation. At the same time, studies of the brain show that individual characteristics are far from fixed – there is constant interaction between genetic function and experience and plasticity, such that the notion of what constitutes an individual's capacities should be treated with considerable caution.

But, on the other side, such individual applications of neuroimaging may also lead to even more powerful devices for selection and exclusion than are currently available. A biological CV would be open to profound risks, while being potentially attractive to such users as universities or employers. It would be an abuse of the valuable tools of

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neuroimaging if they were deployed in the negative ways of rejecting students or candidates on the grounds that they do not show sufficient learning capacity or potential (especially when the plasticity of the brain shows how open to development is the capacity to learn). The excessively "scientific" conception of education described in Chapter 7 – used as the basis for selecting students and teachers alike – would be anathema to many.

Key areas for further educational neuroscientific research

> If we value the pursuit of knowledge, we must be free to follow wherever that search may lead us.
>
> *Adlai E. Stevenson Jr.*

The below research areas do not pretend to be exhaustive of interesting fields of educational neuroscientific enquiry; instead, they have emerged from the analysis of this report as priority areas. Some of them represent the need to deepen knowledge where at present our understanding is sketchy.

It is also about setting an educational agenda for neuroscience as well as the medical agenda which has naturally tended to dominate it up to now. It is for the neuroscientific community to realise how valuable its contributions are to better understanding the key human activity of learning for educational purposes as it applies for all – gifted through disabled, young through old – and not only for those requiring remediation.

- Better understanding of optimal timing for what forms of learning, especially in relation to adolescents and older adults where the review shows that the knowledge base is not yet well developed (Chapter 2). This includes "sensitive periods" – when the capacity to learn is greatest – in specific areas such as language learning.
- Understanding the interaction between increasing knowledge and declining executive function and memory. More research into the ageing process, and not only among the elderly but also adults in their middle years – both in terms of capacity to learn and in terms of the role of learning to delay the deleterious effects of ageing.
- Much is needed on emotions in the brain. Further investigation using psychological and neuroimaging studies is needed of the neurobiological mechanisms which underlie the impact of stress on learning and memory, and the factors that could reduce or regulate it. A specific question for further investigation is how the adolescent's emotional brain interacts with different kinds of classroom environments.
- Better understanding of how laboratory conditions influence findings, and the applicability and transferability of results in different settings other than those in which they were generated. The key role of appropriate learning materials and specific environments needs to be analysed so as to move away from the crude formulations which ask whether environment does or does not make a difference.
- Confirmatory studies showing how beneficial nutrition can impact positively on brain development and more studies directly related to the educational domain. The same applies to physical exercise, sleep, music and creative expression.
- Much more is needed on what types of learning requires the interaction of others and on the role of cultural differences. This should be further broken down in terms of student demographic (especially gender) and socio-cultural differences, but it is also a minefield for misinterpretation. Neuroscience should certainly not be brought into the service of racist or sexist stereotypes.

- Research can help lead to the better understanding of multi-dimensional pathways to competence, for instance in reading. The need to expand the focus to real-world educational situations and applications, *e.g.* whole sentences rather than single words or characters.
- It would be very useful to further build up the differentiated map of mathematics in the brain, which builds on the insights gained already on the apparently paradoxical combination of dissociable skills and brain functions, on the one hand, and interconnectivity, on the other. Identification of approaches to overcome "mathematics anxiety" would be very useful.
- Understanding different brain activity – neural networks, role of cognitive function and memory – among "experts" as compared with average learners as compared with those with genuine problems. This will inform both the identification of successful learning and of effective, targeted teaching methods.

Birth of a learning science

Recent advances in neuroscience have produced powerful insights while educational research has accumulated a substantial knowledge base. A neuroscientific perspective adds a new, important dimension to the study of learning in education, and educational knowledge could help direct neuroscience research towards more relevant areas. Because both fields are well-developed, however, they have deeply-rooted disciplinary cultures with field-specific methods and language which make it extremely difficult for experts from one field to use the knowledge from the other. A new trans-disciplinarity is needed which brings the different communities and perspectives together. This needs it to be a reciprocal relationship, analogous to the relationship between medicine and biology, to sustain the continuous, bi-directional flow of information necessary to support brain-informed, evidence-based educational practice. Researchers and practitioners can work together to identify educationally-relevant research goals and discuss potential implications of research results. Once brain-informed educational practices are implemented, practitioners should systematically examine their effectiveness and provide classroom results as feedback to refine research directions. Establishing research schools with educational practice intimately connected to brain research is a promising way to stabilise trans-disciplinary work.

Educational neuroscience can help to drive the creation of a real learning science. It might even serve as a model of trans-disciplinarity for other fields to emulate. We hope that this publication will help give birth to this real learning science, as well as a model for continued trans-disciplinary fusion.

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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.

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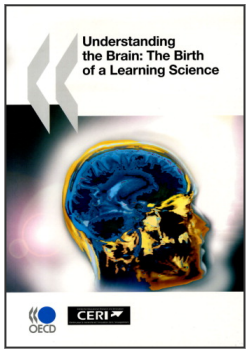

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