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Understanding the Brain: The Birth of a Learning Science

PART I

Chapter 1

An "ABC" of the Brain

The only good is knowledge and the only evil is ignorance.

Socrates

Not to know is bad. No to wish to know is worse.

(*African Proverb*)

Chapter 1 provides an "ABC" of the contents of the report by listing keywords and concepts in alphabetical order covered in the chapters to follow. It begins with **A***cquistion of knowledge and* **B***rain, and runs through to* **V***ariability,* **W***ork and* **XYZ**. *The reader can choose a particular topic of interest, and the corresponding description points to the relevant chapter(s) which provide more in-depth coverage of the issue. This chapter is relevant for all those who are interested in the issue of "learning sciences and brain research" including learners, parents, teachers, researchers and policy makers.*

Acquisition of knowledge

The neuroscientific approach to learning provides a hard-scientifically based theoretical framework for educational practices. This rapidly emerging field of study is slowly but surely building the foundations of a "Science of Learning".

A living being is made up of various levels of organisation. The result is that a single human process may be defined differently depending on the level used as a reference. This is true of the learning process where the definition varies depending on the perspective of the person who describes it.

The differences between cellular and behavioural definitions reflect the contrasting views of neurosciences and educational sciences. Neuroscientists consider learning as a cerebral process where the brain reacts to a stimulus, involving the perception, processing and integration of information. Educators consider this as an active process leading to the acquisition of knowledge, which in turn entails lasting, measurable and specific changes in behaviour.

Brain

Even though it plays a fundamental role, the brain remains one single part of a whole organism. An individual cannot solely be reduced to this organ as the brain is in constant interaction with other parts of the human body.

The brain is the seat of our mental faculties. It assumes vital functions by influencing heart rate, body temperature, breathing, etc., as well as performing so-called "higher" functions, such as language, reasoning and consciousness.

This organ includes two hemispheres (left and right), with each further divide into lobes (occipital, parietal, temporal and frontal) – further described in Chapter 2.

The main components of cerebral tissue are glial and nerve cells (neurons). The nerve cell is considered as the basic functional unit of the brain because of its extensive interconnectivity and because it specialises in communication. Neurons are organised in functional networks that are situated in specific parts of the brain.

Cognitive functions

Having been studied at various levels, cognitive functions benefit from a rich multidisciplinary research effort. Therefore, in a complementary way, neurosciences, cognitive neuroscience and cognitive psychology seek to understand these processes.

Cognition is defined as the set of processes enabling information processing and knowledge development. These processes are called "cognitive functions". Among these, the higher cognitive functions correspond to the human brain's most elaborate processes. They are the product of the most recent phase of the brain's evolution and are mainly centred in the cortex, which is a particularly highly developed structure in humans (see Chapter 2).

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Examples of these functions are certain aspects of perception, memory and learning, but also language, reasoning, planning and decision-making.

Development

The brain is continually changing – developing – throughout life. This development is guided by both biology and experience (see Chapter 2). Genetic tendencies interact with experience to determine the structure and function of the brain at a given point in time. Because of this continuous interaction, each brain is unique.

Though there is a wide range of individual differences in brain development, the brain has age-related characteristics that can have important consequences for learning. Scientists are beginning to map out these maturational changes and to understand how biology and experience interact to guide development.

Understanding development from a scientific perspective could powerfully impact educational practice. As scientists uncover age-related changes in the brain, educators will be able to use this information to design didactics that are more age-appropriate and effective.

Emotions

Emotional components have long been neglected in institutional education. Recent contributions of neuroscientists are helping to remedy this deficiency by revealing the emotional dimension of learning (see Chapter 3).

As opposed to "affect", which is their conscious interpretation, emotions arise from cerebral processes and are necessary for the adaptation and regulation of human behaviour.

Emotions are complex reactions generally described in terms of three components: a particular mental state, a physiological change and an impulsion to act. Therefore, faced with a situation perceived as dangerous, the reactions engendered will simultaneously consist of a specific cerebral activation of the circuit devoted to fear, body reactions typical of fear (*e.g.* accelerated pulse, pallor and perspiring) and the fight-or-flight reaction.

Each emotion corresponds to a distinct functional system and has its own cerebral circuit involving structures in what we call the "limbic system" (also known as the "seat of the emotions"), as well as cortical structures, mainly the prefrontal cortex which plays a prime role in regulating emotions. Incidentally, the prefrontal cortex matures particularly late in human beings, concluding its development in the third decade of an individual's development. This means that cerebral adolescence lasts longer than was, until recently, thought, which helps to explain certain features of behaviour: the full development of the prefrontal cortex, and therefore the regulation of emotions and compensation for potential excesses of the limbic system, occur relatively late in an individual's development.

Continual exchanges make it impossible to separate the physiological, emotional and cognitive components of a particular behaviour. The strength of this interconnectivity explains the substantial impact of emotions on learning. If a positively perceived emotion is associated with learning, it will facilitate success, whereas a negatively perceived emotion will result in failure.

Functionality, neural base of learning

The neuroscientific definition of learning links this process to a biological substrate or surface. From this point of view, learning is the result of integrating all information perceived and processed. This integration takes form in structural modifications within the brain. Indeed, microscopic changes occur, enabling processed information to leave a physical "trace" of its passage.

Today, it is useful, even essential, for educators and anyone else concerned with education to gain an understanding of the scientific basis of learning processes.

Genetics

The belief that there is a simple cause and effect relationship between genetics and behaviour often persists. Imagining a linear relationship between genetic factors and behaviour is only a short step away from full-blown determinism. A gene does not activate behaviour but instead consists of a sequence of DNA containing the relevant information to produce a protein. The expression of the gene varies on the basis of numerous factors, especially environmental factors. Once a protein is synthesised in the cell, it occupies a specific place and plays a role in the functioning of this cell. In this sense, it is true that if genes affect function, they consequently mould behaviour. However, this is a complex non-linear relationship with the various levels of organisation influencing one another.

As research slowly but surely advances, belief in a frontier between the innate and the acquired is disappearing, giving way to understanding the interdependence between genetic and environmental factors in brain development.

To predict behaviour on the basis of genetics will be incomplete: any approach solely influenced by genetics is not only scientifically unfounded but also ethically questionable and politically dangerous.

"Hands on" and Holistic – learning by doing

"I hear and I forget,
I see and I remember,
I do and I understand"

Confucius

Long forgotten by educators, this quote regained prominence in the 20th century with the advent of constructivism. Contrary to theories focused on expert educators who transmit knowledge, this current advanced a new concept of learning: the construction of knowledge. Learning becomes learner-centred and relies on the development of prior knowledge, based on the experience, desires and needs of each individual.

Therefore, this theoretical upheaval has given rise to the so-called active or experiential practices of "learning-through-action". The objective is to actively involve learners in interacting with their human and material environment, based on the idea that this will lead to a more profound integration of information than perception. Action necessarily implies operationalisation – the implementation of concepts. The learner not only needs to acquire knowledge and know-how, but must also be able to render them operational in real applications. Therefore the learner becomes "active", implying a better level of learning.

Not all neuroscientific discoveries give rise to innovations in terms of didactics. However, they provide a solid theoretical basis for well-tried practices which have been consolidated through experience. These scientific insights then serve to underpin the body of empirical and intuitive knowledge already accumulated, and explain why some practices fail or succeed.

Intelligence

The concept of intelligence has always been a subject of controversy. Can a single concept account for all of the intellectual faculties of an individual? Can these faculties be separated and measured? And in particular, what do they show and predict about the cerebral functioning of an individual and about social behaviour?

The notion of intelligence evokes “skills”, whether they are verbal skills, spatial skills, problem-solving skills or the very elaborate skill of dealing with complexity. However, all of these aspects neglect the concept of “potential”. Yet, neurobiological research on learning and cognitive functions clearly shows that these processes undergo constant evolution and are dependent on a number of factors, particularly environmental and emotional ones. This means that a stimulating environment should offer each individual the possibility to cultivate and develop his/her skills.

From this point of view, the many attempts to quantify intelligence using tests (such as IQ measurements or others) are too static and refer to standardised and culturally (sometimes even ideologically) biased faculties.

Based on a priori *assumptions, intelligent tests are restrictive and therefore problematic. Based on this “intelligence calculation” or the debatable assignation of individuals to different levels of intelligence, what should be concluded for the practices or even the choices related to career orientation?*

Joy of learning

“Tell me and I forget
Teach me and I remember
Involve me and I learn”

Benjamin Franklin

This maxim restores involvement to its role as an essential condition of significant learning. Involvement can be summed up as the commitment of an individual within a given action. In this sense, it results directly from the process of motivating the individual to behave in a certain way or to pursue a particular goal. This process can be triggered by internal or external factors. This is why we speak of intrinsic motivation, which solely depends on the learner’s own needs and desires, or extrinsic motivation, which takes into account external influences on the individual. Motivation is largely conditioned by self-assurance, self-esteem and by the benefits the individual may accrue in terms of a targeted behaviour or goal.

The combination of motivation and self-esteem are essential to successful learning. In order to give these factors their rightful place within learning structures, the system of tutoring is gaining ground. It offers the learner personalised support and is better adapted to his/her needs. A more personal climate for learning serves to motivate learners but should not disregard the crucial role of social interactions in all modes of learning. Personalisation should not mean the isolation of learners.

Motivation has a pivotal role in the success of learning, especially intrinsic motivation. The individual learns more easily if s/he is doing it for him/herself, with the desire to understand.

Although it is currently difficult to construct educational approaches that could go beyond “carrot and stick” systems and target this intrinsic motivation, the benefits of this approach are such that it is of paramount importance for research to orient its efforts towards this domain.

Kafka

By describing in "The Castle" the vain efforts of the protagonist to attain his objectives ("There is a goal, but no way": "Es gibt zwar ein Ziel, aber keinen Weg zum Ziel"), Franz Kafka relates the feeling of despair that an individual can feel when being confronted with a deaf and blind bureaucratic machine. Reminiscent of this work, Dino Buzzati's story "K" is a tragedy of a misunderstanding, emphasising how sad, but also dangerous it can be to understand certain realities too late…

There is abundant resistance to taking on board neuroscientific discoveries for educational policies and practices, sufficient to discourage even the most fervent advocates. The reasons may be various – simple incomprehension, mental inertia, the categorical refusal to reconsider certain "truths", through to corporate reflexes to defend acquired positions, even staunch bureaucracy. The obstacles are numerous to any trans-disciplinary effort to create a new field, or even more modestly to shed new light on educational issues. This poses a delicate problem of "knowledge management". Even if some constructive scepticism can do no harm, every innovative project finds itself in the position of "K" at one point or another, seeking to reach the Castle. Despite such difficulties, a way exists; to quote Lao Tzu: "The journey is the destination."

Moreover, neuroscience unintentionally generates a plethora of "neuromyths" founded on misunderstandings, bad interpretations, or even distortions of research results. These neuromyths, which become entrenched in the minds of the public by the media, need to be identified and dispelled. They raise many ethical questions which in democratic societies need to be addressed through political debate.

We can ask whether (in the mid-term at least), it is acceptable, in any reflection about education, not to take into consideration what is known about the learning brain. Is it ethical to ignore a field of relevant and original research that is shedding new light and fundamental understanding on education?

Language

Language is a specifically human cognitive function which is also dedicated to communication. It opens up the use of a system of symbols. When a finite number of arbitrary symbols and a set of semantic principles are combined according to rules of syntax, it is possible to generate an infinite number of statements. The resulting system is a language. Different languages use phonemes, graphemes, gestures and other symbols to represent objects, concepts, emotions, ideas and thoughts.

The actual expression of language is a function that relates at least one speaker to one listener, and the two can be interchangeable. This means language can be broken down into a direction (perception or production) and also into a mode of expression (oral or written). Oral language is acquired naturally during childhood by simple exposure to spoken language; written language, on the other hand, requires intentional instruction (see Chapter 4).

Language was one of the first functions to be shown to have a cerebral basis. In the 19th century, studies of aphasia by two scientists (Broca and Wernicke) revealed that certain areas of the brain were involved in language processing. Since then, studies have confirmed that these areas belong to the cerebral circuits involved in language (see Chapter 4).

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Accumulating a large body of neuroscientific knowledge on language was possible because of neuroscience's major interest in this function. The understanding of language mechanisms and how they are learned has already had an important impact on educational policies.

Memory

During the learning process, traces are left by the processing and integration of perceived information. This is how memory is activated. Memory is a cognitive process enabling past experiences to be remembered, both in terms of acquiring new information (development phase of the trace) and remembering information (reactivation phase of this trace). The more a trace is reactivated, the more "marked" memory will be. In other words, it will be less vulnerable and less likely to be forgotten.

Memory is built on learning, and the benefits of learning persist thanks to it. These two processes have such a profound relationship that memory is subject to the same factors influencing learning. This is why memorisation of an event or of information can be improved by a strong emotional state, a special context, heightened motivation or increased attention.

Learning a lesson too often means being able to recite it. Training and testing are usually based on retrieving and therefore on memorising information often to the detriment of mastering skills and even of understanding content. Is this role given to memory skills in learning justified? This is a pivotal question in the field of education, and is beginning to attract the attention of neuroscientists.

Neuron

Organised in extensively interconnected networks, neurons have electrical and chemical properties that enable them to propagate nerve impulses (see Chapter 2, especially Figure 2.1). An electrical potential is propagated within a nerve cell and a chemical process transmits information from one cell to another. These nerve cells are consequently specialised in communication.

The electrical propagation within the cell is uni-directional. Inputs are received by the neuron's dendrites or the cell body. In response to these inputs, the neuron generates action potentials. The frequency of these potentials varies according to these inputs. Therefore, the action potentials propagate through the axon.

A zone called the *synapse* serves as a junction between two neurons. The synapse consists of three components: the axon ending, the synaptic gap and the dendrite of the postsynaptic neuron. When the action potentials reach the synapse, it releases a chemical substance called the neurotransmitter, which crosses the synaptic gap. This chemical activity is regulated by the type and amount of neurotransmitters, but also by the number of receptors involved. The amount of neurotransmitters released and the number of receptors involved are responsive to experience, which is the cellular basis of plasticity (see below). The effect on postsynaptic neurons may be excitatory or inhibitory.

Therefore, this combination of electrical and chemical activity of the neurons transmits and regulates information within the networks formed by neurons.

In order to improve the understanding of cerebral activity, various functional imaging technologies (fMRI, MEG, PET, OT, etc.) (see Annex B) are used to visualise and study the activity of the changes in blood flow induced by neuronal activities.

Studies localising cerebral networks open an important door to our understanding of learning mechanisms. The better the temporal and spatial resolution, the more precise the localisation and consequently the better our understanding of cerebral function.

Opportunity windows for learning

Certain periods in an individual's development are particularly well-suited to learning certain skills. During these key moments the brain needs certain types of stimulations in order to establish and maintain long-term development of the structures involved. These are the stages at which the individual's experience becomes an overriding factor, responsible for profound changes.

These periods are called "sensitive periods" or windows of opportunity, because they are the optimum moments for individuals to learn specific skills. They are part of natural development, but experience is needed so that a change (learning) can be effective. This process can be described as "experience-expectant" learning, such as oral language (see Chapter 4). It is not the same as "experience-dependent" learning such as written language, which can take place at any moment in an individual's lifetime.

If learning does not occur in these windows of opportunity, it does not mean it cannot occur. Learning takes place throughout a whole lifetime although outside these windows of opportunity, it takes more time and cognitive resources and it will often not be as effective.

A better understanding of sensitive periods and the learning that occurs during those periods is a crucial avenue of future research. An increasingly complete map will enable us to better match instruction to the appropriate sensitive period in educational programmes with a corresponding positive impact on the effectiveness of learning.

Plasticity

The brain is capable of learning because of its flexibility (see Chapter 2). It changes in response to stimulation from the environment. This flexibility resides in one of the intrinsic properties of the brain – its plasticity.

The mechanism operates in various ways at the level of the synaptic connections (Figure 2.1). Some synapses may be generated (synaptogenesis), others eliminated (pruning), and their effectiveness may be moulded, on the basis of the information processed and integrated by the brain.

The "traces" left by learning and memorisation are the fruit of these modifications. Plasticity is consequently a necessary condition for learning and an inherent property of the brain; it is present throughout a whole lifetime.

The concept of plasticity and its implications are vital features of the brain. Educators, policy makers and all learners will all gain from understanding why it is possible to learn over a whole lifetime and indeed brain plasticity provides a strong neuroscientific argument for "lifelong learning". Would not primary school be a good place to start teaching learners how and why they are capable of learning?

Quality existence and healthy living

Like any other organ in the human body, the brain functions best with healthy living. Recent studies have looked into the impact of nutrition and physical activity on cerebral faculties and particularly on learning. Results show that a balanced diet contributes to the development and functioning of the brain, while also preventing some behavioural and learning problems (see Chapter 3). In the same respect, regular physical activity has a positive effect on the functioning of human cognition, modifying the activity in certain regions of the brain.

Sleep is also a determining factor in brain development and function (Chapters 3 and 6). Anyone who has lacked sleep knows that cognitive functions are the first to suffer. It is during sleep that some of the processes involved in plasticity and consolidation of knowledge take place, processes that consequently play a pivotal role in memorising and learning.

Environmental factors (noise, ventilation, etc.) and physiological factors (diet, exercise, sleep, etc.) influence learning. In the short run, advances in this area should lead to concrete applications in terms of school and educationally-related practices.

Representations

Human beings are constantly perceiving, processing and integrating information, *i.e.* they learn. Individuals have their own representations, which gradually build up on the basis of their experience. This organised system translates the outside world into an individual perception. An individual's system of representation governs his/her thinking processes.

Since Plato's Cave, philosophy has pondered the question of representations. Evidently, the objective here is not to respond to the eternal questions of humanity, although it is not impossible that one day our knowledge of brain functioning is such that it will bring about new elements to these eternal philosophical debates.

Skills

The term "skills" is frequently used in English when behaviour and learning are being discussed. A given behaviour can be broken down into skills, understood as the "natural units" of behaviour.

Language, for instance, can be broken down into four "meta-skills" according to transmission or reception and the means of communication. These meta-skills are oral understanding, oral production, reading and writing. Each of these meta-skills in turn can be further broken down into more distinct skills. Oral understanding, for example, consists of some ten skills, which include short term memorisation of series of sounds, discrimination of a given language's distinctive sounds, and distinction of words and identification of grammatical categories.

Each skill corresponds to a specific class of activities. This raises questions about evaluating individual progress and the distinction between skills and knowledge. What do we expect of children? Skills or knowledge? What do we want to "measure" when we test children?

Team and social interactions

Social interactions catalyse learning. Without this sort of interaction, an individual can neither learn nor properly develop. When confronting a social context an individual's learning improves in relation to the wealth and variety of that context.

Discovery triggers the processes of using and building knowledge and skills. Dealing with others enables individuals to develop strategies and refine their reasoning. This is why social interaction is a constituent condition both for early development of cerebral structures and for the normal development of cognitive functions (see Chapter 3).

What place do schools leave for interaction between learners? The appearance of new technologies in the educational sector has had far-reaching repercussions on interactivity in learning situations. What will be the impact of these changes on learning itself?

These questions are being addressed by the rapidly emerging field of social neuroscience, which deals with social processes and behaviour.

Universality

Numerous features characterise the human kind, the development of the brain being one of them. It follows a programme recorded in the genetic heritage of each individual, and is programmed as part of a "ballet" where perfectly regulated genes are constantly nourished by experience.

One of the intrinsic properties of the brain is its plasticity (see Chapter 2). The brain continually perceives, processes and integrates information derived from personal experience, and therefore undergoes changes in the physical connections within its networks of neurons. This continual development is the result of the brain's normal operation and implies a permanent learning capacity. This means that development is a constant and universal feature of cerebral activity and that a human being can learn throughout the lifespan.

"*Everyone has the right to education*" *(Universal Declaration of Human Rights, United Nations, 10 December 1948, Article 26). Education regulates learning so that everyone has access to the fundamentals of reading, writing and arithmetic (see Chapters 4 and 5).*

International evaluations are performed to check the equality and durability of the various educational systems. Although it is difficult to "measure" acquired knowledge across cultural borderlines, such evaluations heighten awareness of the need for constant improvement in education.

Variability

Experience plays a fundamental role in individual development and the make-up of a human being, but it remains personal and subjective. Representations resulting from experience are consequently different from one person to another. Experience also plays a major role in building preferential styles, leading the learner to use particular learning strategies according to the situation.

Specific learning causes changes – transitions from one state to another. Yet, the diversity of personal experience and representations implies different conditions at the outset for each person. In addition, modifications resulting from learning vary according to learning motivations, interactions and strategies. This is why the impact of instruction differs from one person to another, and why we speak of variability.

Students in the same class, taking the same course will not learn the same things. Their representations of the concepts presented will vary as they do not all start with the same basic knowledge nor the same mode of learning. The result is that their representations will not develop in the same manner. They will all maintain traces of this learning experience, but these traces will be different and specific to each individual.

Learning experiences need to take into account individual differences, so that diversification of the curriculum to accommodate them is an increasingly important educational goal.

The question of cortical differences between men and women is frequently raised. As yet, neuroscientific data neither confirm nor disprove this conjecture.

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Work

A lot of work has been done and a major task has been achieved in recent years to develop educational neuroscience, and this is helping give birth to a still larger, trans-disciplinary learning science (see Chapter 7). These achievements will seem small, however, in comparison with what is still to come from those who follow us into this field. One can hope that they will meet fewer barriers, especially as they will have to deal with a much larger knowledge base. For it happens that…

… XYZ

… the story is far from ended. This CERI project is merely the beginning of an adventure and it is now up to others to take up the baton. Many have already engaged on such ways (see Chapter 7). There is much more than these three remaining letters to write into our brain alphabet. Our knowledge of the brain is like the brain itself: a continual evolution…