# NEUROSCIENCE AND EDUCATION

## LOOKING OUT FOR THE FUTURE OF LEARNING


**ANA LUIZA NEIVA AMARAL**
**LEONOR BEZERRA GUERRA**



SESI
Brazilian Social Service for Industry
THE FUTURE OF WORKFORCE

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# FOREWORD

The capacity to learn across the lifespan is growing in importance to become a fundamental resource in the 21st century. As a result of the fast-paced changes brought about by the digital economy, modern society requires new approaches to evidence-based, innovative teaching and learning processes. Neuroscience research has taken long strides in understanding how the brain learns. But to build the necessary bridge between Science and Education, this knowledge needs systematizing and communication.

Bringing discoveries in neuroscience to the educational context is a fundamental step for teachers to innovate in pedagogical strategies and for students to choose more effective study practices. In addition, this step allows parents to offer more conducive learning contexts and leaders to use scientific evidence to ground public policies that effectively impact school performance.

This context enabled the Industrial Social Service (*Serviço Social da Indústria - SESI*) to present this study – born out of a dialogue between a neuroscientist and an educator. The document showcases 12 principles in neuroscience related to learning and 22 trends shaping the future of education. The study provides critical insights in accessible language to build an educational trajectory more aligned with forming people that can tackle enormous challenges - both present and future.

Enjoy your reading.

**Robson Braga de Andrade**
CNI President
SESI National Department Director

# PROLOGUE

Brazil has historical challenges to face in the educational arena. That is why the dialogue between scientific research and the classroom has to be a national cornerstone. This book brings fundamental reflections to advance the quality of education based on scientific evidence. In accessible language and infographics, central paths to a more effective pedagogical practice are mapped out.

Based on the review of 840 studies and research developed in Brazil and 50 other countries, the authors present crucial discoveries in Neuroscience related to learning. They also make clear how teachers can put this scientific evidence into action in the classroom. Readers are invited to rethink the purposes of education in a world revamped by artificial intelligence and loaded with challenges. In the last chapter, 22 trends lay out the future of education around the world with innovations in all dimensions of the teaching and learning process.

Education needs innovation. Despite the achievements observed in recent decades, the current Brazilian educational framework is fraught with weaknesses showing that the country is far from providing the desirable learning patterns for the population.

In 2019, 69% of students who started elementary school completed high school. However, a third dropped out. Besides attendance, Brazil lacks effectiveness in learning outcomes. Data from the National Basic Education Assessment System (T.N.) indicates that, in the last 20 years, the country has kept low learning indexes, with 1 out of 10 students completing high school with adequate learning scores in mathematics.

Brazil's failures in the educational field have resulted in a waste of talent and resources. This created a major social national problem with around 12 million young people, between 15 and 29 years old, not in education, employment, or training.

Besides such challenges, the authors highlight a feature in need of change. Several of the nation's educational systems still favor passive-reproductive methodologies where students merely repeat information. That goes against the principles of Educational Neuroscience explained throughout the book.

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Translator's Note: It stands for Saeb, the Brazilian Portuguese acronym for *Sistema de Avaliação da Educação Básica.*

For Brazil to find new paths for evidence-based education, we must foster a dialogue between researchers, educators, and public education leaders. Further, teachers must have the necessary knowledge to redesign pedagogical practice in the 21st century. This need gets addressed in this book.

With the covid-19 pandemic, Brazil is experiencing an unprecedented crisis in education. Such a scenario requires immediate action to mitigate and reverse the literacy delay and learning losses. The country needs to invest in effective teaching strategies aligned with cutting-edge scientific research for better results in education.

In essence, a country's social and economic development involves a solid education system with universal access attuned to the advances in society, science, and technology. There is no time to waste. We need to make change happen.

**Rafael Lucchesi**
Education and Technology Director for *CNI*
Director-Superintendent for *SESI*

# AUTHOR INFORMATION

## ANA LUIZA NEIVA AMARAL

A teacher with a psychopedagogy specialization, Ana has a Masters' and Ph.D. in Education from the University of Brasília (UnB) with over 30 years of experience in Education. Ana currently coordinates education studies and research at the Industrial Social Service (SESI). She is the author of "*Mapa da evolução da aprendizagem no Brasil*" ("*Map of learning evolution in Brazil*") and coauthor of "*A complexidade da aprendizagem: destaque ao Ensino Superior*" ("*The complexity of learning: an emphasis on higher Education*").

## LEONOR BEZERRA GUERRA

A medical doctor and neuropsychologist with a Masters' in Physiology and a Ph.D. in Cellular Biology from the Federal University of Minas Gerais (UFMG), Leonor is the Neuroanatomy professor at the Department of Morphology and at the Graduate Program in Neurosciences at the Biological Sciences Institute at UFMG. She was the former coordinator of the *NeuroEduca* Extension Program, a pioneer program for teacher formation in Neurosciences. Author of "*Neurociência e Educação: como o cérebro aprende*" ("*Neuroscience and Education: how the brain learns*").

# INTRODUCTION

The brain is not ready at birth. As part of the human species, we need social interaction to learn and develop. Across development, even counting on 86 billion neurons[1], it is the quality of our experiences and our learning that impacts brain architecture and function. The problem lies in the absence of a manual at birth for how to use our brains, a guide on how to learn or leverage our learning processes. Therefore, students, parents, teachers, and leaders do not count on a compass that points north, that is, to the best pathways for meaningful and wholesome learning. Against this backdrop, a major challenge in Educational Neuroscience is translating discoveries from the laboratory into principles and practical guidelines. This could steer the daily work of teachers and undergird public policies.

Research in modern Neuroscience started in the late 19th century. However, in the last three decades, novel and powerful neuroimaging techniques for brain analyses brought a noticeable acceleration in research to shed light on neural networks for learning. Today, new imaging techniques enable measuring brain activity for people in motion. Such advances gave scientists leeway to investigate the brain in real-time and gather information on students' brain functioning as learning unravels. For Education, that means research is no longer constrained to the laboratory. It can happen in classrooms while real students interacting and experiencing authentic learning situations.

Neuroscience today can make use of a robust evidence base to contribute to education. The findings highlight how adequate educational support may lead to positive brain – and mind – changes. However, the dialogue between neuroscience and education has not always been fruitful. As so often happens, scientific evidence is hard to interpret and does not connect straight to the classroom routine. Nevertheless, moving forward with research on how the brain learns is only part of the equation. The rest lies in furnishing teachers with the necessary knowledge to redesign pedagogical practices for the 21st century.

1 The number of neurons in several structures of the nervous system has been under investigation for long time. Most recent data show that the encephalon - formed by the cerebrum, cerebellum, and brain stem - has around 86 billion neurons.
Herculano-Houzel, S. (2009). The human brain in numbers: a linearly scaled-up primate brain.
Azevedo, F. A. *et al.* (2009). Equal numbers of neuronal and nonneuronal cells make the human brain an isometrically scaled-up primate brain.
von Bartheld, C. S. *et al.* (2016). The search for true numbers of neurons and glial cells in the human brain: A review of 150 years of cell counting.

The current educational design does not foster learning, and it often goes against what neuroscience has unraveled. This makes learning more difficult for students. Many learning systems have not succeeded in moving past encyclopedic teaching focused on information reproduction and lacking in personalization and emotional connectivity. Therefore, there is a misstep between what school offers and what students and society expect, thus revealing a growing discontent and disenchantment with academic activities.

The socioeconomic cost of an educational system that does not foster learning nor safeguards the cognitive-emotional cornerstones for lifelong learning is very high. It is time to rethink our goals for education in this new world shaped by artificial intelligence and full of challenges and ethical dilemmas. Such transformation requires reflecting on new parameters to form children and youngsters ready to deal with the complex situations and constant metamorphosis of modern society. Current times request people who are in charge of their learning and make the necessary changes for better living.

This is the backdrop for the present study which was born out of a dialog between a neuroscientist and an educator. It presents 12 principles in neuroscience that can contribute to base innovative teaching that fosters learning. Each principle has two parts. In the first part, we explain the results of a body of recent research that undergirds each neuroscientific principle. In the second part – *Transforming the principle into action* – we present examples and suggestions to translate each principle into pedagogical practice. The last chapter offers a historical review of education with an analysis of the current educational scenario to reveal 22 emerging trends that run in tandem with discoveries in neuroscience.

To substantiate this outline, we have performed a major literature review – both in Brazilian and international sources – comprising 840 studies and research papers from 51 countries. The international scope reveals that the movement initiated in the USA defining the 1990s as the Decade of the Brain has spread throughout the globe and ignited a scientific revolution in a mounting multidisciplinary endeavor.

We organized chapters to offer the reader a growing understanding of many concepts that integrate neuroscience and education. After presenting the methodology, chapter two defines and provides a historical context for neuroscience. In chapter three we make clear the bridge between neuroscience and education. In chapter four, we define learning and specify human brain development. In chapter five, we explain how the brain processes learning together with the main mental functions involved. In chapter six, we present 12 neuroscience principles that contribute to effective learning when applied in educational settings. Lastly, in chapter seven we highlight emerging trends for the future of education. In the end, references are listed by chapter, and a glossary presents definitions of main concepts in neuroscience highlighted in bold the first time they appear in each chapter and subchapter.

Neuroscience is gaining importance and interest in education. A growing number of publications integrating neuroscience, learning, and education testifies to that. Thus, we do not aim to cover all the principles and their unfoldings in the educational process. We aim to present the central findings in neuroscience related to the learning process and to motivate teachers for an ongoing formation in this area, thus spurring them to rethink and rebuild classroom practices. Thus, the present study is a spark to ignite teachers and leaders in pursuit of neuroscientific evidence for meaningful learning that mobilizes the infinite potential of each learner.

# 1 METHODOLOGY

We developed the study based on a vast literature review, both in Brazilian and International sources, via bibliographic search in these data banks: Coordination for the Improvement of Higher Education Personnel (*CAPES*), Google Scholar, Scientific Electronic Library Online (SciELO), and Pubmed (U.S. National Library of Medicine). In prioritizing the most recent publications made available from 2010 to 2020, we selected original and review papers, books, book chapters, and theses. In addition, we consulted the works of renowned authors in neuroscience, education, and educational neuroscience and studies by national and international organizations.

Studies and research papers selected in a six-step literature review included the themes presented below. In each step, we used specific descriptors in several combinations.

1) **Neuroscience:** introduction to neuroscience through a brief background.
**Descriptors:** *neuroscience, history of neuroscience, decade of the brain, brain, organization, structure, function, neuroanatomy.*
2) **Neuroscience and Education:** panorama on the relationship between their epistemologies.
**Descriptors:** *neuroscience, education, brain, learning, educational neuroscience, science of learning, brain-based learning.*
3) **The neurobiological and neuropsychological basis for learning**: brain development and functioning, and mental functions involved in learning.
**Descriptors:** *learning, brain, learning brain, brain development, cognitive function, cognitive neuroscience, cognitive development, attention, memory, emotion, motivation, executive function.*
4) **Definition of neuroscientific principles:** identification of topics and principles in neuroscience regarded as relevant for the learning process.
**Descriptors:** *neuroscience, learning, brain, cognitive function, cognitive neuroscience, science of learning, brain-based learning, educational neuroscience, principles, classroom, education, academic achievement, academic performance, implications, strategies.*

5) **Principle explanation:** brain functioning and relationship with learning and principle application in pedagogical practice.
   **Descriptors:** vary according to the principle. For example, in searching for the principle "the brain does not multitask", we used the following descriptors: *human, brain, neuroscience, learning, attention, multitasking, neuroimage, neural correlates, brain basis, teaching, academic performance, academic achievement, classroom, school*.
6) **Future of education:** emerging trends that are delineating education in the 21$^{st}$ century.
   **Descriptors:** *future of education, learning in the 21$^{st}$ century, innovative pedagogy, creative learning, educational technology, personalized teaching, digital literacy, deep reading, assessment, curriculum, soft skills, school of the future*.

The literature review yielded identification and analyses of 840 studies and research papers conducted in 51 countries: Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Colombia, Cuba, Cyprus, Denmark, Ecuador, England, Finland, France, Germany, Greece, Hong Kong, India, Iran, Ireland, Israel, Italy, Japan, Kuwait, Luxembourg, Malaysia, Mexico, Netherlands, New Zealand, Norway, Oman, Peru, Philippines, Poland, Portugal, Russia, Scotland, Singapore, Slovenia, South Africa, South Korea, Spain, Sweden, Switzerland, Turkey, United Arab Emirates, United States of America, Uruguay, and Vietnam.

# 2 WHAT IS NEUROSCIENCE?

*This chapter makes clear what neuroscience is and why this knowledge field has gained so much importance since the last decade of the 20th century.*

Neuroscience or neurosciences is an umbrella term coined – to the best of our knowledge – by Ralph Waldo Gerard, an American neurophysiologist from the University of Chicago in the 1950s. However, it was Francis Otto Schmitt, biophysicist, chief at the Biology Department at the Massachusetts Institute of Technology (MIT) that made the term famous in the 1960s[2]. He used the term 'neuroscience' to refer to an interdisciplinary knowledge field that studies the **nervous system.**

In 1962, Schmitt oversaw the creation of a Neurosciences Research Program (NRP) that gathered scientists from the USA and other countries with different backgrounds but interested in understanding how the **brain** controls behavior in general and the human mind, specifically. They regarded that understanding how the brain and mind worked was beyond the grasp of an individual or a group of researchers. To that effect, a joint effort from professionals from different knowledge areas would be necessary to explain mechanisms underlying learning, memory, motion control, emotional regulation, and other aspects of human behavior. Hence, theories for multilayered brain functioning - from molecules to behavior - could be formed by gathering specialists in different areas such as neuroanatomists, cytologists, physicists, neurochemists, physiologists, zoologists, pharmacologists, neurologists, psychologists. Researchers involved in the program regarded that only with such an interdisciplinary approach[3] to study the universe's most complex structure, significant knowledge breakthroughs in mind and behavior would be possible.

In 1963 the Neurosciences Research Program Bulletin, the official NRP journal, used the term 'neuroscience' and 'neuroscientists' to refer to researchers of different aspects of the nervous system. They organized scientific meetings to discuss important themes about the nervous system and published - journal aside - many books over the following 20 years. Their initiative contributed to establishing a new knowledge field that spurred other research groups: first in Germany, then in Russia and England[4], and in other countries.

2 Adelman, G. (2010). The Neurosciences Research Program at MIT and the beginning of the modern field of Neuroscience.
3 Sabbatini, R. M. E., & Cardoso, S. H. (2002). Interdisciplinarity in the neurosciences.
4 Rose, S. (2015). The art of medicine: 50 years of neuroscience.

This resulted in the pollination of neuroscientific research that attracted general public interest for brain, mind, and behavior. This interdisciplinarity, which proved essential to advance research in brain and mind, has been coined Network Neuroscience[5].

*Neuroscience, also known as Neurosciences, is an interdisciplinary area of knowledge that studies the brain, the mind, and human behavior. It draws together many subareas or knowledge fields whose scope is to investigate the nervous system.*

## 2.1 BRIEF HISTORY OF NEUROSCIENCE

Although neuroscience as an interdisciplinary knowledge area came about in the 1960s, both interest in the brain and the idea that behavior and **mental functions** were interrelated dated from much earlier[6].

The observation that brain traumas caused behavioral and perceptual alterations with loss of consciousness and memory has probably contributed to associations between brain and mind activity. Evidence for that dates back ages. Palaeontologic findings of prehistorical skulls with perforations made in life, also known as trepanations dating more than 10.000 years ago, showed that cavemen messed with the brain, mainly thinking that they could pull evil spirits away from the suffering body[7]. In ancient civilizations in Egypt, India, China, and Greece, the notion that our heart controlled mental processes was prevalent[8]. This idea still lingers in common-sense observations when we say that we know something 'by heart' for something stored in our memories. Such association, made long ago, is probably due to a faster, stronger heartbeat when expressing emotions. It happens as the **sympathetic autonomic nervous system,** part of the nervous system, takes over during emotion expression and acts on the heart, increasing heart rate and its force of contraction. A further example is the verb 'record' derived from the Latin *recordis* to mean reflowing through the heart. Despite neuroscientific evidence that the seat of emotional processing lies in the brain – not the heart – such expressions reveal the intrinsic relationship between memory and emotions. We will go over that in depth in chapter five.

5 Bassett, D., & Sporns, O. (2017). Network neuroscience.
6 Finger, S. (2001). *Origins of Neuroscience: A history of explorations into brain function.*
7 Cosenza, R. M. (2002). Espíritos, cérebros e mentes. A evolução histórica dos conceitos sobre a mente.
8 Castro, F. S., & Landeira-Fernandez, J. (2010). Alma, mente e cérebro na pré-história e nas primeiras civilizações humanas.

Over time, evidence of the brain as the fundamental seat for mental functions began to surface. The Edwin Smith papyrus, written around 1700 BCE (T.N.) and attributed to the Egyptian physician Imhotep, brings clinical brain and **spinal cord** injury accounts, relating lesions associated with motor and language alterations, loss of urinary control, and others[9]. As far as we know, this is the first account with descriptions of some nervous system structures and their association with other bodily functions.

In western culture, Alcmaeon of Crotona, Greece (500 BCE) was the first to relate the brain to mental functioning while dissecting some **nerves** – optic nerves included. He discovered that some sensory pathways ended in the brain. In his view, the different nerves transmitted information to the brain where each sensory modality had its neural territory.

Also in ancient Greece, Hippocrates (460-379 BCE) already believed that the brain was the seat for the mind. Plato (428-348 BCE) also regarded the brain as the seat for mental processes and responsible for controlling bodily functions. Aristotle (384-322 BCE) wrote about sleep but stood against his counterparts as he regarded the heart as the organ for emotions. Herophilus (335-280 BCE) dissected the **brain ventricles** and suggested that human intelligence sat in these cavities[10]. In ancient times, studying the brain and other structures within the skull – together known as the **encephalon** – was very hard as there was no tissue fixation. Without fixation, this structure presents a gelatinous consistency and easily deforms when manipulated. This might explain the interest some philosophers and physicians had in brain ventricles as the seat of the mind, according to Galeno (130-200).

From Renascence on, ideas about how the brain works and how it relates to mind and behavior got revisited by several scholars. Some ideas were, at given points, very different from what we know today[11]. These contributions – cornerstones in the history of neuroscience – can be accessed by an interesting timeline, the Milestones in Neuroscience Research[12], organized by the University of Washington in Seattle (USA). Even so, they represent a fraction of the dedication countless scholars have given to studying the nervous system across time[13].

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*Translator's Note: BCE stands for before the common (or current) era and has been widely adopted in academia for its non-partisan status.*

9 van Middendorp, J. J. *et al.* (2010). The Edwin Smith papyrus: A clinical reappraisal of the oldest known document on spinal injuries. Stiefel, M. *et al.* (2006). The Edwin Smith papyrus: The birth of analytical thinking in medicine and otolaryngology.

10 Cosenza, R. M. (2002). Espíritos, cérebros e mentes. A evolução histórica dos conceitos sobre a mente.

11 Brown, R. E. (2019). Why study the history of Neuroscience?

12 Milestones in Neuroscience Research: https://faculty.washington.edu/chudler/hist.html.

13 Finger, S. (1994). *Origins of Neuroscience: A history of explorations into brain function.*

The development of histological techniques for nervous tissue fixing and staining at the end of the 19th century was a milestone for modern neuroscience as it enabled visualization and the resulting study of **neurons** – what became known as the **neuron doctrine**[14]. From then on, meaningful discoveries related to structural and functional aspects of the nervous system opened up research avenues for what we currently know in neuroscience.

Thereby, we know that the nervous system is composed of billions of neurons and **glial cells**, organized in many structures that are visible to the naked eye, such as nerves, spinal cord, **brain stem**, **cerebellum**, and the brain[15]. In each structure, different **neural circuits**, taken as groups of neurons interconnected by structures called **synapses** and glial cells, which are fundamental for the survival and functioning of neurons, can only be observed by using microscopic and electrophysiologic techniques.

Neurons got defined as cells with extensions – **axons** and **dendrites** – that get connected to other neurons through synapses. Neurons also connect with **sensory receptors**, skeletal muscles, glands, and other organs in the human body through nerves.

Neurons got to be known as cells that process and transmit information through electrochemical signaling. In other words, neurons are excitable cells that alter their chemical and electrical state when they are in contact with some form of energy in the environment, termed stimuli. Such stimuli can be electromagnetic (light), mechanical waves (sound), chemical (smell or taste), thermal (hot or cold), and mechanical (pressure, vibration, or touch). When stimuli reach the nerve cells, they cause alterations in the molecules of the cell membrane. This leads to a change in the chemical and electrical state of the neuron – termed **nerve impulse**. Some studies have shown that the nerve impulse generated by one neuron may be transmitted to another neuron by chemical substances – the **neurotransmitters** – at their connection site, the synapses.

In this fashion, we understood how the nervous system can record – by neuron activation – all the interactions one has with the environment. This neural activity generates mental functions and behaviors. Once activated, neurons can act on many body muscles and organs through the nerves. When this happens, there is movement, increased heart rate, bowel movement, hormone secretion, speech production, and other functions related to each structure regulated by the nervous system.

14 Yuste, R. (2015). From the neuron doctrine to neural networks.
15 Lent, R. (2010). *Cem bilhões de neurônios? Conceitos fundamentais de neurociência.*

We know that the nervous system receives and processes daily incoming stimuli via sensory organs – sound, images, smells, tastes, and tactile, thermal, visceral, proprioceptive and vestibule sensations – generating responses expressed by adaptive behaviors. These improve one's odds of survival and preservation. However, our nervous system also enables us to create and transform our surroundings. It is a very creative ability that explains humankind's fantastic evolution across time[16]. This adaptative and creative interaction with the world, nature, objects, people, and culture is essential for the developmental and learning processes[17] (T.N.).

Thus, all human behavior and mental function emerge from nervous system activity, chemical and electrical phenomena in diverse neuron populations forming **neural networks**. Functions related to cognition and emotions that are part of our everyday lives and social relationships – like teaching and learning; feeling and noticing; crying and laughing; sleeping and dreaming; wishing and getting frustrated; breathing and eating; speaking and moving; understanding, reasoning, and calculating; paying attention, remembering and forgetting; planning, judging and deciding; thinking and imagining; getting emotional, loving and taking care – are all behaviors that rely on the integrated workings of different structures in the nervous system, especially the brain.

*The mind is the brain at work. The constant interaction between the nervous system and the environment we live in determines who we are, what we think and do. Interacting with the world, nature, objects, people, and culture is essential for human adaptation and creation.*

Neuroscientists research the nervous system to understand how the 86 billion neurons enable motion, sleep, dreams, feelings, memory, attention, emotions, thoughts, decisions, and consciousness, among other aspects of the human mind and behavior. Likewise, they investigate what happens when the nervous system suffers alterations, such as paralysis, sensory or cognitive impairments, altered states of consciousness, mood and emotional changes related to neurological, neurodegenerative, psychiatric, and neurodevelopmental disorders[18]. Understanding how the nervous system works in physiological and pathological conditions enables interventions that can exponentiate

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16 Fogarty, L. *et al.* (2015). Cultural evolutionary perspectives on creativity and human innovation.

17 Chiao, J. Y. (2018). Developmental aspects in cultural neuroscience.
*Translator's Note: The box containing additional information on this topic in the original version had its content incorporated into the text in the English version for editing purposes.*

18 Thompson, P. M. *et al.* (2020). ENIGMA and global neuroscience: A decade of large-scale studies of the brain in health and disease across more than 40 countries.

mental functioning and, in case of disease, the development of preventive measures, symptom reduction, and even cure in some cases[19].

The 20th century saw great strides and massive breakthroughs in our knowledge about nervous system development, structure, and function in physiological and pathologic conditions. They were made possible by novel research methods and techniques such as data digitalization, electrical brain activity recordings, brain areas visualizations (neuroimaging), molecular biology studies, and interfaces with the nervous systems (neurotechnology). Research on diverse aspects of the nervous system functioning - neuronal action potential, synaptic function, axon growth, sleep and awake states, emotions, language, logical and mathematical reasoning, attention, memory, learning, and stress - enabled a greater understanding of how the brain works. Taken together, they provide an understanding of how we operate[20].

A revision of the localizationist theory of brain function, i.e., each set of neurons in a given brain area has a function – led to what we currently know, that is, brain functioning is based on a connectionist model[21]. In such model, different mental functions relate not only to certain brain circuitry in a certain brain area but also to the integrated activity of neural circuits in different brain areas. Long axon bundles interconnect these areas creating functional neural networks[22]. Distinct neural networks are recruited simultaneously during the expression of behavior. For instance, when students write an essay, they recruit memories, convert their thoughts into words, make the necessary movement for writing, check if their writing is correct, evaluate whether they like the idea on paper, and modify it, if needed. In this process, neural networks related to memory, creativity, motion, vision, attention, performance control, and others spring into action. A network organization causes a brain area to act on the activity of another brain area. This is the reason why a teacher's comment - be it some praise or some information on the time remaining - may come to influence students' essay outcomes. Behavior gets generated by the activity of such neural networks comprising millions of neural circuits essential for information processing, both that stored in the brain and the information students receive at any moment[23].

Until the 1970s, we could only examine the brain by opening up the skull of patients with severe lesions or the deceased. Animal models, whose brains could be examined, were

19 Stein, D.J. *et al.* (2015). Global mental health and neuroscience: Potential synergies.
Erickson, K. I. *et al.* (2014). Health neuroscience: Defining a new field.

20 Lent, R. (2008). *Neurociência da mente e do comportamento.*

21 Mill, R. D. *et al.* (2017). From connectome to cognition: The search for mechanism in human functional brain networks.

22 Herbet, G., & Duffau, H. (2020). Revisiting the functional anatomy of the human brain: Toward a meta-networking theory of cerebral functions.

23 Lent, R. (2019). *O cérebro aprendiz: Neuroplasticidade e educação.*

– and remain so – insufficient for the investigation of the particulars of human behavior. With the development of neuroimaging techniques[24] (computerized tomography, functional magnetic resonance imaging, **tractography**, and **functional near-infrared spectroscopy – fNIRS**) allowed for registering brain activity before, during, and after certain stimuli, thus showing activation and connectivity of regions involved in different tasks. Today, fNIRS technology enables measuring the brain activity of people in motion. Hence, scientists can examine the human brain in real time and store information on students' brain functioning as behavior happens. This means that research for education is no longer constrained to laboratories. It can happen in classrooms with real students interacting and experiencing authentic learning situations.

Advances in neurotechnology[25]made possible a direct connection between technical components and the nervous system. Electrodes, computers, or intelligent prosthetics can record brain signals and translate them into technical command controls or manipulate brain activity by using electrical or optical stimuli. The human-machine interface brought intervention perspectives for diseases causing movement loss such as amyotrophic lateral sclerosis. Neurotechnology also allowed for an investigation of cognitive and emotional processes and enabled interventions for improved mental health and quality of life.

## 2.2 INVESTMENTS AND ADVANCES IN NEUROSCIENCE

The study of the nervous system has attracted huge investments and incentives since the 1990s. Former USA President George Bush's initiative to declare the Decade of the Brain[26] pushed the country to invest large sums in laboratories that investigated the nervous system. This has sped breakthroughs in neuroscience at the end of the 20$^{th}$ century[27] and over the first two decades of the 21$^{st}$ century[28]. The movement rooted in the USA spread over many countries and currently comprises thousands of neuroscientists and billions in investments[29]. This has stirred the current global revolution in an ever-increasing, multidisciplinary, ambitious effort[30].

24 Vasung, L. *et al.* (2019). Exploring early human brain development with structural and physiological neuroimaging.
Annavarapu, R. N. *et al.* (2019). Non-invasive imaging modalities to study neurodegenerative diseases of aging brain.
Balardin, J. B. *et al.* (2017). Imaging brain function with functional near-infrared spectroscopy in unconstrained environments.

25 Müller, O., & Rotter, S. (2017). Neurotechnology: Current developments and ethical issues.

26 Goldstein, M. (1994). Decade of the brain: An agenda for the nineties

27 Tandon, P. N. (2000). The decade of the brain: A brief review.
Volkow, N. D. *et al.* (2010). A decade after the Decade of the Brain.

28 Albus, J. S. *et al.* (2007). A proposal for a decade of the mind initiative.
Abbott, A. (2013). Neuroscience: Solving the brain.

29 Rosso, C. (2018). The funding spree for neuroscience startups.

30 Grillner, S. *et al.* (2016). Worldwide initiatives to advance brain research.
Yeung, A. W. K. *et al.* (2017). The changing landscape of neuroscience research, 2006–2015: A bibliometric study.

In the USA, the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative[31] got support from former President Barack Obama. The initiative encompasses federal agencies, foundations, institutes, universities, and industries. It aims at developing and applying innovative technologies for a dynamic comprehension of brain functioning, catapulting current knowledge about the human brain. The BRAIN supports discoveries related to brain alterations such as Alzheimer's and Parkinson's in depressions and traumatic brain injury.

The Human Connectome Project (HCP)[32] at the National Institutes of Health, in the USA, is building a map of neuronal connections (connectome) that showcases anatomical and functional connectivity of a healthy brain. In addition, it will yield data facilitating research on brain alterations in disorders such as dyslexia, autism, Alzheimer's, and schizophrenia.

In 2013, the European Commission kicked off the Human Brain Project (HBP)[33] via the funding program Future and Emerging Technologies program. HBP is building cutting-edge collaborative translational (scientific) research infrastructure based on information and communication technologies. This project will enable European researchers and technicians to advance their knowledge base in neuroscience, computation, medicine, and technology inspired by brain mechanisms such as artificial intelligence. Their goal is to translate basic research into medical applications for new brain-related diagnostics and therapies.

With incentives of this kind, many research centers for neuroscience development as well as networks among researchers have blossomed in many countries, including Brazil, which counts with 280 neuroscience research communities[34], registered at the National Council for Scientific and Technological Development (*Conselho Nacional de Desenvolvimento Científico e Tecnológico* - CNPq). They are in health and biology, education, modern languages, law, philosophy, anthropology, sociology, arts, communication, administration, architecture, computation, physics, and mathematics.

## 2.3 NEUROSCIENCE AND ITS CONTRIBUTIONS TO OTHER KNOWLEDGE FIELDS

As a result of investments made during the Decade of the Brain (1990-1999), vast scientific dissemination related to neuroscientific discoveries took place and turned this area into a very well-known and accessible knowledge base[35]. Neuroscience departed

31 BRAIN Initiative: https://www.braininitiative.org
32 Human Connectome Project: http://www.humanconnectomeproject.org/about/
33 Human Brain Project: https://www.humanbrainproject.eu/en/
34 CNPq: http://dgp.cnpq.br/dgp/faces/consulta/consulta_parametrizada.jsf
35 Illes, J. *et al.* (2010). Neurotalk: Improving the communication of neuroscience research.

from academic niches and became an all-interest arena for areas that deal with human behavior. It comes as no surprise that people got so interested in the topic. Neuroscience concerns our thoughts, who we are, how we operate, learn, change and live. It helps us understand life a little bit better, why we dream, why we like a place more than others, why we get angry, how we make decisions, how we get frustrated. It gives people the opportunity to know the brain so that they can care for their mental health[36].

Of note, in studying the bases of human behavior, neuroscience can contribute to the understanding of many aspects of other knowledge areas with different epistemologies not traditionally tied to knowing how the nervous system operates. Such areas did not rely on neuroscience for their knowledge base as well-rounded knowledge of the nervous system was not available at the time of their construction. As human behavior got explained, many knowledge fields – whose scope is not the study of the nervous system per se but that rely on human behavior – have come to consider neuroscientific discoveries as a source of scientific evidence for their theory and practice[37]. Some areas that count on neuroscience contributions are education, linguistics, philosophy, music, arts, marketing, economy, sociology, anthropology, law, ethics, to name a few.

By taking neuroscience as a new scientific perspective that constitutes the theoretical bases of other knowledge areas and their praxis, improvements in their knowledge base exponentiate Recovering the thought by E O. Wilson in the book *Consilience* (1998)[38] the knowledge to be developed by the human mind will inevitably spring from the cooperation of natural and human sciences.

Some areas like psychiatry and psychology[39] have already benefited from a greater understanding of the brain, behavior, and mental functions. Other areas have flirted with neuroscience but are yet to take better advantage of the evidence neuroscience can offer. Education is one of them. The next chapter focuses on the dialogue between neuroscience and education.

36 Erickson, K. I. *et al.* (2014). Health neuroscience: Defining a new field.

37 Kedia, G. *et al.* (2017). From the brain to the field: The applications of social neuroscience to economics, health and law.
Churchland, P. S., & Phil, B. (2008). The significance of neuroscience for philosophy.

38 Wilson, E. O. (1998). *Consilience: The unity of knowledge.*

39 Ross, D. A. *et al.* (2017). An integrated neuroscience perspective on formulation and treatment planning for posttraumatic stress disorder: An educational review.
Hyman, S. (2007). Can neuroscience be integrated into the DSM-V?

# 3 WHY NEUROSCIENCE AND EDUCATION?

*This chapter explains why neuroscience became relevant for educators and how it can improve education.*

## 3.1 LEARNING: THE BRIDGE BETWEEN NEUROSCIENCE AND EDUCATION

With 86 billion **neurons**[40], the human **brain** accounts for only 2% of body weight but takes up around 20% of the oxygen we breathe and 25% of the energy available, around 500 kcal/day[41]. By combining 100 trillion connections in infinite ways, the brain can incessantly process a huge amount of incoming information via sensory organs.

Outnumbering stars in our galaxy, brain connections store around 1.000 *terabytes* of information[42]. It is a learning factory for concepts, new ideas, and interpretations that works around the clock. When we are awake, the brain is in full mode but, even at rest, it generates enough energy to light up a 25-watt bulb[43]. This amazing neuronal activity in the distinct structures of the **nervous system**, which get spurred and regulated by the experiences we have, generates what we call the **mind**. It is this brain activity that enables learning. But what is learning from a brain perspective? What happens in the brain when we learn?

40 Herculano-Houzel, S. (2012). The remarkable, yet not extraordinary, human brain as a scaled-up primate brain and its associated cost.

41 Watts, M. E. *et al.* (2018). Brain energy and oxygen metabolism: Emerging role in normal function and disease.

42 Bartol Jr, T. M. *et al.* (2015). Nanoconnectomic upper bound on the variability of synaptic plasticity.
Interlandi, J. (2016). New estimate boosts the human brain's memory capacity 10-fold.

43 Korade, Z., & Mirnics, K. (2014). Programmed to be human?

Learning happens via the reorganization of **synapses**, **neuronal circuits**, and interconnected **neural networks**[44] distributed throughout the brain. This reorganization also encompasses and boosts the development of **mental functions** such as attention, emotion, motivation, memory, language, and logical-mathematical reasoning.

Mental functions get improved by pedagogical strategies used by educators in teaching and learning processes. They lead to nervous system reorganization enabling new knowledge, abilities, and attitudes. This is why the brain is the organ of learning[45].

Every day, educators – parents and teachers – act as agents in the brain changes that lead to learning. They furnish the context, stimuli, social interactions, models, and values that the learning brain processes. Nevertheless, they generally lack knowledge about how the brain works[46]. Thus, the need for a dialogue between neuroscience and education that keeps learning at the core.

To know about: how we learn; how mental functions get involved in learning; how sensitive periods work; how cognition, emotion, motivation, and performance correlate; the potentials and the limitations of the nervous system; learning difficulties; and interventions for remediation can contribute for understanding several issues in schooling[47].

*The brain is the organ of learning. Educational neuroscience provides scientific evidence for how the brain learns effectively and finds a way to apply it in education.*

In this perspective, knowing about neuroscience findings can contribute to all stakeholders in the learning/teaching process. Teachers, for instance, can become more confident, autonomous, and creative in selecting pedagogical strategies. Also, they can better understand their role as learning mediators. This confers a heightened value to their connection with students[48]. Students, on the other hand, can understand

44 Lent, R. (2019). *O cérebro aprendiz: Neuroplasticidade e educação.*

45 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e Educação: Como o cérebro aprende.*

46 Herculano-Houzel, S. (2002). Do you know your brain? A survey on public neuroscience literacy at the closing of the decade of the brain.
Howard-Jones, P. A. (2014). Neuroscience and education: Myths and messages.

47 Blakemore, S.-J., & Frith, U. (2005). The learning brain: Lessons for education: A précis.

48 Ansari, D. *et al.* (2017). Developmental cognitive neuroscience: Implications for teachers' pedagogical knowledge.
Coch, D. (2018). Reflections on neuroscience in teacher education.
Darling-Hammond, L. *et al.* (2020). Implications for educational practice of the science of learning and development.
Schwartz, M. S. *et al.* (2019). Neuroscience knowledge enriches pedagogical choices.

how their brains learn and feel more accountable for their learning[49]. Once aware of this leading role, students can choose more effective study practices that go in tandem with brain functioning. They can also self-regulate their learning and develop metacognition which will lead to learning how to learn[50]. By acknowledging the importance of participation in learners' development, parents can facilitate a conducive context for learning by furnishing opportunities, activities, values, and the necessary support[51]. Public leaders have scientific evidence at their disposal that can support public policy design and implementation. Once they become effective, such policies can lead to better education indicators[52].

Figure 1 displays a synthesis of the relationship between neuroscience and education.

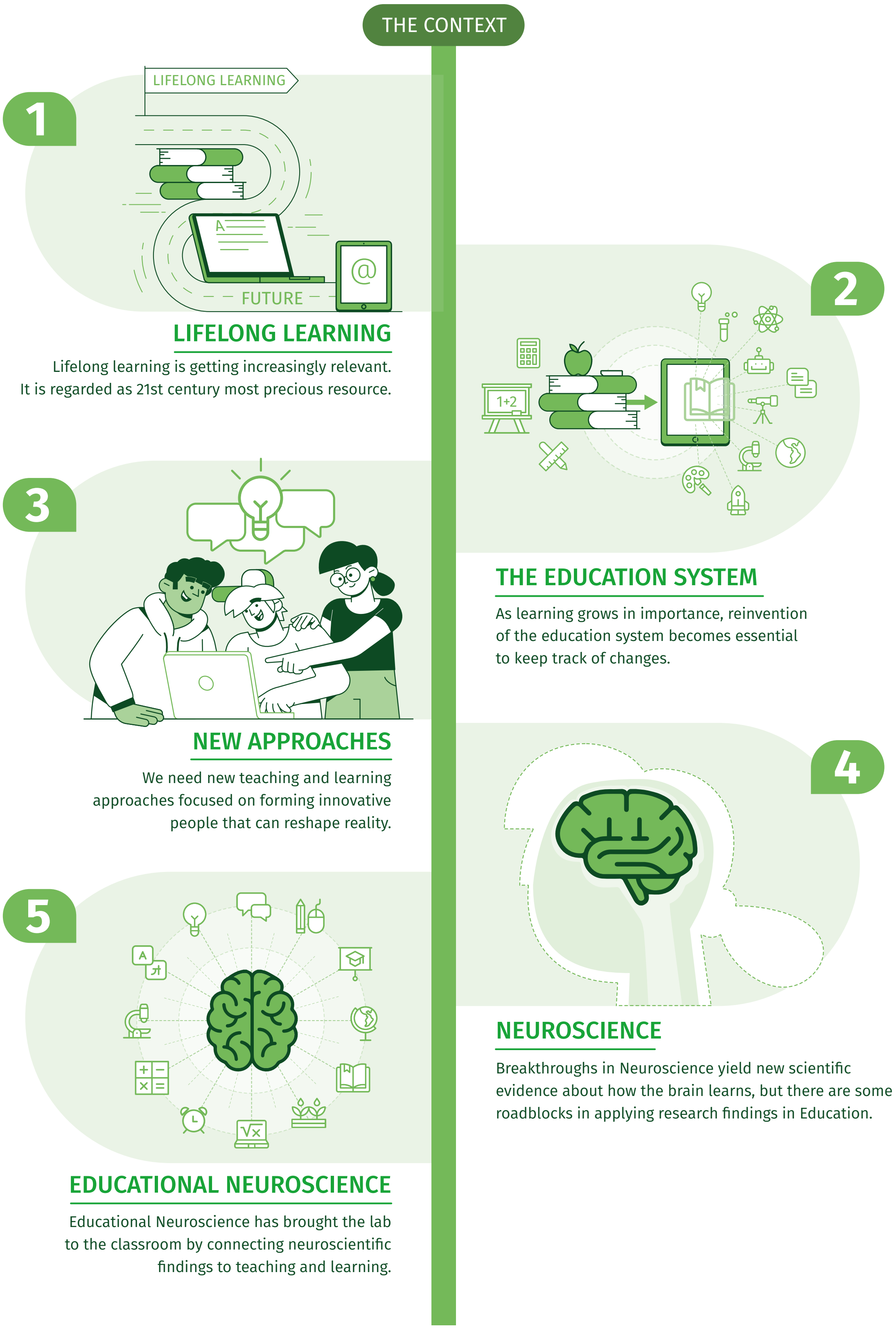
49 Cherrier, S. *et al.* (2020). Impact of a neuroscience intervention (NeuroStratE) on the school performance of high school students: Academic achievement, self-knowledge and autonomy through a metacognitive approach.

50 Castro, C. M. (2015). *Você sabe estudar? Quem sabe, estuda menos e aprende mais.*

51 Jamaludin, A. *et al.* (2019). Educational neuroscience: Bridging theory and practice.

52 Shonkoff, J. P., & Levitt, P. (2010). Neuroscience and the future of early childhood policy: Moving from why to what and how.
Shonkoff, J. P. (2011). Protecting brains, not simply stimulating minds.
Ribeiro, S. *et al.* (2016). Rumo ao cultivo ecológico da mente.

**FIGURE 1 –** When Neuroscience Meets Education



## 6

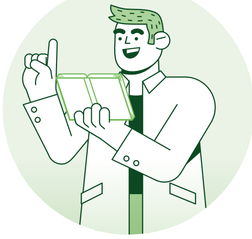
CONTRIBUTIONS FROM EDUCATIONAL NEUROSCIENCE

**EVIDENCE-BASED EDUCATION FOR**

### STUDENTS

Use **study practices** that **boost their learning**.

### TEACHERS



Adopt **innovative, effective pedagogical strategies**.

### LEADERS

Develop **educational management and public policies** for improved results.

### PARENTS

Offer **favorable conditions and interactions** for **children's full development**.

## 7

DIALOGUE AND COLLABORATION

### COMMUNICATION

Communication of scientific evidence in accessible language and through different channels.

### FORMATION

Inclusion of Educational Neuroscience in teachers' initial and ongoing development.

### RESEARCH

Educational Neuroscience researchers' familiarity with educational concepts and practices.

## 8

INVESTMENT

Ongoing investment in cutting edge research to generate new scientific evidence.

## 3.2 FROM THE LABORATORY TO THE CLASSROOM

During the Decade of the Brain, neuroimaging and electrophysiology techniques spurred discoveries in neuroscience that led to considerable progress in cognitive neuroscience – an area that investigates the neural basis of cognitive psychology[53]. Psychological theories about how the mind works relative to attention, memory, emotions, and language got structured based on human behavior analysis. Cognitive neuroscience explores the neural basis for these mental functions. This is done by measuring electrochemical activity in the brain and checking neural activity through neuroimaging. Cognitive neuroscience has explained many aspects of brain functioning related to human behavior[54]. Even though cognitive processing is not entirely clear due to technical and ethical limitations imposed on human behavioral studies, there have been massive advances to vouch for a more neuroscientific approach to teaching and learning[55].

These discoveries have outgrown neuroscientific academic niches and overflown into other areas, like education. Also, through scientific dissemination and considerable media coverage – in sites, digital media, television, newspaper, and books though not always true to what science reveals – neuroscientific advances have reached the great public.

Vast audiences today have both trustworthy and elucidative information as much as wrong inferences and conclusions, also known as 'neuromyths', that lead to practices and applications without an evidence base[56]. For instance, "we only use 10% of our brain" or "the left brain is logical, and the right brain is emotional and creative" or even "listening to Mozart makes us more intelligent"[57]. This last one came about in 1993 after a prominent scientific journal published a study showing that undergrads had a better, yet transitory, performance in spatial reasoning tasks after listening to a Mozart sonata for 10 minutes[58]. Media overblew this finding and cast it as "Mozart music made people more intelligent". The news took a life of its own among the general public and contaminated educational policies in the USA at the time. This led to Mozart recordings being deemed commendable for children's intelligence development. Later, the study got replicated by different research groups, but results differed[59]. That underscores

53 Frank, M. J., & Badre, D. (2015). How cognitive theory guides neuroscience.
54 Lent, R. (2010). *Cem bilhões de neurônios? Conceitos fundamentais de neurociência.*
55 Horvath, J. C. *et al.* (2017). *From the laboratory to the classroom: Translating science of learning for teachers.*
56 Gleichgerrcht, E. *et al.* (2015). Educational neuromyths among teachers in Latin America.
57 Düvel, N. *et al.* (2017). Neuromyths in music education: Prevalence and predictors of misconceptions among teachers and students.
58 Rauscher, F. *et al.* (1993). Music and spatial task performance.
59 Pietschnig, J. *et al.* (2010). Mozart effect–Shmozart effect: A meta-analysis.

the importance of judicious scientific dissemination – without sensationalism – that restrains unwarranted use of scientific knowledge[60].

With the scientific dissemination of neuroscientific findings, teachers, coordinators, school leaders, and parents have taken up the role of agents in the neurobiological changes that lead to learning by acknowledging the brain as the organ of learning[61]. Reflections from this approximation have spurred a relevant question: what is the real contribution that neuroscience, cognitive neuroscience in specific, brings to education? Does knowledge about the brain effectively contribute to teaching and learning processes? Thus, from the late 2000s on, an interface between neuroscience and education became known as Mind, Brain, and Education (MBE),[62] and was highly proclaimed. Since then, the field of educational neuroscience[63] , which covers the same realm as MBE, has dealt with research, topics, and issues related to learning and their possible contributions to education[64].

Between 1999 and 2005, the Organisation for Economic Co-operation and Development (OECD) developed the project *Learning Sciences and Brain Research*[65] and promoted two global forums with a two-fold aim: to analyze the interface between neuroscience and education, and debate issues for investigations of human learning including ascertaining how nature (genes) and nurture (environment, i.e., a safe home and a good school) influence learning success; the crucial importance of the early years for a successful lifelong learning trajectory; age influence on the learning of specific knowledge, abilities, and attitudes; learning differences between young and older people; the meaning of intelligence; how motivation works, and the neuropsychological bases of learning the three Rs (**r**eading, w**r**iting, a**r**ithmetic).

OCDE's initiative spurred scientific investigations to answer those questions. It also generated the publications *Understanding the Brain: towards a new learning science*[66] and *Understanding the brain: the birth of a learning science*[67]. And it has given life to research centers that currently bring together scientists from around the globe for transdisciplinary learning science. The research centers study learning from a triple perspective involving neuroscience, psychology, and education. They establish a translational dialogue between scientists and educators so that research findings can

60 Figdor, C. (2017). (When) is science reporting ethical? The case for recognizing shared epistemic responsibility in science journalism.

61 Ansari, D. (2012). Culture and education: New frontiers in brain plasticity.

62 Fischer, K.W. *et al.* (2007). Why mind, brain, and education? Why now?

63 Szucs, D., & Goswami, U. (2007). Educational neuroscience: Defining a new discipline for the study of mental representations.

64 Owens, M. T., & Tanner, K. D. (2017). Teaching as brain changing: Exploring connections between neuroscience and innovative teaching.

65 OECD (1999). Learning sciences and brain research.

66 OECD (2002). *Understanding the brain: Towards a new learning science.*

67 OECD (2007). *Understanding the brain: The birth of a learning science.*

become practices that improve educational processes and well-being throughout life[68]. Some of these centers are the *Center for Neuroscience in Education*[69], in Cambridge, England; the *International Mind, Brain and Education Society*[70] (IMBES), in Stanford, USA; the *Center for Educational Neuroscience*[71], in London, England; the *Science of Learning Research Centre*[72], connected to Queensland University, in Brisbane, Australia. In Brazil, the National Science Network for Education (*Rede Nacional de Ciência para Educação*[73], *Rede CpE*,), created in 2014, congregates scientists from Brazilian universities for research on different knowledge fields that promote better scientific, evidence-based educational practices and policies[74]. The mission that such institutions hold includes fomenting, making, and disseminating **translational research**[75] in education to bring knowledge from the laboratory to the classroom.

Moving beyond the topics proposed by OECD over 20 years ago, neuroscience has produced research related to different learning areas such as relationships between emotion and cognition[76]; the importance of **executive functions** and metacognition[77] for learning; understanding the **neural networks** for creative thinking[78]and the characteristics of neuronal connections for the different kinds of memory[79]. This set of studies in cognitive neuroscience allowed for principles for learning that impact teaching explored in chapter six.

## 3.3 NEUROSCIENCE IN A DIALOGUE WITH PIAGET, AUSUBEL, VYGOTSKY, DEWEY, AND WALLON

Neuroscientific discoveries have contributed to a group of concepts about the different theories in education and human developmental psychology. Before these advances in neuroscientific research, the only tool available for understanding developmental

68 Fischer, K.W. *et al.* (2010). The future of educational neuroscience.

69 https://www.cne.psychol.cam.ac.uk/

70 https://imbes.org/

71 http://www.educationalneuroscience.org.uk/

72 https://www.slrc.org.au/

73 http://cienciaparaeducacao.org/

74 Lent, R *et al.* (2017). *Ciência para educação: Uma ponte entre dois mundos.*

75 Donoghue, G. M., & Horvath, J. C. (2016). Translating neuroscience, psychology and education: An abstracted conceptual framework for the learning sciences.
Stafford-Brizard, K. B. *et al.* (2017) Building the bridge between science and practice: Essential characteristics of a translational framework.
Dresler, T. *et al.* (2018). A translational framework of educational neuroscience in learning disorders.

76 Dolcos, F. *et al.* (2020). Neural correlates of emotion-attention interactions: From perception, learning, and memory to social cognition, individual differences, and training interventions.

77 Roebers, C. M. (2017). Executive function and metacognition: Towards a unifying framework of cognitive self-regulation.

78 Beaty, R. E. *et al.* (2018). Robust prediction of individual creative ability from brain functional connectivity.

79 Brem, A. K. *et al.* (2013). Learning and memory.

and learning processes was observing children's behavior in interacting with the environment. Systematic observation led Piaget, Ausubel, Vygotsky, Dewey, and Wallon to propose their theories and anticipated ideas about human behavior. Based on the available current knowledge, neuroscience has been revisiting theories with evidence on how the brain operates.

For Piaget[80], our cognitive structures are not mature at birth and undergo construction throughout development in four different stages. In line with Piaget's theory, children and youngsters in school are not at the same cognitive developmental stage, nor learn in the same way or pace. Some studies showed[81] – through electroencephalography (EEG) techniques, for instance – measurements of mental functions in different ages and speed of conduction in **axon** bundles confirming that the brain is indeed not born ready, and changes in interacting with the environment throughout life. These studies confirm variations in brain maturation for same-aged children[82] and that there are cyclical periods of stability in brain structure and function followed by periods of brain restructuring (changes) resulting in better functional performance[83]. Another idea spurred by Piaget is that cognitive conflict is essential for building new knowledge. Neuroscientific evidence shows that cognitive conflict makes the brain adapt its internal mental model[84]. This conflict would change the brain's physical structure and exponentiate learning by imposing new patterns of brain reorganization. Studies[85] in neuroscience align with Piaget's basic ideas and underscore their relevance for reflecting on teaching and learning processes.

For Ausubel[86], learning is meaningful when new information is associated with previous knowledge. Studies[87] demonstrate that new brain connections get organized and reinforced if built upon existing ones. Thus, when one learns new concepts, it is crucial to understand and consolidate information so that it may be later encoded. In addition, the greater the number of mental representations and neural circuits associations, the greater the consolidation of knowledge in long-term memory. This safeguards meaningful and wholesome learning.

80 Piaget, J. (1978). *A formação do símbolo na criança.*

81 Crossland, J. (2015). Is Piaget wrong?

82 Demetriou, A. *et al.* (2013). Cycles in speed-working memory-G relations: Towards a developmental–differential theory of the mind.

83 Fischer, K. W. (2008). *Dynamic cycles of cognitive and brain development: Measuring growth in mind, brain, and education.*

84 Danek, A. H., & Flanagin, V. L. (2019). Cognitive conflict and restructuring: The neural basis of two core components of insight.

85 Arsalidou, M., & Pascual-Leone, J. (2016). Constructivist developmental theory is needed in developmental neuroscience.
Bolton, S., & Hattie, J. (2017). Cognitive and brain development: Executive function, Piaget, and the prefrontal cortex.

86 Ausubel, D. P. (1968). *Educational psychology: A cognitive view.*

87 van Kesteren, M. T. R. *et al.* (2020). Congruency and reactivation aid memory integration through reinstatement of prior knowledge.
Liu, Z.-X. *et al.* (2017). The effect of prior knowledge on post-encoding brain connectivity and its relation to subsequent memory.

For Vygotsky[88], learning is essentially mediated by cultural and social relationships. His ideas about the zone of proximal development (ZPD) and communication as crucial for children's social mind formation got revamped with studies on the connections between the brain and the **cerebellum**. This structure, primarily involved in motor functions, also takes part in mental activity when children improve their ability to deal with new and complex problems when interacting with people and culture[89]. This reinforces the importance of play, teacher-student rapport, and students' classroom interactions for the learning process.

For Dewey[90], learning is more effective when there is an integration of theory and practice. Students should be regularly stimulated with practical activities that favor experience and problem-solving. Neuroscientific research has underscored students' active participation in learning[91]. Findings show that learning is based on experiences that lead to neuronal reorganization and benefits from multisensory experiences. By stimulating different sensory organs – as in a practical situation when one physically interacts with the learning object – several neural circuits get activated and generate a more consistent mental representation of the learning experience. Learning gets a boost when problem-solving situations ignite students' interest.[92] It spurs the recruitment of existing neural circuits and new interactions among them leading to a built-up effect in **neural circuitry** reorganization that consolidates experiences and knowledge in memory.

For Wallon[93], children's development is dependent on internal and external interrelated factors. The development of self-awareness and acknowledgment of boundaries between the self and others happen through social interaction. In such instances, imitation, body awareness, and reciprocal emotions – emotional contagion – are essential for children's mental restructuring. Findings in neuroscience confirm Wallon's propositions. They specified a system of **mirror neurons**, made of neural circuits in the frontal and parietal regions of the brain, involved with the development of self-awareness[94] and with imitation, empathy, and other aspects of social cognition[95]. Besides, proprioception

88 Vygotsky, L. S. (1989). *A formação social da mente.*

89 Vandervert, L. (2017). Vygotsky meets neuroscience: The cerebellum and the rise of culture through play.

90 Dewey, J. (1976). *Experiência e Educação.*

91 Mavilidi, M. F. *et al.* (2018). A narrative review of school-based physical activity for enhancing cognition and learning: The importance of relevancy and integration.
Macedonia, M. (2019). Embodied learning: Why at school the mind needs the body.

92 Murayama, K. (2018). The science of motivation.

93 Wallon, H. (1968). *A psicologia da criança.*

94 Keromnes, G. *et a.l* (2019). Exploring self-consciousness from self- and other-image recognition in the mirror: Concepts and evaluation.

95 Iacoboni, M. (2009). Imitation, empathy, and mirror neurons.
Rizzolatti, G., & Sinigaglia, C. (2016). The mirror mechanism: A basic principle of brain function.
Meltzoff, A. N., & Marshall, P. J. (2018). Human infant imitation as a social survival circuit.

generated via movement also contributes to self-awareness[96]. In Wallon's theory, emotional development precedes cognitive development[97], although both have equal status. Wallon also states that they are indeed indissociable. Neuroimaging[98]has clearly shown the neural basis of such emotion/cognition association such as the reciprocal connections in brain areas that process emotions, working memory, and decision-making.

## 3.4 NEUROSCIENCE AND EDUCATION: THE DIALOGUE GOES ON

Neuroscientists' lack of knowledge – of education's theoretical basis and of how teaching and learning happen in schools – hampers research about real classrooms issues. Likewise, educators' lack of knowledge and experience in neuroscientific research has made it difficult to interpret the meaning and critically analyze data presented by neuroscientists[99].

We need a common language for both areas that makes neuroscientific findings accurately clear for effectual use in education. This demands seriousness and ethical commitment from scientific dissemination channels and critical analysis by target audiences so that this knowledge can become applicable in classroom contexts. Taking into consideration that what teachers 'see' are not activated neurons but behaviors from a learning brain[100], there is no doubt that an interface between neuroscience and education needs to count on psychology. Educational neuroscience may form professionals that can integrate neuroscience, psychology, and education to mediate the dialogue among these fields[101]. Educators trained in elementary neuroscience may contribute to research coordinated by neuroscientists and the adequate application of neuroscientific findings in the classroom, thus promoting collaboration among these areas.

However, to effectively integrate neuroscience and education, a neuroscientific basis for learning processes must be present in educators' initial instruction[102]. Pedagogy undergraduates and students in other licensures need to understand learning from a cognitive neuroscientific perspective. This initiative will contribute to a fresh appraisal

96 Marmeleira, J., & Santos, G. D. (2019). Do not neglect the body and action: The emergence of embodiment approaches to understanding human development.

97 Van der Veer, R. (1996). Henri Wallon's theory of early child development: The role of emotions.

98 Dolcos, F. *et al.* (2011) Neural correlates of emotion–cognition interactions: A review of evidence from brain imaging investigations.

99 Castorina, J. A. (2016). La relación problemática entre neurociencias y educación: Condiciones y análisis crítico.

100 Horvath, J. C., & Donoghue, G. M. (2016). A bridge too far-revisited: Reframing Bruer's neuroeducation argument for modern science of learning practitioners.

101 Zadina, J. N. (2015). The emerging role of educational neuroscience in education reform.

102 Walker, Z. *et al.* (2017). *Brain literacy empowers educators to meet diverse learner needs.*

of learning[103] and novel meanings to social, psychological, cultural, and anthropological aspects traditionally learned by student teachers.

The practicing educator has sought means to get skilled in neuroscience by participating in congresses, courses – graduation certificates included – and accessing different digital media in the hope that such formations may contribute to solving issues at school. Of note, neuroscience does not propose a new pedagogy or magic solutions for learning difficulties. It does explain aspects of the learner's brain functioning that add a fresh perspective to pedagogical practice and give more autonomy and creativity for learning designs. Neuroscience lays the ground for a set of principles that exponentiate learning by attributing meaning to pedagogical practices already in use and by inspiring ideas for other interventions. Some principle-based classroom practices have already been investigated by neuroscience[104] and allow for evidence-based education. Pedagogical strategies that respect how the brain works[105] are likely to be more effective. Neuroscience may give a more scientific approach to teaching and learning, but it is far from being a silver bullet for education problems.

Neuroscience is a natural science that investigates, describes, and interprets data. It uncovers principles for brain structuring and functioning. Thus, it furnishes an understanding of behavioral and mental processes observed. Education has a different nature and scope and cannot be investigated or explained as done with brain functioning[106]. Education is not regulated by physical laws but by complex aspects like teacher formation, school infrastructure, classroom dynamics, teaching methodologies, family support, community participation, and public policy implementation. Accordingly, not all in neuroscience can become pedagogical practices for better results. A learning process is dependent on other influences besides brain function[107]. Knowing how the brain learns is vital, though it cannot safeguard the 'magic of teaching and learning'.

There is a considerable difference between knowing how the brain processes learning and the application of this knowledge. For findings in cognitive neuroscience to be translated into effective pedagogical practices, that is, for an evidence-based education[108],

103 Sokolowski, H. M., & Ansari, D. (2018). Understanding the effects of education through the lens of biology.

104 Weinstein, Y. *et al.* (2018). Teaching the science of learning.
Howard-Jones, P. (2014). *Neuroscience and Education - A review of educational interventions and approaches informed by neuroscience.*

105 Royal Society. (2011). Brain waves module 2: Neuroscience: Implications for education and lifelong learning.

106 Ansari, D., & Coch, D. (2006). Bridges over troubled waters: Education and cognitive neuroscience.

107 Sigman, M. *et al.* (2014). Neuroscience and education: Prime time to build the bridge.

108 Rede Nacional de Ciência para Educação: http://cienciaparaeducacao.org/

a rigorous scientific investigation of findings applicable to classrooms is necessary before any educational applications become the widespread norm[109].

> *The way towards evidence-based education weaves through common ground between researchers, educators and leaders. This is necessary to discuss the science of learning and its political and practical applications, to foster and conduct research on learning and teaching, and to test pedagogical hypotheses via experimentations in educational contexts (Rede CpE)[108].*

Although the dialogue between neuroscience and education has found some resistance[110], recent advances in educational neuroscience[111] have consolidated this knowledge area and attracted researchers and educators. Still, there may be a long way ahead for real impacts on teacher formation, education public policy, curricula, and classroom routines[112].

Knowing how the brain learns is essential for a better understanding of the relationship between neuroscience and education as it allows for neuroscientific contributions to inspire pedagogical practice. In chapter four we explain the importance of learning for human development while in chapter five we explain how the brain processes learning.

109 De Smedt, B. (2018). Applications of cognitive neuroscience in educational research.
Goswami, U. (2015). Neurociencia y Educación: ¿Podemos ir de la investigación básica a su aplicación? Un posible marco de referência desde la investigación en dislexia.

110 Bowers, J. S. (2016). The practical and principled problems with educational neuroscience.
Bowers, J. S. (2016). Psychology, not educational neuroscience, is the way forward for improving educational outcomes for all children. Reply to Gabrieli (2016) and Howard-Jones et al. (2016)
Bruer, J. T. (2016). Neuroeducación: Un panorama desde el puente.

111 Gabrieli, J. D. E. (2016). The promise of educational neuroscience: Comment on Bowers.
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Thomas, M. S. C. *et al.* (2019). Annual Research Review: Educational neuroscience: Progress and prospects.

112 Carew, T. J., & Magsamen, S. H. (2010). Neuroscience and education: An ideal partnership for producing evidence-based solutions to guide 21st century learning.

# 4 LEARNING MAKES US HUMANS

*This chapter presents the definition of learning and explains how the brain develops singularly in human beings.*

Humans are in constant interaction with their environment like all other living beings. This interaction makes them prone to identifying different situations and responding in adaptive, creative ways essential for surviving[113]. Learning is essential in this process as it spurs the development of **mental functions** and the acquisition of new competencies. That is how the learning **brain** gets changed. The capacity to learn grants us knowledge, abilities, and attitudes that transform our lives and the world around us[114]. When we learn how to act within the world, we improve our odds of having a better life and fulfilling our potential.

In general, animals can learn, but their **nervous system** setup, including the lack of language, limits their learning development and transmission at large[115]. Besides, most of their **neural circuits** responsible for survival behaviors are naturally programmed, that is, by the species genetic code that gets organized and ready to function at birth[116]. For instance, some animals do not need to 'learn' to walk – a baby calf can stand on its legs right at birth – while it takes months to happen for human babies. Although the diverse neural circuits needed for a baby to walk were in development throughout gestation, they are not ready to function. For their maturation, environmental stimuli and social interactions are essential. It is thus that a human baby can walk[117].

The human brain is very immature at birth, so babies need extra care and stimuli for longer to develop a more complex neural structure capable of producing behaviors, unlike any other animal. The changes that take place right after birth[118] – **synapse** formation, increase

113 Boyd, R. *et al.* (2011). The cultural niche: Why social learning is essential for human adaptation.

114 Van Schaik, C. P., & Burkart, J. M. (2011). Social learning and evolution: The cultural intelligence hypothesis.

115 Pinker, S., & Bloom, P. (1990). Natural language and natural selection.

116 Xu, X. (2013). Modular genetic control of innate behavior.
Blumberg, M. S. (2017). Development evolving: The origins and meanings of instinct.

117 Adolph, K. E., & Franchak, J. M. (2017). The development of motor behavior.

118 Lenroot, R. K., & Giedd, J. N. (2006). Brain development in children and adolescents: Insights from anatomical magnetic resonance imaging.

in **axonal** and **dendritic processes**, **myelination**, and **glial cells** proliferation[119] – contribute to an increase from around 400 grams at birth to 800 grams in brain weight and size at the end of the first year of life[120] to a total of 1.500 grams at the end of adolescence[121].

We came to a trade-off with nature: our brains are born more immature but with higher development potential when compared to other animals. That is why we need to interact with the world to develop our brains in full[122]. Human behaviors get learned for the most part in contrast with animal behavior. As our genetic code does not grant us immediate adaptation, it is during infancy that we need to 'learn' to walk, eat, speak, and control our sphincters. As we develop, we conquer more complex learning, such as reading, writing, and arithmetic, decision making, and choosing a partner[123].

We come to this world with language-specific brain areas that grant us the ability to speak[124]. However, we only develop these areas when another human being interacts with us[125]. If we learned to talk, it is because someone spoke to us and stimulated our vocabulary development through interaction[126]. Besides, the language that we "learn" to speak does not get determined by our genetic makeup[127]. Although the human brain is born with the capacity to learn any language on the planet, what determined that we speak Portuguese, Mandarin, or German is the place where we were born and the people we relate to[128]. In short, *where, how, and with whom* we learn to speak are determining factors in this process.

Humans do not instinctively know how to make a nest, for instance. Throughout evolution, we needed to learn how to build a home, so our way of living also got changed. The fact that humans needed to learn to adapt safeguarded a historical destiny. Why? As we could not solely rely on our genes, we got the possibility of creating, changing, transforming, and building history, be it in architecture, philosophy, education, science, or technology[129]. This history gets reflected in our culture, habits, and costumes[130].

119 Kolb, B. & Gibb, R. (2011). Brain plasticity and behaviour in the developing brain.
Tierney, A. L., & Nelson III, C. A. (2009). Brain development and the role of experience in the early years.
Jernigan, T. L., & Stiles, J. (2017). Construction of the human forebrain.

120 Holland, D. *et al.* (2014). Structural growth trajectories and rates of change in the first 3 months of infant brain development.
Cao, M. *et al.* (2017). Developmental connectomics from infancy through early childhood.

121 Giedd, J. N., & Rapoport, J. L. (2010). Structural MRI of pediatric brain development: What have we learned and where are we going?

122 Thompson, B. *et al.* (2016). Culture shapes the evolution of cognition.

123 Belsky, J. (2010). *Desenvolvimento humano: Experienciando o ciclo da vida.*

124 Kuhl, P. K. (2010). Brain mechanisms in early language acquisition.

125 Kuhl, P. K. (2011). Early language learning and literacy: Neuroscience implications for education.

126 Friedmann, N., & Rusou, D. (2015). Critical period for first language: The crucial role of language input during the first year of life.

127 Goksan, S. *et al.* (2020). Early childhood bilingualism: Effects on brain structure and function.

128 Li, P., & Jeong, H. (2020). The social brain of language: Grounding second language learning in social interaction.

129 Legare, C. H. (2017). Cumulative cultural learning: Development and diversity.

130 Heyes, C. (2012). Grist and mills: On the cultural origins of cultural learning.

Natural selection made us *Homo sapiens*, but cultural appropriation makes us human through learning habits, costumes, knowledge, and values. When a baby is born, it inherits a 'human genome'[131]. However, it needs to learn and make human learning its own to become a human being. Being human means talking, eating, dressing, living as any other human being. But it also means taking stock of scientific knowledge over time[132]. The possibility to learn and transmit it to the next generation is the ability that singles us out from other animals. That is why we say that learning makes us human[133].

Learning is deeply related to the evolution of the human species[134]. It is an intrinsically human characteristic and essential for our survival[135]. The nervous system, and the brain in specific, have evolved to become specialized in learning[136].

## 4.1 THE BRAIN IS NOT BORN READY

As previously explained, and even considering the intense development that the human brain undergoes during gestation[137], it is not mature at birth. Thus, who we are, what and how we think and do, bears upon the structural and functional organization of the nervous system[138], which gets guided by genetic factors[139] and gets potentially changed by contextual and **epigenetic factors**[140] that lead to **neuroplasticity**[141]. We are not our genes. We are the unique result of the interaction between our genes and environment[142].

Neuroplasticity or neural plasticity[143] means the changing capability of our nervous system. It encompasses connecting and disconnecting **neurons** and results from our constant interaction with our body's internal and external environment. It is a neuronal property essential for memory formation mechanisms, so it constitutes the biological basis for learning[144]. When a **neuron** gets constantly activated, it begins to produce proteins and other substances used in synapses formation or restructuring during sleep

131 Korade, Z., & Mirnics, K. (2014). Programmed to be human?

132 Hogenboom, M. (2015). The traits that make human beings unique.

133 Caldwell, C. A. *et al.* (2018). Human teaching and cumulative cultural evolution.

134 Muthukrishna, M. *et al.* (2018). The cultural brain hypothesis: How culture drives brain expansion, sociality, and life history.

135 Csibra, G., & Gergely, G. (2011). Natural pedagogy as an evolutionary adaptation.
Heyes, C. (2016). Born pupils? Natural pedagogy and cultural pedagogy.

136 Sousa, A. M. M. *et al.* (2017). Evolution of the human nervous system function, structure, and development.

137 Darnell, D., & Gilbert, S. F. (2017). Neuroembriology.

138 Stiles, J. (2017). Principles of brain development.

139 Silbereis, J. C. *et al.* (2016). The cellular and molecular landscapes of the developing human central nervous system.

140 Center on the Developing Child Harvard University e Núcleo Ciência pela Infância. (2010). *O que é epigenética?*

141 Kolb, B. *et al.* (2017). Principles of plasticity in the developing brain.

142 Bateson, P. (2017). Robustness and plasticity in development.
Institute of Medicine & National Research Council. (2015). The interaction of biology and environment.

143 Lent, R. (2019). *O cérebro aprendiz: Neuroplasticidade e educação.*

144 Abraham, W. C. *et al.* (2019). Is plasticity of synapses the mechanism of long-term memory storage?

periods. This process is known as **synaptogenesis**[145]. If the neuron fails to activate, these synapses get undone in what is also known as **synaptic pruning**[146]. It also happens as a natural process preprogrammed by our genetic makeup throughout development, mainly during childhood and adolescence.

Neuroplasticity encompasses the formation of new synapses and an increase in the efficiency of synapses already used[147]. This facilitates information flow in a **neural circuit** or the passing of a **nerve impulse.** It is what happens when we practice a new language, when we study the piano daily or when we apply a mathematical formula in problem-solving.

In addition, neuroplasticity[148] is in charge of connecting previously independent neural circuits. For instance, when a new concept is learned based on previous knowledge, neuroplasticity allows for structural and functional reorganization of neural circuitry from environmental stimuli. Thus, it constitutes an essential biological mechanism for memory formation, learning, and, consequently, acquiring new competencies that lead to new behaviors.

The nervous system is very plastic in the first years of life. That means a large capacity for making and unmaking synapses[149]. It signals that adequate stimuli will more easily lead to neural circuitry reorganization and learning development. But it also means that a lack of such stimuli will also massively impact that capacity[150]. Children that get little or no environmental stimuli, including social interactions[151], may face some learning roadblocks or even not get proper development[152].

## 4.2 BRAIN IN CONSTANT DEVELOPMENT

Throughout nervous system maturation, there is a human-specific chronological pattern for the emergence of several mental functions[153]. This pattern indicates that connections between neurons, myelination of nerve fibers, and neural circuitry organization may depend upon a time frame defined by our genes[154]. There lies the reason for setting

145 Seibt, J., & Frank, M. G. (2019). Primed to sleep: The dynamics of synaptic plasticity across brain states.
146 Sakai, J. (2020). How synaptic pruning shapes neural wiring during development and, possibly, in disease.
147 Baroncelli, L. *et al.* (2010). Nurturing brain plasticity: Impact of environmental enrichment.
148 Voss, P. *et al.* (2017). Dynamic brains and the changing rules of neuroplasticity: Implications for learning and recovery.
149 Graaf-Peters, V. B., & Hadders-Algra, M. (2006). Ontogeny of the human central nervous system: What is happening when?
150 Power, J. D., & Schlaggar, B. L. (2017). Neural plasticity across the lifespan.
151 Lipina, S. J., & Posner, M. I. (2012). The impact of poverty on the development of brain networks.
152 Hair, N. L. *et al.* (2015). Association of child poverty, brain development, and academic achievement.
153 Institute of Medicine & National Research Council. (2015). Child development and early learning.
154 Huang, H. *et al.* (2015). Development of human brain structural networks through infancy and childhood.

development milestones[155], despite individual differences. Children walk unaided between 12 and 15 months old, control their sphincters between 21 and 48 months old, and begin talking around 18 months.

Critical and sensitive periods[156] for brain development mean that nervous system structures are more malleable to specific environmental stimuli and thus get their connections reorganized more easily. In these periods neuroplasticity and myelination get more intense and apt for fulfilling one's learning potential.

Sensitive periods justify easier and faster learning. That is why children learn so easily. However, when we do not carry out activities that involve specific neural circuitry for perception, language, memory, movement, and reasoning, synapses between neurons are lost. It also happens when someone gets deprived of certain environmental stimuli[157]. Therefore, neurons that are not in use undo their connections and may even get eliminated. This can cause delays in the acquisition of motor, cognitive and social skills[158]. However, if there is some missed opportunity during these sensitive periods, it can be partially or fully recovered in the future to the cost of more intense stimulation and more directed interventions[159].

There are two highly important periods in human development[160]. The first happens at birth when there is an adjustment of total neuron count, that gets extended into early years[161] when redundant synapses made during the prenatal period get pruned. This adjustment preserves neurons and synapses that will get effectively used in the circuitry needed for several mental functions. Their specialization happens during the first 5 to 10 years of life[162]. That is why a high number of motor, perceptual, cognitive, and emotional abilities can get developed better until age 10.

The second moment happens during adolescence[163] when the **cerebral cortex** gets thinner due to an accelerated process of synapse elimination. Also, axonal and dendritic extensions become altered in different regions of the cerebral cortex, mainly in the

155 Sheldrick, R. C. *et al.* (2019). Establishing new norms for developmental milestones.
156 Ismail, F. Y. *et al.* (2017). Cerebral plasticity: Windows of opportunity in the developing brain.
157 Inguaggiato, E. *et al.* (2017). Brain plasticity and early development: Implications for early intervention in neurodevelopmental disorders.
158 Löwel, S. *et al.* (2018). Environmental conditions strongly affect brain plasticity.
159 Sale, A. *et al.* (2014). Environment and brain plasticity: Towards an endogenous pharmacotherapy.
160 Stiles, J., & Jernigan, T. L. (2010). The basics of brain development.
161 Gilmore, J. H. *et al.* (2018). Imaging structural and functional brain development in early childhood.
Haartsen, R. *et al.* (2016). Human brain development over the early years.
162 Girault, J. B. *et al.* (2020). Cortical structure and cognition in infants and toddlers.
163 Foulkes, L., & Blakemore, S-J. (2018). Studying individual differences in human adolescent brain development.

prefrontal area - essential for reasoning, planning, and social communication[164]. Besides, there is a considerable increase in white matter relative to the myelination of nerve fibers in neural circuitry. This process makes them more efficient[165]. The adolescent brain increases its capacity to use and elaborate what has already been learned as it presets the individual for adult-life challenges and improves their problem-solving, self-regulation, emotional management, and decision-making abilities[166].

Of note, nervous system plasticity makes children more prone to the epigenetic factors of stressful situations, such as violence and maltreatment, social deprivation, malnutrition, maternal prenatal exposure to drugs, and infections that may influence brain development[167] and, consequently, mental functions[168]. That is why attention and care are fundamental in this stage of our life course[169].

With time, the mechanisms responsible for neuroplasticity demand more time and sensorial input frequency, although it is still functional[170]. Brain structures remain plastic and sensitive to experience even late in life. That means the brain is in constant change throughout our lifespan[171].

## 4.3 SINGULAR BRAIN: THE UNIQUE WAY OF BEING AND LEARNING

Each one of us has a unique nervous system, so a unique brain[172]. There are no two human brains alike. However, we all have neural circuits related to movement, sensations, language, logical reasoning, among other mental functions that follow typical, human-specific patterns[173]. Characteristics of such circuits come preprogrammed in the genetic neuron information and shape the general structure of the nervous system in the mother's womb during embryonic and fetal periods.

164 Blakemore, S-J., & Choudhury, S. (2006). Development of the adolescent brain: Implications for executive function and social cognition.
Dumontheil, I. (2016). Adolescent brain development.

165 Casey, B. J. *et al.* (2008). The adolescent brain.

166 Balvin, N., & Banati, P. (2017). *The adolescent brain: A second window of opportunity: A compendium.*
Griffin, A. (2017). Adolescent neurological development and implications for health and well-being.

167 Gao, W. *et al.* (2019). A review on neuroimaging studies of genetic and environmental influences on early brain development.

168 National Scientific Council on the Developing Child (2010). *Early experiences can alter gene expression and affect long-term development.*

169 Institute of Medicine & National Research Council. (2015). *Transforming the workforce for children birth through age 8: a unifying foundation.*

170 Arcos-Burgos, M. *et al.* (2019). Neural plasticity during aging.

171 Lindenberger, U., & Lövdén, M. (2019). Brain plasticity in human lifespan development: The exploration-selection-refinement model.

172 Wang, D., & Liu, H. (2014). Functional connectivity architecture of the human brain: Not all the same.

173 Johnson, M. H. (2011). Interactive specialization: A domain-general framework for human functional brain development?

When a child is born, this set of circuits is already formed in one's brain, albeit not in full working mode. Besides the genes, what makes each brain unique is that the intricacies of neuronal connections are defined and modified according to one's own life story[174]. This story will make, unmake and continually reorganize the synaptic connections among the billions of neurons in the nervous system.

In the womb, one's ancestors' genetic information influences the developing nervous system. But factors that impact gestation, like nutrition, emotions, infections, and toxic substances also impact this formation. Such combination gives us typical human patterns coupled with an individual's genetic blueprint[175]. Thus, the unique characteristics of each combination are responsible not only for differences in formation, localization, and connections between neurons but also for molecular and biochemical differences. These may affect the production and function of chemicals that act on the nervous, such as **neurotransmitters.**

Because of specific conditions related to gestation, neuroplasticity, and epigenetic factors[176], the nervous system may present changes in localized neural circuits[177] responsible for distinct functions like language, or even circuits responsible for many cognitive functions like the **prefrontal cortex**, the most anterior part of the **frontal lobe**. It is thus that individual differences related to several mental functions[178], like attention, memory, emotional control, **executive functions**[179], motivation, response inhibition, planning, language, spatial perception, and logical reasoning get set. Such differences may become roadblocks or gifts for academic learning, socioemotional behavior, communication, social interactions, and routine activities.

Therefore, the impact of brain differences and consequent behaviors is not bound to academic performance and context; it can affect one's daily life. And this is true for learners in the population average, but also those with neurological disorders (epilepsy, cerebral palsy), learning disorders (dyslexia, dyscalculia), or neuropsychiatric disorders (ADHD, schizophrenia, ASD, Down Syndrome, Williams Syndrome) related to neurodevelopmental alterations[180].

174 Bick, J., & Nelson, C. A. (2017). Early experience and brain development.

175 Charney, E. (2017). Genes, behavior, and behavior genetics.

176 Moore, D. S. (2017). Behavioral epigenetics.
Herzberg, M. P., & Gunnar, M. R. (2020). Early life stress and brain function: Activity and connectivity associated with processing emotion and reward.

177 Brown, T. T. (2017). Individual differences in human brain development.
Mueller, S. *et al.* (2013). Individual variability in functional connectivity architecture of the human brain.

178 Kanai, R., & Rees, G. (2011). The structural basis of interindividual differences in human behaviour and cognition.

179 Blair, C. (2017). Educating executive function.

180 D'Sousa, H., & Karmiloff-Smith, A. (2017). Neurodevelopmental disorders.

Even identical twins[181], that share the same genetic material, present phenotypical differences, that is, differences in how their genes get expressed, as they interact with different environmental and social stimuli. These differences shape brains that respond to stimuli, perceive the world, think and behave distinctively. That is why different brains, or neurodiverse[182] individuals, learn differently.

To say that learners are different means that they learn by different routes. So, the educational process cannot offer a single learning way for all. Diversifying pedagogical practices and resources favors a personalized learning process. This, in turn, lets each one recruit their learning style. Thus, a learner's brain structure can be better used, and competency development exponentiates.

To foster learning, mediators – teachers, family, community – need to set a favorable context[183] where learners with specific needs can develop their potential in school and life. This means fulfilling their learning potential and developing their interests, talents, and abilities.

## 4.4 LIVING IS INTERACTING. INTERACTING TO LEARN. LEARNING TO LIVE

As we have seen, learning makes us human. At birth, we are vulnerable, with no abilities or knowledge. Throughout development, we learn and, according to each one's life story, we become adults and can work as teachers, lawyers, firefighters, astronauts, or any other work we may fathom.

Professional work aside, we learn something when we acquire competencies. They can be about dealing with new situations, solving problems, creating new possibilities, establishing social and emotional connections, and performing daily tasks essential for survival by implementing strategies conducive to better health, well-being, personal and social fulfillment.

181 Gage, F. H., & Muotri, A. R. (2012). What makes each brain unique.
182 Armstrong, T. (2017). Neurodiversity: The future of special education?
183 Black, M. M. *et al.* (2017). Early childhood development coming of age: Science through the life course.

*Learning is the acquisition of new competencies (knowledge, abilities, and attitudes) related to brain changes enacted when learners interact with their environment. It is a process instantiated by the formation and consolidation of neuronal connections resulting from changes in the brain's chemistry and structuring. And it takes time and energy. Therefore, learning equals experience-dependent brain changes.*

Learning is thus a process that happens in the nervous system that relies for the most part on the neural circuits' activity spurred by stimuli that come from interactions between the learner and the environment. In that perspective, learning is an individual process, as it follows one's life story, and a social process as it takes in interactions with the world that steers the development of every single brain.

Among all the basic organizational features of the nervous system[184], perhaps one is more prominent – how a **neuron** changes its electrochemical state when activated by incoming contextual energy modalities via sensory organs carrying information from the world around and within us to the brain. Sounds, images, smells, tastes, vibrations, heat, cold, tactile, and painful sensations produced by physical and chemical environmental elements, by nature, culture, and social relationships are all examples of stimuli. And they activate neurons in the brain. The same goes for information from our bodies, coming from muscles, joints, and organs (heart, lungs, gastrointestinal tract, blood vessels, etc.) that also activate neurons updating the brain on what goes on in the rest of the body[185]. The brain constantly "knows" how our bodies react to the experiences we have.

This incoming external and internal information gets translated into **electrochemical language** by neurons that are sensitive to the stimuli[186]. When a **sensorial neuron** gets activated, it releases neurotransmitters that activate the next neuron to which it is connected (synapse). This second neuron activates another one, and so on until the information gets processed. Neurons transmit a stimulus or information from the sensory organ to the brain, also known as the **sensory pathway** – visual, auditory, olfactory, tactile, gustatory, or **proprioceptive** – that is sense-specific and unique. When information from a given sensory pathway gets to the brain, it initially activates neurons from the brain's primary area. That is where sensation occurs. Then, neurons from brain

184 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e Educação: Como o cérebro aprende.*
185 Lent, R. (2010). *Cem bilhões de neurônios? Conceitos fundamentais de neurociência.*
186 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende.*

regions called secondary are activated. That is where perception occurs, meaning that the different characteristics of that sensorial stimulus get interpreted.

Sensory-specific primary and secondary regions are found in different lobes. They are the **parietal** (tactile, gustatory, proprioceptive), **temporal** (auditory and olfactory), and **occipital** (vision). The sensory information processed in each secondary area gets integrated into the tertiary areas (**temporoparietal and frontal cortices**). It is this integration that gives meaning to sensorial-perceptual experience[187]. Take an apple, for instance. The moment we see it, the **primary visual area** detects the visual stimulus, and neural circuits in the **secondary visual area** perceive the stimulus as round, red, and still. The tertiary area may initially analyze such perceptions as a 'red ball''. The tertiary area must receive the perceived tactile, gustatory, and olfactory information to elaborate a distinct meaning from the initial one when only the visual stimulus was available. It is only in this way, by the integrated processing of distinct information about an object, that the brain can conclude that the "red ball" is an "apple".

Brain areas that make meaning out of incoming stimuli aside, the human brain is well-equipped with neural circuits for recognizing and interpreting social signs such as facial expressions, tones of voice, body, and eye movements. These neural circuits constitute the social brain[188]. It allows us to interpret emotional and mental states and other people's intentions guiding our behavior towards them.

Neural circuits in the social brain[189] specially activated during social interactions are distributed in frontal, prefrontal, parietal, and temporal areas organized in two systems. One is the **mirror neuron system**[190] that activates one's behavior-related areas based on observation of someone else's behavior, thus making it possible for us to understand the goals, intentions, and emotions of someone else[191]. Mirror neurons are involved in learning by imitation[192], in putting oneself in somebody else's place (empathy)[193] and with action coordination during cooperative interactions[194]. The other system in the social brain is the **mentalizing system**[195] recruited for predicting another's future intentions

187 Cao, Y. *et al.* (2019). **Causal inference in the multisensory brain.**

188 Adolphs, R. (2009). The social brain: Neural basis of social knowledge.

189 Vogeley, K. (2017). Two social brains: Neural mechanisms of intersubjectivity.

190 Rizzolatti, G., & Sinigaglia, C. (2016). The mirror mechanism: A basic principle of brain function.
Jeon, H., & Lee, S-H. (2018). From neurons to social beings: Short review of the mirror neuron system research and its socio-psychological and psychiatric implications.

191 Catmur, C., & Heyes, C. (2019). Mirroring 'meaningful' actions: Sensorimotor learning modulates imitation of goal-directed actions.

192 Campbell, M. E. J., & Cunnington, R. (2017). More than an imitation game: Top-down modulation of the human mirror system.

193 Waal, F. B. M., & Preston, S. D. (2017). Mammalian empathy: Behavioural manifestations and neural basis.

194 Endedijk, H.M. *et al.* (2017). Neural mirroring and social interaction: Motor system involvement during action observation relates to early peer cooperation.

195 Luyten, P., & Fonagy, P. (2015). The neurobiology of mentalizing.
Heleven, E., & van Overwalle, F. (2018). The neural basis of representing others' inner states.

and actions independently of actual observation. To that end, we consider what we know about someone, their beliefs, wishes, and knowledge. When interacting socially, participants' clues during this interaction – which are bidirectional, and influenced by the cognitive, affective, and memory states[196] of their coparticipants – activate such systems. In this dynamic and reciprocal process, impressions, opinions, and expectations guide actions from one towards another.

Both the mirror neuron and the mentalizing systems, albeit independently and engaging distinct brain regions, act in tandem when we judge people's mental states, intentions, and ideas[197]. Besides, they both interact with neural circuits that process emotion (**amygdala**, anterior portion of the **cingulate gyrus,** and **insula**) and motivation (**nucleus accumbens**)[198]. It is not pure chance that gets students to enjoy togetherness and yields peer-learning success outcomes. Our mental evaluation processes are dynamic and constantly shaped by self-reflection and external feedback mechanisms – a reciprocal attempt at understanding interacting minds – that get translated into what we call "social cognition"[199].

Varied stimuli, including social relationships, activate neural circuits in an integrated activity which yield **mental representations** of our interactions over our life course[200]. We hold mental representations for every object, person, or situation that we experience[201]. For instance, when we get incoming visual stimuli for a word, we relate the word to meaning. We activate a set of neurons, both for the word's image and meaning, that becomes the mental representation for that word. If the meaning invokes an emotion, neurons processing it will also become part of the mental representation for that word[202]. As each brain is unique, the mental representation for an experience will never be the same for two people. Everyone processes experiences and learns from them according to the mental representations that one's brain holds. They were built by one's genes and by interacting with the environment.

If those mental representations get repeated or become highly relevant for the learner, they get registered in the nervous system in a more definitive form. This representation is what we call memory[203]. Memories get formed in a complex process that recruits different brain regions and depend on encoding, storage, retrieval of information/

196 Redcay, E., & Schilbach, L. (2019). Using second-person neuroscience to elucidate the mechanisms of social interaction.
197 Sperduti, M. *et al.* (2014). The mirror neuron system and mentalizing system connect during online social interaction.
198 Müller-Pinzler, L. *et al.* (2017). The social neuroscience of interpersonal emotions.
199 Frith, C. D., & Frith, U. (2012). Mechanisms of social cognition.
200 Szucs, D., & Goswami, U. (2007). Educational neuroscience: Defining a new discipline for the study of mental representations.
201 Kragel, P. A. *et al.* (2018). Representation, pattern information, and brain signatures: From neurons to neuroimaging.
202 Salzman, C. D., & Fusi, S. (2010). Emotion, cognition, and mental state representation in amygdala and prefrontal cortex.
203 Lent, R. (2010). *Cem bilhões de neurônios? Conceitos fundamentais de neurociência.*

experience as a mental representation. There is no learning without memory. Difficulties in learning may reflect, among other factors, failures in any one of these memory processing stages. The more memory gets well encoded and stored, the greater the chances of retrieving it in the future.

This is the reason why context for a learner's development is so relevant for learning. Social relations' attributes, incoming stimuli, and experiences learners get are essential for new mental representations and memory[204]. Genetic shortcomings apart, someone learns a language when exposed to it; learns math in doing arithmetic; learns to decide when facing problems or doubts; learns to be violent when facing violence; learns to be empathetic when exercising it. The brain learns by interacting with the environment.

Neuroplasticity generates changes in neural circuitry by increasing information flow in the brain, that is, by facilitating and registering the "talk" between neurons. Accordingly, learning becomes a byproduct of such neuroplasticity[205]. In preexisting synapses, biochemical mechanisms get activated. This liberates more neurotransmitters or increases their efficiency in the **post-synaptic membrane** leading to a better information flow. Even when there is no new synapse, preexisting ones become more efficient. For effective, lasting learning, neural circuits representing the knowledge, ability, or attitude to be learned must get reactivated. When this happens, neurons produce proteins for synapse building and reorganization during our sleep periods[206]. The chemical reactions that happen in such processes demand time, nutrients[207] and energy.

If a given neural circuit becomes inactive – like what happens in interrupting English or piano lessons, quitting trigonometry, or getting all contact numbers on speed dial – the synapses holding the mental representations for these abilities or knowledge cannot keep their structure and wither away until most of what was once learned gets forgotten[208].

We live and survive because learning grants us the possibility of registering and storing knowledge, abilities, and attitudes relevant to our existence. Information that lacks meaning for our interaction with the world tends towards fast forgetting or skips registering entirely. In the next chapter, we go deeper into how the brain processes learning and explain the main mental functions for this processing.

204 Clewett, D. *et al.* (2019). Transcending time in the brain: How event memories are constructed from experience.
205 Lent, R. (2019). *O cérebro aprendiz: Neuroplasticidade e educação.*
206 Seibt, J., & Frank, M. G. (2019). Primed to sleep: The dynamics of synaptic plasticity across brain states.
207 Cusick, S. E., & Georgieff, M. K. (2016). The role of nutrition in brain development: The golden opportunity of the "first 1000 days"
208 Davis, R. L., & Zhong, Y. (2017). The biology of forgetting: A perspective.
Izquierdo, I. *et al.* (2006). A arte de esquecer.

# 5 HOW DO WE LEARN?

*This chapter explains how the brain learns and which mental functions are involved in the learning process.*

It is not possible to know how much knowledge students take home after a school day. While activities, projects, tests, and exams may partially show what got learned, it is ultimately hard to measure what students have stored in their 'personal file'. Likewise, the educator cannot verify how the learner experiences this process given learning is a personal, internal process [209]. There is certainly a lot to be explored in this uncharted terrain, but neuroscience[210] made progress in understanding how the **brain** receives, processes, stores and uses information. This has vouched for explanations to educators on how this 'invisible' process happens in a learner's mind.

As we have seen, from a neuroscientific perspective, learning stems from a reorganization of neuronal connections[211] engineered from **neuron** activation stimulated by internal and external information. From the new organizational pattern for **neural circuits**, novel knowledge, abilities, and attitudes emerge to modify behaviors and, therefore, our expression and action in the world[212].

But how do we come to learn the periodic table of elements, history of humankind, and mathematical formulae? And how does learning happen from a brain perspective? In previous chapters, we presented many concepts related to the neural basis for learning. Now, we explain the main **mental functions** involved in this process. First, we bring a schema for the learning route in the brain, highlighting the crucial moments for the acquisition, processing, and storage of new information or experience. Figure 2 shows our main brain "routes" in the learning process.

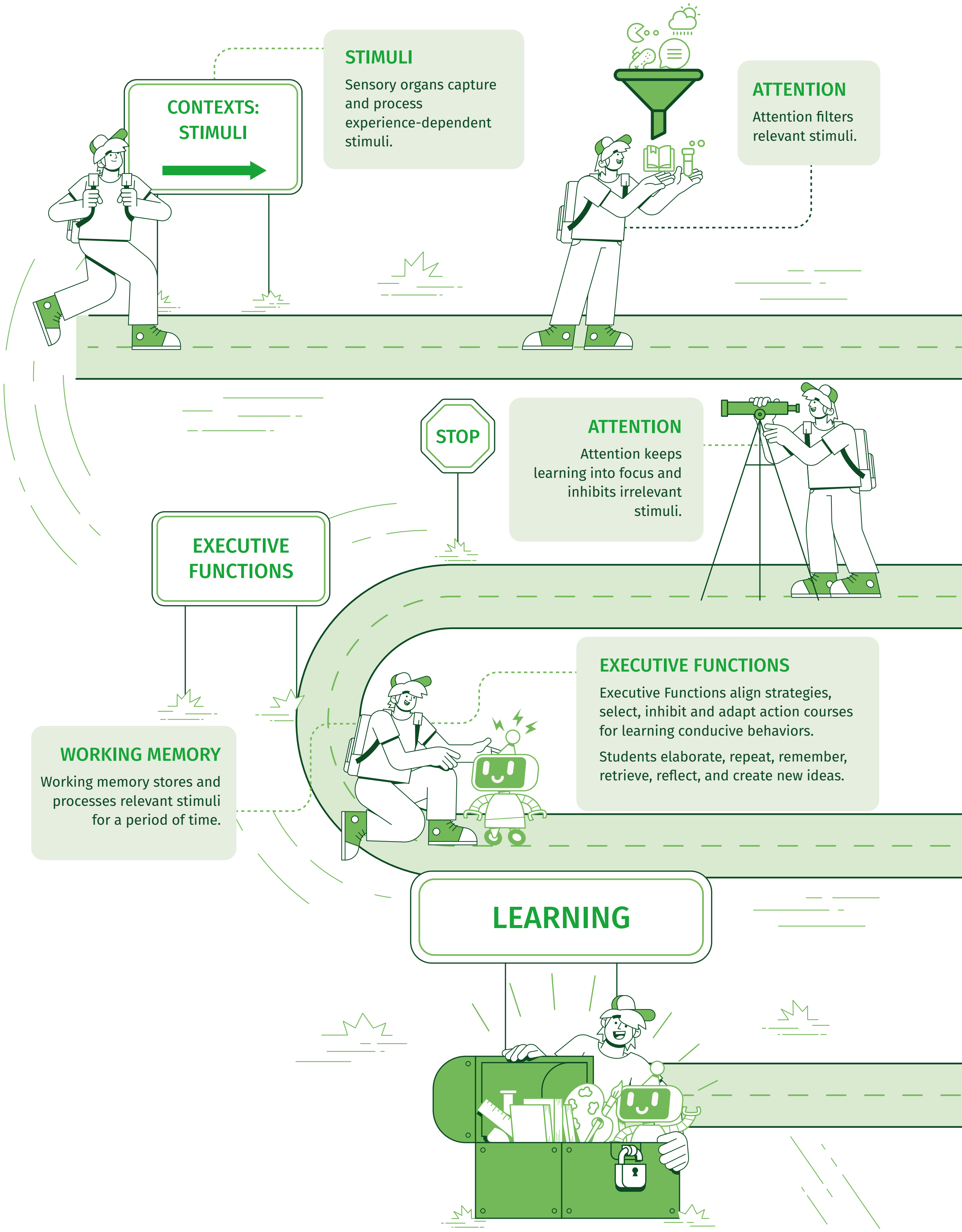
209 Stern, E. (2017). Individual differences in the learning potential of human beings.

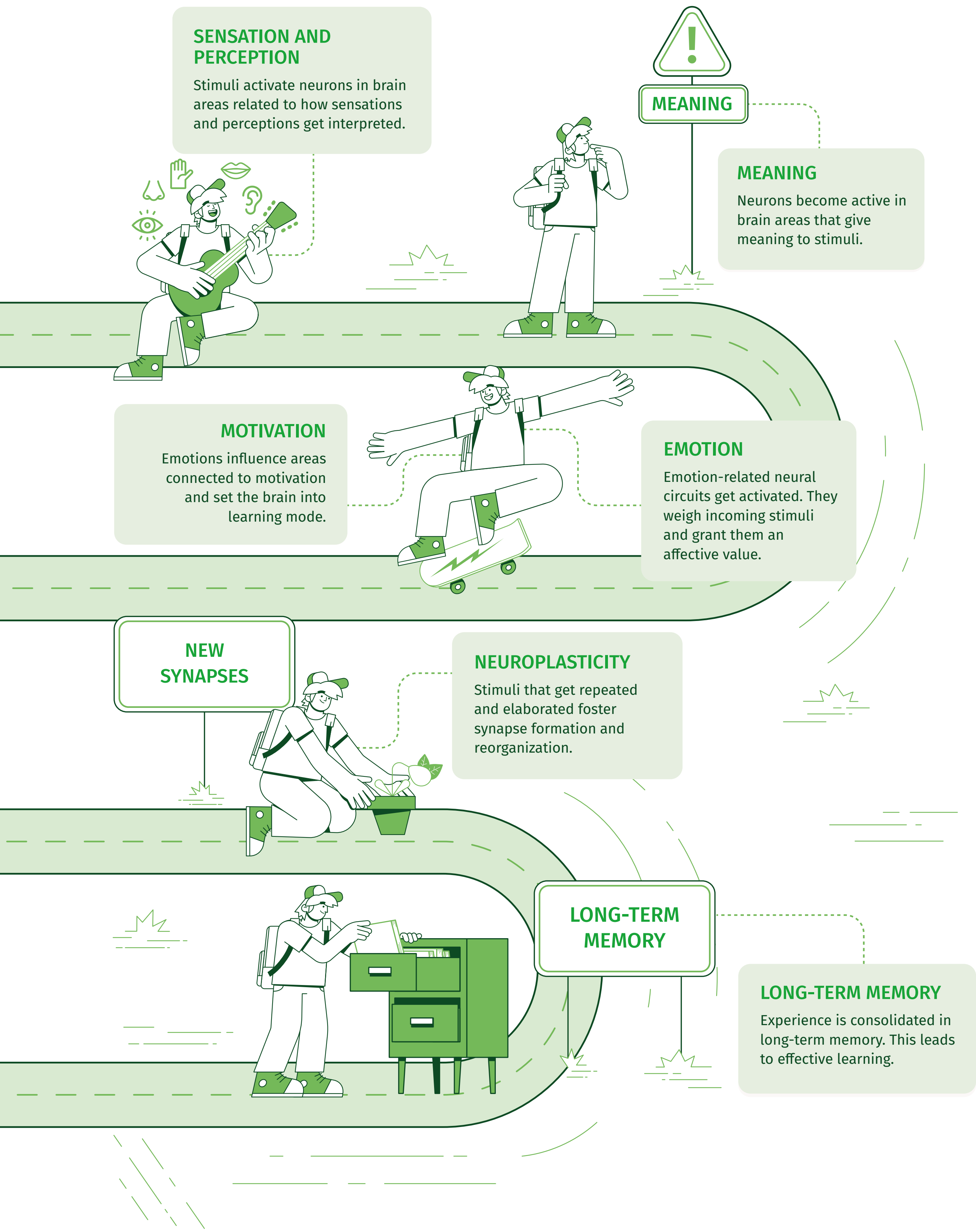
210 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende*. This book explains the neural basis and main mental functions related to learning. It can be used as an overarching reference for Chapter 5.

211 Lent, R. (2019). *O cérebro aprendiz: Neuroplasticidade e educação*.

212 Van Schaik, C. P., & Burkart, J. M. (2011). Social learning and evolution: The cultural intelligence hypothesis.

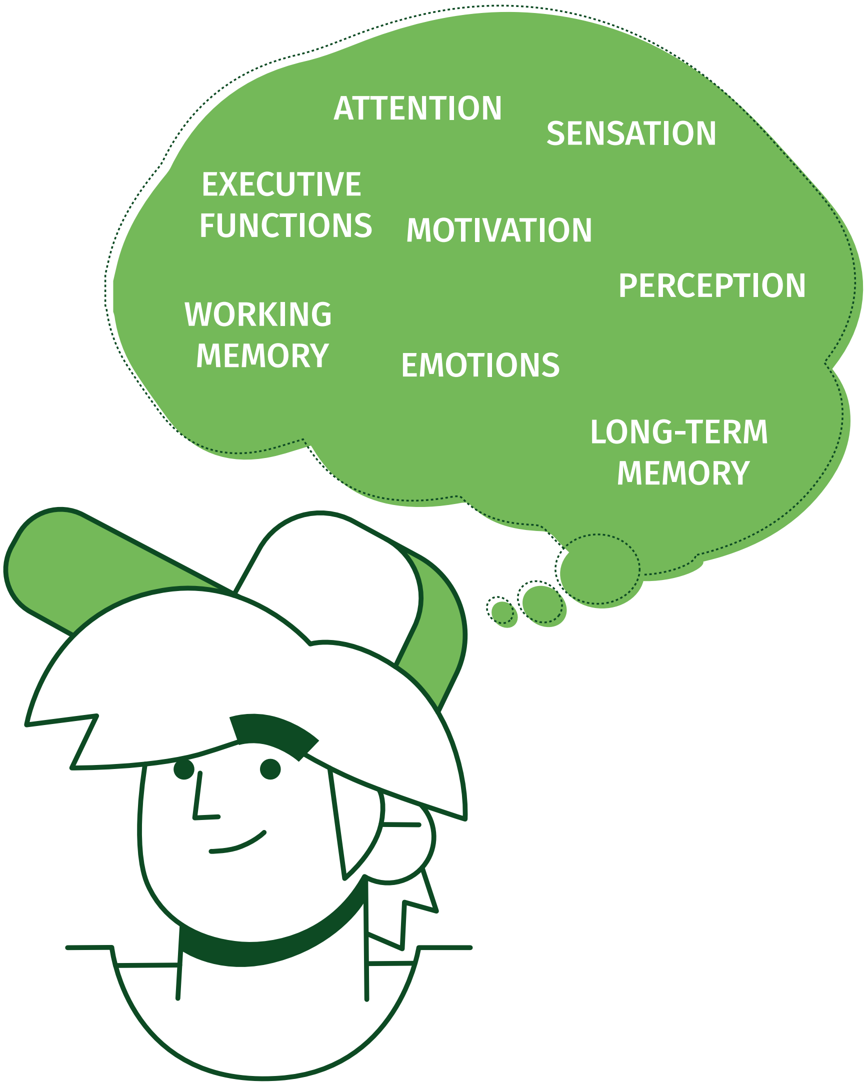
**FIGURE 2 –** How does the brain learn? Learning Roadmap




SENSATION AND PERCEPTION
Stimuli activate neurons in brain areas related to how sensations and perceptions get interpreted.
MEANING
MEANING
Neurons become active in brain areas that give meaning to stimuli.
MOTIVATION
Emotions influence areas connected to motivation and set the brain into learning mode.
EMOTION
Emotion-related neural circuits get activated. They weigh incoming stimuli and grant them an affective value.
NEW SYNAPSES
NEUROPLASTICITY
Stimuli that get repeated and elaborated foster synapse formation and reorganization.
LONG-TERM MEMORY
LONG-TERM MEMORY
Experience is consolidated in long-term memory. This leads to effective learning.

Each one of these 'routes' depends on distinct brain neural circuits. Their joint (and almost simultaneous) activation engages and develops crucial mental functions for any learning. These functions are essential for learning how to read, calculate, drive, cooperate and empathize, dance, play an instrument, speak a new language, understand philosophy and robotics and so it goes. It is precisely the activity of such mental functions that leads to the **mental representations** of our experiences. Figure 3 shows the main mental functions involved in the learning process that will get explained throughout this chapter.

**FIGURE 3 –** Main Mental Functions related to Learning



## 5.1 EMOTION AND MOTIVATION

The brain receives information about how the body reacts to experiences, including those related to learning, in a nonstop frequency. Emotions are our brain's appraisal of physiological changes that keep happening[213]. Emotions confer value to interactions and actions and signal how positive or negative, meaningful or meaningless something is[214]. This is the reason why they work as an internal marker that shows when something important is taking place, and influence behaviors we have towards the different challenges we face in life[215].

Emotions manifest through peripheral physiological changes such as an increase in cardiac frequency (racing heart), changes in facial expression, or intestinal motility (butterflies in the stomach)[216]. These bodily changes go in tandem with a conscious experience of emotions – the brain's perception of that specific functional state. Often, we can identify the emotion we call 'feeling' such as fear, sadness, surprise, disgust, anger, joy, ecstasy, apathy, irritation, boredom, and indifference.

Many structures in the **nervous system**[217] are engaged in emotions, including those that are part of the **limbic system**[218]**.** In general, these structures allow for appraisal of interactions and elaboration of behaviors towards such interactions[219] signaling what needs registering as memory and thus learned. Among these structures, we highlight the **amygdala** and **nucleus accumbens** (the main structure in the **reward system**).

The amygdala[220] crucially signals stimuli, either those that generate positive[221] and those for negative emotions - a threat to one's survival. For example, when a teacher gives a pop quiz, the amygdala gets activated and influences students' attention, perception, motivation, memory, and even their metabolism so that they can engage and produce adaptive responses to the challenging stimulus[222]. In the example above, if students are sharp, they can recruit their attention and memory to do the quiz. If not, fear of failure might set in, and they can feel unwell and even forget the little they already know.

213 Tsakiris, M., & Critchley, H. (2016). Interoception beyond homeostasis: Affect, cognition and mental health.
214 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende.*
215 LeDoux, J. (2012). Rethinking the emotional brain.
216 Lent, R. (2010). *Cem bilhões de neurônios?: Conceitos fundamentais de neurociência.*
217 Venkatraman, A. *et al.* (2017). The brainstem in emotion: A review.
218 Esperidião-Antônio, V. *et al.* (2008). Neurobiologia das emoções.
219 Canteras, N. S., & Bittencourt, J. C. (2008). Comportamentos motivados e emoções.
220 Pessoa, L., & Adolphs, R. (2010). Emotion processing and the amygdala: From a 'low road' to 'many roads' of evaluating biological significance.
221 Bonnet, L. *et al.* (2015). The role of the amygdala in the perception of positive emotions: An "intensity detector".
222 Weymar, M., & Schwabe, L. (2016). Amygdala and emotion: The bright side of it.

When the reward system[223] gets activated by stimuli perceived as being good, interesting, and meaningful, it yields feelings of pleasure and well-being. For example, when the student indeed invested in the test and performed well. In that case, when the result is pleasure, satisfaction, and well-being, the bodily physiological state hints to the brain that such behavior – studying – is effort-worthy and should thus be repeated as the brain assesses a high likelihood of success in future instances. Next, the brain can anticipate the reward it will get for studying. Hence, motivation begins.

Motivation is thus the anticipated activation of the reward system that propels us towards an action[224]. It is what makes us wake up, face the day, give our best at work, in studying, in challenges, to the unexpected, to discoveries, to learning and, to life at large. A factor that impacts motivation is the belief one holds of being able[225] to complete a task or deal with a situation, also known as self-efficacy. Perception of self-efficacy increases motivation. It makes us feel that dedication to a task is worth the effort and predisposes us to repeat the experience. Though intriguing yet clearly plausible, the reward system has connections with a brain area related to strategic behavior planning, the area known as the **prefrontal cortex**[226]. Once the reward system gets activated, it engages the prefrontal cortex that will plan an action course to reach a goal and yield, once again, pleasure, well-being, and the feeling of self-efficacy.

The reward system activation fulfills a core role for learning[227]. Motivation facilitates the brain's physiological process for learning by engaging students and recruiting their commitment. The more they commit, the better learning gets practiced. This consolidates learning and increases the likelihood of a successful performance. The relationship between motivation, practice, and positive results engenders a virtuous cycle that is highly favorable to the learning process[228].

Learners' reward system[229] can get activated by engrossing activities, self-efficacy experiences, and a teacher's positive feedback[230]. This last aspect is crucial. A teacher's encouragement in treating mistakes as a path to learning instead of punishment will progressively make students less afraid of mistakes and more trustful in their capacities.

223 Arias-Carrión, O. *et al.* (2010). Dopaminergic reward system: A short integrative review.

224 O'Doherty, J. P. *et al.* (2017). Learning, reward, and decision making.

225 Bejjani, C. *et al.* (2019). Intelligence mindset shapes neural learning signals and memory.

226 Braver, T. S. *et al.* (2014). Mechanisms of motivation-cognition interaction: Challenges and opportunities.

227 Hidi, S. (2016). Revisiting the role of rewards in motivation and learning: Implications of neuroscientific research.
Mizuno, K. *et al.* (2008). The neural basis of academic achievement motivation.

228 Hohnen, B., & Murphy, T. (2016). The optimum context for learning: Drawing on neuroscience to inform best practice in the classroom.

229 Telzer, E. H. (2016). Dopaminergic reward sensitivity can promote adolescent health: A new perspective on the mechanism of ventral striatum activation.

230 DePasque, S., & Tricomi, E. (2015). Effects of intrinsic motivation on feedback processing during learning.

This, in turn, will make them prone to new experiences and pathways to strengthen their learning. It is essential to get empathetic with teachers in a safe, comfortable, supportive, and attuned classroom environment. This is the reason why teachers must take care of and notice students' emotions[231]. This is conducive to individual and collective well-being[232]. Emotion is a learning's flagship – it can (and should) be get set by the teacher.

*Emotions signal to the brain what is vital for survival. One learns what makes one emotional, what is meaningful and necessary to live well but forgets what is no longer relevant for living.*

The indissociable relationship between emotion and cognition got confirmed by neuroscientific breakthroughs. Yet, it had been professed by Vygotsky and fellow researchers. Brain regions that process emotions[233] connect with and influence other regions in the nervous system related to mental functions like memory, perception, language, logic-mathematical reasoning and strategic planning, and motor control. Thus, activity in emotion-related brain areas can change cognitive performance and vice-versa as our thoughts, how we perceive experiences and ourselves can influence our emotions[234]. That is why we say that emotion and reason are indissociable. Pleasant, stimulating, challenging learning situations permeated by warmth – or even by short, transitory stress – when we face a surmountable challenge, followed by contentment with the right solutions, are more effective. In contrast, low self-esteem, stress, and anxiety influence learning negatively.

## 5.2 ATTENTION

As we have seen, sensory pathways lead to neural circuitry activation and reorganization and generate new knowledge, abilities, and attitudes. This is why access to different stimuli, situations, contexts, and people in the learning process is critical. Because the brain cannot simultaneously process all incoming information, it relies on a mental function that selects information: attention[235]. The ability to select, focus, and orient engendered by attention makes it essential for memory formation and learning[236].

231 Casey, B. J. *et al.* (2019). Development of the emotional brain.
232 Benningfield, M. M. *et al.* (2015). Educational impacts of the social and emotional brain.
233 Rolls, E. T. (2015). Limbic systems for emotion and memory, but no single limbic system.
234 McRae, K. (2016). Cognitive emotion regulation: A review of theory and scientific findings.
235 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende.*
236 Rusch, T. *et al.* (2017). A two-way street between attention and learning.

It is worth remembering that the human brain was perfected by nature over a lengthy, million-long evolutionary process that enabled a stimuli-detection capacity for what is relevant and to learn from interacting with such stimuli.

That is why we say that attention is the entrance gate for learning[237] from where incoming information will get processed by different memory systems. If learners do not pay attention[238], their brain cannot process the information and it goes unregistered. Therefore, learning will not happen.

The brain relies on three neural circuits for attention[239]. The first, termed **Ascending Reticular Activating System (ARAS)**, is situated in the **brain stem** and answers for our awake states. To be awake and alert is the first and foremost condition for attention to get recruited. If a student is sleepy during class, s/he is not fully processing what is taking place. When the ARAS acts on the **cerebral cortex**, it also becomes responsible for automatic or bottom-up attention that gets recruited when an intense and sudden sound (e.g., the recess bell) or when an unusual, odd object gets captured by our eyesight. If the stimulus is not relevant, we immediately discard it.

The second circuit, termed orienting circuit, is situated in the **parietal cortex** and is responsible for the so-called voluntary or top-down attention. It consciously allocates the attentional focus from one target to another because of a seemingly more relevant stimulus. This allows for a greater stimulus discrimination and enables fine-tunned information processing. Voluntary attention gets influenced by internal body states, like thirst and hunger, personal preferences, specific circumstances, previous experiences, or goals. In addition, it can be selective such as when a student attends to classmates' small talk but not to the teacher talking.

The third circuit, also involved with voluntary attention, is known as the executive circuit and is related to the anterior portion of the **cingulate gyrus**, located in the medial **prefrontal area,** and responsible for keeping voluntary attention on a specific stimulus while inhibiting distracting stimuli. It keeps attention on what we intend to focus on despite external (conversations, noises, people, images) or internal (uneasiness, emotions, disturbing thoughts, thirst, or hunger) distractions.

Attention regulation can thus happen reflexively or voluntarily. When we read or talk with a surrounding sound, it may go unnoticed. If it becomes more intense, bottom-up attention makes us notice it to discard next. But if it is familiar, like the mobile ringtone, voluntary

237 Lent, R. (2010). *Cem bilhões de neurônios?: Conceitos fundamentais de neurociência.*

238 Stevens, C., & Bavelier, D. (2012) The role of selective attention on academic foundations: A cognitive neuroscience perspective.

239 Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after.
Amso, D., & Scerif, G. (2015). The attentive brain: Insights from developmental cognitive neuroscience.

attention redirects our focus to the relevant stimulus. Depending on need, context, or motivation, the executive circuit will keep our focused, deliberate attention on the mobile, and it will get picked up. Reading and talking will get momentarily forgotten.

When attention is on searching for a lost object or when focused on reading despite other stimuli, the executive circuit springs into action. Nevertheless, when alterations affect this circuit, the ability to hold attention is diminished and the person gets distracted very easily[240]as in children with Attention Deficit Hyperactivity Disorder (ADHD)[241]. Thus, we have realized how much voluntary attention is essential for the learning process.

Importantly, brain attentional circuits process each stimulus at a time. This means we cannot simultaneously keep our focus on two different stimuli[242]. Indeed, we can alternate attention between stimuli or between cognitive-demanding tasks, although it ultimately means losing out on the information or task. One cannot pay attention to a lecture if one keeps sending SMSs.

*The belief that multitasking augments productivity is a myth. Instead of saving time, multitaskers take longer to finish activities and make more mistakes than those who concentrate on one task at a time.*

Of note, in the anterior portion of the cingulate gyrus, there are specific, distinct and coexisting neural circuits for attention regulation of emotional and cognitive processes. Scientific evidence[243] shows that activity in one circuit may inhibit another. This is why intense emotions, especially negative ones, may harm attention in cognitive processing.

Attention selects what is most relevant for each individual according to their physical, cognitive, and emotional needs. The brain seeks meaning in what gets experienced and perceived in the environment. Attention is mobilized by relevant, meaningful, or novel situations and topics or by those that generate well-being[244] – in sum, what motivates us. This is why there is a strong bond between attention and motivation[245]. When we are motivated, emotionally engaged, our attention turns to what we are experiencing and activates specific neural circuits. Once repeated, activation of such circuits generates memories, thus enabling learning.

240 Rueda, M. R. *et al.* (2015). Cognitive neuroscience of attention: From brain mechanisms to individual differences in efficiency.

241 Rubia, K. (2018). Cognitive neuroscience of attention deficit hyperactivity disorder (ADHD) and its clinical translation.

242 Rothbart, M. K., & Posner, M. I. (2015). The developing brain in a multitasking world.

243 Rolls, E. T. (2019). The cingulate cortex and limbic systems for emotion, action, and memory.

244 Banerjee, S. *et al.* (2014). Interests shape how adolescents pay attention: The interaction of motivation and top-down attentional processes in biasing sensory activations to anticipated events.

245 Bourgeois, A. *et al.* (2016). How motivation and reward learning modulate selective attention.

## 5.3 MEMORY

The structure of the human brain is similar to a set of pathways built by neural circuits that harbor some connectivity but that can improve existing connections or establish novel ones. When we get in touch with something completely new, novel stimuli generated by the experience create new brain pathways by reorganizing neuronal connections. If this new pathway is relevant, it will get used often. Thus, this new form of neural circuitry organization will get consolidated. It works like a road that once trailed needs clearing up. As we use it more often, it clears up naturally. We refer to this easier trailed path as memory.

When some information or experience goes through our attentional filter, it gets encoded and registered in our brain as memory[246]. We only register in our memory experiences that have aroused our attention. There are many different brain regions involved with different types of memory[247], such as short- or long-term memories[248]. Short-term memories are transient and responsible for storing recent information for a brief period. Long-term memories register information for lasting periods and answer for our 'treasure trove'.

### WORKING MEMORY

As you begin reading this paragraph, you need to keep track of the first words, sentences, and expressions so that, after reading it, you can have a wholesome understanding of the information presented. It is not by chance that long paragraphs and sentences are harder to grasp. They do demand attentive reading and often, a second reading. The memory that enables storing information for a brief period is known as working memory[249].

Thus, working memory[250]is the transient, short-term storage for information needed when consciously performing a task. It works as an online, dynamic filing system – a computer RAM. We are using our working memory when we memorize our parking spot or a telephone number till dialing,

Working memory functioning is related to neural circuitry in the prefrontal cortex and relies on repeated activation of such information-related circuitry demanding

246 Cammarota, M. *et al.* (2008). Aprendizado e memória.
247 Lent, R. (2010). *Cem bilhões de neurônios?: Conceitos fundamentais de neurociência.*
248 Eichenbaum, H. (2017). Memory: Organization and control.
249 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende.*
250 Chai, W. J. *et al.* (2018) Working memory from the psychological and neurosciences perspectives: A review.

attention. How many times do we get distracted on the way to the living room and end up forgetting what we needed to get there? Working memory processes several kinds of information such as sounds, images, words, thoughts, and keeps them available until usage. However, this memory is limited in the number of stored items and works like a juggler holding balls in the air.

In schools, students often prepare for tests and keep a large amount of information without much elaboration in their working memories. As this memory is transient, they speed over the test to provide answers and discard the information afterward. The result is fast forgetting. This process, widely known as *cramming*, does not secure learning. Learning only happens when new information gest consolidated in long-term memory as it needs time and personal effort over a certain period – not only right before a test.

Of note, however, is the relevant role that working memory has in learning processes[251]. It is crucial for understanding what teachers say in the classroom, for reading comprehension, and arithmetic. In addition, it is essential for performing daily chores. A student needs to remember class schedules, upcoming tasks, tests dates, and assignments to thrive in school. Often, information like that gets registered in working memory or in a diary – and this helps as it gives room for new memory registrations.

## LONG-TERM MEMORY

As previously described, when relevant information gets filtered by attention and generates neuronal activation, there is information encoding, that is, it gets processed by working memory, which is transient. Depending on the relevance of the information and the way it gets (re)activated, there are some structural and functional alterations in these specific neural circuits[252]. Their **synapses** get more efficient and facilitate the creation of more permanent registration in long-term memory. Extra work is necessary for information to get registered for a longer time in the brain as it needs to go through repetition, elaboration, and consolidation[253].

Repetition corresponds to the repetitive use of information; elaboration relates to associating the information with previous memory registrations. The more the learner repeats the information in varied ways and the more associations or 'hooks' s/he gets to

251 Blankenship, T. L. *et al.* (2015). Working memory and recollection contribute to academic achievement.
Nutley, S. B., & Söderqvist, S. (2017). How is working memory training likely to influence academic performance? Current evidence and methodological considerations.

252 Abraham, W. C. *et al.* (2019). Is plasticity of synapses the mechanism of long-term memory storage?

253 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende.*

connect them to previously learned material, the better chances s/he has of turning it into a more permanent registration in the brain. This, by the way, defines consolidation.

Repetition and elaboration can happen in simple and complex ways and involve different processing levels that determine the strength of the registrations or memory traces in formation. Information effectively repeated and elaborated generates new connections. The constant exposure to varied formats in increasingly complex levels results in stable neural connections. These become strong registrations that may stand the test of time.

Repetition makes the neural circuits for some information be often activated whereas elaboration enables activation of other neural circuits. These circuits become associated with the circuits already activated by information. But these processes demand time and alter synapses which consolidate information in long-term memory.

Long-term memory relies on consolidation of both the newly formed synapses and modifications of preexisting ones[254]. This does not happen at once. It happens over time, during each sleep cycle[255] when brain chemical conditions are conducive to **neuroplasticity**. During sleep, our brain reorganizes synapses, generates new ones, discards those no longer in use, and strengthens the ones important to our daily lives[256]. Beyond quality sleep, a balanced diet is also necessary[257] as this reorganizing process demands chemical reactions and protein production.

It is worth noticing that there is no 'memory brain area' where memories get stored. Memory gets registered in neural circuits distributed throughout different brain regions[258] as per their function. For example, visual memories get stored in the visual cortex and motor memories in the motor cortex. Circuits thus get associated and form neural networks for the different knowledge and experiences one has. Today we know that memory registration in the cerebral cortex relies on the **hippocampus**, a structure in the **temporal lobe** crucial for processing and consolidating new information. Therefore, memory formation spread throughout the brain gets managed by the hippocampus and the prefrontal cortex. Individuals sustaining bilateral lesions in the hippocampus can recall old memories, but they can no longer form new ones.

254 Lent, R. (2019). *O cérebro aprendiz: Neuroplasticidade e educação.*

255 Ribeiro, S., & Stickgold, R. (2014). Sleep and school education.

256 Louzada, F. M., & Ribeiro, S. T. G. (2018). Sono, aprendizagem e sala de aula.

257 Naveed, S. *et al.* (2020). An overview on the associations between health behaviors and brain health in children and adolescents with special reference to diet quality.

258 Albo, Z., & Gräff, J. (2018). The mysteries of remote memory.
Tonegawa, S. *et al.* (2018). The role of engram cells in the systems consolidation of memory.

Importantly, not all the memories that we register involve conscious brain processes[259]. Memory that gets processed unconsciously is known as implicit memory while explicit memory is the one that we are aware of as it demands conscious processing. Explicit memory is responsible for registering facts, dates, people, names, objects, places, sounds, and images that can be remembered and used consciously.

Implicit memory[260] enables registration without conscious effort or intention. These registrations get usually connected to motor memories, related to 'doing something' like tying up shoelaces, driving a car, riding a bicycle, or playing an instrument. They do not rely on the hippocampus but on motor processing structures like the **cerebellum** and the **basal ganglia**. To be stored, memories need repetition, and their organization happens via synapse formation in the circuits for such activities coupled with practice-based reinforcement. A sensorimotor schema for automaticity in activities is developed via implicit memory. For instance, while driving, we do not need to think to change gears. Likewise, when riding a bicycle, we do not reason to keep our balance.

Brain capacity to memorize sensorimotor schema is crucial for learning[261]. The possibility of reading and writing automatically liberates attention for interpreting content and making meaning during these activities. We do not need to think about the movement of writing every letter or the phonemes that each one represents in reading. Not having to do these processes liberates our imagination to write an essay or read a book.

Memorization implies establishing new synapses and modifying preexisting neuronal connections. Learning, thus, relies on mechanisms that produce memories. But what is the difference between learning and memory? While learning refers to how we acquire new knowledge, abilities, and attitudes, memory refers to the persistence of registrations of experiences and information in the nervous system. Many registrations do not get consolidated in long-term memory nor become learning. A critical aspect of this difference is that learning is a complex process involving several mental functions. Memory, on the other hand, is just one of these functions.

259 Brem, A. K. *et al.* (2013). Learning and memory.
Camina, E., & Güell, F. (2017) The neuroanatomical, neurophysiological and psychological basis of memory: Current models and their origins.

260 Reber, P. J. (2013). The neural basis of implicit learning and memory: A review of neuropsychological and neuroimaging research.

261 Conway, C. M. (2020). How does the brain learn environmental structure? Ten core principles for understanding the neurocognitive mechanisms of statistical learning.
Dehaene, S. *et al.* (2015). Illiterate to literate: Behavioural and cerebral changes induced by reading acquisition.
Kiefer, M. *et al.* (2015). Handwriting or typewriting? The influence of pen- or keyboard-based writing training on reading and writing performance in preschool children.
Sawi, O. M., & Rueckl, J. G. (2019). Reading and the neurocognitive bases of statistical learning.

*Memory is an essential mental function for learning as it enables a more permanent registration of experiences we have. But there is more to learning than memorizing; it is a process of acquiring knowledge, abilities, and attitudes that enables an adaptative and creative interaction with our environment.*

## 5.4 EXECUTIVE FUNCTIONS

**Executive functions**[262] refer to a set of mental functions that enable planning and executing what is needed to achieve goals, solve problems, interact with the world in varied situations. They have an essential role in learning as they allow students to harness conducive behaviors.

When we interact with the world and with people, we constantly need to focus, analyze situations, think about how to deal with them, plan and execute all required at that moment. And we do this by following rules, resisting temptations, changing tactics, and trying to finish what we had started. Acting on autopilot, without employing our executive functions and relying on our intuition without any planning may be reckless, insufficient, and a bad idea to solve problems and face challenges – including those in academic life.

To learn in school or any other context, one needs a repertoire that encompasses focusing attention on what one wants to learn and not getting distracted with other stimuli. One also needs discipline, organization, and planning to commit to learning. The repertoire also involves knowing how to work in a group, thinking about solving the questions that arise, letting go of activities that one would like to do to concentrate on homework, or preparing for tests even if one does not know if success is guaranteed.

Executive functions[263] are the mental processes enabling learners to select and set goals, plan some necessary steps to achieve such goals, monitor these steps, and, if needed, change strategies to get there. According to the neuroscientist Adele Diamond[264], these functions "make possible mentally playing with ideas; taking the time to think before acting; meeting novel, unanticipated challenges; resisting temptations; and staying focused." (Diamond, 2013, p. 135). They orient the learner about appropriate behaviors towards a situation or relative to the social rules and cultural standards. They

262 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende.*
Lent, R. (2010). *Cem bilhões de neurônios?: Conceitos fundamentais de neurociência.*

263 Zelazo, P. D. *et al.* (2016). *Executive function: Implications for education.*

264 Diamond, A. (2013). Executive functions.

are part of daily chores and long-term planning related to career choices, professional development, family formation, purchasing a house, and traveling. Executive functions are fundamental for learner success in every step of the educational process and a healthy, fulfilling adulthood as a happy person, citizen, professional.

Executive functions[265] are related to the neural circuits from distinct regions of the prefrontal cortex, the most anterior portion of the **frontal lobe**. Each prefrontal region is connected to different aspects of executive functioning and has reciprocal connections with many **cortical** and **subcortical areas** that process emotions, attention, memory, motor planning, sensations, and visceral responses. The prefrontal cortex receives information from some of these areas and relays them to other areas. Thus, the prefrontal cortex organizes our thinking - taking into stock registrations encoded in our memories, emotions, and bodily sensations as much as expectations we hold - to recruit behavioral strategies while focusing our attention and directing our actions towards end-goals.

We can identify three mental functions taken as key executive function skills[266]: inhibitory control, cognitive flexibility, and working memory previously introduced in this chapter. Based on these three key skills, more complex executive functions may get performed, such as behavior planning, action and thinking flexibility, error detection, risk assessment, response inhibition, problem-solving, and metacognition. Basic and complex executive functions are essential for self-regulation – the capacity to regulate behavior concerning the cognitive, emotional, and social demands of a given context[267]. Self-regulation enables monitoring thought and action, managing socioemotional aspects, decision making, organization, time management, and other processes for goal setting and achievement. For example, a student using basic and complex executive functions when planning studying times will evaluate how to study some content. S/he will acknowledge what topics need more dedication and forego a party to study for a test if need be. This is how one self-regulates learning.

Inhibitory control[268] is the capacity to control one's attention, actions, thoughts, and emotions so that one can do what is most appropriate or required – time and context permitting. Inhibitory control relies on the executive circuit, the same involved with voluntary attention, and takes part in interrelated behaviors, such as self-control, discipline, selective and sustained attention, already discussed. When we employ our inhibitory control, we let go of a given behavior. This behavior, termed prepotent, implies

265 Diamond, A. (2013). Executive functions.
Perone, S. *et al.* (2018). Toward an understanding of the neural basis of executive function development.

266 Zelazo, P. D. (2015). Executive function: Reflection, iterative reprocessing, complexity, and the developing brain.

267 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende.*

268 Diamond, A. (2013). Executive functions.

an internal predisposition (like playing a videogame) or a strong, external appeal (like playing with friends) that gets suppressed in favor of doing what is necessary or more adequate, keeping our focus on the task (studying for a math test). Inhibitory control is crucial for conscious learning because it demands that learners plan, select and prioritize necessary behaviors for successful completion.

Self-control[269], a facet of inhibitory control, refrains us from acting impulsively. It is what makes us 'count to ten' before we say or act on the spur of the moment, resist temptation and desires, follow rules (like not cheating on the test), act in tandem with social norms or someone's feelings (like resisting getting what belongs to someone else as they might feel cheated or sad).

Discipline is also related to inhibitory control and makes us stay on a task till completion, avoiding distractions or the urge to drop the task, change to an easier or more interesting task, or even interrupt the task to get some fun. Discipline is also related to gratification delay when one resists and foregoes immediate pleasures like playing a videogame with friends in exchange for a greater future gratification like getting a good grade in Math after heavy studying. Without discipline, no one can terminate a long and arduous task like exam preparation, learning to play an instrument, or mastering a language.

Cognitive flexibility[270] is the capacity to alter perspectives or strategies changing thoughts and actions along the way. For instance, when we ask ourselves: how can a situation be seen from a different angle? or how can we solve a problem in another way? Perspective or strategic change demands inhibition of some ideas registered in favor of investing on new ones in working memory. To that end, cognitive flexibility is based on and recruits inhibitory control and working memory. For example, if a way to solve a problem is not working, we can employ cognitive flexibility to try a new way of working it out or interpreting it. Consequently, it requires changing the way we think about something. Cognitive flexibility enables 'out-of-the-box' thinking and creativity and encompasses fast and flexible adaptation to change, like adjusting to unforeseen demands and priority changes, overcoming sudden obstacles, admitting to being wrong in face of new information, changing plans when unexpected opportunities arise, altering the way we see the world and people when circumstances change. Cognitive flexibility is crucial for facing varied challenges including those related to socializing.

269 Duckworth, A. L. *et al.* (2019). Self-control and academic achievement.

270 Diamond, A. (2013). Executive functions.

The prefrontal cortex, which concentrates neural circuits related to executive functions, is the brain region that matures the longest. It is preset at birth and gets developed throughout childhood when attention and planning capacity are maturing[271]. Babies can pay attention to specific stimuli while ignoring irrelevant ones. At around age 2, they already employ simple strategies to solve problems, like reaching for a toy or unscrewing a lid. By age 7, planning and flexibilization capacity improve, and children can already understand why homework comes before playtime. Children learn culture-specific procedures and knowledge according to exposure. Socialization[272], mediated by parents, school, and other bonds contributes for the child to learn about their emotions and those belonging to someone else, and to develop a repertoire of socioemotional abilities[273]. These are the abilities that allow them to apologize to a peer for having taken a play toy without asking first, for example.

The prefrontal cortex peaks in maturation only in adolescence[274]. Changes in the adolescent brain culminate with a significant improvement of several aspects of executive functioning[275]. Working memory and resistance to distractions improve, thus enabling greater selective attention. Information gets processed faster generating agile, efficient answers – essential for higher abstract reasoning and problem-solving. Impulse control gets more efficient and contributes to self-regulated actions and emotional response management. The capacity for introspection and insights over own's thinking and the perception of others' dispositions and intentions get improved. Both add to adolescents' capacity for judgment, interpersonal communication, responsibility, empathy – in sum, the development of a set of socioemotional abilities. This is when adolescents come to employ emotions to guide decisions. They regret, learn from mistakes, anticipate consequences, change opinions, and adapt strategies and actions.

It is not a coincidence that this is the period of considerable changes in one's behavior and a cornerstone in personal[276] and academic life. Adolescents realize that they do not always have to adopt available models in seeking reasons to do or not do something. From this period on, competencies acquired in childhood can change as executive function maturation confers young adults the chance to set their own goals and strategies, based on their motivations, life story, and current experience. Maturation generates autonomy and creativity; it enables fulfillment in varied and unexpected territories.

271 Fiske, A., & Holmboe, K. (2019). Neural substrates of early executive function development.

272 Moriguchi, Y. (2014). The early development of executive function and its relation to social interaction: A brief review.

273 Barros, R. P. *et al.* (2018). Desenvolvimento socioemocional: Do direito à educação à prática na escola.

274 Herculano-Houzel, S. (2005). O cérebro em transformação.

275 Fuhrmann, D. *et al.* (2015). Adolescence is a sensitive period of brain development.
Choudhury, S. *et al.* (2008). Development of the teenage brain.

276 Ahmed, S. P. *et al.* (2015). Neurocognitive bases of emotion regulation development in adolescence.

Executive functions are constantly present in interactions with the environment and personal relationships. This is precisely why contextual factors are so relevant for executive functioning development. It is incumbent on families, schools, and community to offer adolescents opportunities[277] to exercise and improve executive functions while avoiding harmful situations, like stress, sleep deprivation, loneliness, and lack of physical exercise.

Executive functions are essential for cognitive, psychological, and social development, school adaptation[278] , and academic success from first grades till graduate school. In addition, they are critical for establishing and keeping friendships, marital harmony, career success, citizenship, mental and physical health[279]. In sum, executive functions are adamant for a healthy and fulfilling life.

Children and adults learn by employing the same mental functions and brain mechanisms. Differences are related to the diversity and quantity of previous memories, children's more efficient neuroplasticity, and adults' better self-regulation. What is valid for everyone is that effective learning has to be meaningful; it has to make the learners feel that they have grown different, more adapted to the environment, and ready for solving new problems. Brain structures and chemical substances allow for learning if what is to be learned matters. The nervous system works to produce and use competencies that increase the likelihood of well-being and survival. We end up learning what is generally relevant for our lives.

*Executive Functions enable learners to identify and select objectives related to their learning, thus allowing for end-goal action planning, monitoring, and, if necessary, strategic rerouting for a prized goal: effective learning.*

In sum, learning is a process developed in the nervous system as a function of one's interaction with the environment. As a process, it relies on several contextual conditions and mental functions. While sensory organs process stimuli, attention filters what is relevant, and working memory stores transient records. Further in the process, neuroplasticity enables more permanent experience registration in long-term memory, and executive functions select, plan, inhibit and diversify behaviors conducive to learning. In common, all get influenced by emotion-regulated motivation, responsible for steering the learning process.

277 Serpell, Z. N., & Esposito, A. (2016). Development of executive functions: Implications for educational policy and practice.

278 Pascual, A. C. *et al.* (2019). The relationship between executive functions and academic performance in primary education: Review and meta-analysis.

279 Moffitt, T. E. *et al.* (2011). A gradient of childhood self-control predicts health, wealth, and public safety.

# 6 NEUROSCIENCE PRINCIPLES THAT MAY ENHANCE LEARNING

*This chapter presents the main discoveries in neuroscience and describes ways to transform principles into action to enhance learning.*

The **brain** is not born ready. We need social interaction to learn and prosper. Aside from 86 billion **neurons** at our disposal, both the quality of our experiences and learning instances impact our neural architecture and functioning throughout development. However, our brains do not come with a user guide on learning and enhancing this process. Students, parents, teachers do not rely on a compass to steer them towards the best pathways for fulfilling and meaningful learning. There lies one of neuroscience's most distressing challenges, i.e., translating findings into principles and practical guidelines that can steer teachers' routine practices and substantiate public policies.

Therefore, the present chapter aims at explaining 12 neuroscience principles identified via literature review. They can instantiate practices to enhance learning and contribute to changing 21st -century education processes.

Although each principle is more related to one of the mental functions addressed in chapter 6, they all generally relate to other **mental functions**. As previously discussed, the brain works through connections. That means the simultaneous activation of different interconnected **neural circuits** forms **neural networks** that generate mental processes.

There are some principles related to a learner's general health and physiological factors that influence learning, the most relevant being:

- An adequate diet furnishes nutrients needed for chemical reactions and protein synthesis, thus resulting in **synapse** formation and pruning, memory construction and consolidation, i.e., learning.
- Sleep consolidates all that was processed while one is awake. It is a physiological state where neural circuits are reactivated and reorganized via **neuroplasticity**.
- Physical activity boosts cognitive performance and ends up influencing attention, memory, and **executive functions**.

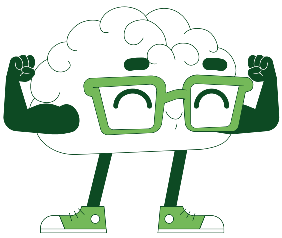
In this chapter, these three principles will not get addressed. They relate to aspects not directly implicated in teachers' classroom practices. A teacher can recommend them but cannot act directly on a learner's dieting, sleeping routine, and physical exercises. These are principles whose outcomes rely on public policies, schools' regulations, and family initiatives.

Next, we present 12 neuroscience principles underscoring innovative teaching to enhance learning. Each one has a two-part layout. First, we explain findings from a body of research that furnishes its base. In the second part – termed 'transforming the principle into action" – we present examples and suggestions on how each can turn into pedagogical practice.

Of note, even when there is scientific evidence that vouches for a principle, learners' results ultimately rely on a set of factors related to school, family, and social contexts that will enable – or not – this principle to become actionable.

Figure 4 presents at a glance the 12 principles for effective learning.

**FIGURE 4 –** 12 Neuroscience Principles for Effective Learning

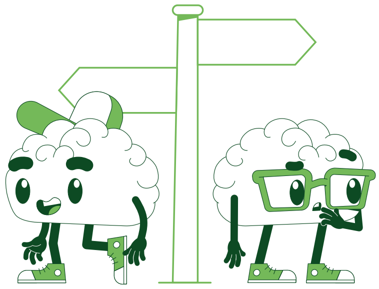


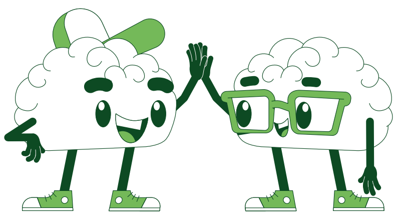
## 1 LEARNING CHANGES THE BRAIN

Those who teach change learners' brains. Pedagogical strategies stimulate reorganization of neural connections. This generates knowledge, abilities, and attitudes.

## 2 HOW WE LEARN IS UNIQUE

Brains are different because of their genetic makeup and due to changes resulting from interactions experienced. A teacher works with the same content for everyone, but each student's brain processes it in unique ways.



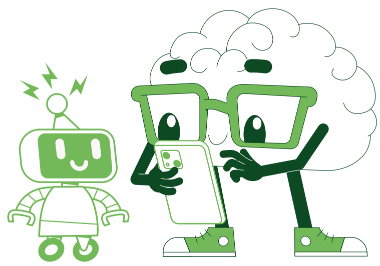


## 3 SOCIAL INTERACTION IS CONDUCIVE TO LEARNING

Iterative social interaction changes brain activity. This improves communication, attentional focus, engagement, motivation, and persistence in a learning situation and leads to greater pedagogical effectiveness.

## 4 TECHNOLOGY USE INFLUENCES INFORMATION PROCESSING AND STORAGE

New technologies have boosted learning personalization. Also, they have fostered collaborative learning, and students' autonomy in searching for information. But without proper guidance, technology use may lead to multitasking and fast, superficial information processing. This jeopardizes learning.

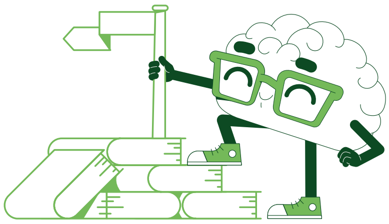


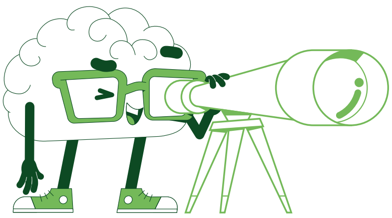
## 5 EMOTION STEERS LEARNING

Emotion signals experience, promotes meaning construction and generates motivation for learning. Emotion and cognition are indissociable. Without emotion, there is no memory, complex thought or meaningful decision-making, and social interactions for learning do not get managed.

## 6 MOTIVATION SETS THE BRAIN INTO LEARNING MODE

The wish to learn coupled with curiosity, choice control, self-led learning and personal fulfillment lead to motivation. Motivation influences brain areas related to decision making and action planning and engages students in the learning process.



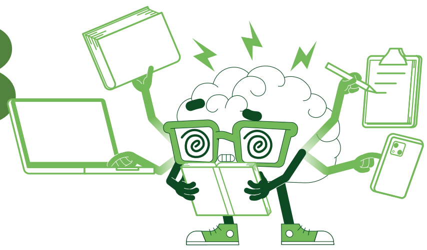


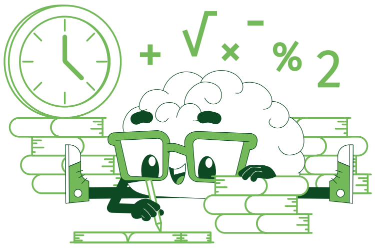
## 7 ATTENTION IS THE GATEWAY FOR LEARNING

Attention selects information and is essential for memory formation. If we do not pay attention, our brain does not process information. Thus, it cannot be registered or learned.

## 8 THE BRAIN DOES NOT MULTITASK

The brain does not adequately process two stimuli at a time. Multitasking behavior dims attention and working memory capacity. It makes students lose focus and reading comprehension grows more difficult. Also, students' ability in note taking wanes and learning is negatively affected.



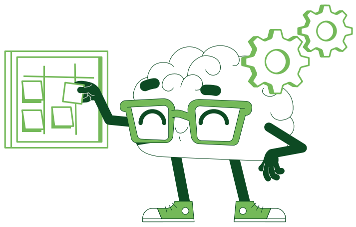


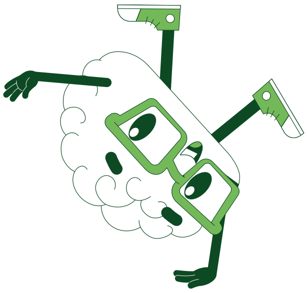
## 9 LEARNING REQUIRES ELABORATION AND TIME TO GET CONSOLIDATED IN MEMORY

Cramming means information overload without much elaboration. This leads to fast forgetting. For effective information registration, information needs to go through repetition, elaboration, retrieving, and consolidation. This takes time and demands active learning.

## 10 SELF-REGULATION AND METACOGNITION BOOST LEARNING

The capacity to monitor thinking processes, emotions and behaviors is essential for self-regulated learning. Channeling time and energy into effective ways of studying and learning gives students the means to proactively manage their own learning independently and without a teacher's constant supervision.



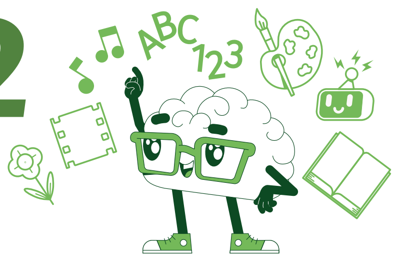


## 11 WHEN THE BODY TAKES PART, LEARNING BECOMES MORE EFFECTIVE

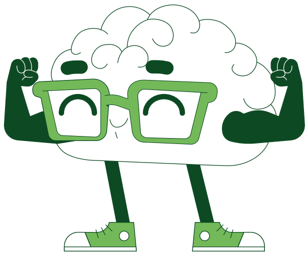
Motion and cognition are strongly related. Practical activities that integrate motion in learning situations make students feel, process and register experiences that reconfigure the brain more effectively. Keeping students seated and passive is not conducive to learning.

## 12 CREATIVITY REORGANIZES MULTIPLE NEURONAL CONNECTIONS AND EXERCISES THE LEARNING BRAIN

The essence of creativity lies in channeling imagination, making new associations, integrating knowledge, and crossing data. Creativity makes students go beyond simple rote learning of concepts and formulae. It activates mental functions and reorganizes multiple neuronal connections.



## 6.1 LEARNING CHANGES THE BRAIN



Current neuroimaging techniques[280] allow for analyses of the **brain** in action during the learning process. They are essential for evidence that learning changes the brain – in structure and function. Such alterations are observed in brain areas related to specific abilities when someone learns to read[281] and write[282]; improves comprehension of a physics concept[283]; develops numerical abilities[284]; takes part in mentoring programs to learn math[285] or in interventions to improve **mental functions** such as **selective attention**[286] and **executive functions**[287], to give a few examples. Thus, by knowing how learning changes the brain[288] and how it responds to certain interventions, we can select practices for effective learning.

Learning to read changes the brain. Neuroscience confirms the remarkable brain changes caused by reading acquisition[289]. The ability to read, differently from oral language which we learn naturally, demands mediation, effort, and repetition. It results from a reorganization of **synapses** in **neural circuits** in the **left hemisphere**, originally responsible for processing visual stimuli and oral language[290]. These circuits have been 'recycled' to give meaning to an abstract visual symbol (letter). This implied more **myelination** in **axons** and an increase in the neural circuits' connectivity that processes letter form in the occipitotemporal cortex and those circuits for speech sounds in the temporoparietal cortex. Therefore, letters and sounds become associated. For such brain structural remodeling, contextual factors must stimulate literacy[291] and executive function development. A study[292] from Harvard University and the Massachusetts Institute of Technology (MIT) showed that an intervention program for children in low socioeconomic strata with reading difficulties generated improvements in reading and an increase in the **gray matter** that subserves reading brain processing. These results

280 Seghier, M. L. *et al.* (2019). Educational fMRI: From the lab to the classroom.
281 Chyl, K. *et al.* (2018). Prereader to beginning reader: Changes induced by reading acquisition in print and speech brain networks.
282 James, K. H., & Engelhardt, L. (2012). The effects of handwriting experience on functional brain development in pre-literate children.
283 Mason, R. A., & Just, M. A. (2015). Physics instruction induces changes in neural knowledge representation during successive stages of learning.
284 Emerson, R. W., & Cantlon, J. F. (2015). Continuity and change in children's longitudinal neural responses to numbers.
285 Jolles, D. *et al.* (2016). Reconfiguration of parietal circuits with cognitive tutoring in elementary school children.
286 Isbell, E. *et al.* (2017). Neuroplasticity of selective attention: Research foundations and preliminary evidence for a gene by intervention interaction.
287 Rosas, R. *et al.* (2019). Executive functions can be improved in preschoolers through systematic playing in educational settings: Evidence from a longitudinal study.
288 Tovar-Moll, F., & Lent, R. (2018). Neuroplasticidade: O cérebro em constante mudança.
289 Buchweitz, A. (2016). Language and reading development in the brain today: Neuromarkers and the case for prediction.
290 Dehaene, S. *et al.* (2015). Illiterate to literate: Behavioural and cerebral changes induced by reading acquisition.
291 Buchweitz, A. *et al.* (2018). Linguagem: Das primeiras palavras à aprendizagem da leitura.
292 Romeo, R. R. *et al.* (2018). Socioeconomic status and reading disability: Neuroanatomy and plasticity in response to intervention.

underscore how adequate interventions are adamant for brain development subserving reading mastery. Reading acquisition generates other gains related to visual stimuli decoding, face recognition by the **right hemisphere**, phonological awareness, speech processing, complex sentence comprehension, semantic fluency, and verbal memory. It also grants access to more knowledge and experiences via reading per se.

Second language exposure also changes the brain – and the earlier, the better. Researchers[293] found that exposure to a second language since birth generates brain alterations (of gray matter and axon myelination) that benefit language processing and reading development in bilingual children (when compared to monolingual children). When bilingual children read words, brain areas related to phonological processing and language expression – and those involved in working memory, attention, reasoning, and information integration – show greater activation. When bilinguals alternate use of different repertoires, they employ their executive functions in selecting and monitoring language alternation. That improves their attention, working memory, and inhibitory control[294]. Bilinguals also learn a third language easier as they display better auditory attention and more precise decoding of sound frequencies.

Math learning and its progressive mastery also bring about brain changes. A study[295] at the University of Tübingen in Germany evaluated adolescents aged 12-14 at two successive school-year end terms while another, at Stanford University[296], evaluated two groups of elementary students aged 7-9 at the end-terms of their 2nd and 3rd grades. In common, students' performances in different arithmetic tasks got measured and their brains mapped. Neuroimaging shows that math reasoning relies on activation of **frontal** and **parietal lobes** – **frontoparietal network** – irrespective of age. At age 7, the frontal regions related to working memory and cognitive control are more activated than **parietal regions** involved in numerical processing and visual and spatial representations. In evaluating children aged 9, researchers identified greater activation of the parietal area in math learning. For ages 12 and 14, greater precision, speed, and efficiency (fewer mistakes), in simple and in complex arithmetic correlated with activity changes in specific parietal neural circuits.

Once we know that learning changes the brain, we invest more effort in changing it. Neuroscience research[297] found interconnections among brain areas related to motivation, cognitive control, and executive functions that orient action. When value-gauging

293 Jasińska, K. K., & Petitto, L. A. (2014). Development of neural systems for reading in the monolingual and bilingual brain: New insights from functional near-infrared spectroscopy neuroimaging.

294 Buchweitz, A., & Prat, C. (2013). The bilingual brain: Flexibility and control in the human cortex.

295 Artemenko, C. *et al.* (2018). The neural correlates of mental arithmetic in adolescents: A longitudinal fNIRS study.

296 Rosenberg-Lee, M. *et al.* (2011). What difference does a year of schooling make? Maturation of brain response and connectivity between 2nd and 3rd grades during arithmetic problem-solving.

297 Ng, B. (2018). The neuroscience of growth mindset and intrinsic motivation.

motivation areas recruited for a task get activated, cognitive control areas recruit task-specific mental functioning. In response, planning and action areas direct the learner towards learning goals. Whereas some research[298] shows that learners who believe intelligence is malleable and that learning changes the brain trust that talents and abilities may develop with constant effort and persistence, other findings also show that students who do not acknowledge that intelligence may increase, show less motivation, self-confidence, resilience (concerning mistakes), and self-regulation (concerning learning).

## *Transforming principle one into action*

For long, common sense endorsed the idea that brain connections got fixed as we aged, and that we lost the ability to make new connections. Neuroscience has already evidenced and continues to do so, that the human brain, via **neuroplasticity**[299]**,** has the astounding capacity to reorganize itself and form new synapses during our life course via experiences and learning processes that stem from interactions[300]. Therefore, scientific evidence confirms that learning changes the brain, and that intelligence is not fixed but malleable throughout life. Given some neuroscientific discoveries discussed before, we offer reflection points for pedagogical practice.

**Tell students that intelligence is malleable.** For not knowing that the brain changes across the lifespan, many students think that intelligence gets set at birth and that even intense efforts will not change their academic performance. Sometimes, these students come to believe that education is an unsurmountable challenge and that they are not intelligent enough to do well in school. Research[301] in neuroscience[302] shows that when students understand that intelligence is malleable and that learning changes brain structure, they can renew their self-confidence and motivation for studying. Results[303] are especially relevant when low academic achievement may partially correlate with stereotypes of low intellectual achievement for black and (or) low socioeconomic status (SES) students. Crucially, these students need quality student-teacher relationships, positive feedback, and teachers' confidence to renew their self-confidence and invest in their learning efforts.

298 Blackwell, L. S. *et al.* (2007). Implicit theories of intelligence predict achievement across an adolescent transition: A longitudinal study and an intervention.

299 Voss, P. *et al.* (2017). Dynamic brains and the changing rules of neuroplasticity: Implications for learning and recovery.

300 Burke, S., & Barnes, C. (2006). Neuroplasticity in the aging brain.

301 Dweck, C. S. (2007). Boosting achievement with messages that motivate.

302 Fitzakerley, J. L. *et al.* (2013). Neuroscientists' classroom visits positively impact student attitudes.

303 Good, C. *et al.* (2003). Improving adolescents' standardized test performance: An intervention to reduce the effects of stereotype threat.

**Make a point of noticing stimuli quality.** Learning changes the brain because of the stimuli students get. But it is not about quantity; what matters is their quality. Quality relationships, resources, teaching methodologies, and everything that learners experience determine the characteristics of their brain changes. These will, in turn, correspond to new abilities, knowledge, and attitudes. Encyclopedic curricula, excessive activities, and reading overload go counter to where neuroscience research is heading. For deep and meaningful learning, it is crucial that a teacher selects what is most relevant and mediates the relationship between students and the varied resources, in special.

**Secure full literacy.** In 2nd grade, around age 7, children generally move from 'learning to read' to 'reading to learn'[304]. This achievement generates a set of considerable brain changes[305]. A child who cannot adequately perform this crucial transition will probably face learning roadblocks as reading mastery is key to academic success. Reading difficulties may result from neurodevelopmental changes (dyslexia) but may also be related to inadequacies in the teaching process[306], which weaken literacy, or may correlate with a low stimuli/low SES family context. Teachers need to be attentive. An early diagnosis is crucial to determine appropriate interventions that will be more effective if applied in specific time frames during early development. Those children not adequately supported may have suboptimal cognitive development[307] as their brain areas responsible for reading will have become underdeveloped[308]. Public policy designs that secure full literacy must become a priority as they are essential for the whole learning enterprise[309].

**Foster early second language learning.** Research[310] shows that learning a second language in the early years yields benefits for future reading capacity, academic achievement, general cognition, and brain health. Brain development stimulated by early second language exposure may even reduce the negative impact of SES on the academic performance of low-income children. Evidence is mounting[311] that growing up bilingual increases working memory capacity and executive function – essential for reading, writing, and arithmetic acquisition. Evidence notwithstanding, in the Brazilian scenario for instance, most students are not exposed to a second language till 6th grade because it is not in the federal-mandate curriculum (T.N.).

304 Horowitz-Kraus, T., & Hutton, J. S. (2015). From emergent literacy to reading: How learning to read changes a child's brain.

305 Scliar-Cabral, L. (2013). Avanços das neurociências para a alfabetização e a leitura.

306 Scliar-Cabral, L. (2013). A desmistificação do método global.

307 Ardila, A. *et al.* (2010). Illiteracy: The neuropsychology of cognition without reading.

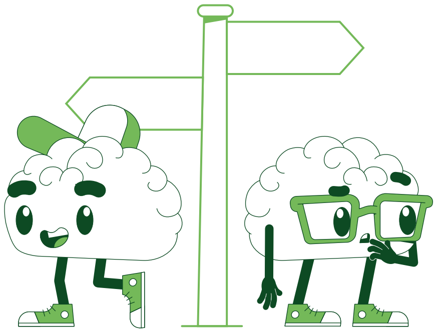
308 Gabriel, R. *et al.* (2016). A aprendizagem da leitura e suas implicações sobre a memória e a cognição.

309 Vágvölgyi, R. *et al.* (2016). A review about functional illiteracy: Definition, cognitive, linguistic, and numerical aspects.

310 Zadina, J. N. (2015). The emerging role of educational neuroscience in education reform.

311 Zhang, M. (2018). An overview of the bilingual advantage: History, mechanisms, and consequences.
Blom, E. *et al.* (2014). The benefits of being bilingual: Working memory in bilingual Turkish-Dutch children.
*Translator's Note: The box containing additional information on this topic in the original version had its content incorporated into the text in the English version for editing purposes.*

## 6.2 HOW WE LEARN IS UNIQUE



The **brain**'s structure resembles a vast set of roads where **neural circuits** related to emotion, motivation, attention, movement, language, logical reasoning, and other **mental functions** follow typical human patterns. This roadmap is common to everyone[312], although there are some variations due to hereditary genetic specificity. Our main roads are very similar. However, each one creates unique pathways that are the singular result of how **neurons** get modified and interconnected over our life course[313]. Science has already evidenced that not even identical twins create the same pathways[314]. Therefore, each brain is uniquely wired[315].

Declaring that each brain is unique means that one processes and uniquely learns information due to experiences that influence our genes and build our memories. Each student has an exclusive **neural circuitry** that influences classroom performance[316]. Neuroimaging[317] shows that each time we experience or learn something new, our neurons get physically altered.

Neuroscientific evidence shows that the same problem may get processed at different times and in varied ways by different brains in math learning. Japanese researchers[318] employed a neuroimaging technique (**fNIRS**) to evaluate the **prefrontal cortex** functioning pattern for classroom children while solving a three-phase math problem. The time each child took to figure out the problem's solution differed – the same happened with their brain activity. There was a drastic variation in their brain activity relative to motivation, difficulty, and cognitive effort while developing a problem-solving strategy. However, brain activity became stable when students got to the solution. Eye-tracking used by the same research group[319] also showed different cognitive processing patterns for a math

312 Yang, Z. *et al.* (2016). Genetic and environmental contributions to functional connectivity architecture of the human brain.
Reinenberg, A. E. *et al.* (2020). Genetic and environmental influence on the human functional connectome.

313 Miller, G. (2012). Why are you and your brain unique?
Gu, J., & Kanai, R. (2014) What contributes to individual differences in brain structure?

314 Larsen, S. A. *et al.* (2019). Identical genes, unique environments: A qualitative exploration of persistent monozygotic-twin discordance in literacy and numeracy.
Haque, F. N. *et al.* (2009). Not really identical: Epigenetic differences in monozygotic twins and implications for twin studies in psychiatry.

315 Finn, E. S. *et al.* (2015). Functional connectome fingerprinting: Identifying individuals using patterns of brain connectivity.

316 Bueno, D. (2019). Genetics and learning: How the genes influence educational attainment.

317 Zatorre, R. J. *et al.* (2012). Plasticity in gray and white: Neuroimaging changes in brain structure during learning.

318 Eda, H. *et al.* (2008). NIRS evaluates the thinking process of Mushi-Kuizan task.
Kuroda, Y. *et al.* (2009). Visualization of children's mathematics solving process using near-infrared spectroscopic approach.

319 Okamoto, N., & Kuroda, Y. (2014). Understanding strategy development in mathematics: Using eye movement measurement in educational research.

problem; students that could solve the problem showed few eye movements executed in a specific sequence. However, those that could not yet learn the strategy to solve the problem showed more frequent random eye movements.

German researchers have also noticed individual differences in processing math problems[320]. Taken together, individual differences in math abilities impact performance in complex arithmetic. This got confirmed by studies with neuroimaging, electrophysiological, neuropsychological, and behavioral measures. Those with more developed abilities recruit **frontal areas** related to **working memory** and solve complex math problems more efficiently.

Another aspect that makes learning unique is the meaning-making process. Different research groups[321] have shown that the meaning we make by interacting with the environment recruits diverse neural circuits distributed over several **nervous system** structures and distinct brain areas. These **neural networks** act in tandem to process sensorimotor information, visceral sensations, and emotions to evaluate relevant information, selecting some while inhibiting others[322]. In addition, neural circuits still compare what is perceived with what is stored so that we can associate what is experienced with our (previously built) mental representations.

This meaning-making process happens when we access information through reading, for instance. Eye-tracking studies performed while reading show that around one-third of words in a text do not get read[323]. The process is selective and mediated by an interaction between the 'thinking' brain **cortical areas** and the **thalamus** – a structure bearing reciprocal connections with the **cerebral cortex** that processes stimuli before they get to the cortex[324]. A group of American researchers[325] employed neuroimaging and eye-tracking methods to study the reading process. They found that the reader's brain cortex coordinates eye movement while the reader makes meaning of the text. Based on memories already stored, the cortex selects the information to be processed and

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320 Artemenko, C. *et al.* (2018) The neural correlates of arithmetic difficulty depend on mathematical ability: Evidence from combined fNIRS and ERP.
Artemenko, C. *et al.* (2019). Individual differences in math ability determine neurocognitive processing of arithmetic complexity: A combined fNIRS-EEG study.

321 Immordino-Yang, M.H., & Gotlieb, R. (2017). Embodied brains, social minds, cultural meaning: Integrating neuroscientific and educational research on social-affective development.

322 Oosterwijk, S. *et al.* (2012). States of mind: Emotions, body feelings, and thoughts share distributed neural networks.
Oosterwijk, S. *et al.* (2014). The neuroscience of construction: What neuroimaging approaches can tell us about how the brain creates the mind.

323 Strauss, S. L. *et al.* (2009). Brain research and reading: How emerging concepts in neuroscience support a meaning construction view of the reading process.

324 Crosson, B. (2019). The role of cortico-thalamo-cortical circuits in language: Recurrent circuits revisited.
Klostermann, F. *et al.* (2013). Functional roles of the thalamus for language capacities.

325 Strauss, S. L. *et al.* (2009). Brain research and reading: How emerging concepts in neuroscience support a meaning construction view of the reading process.

makes meaning out of the text. Thus, what one reads results from what was filtered by one's brain. That explains why proficient reading is an efficient process that enables the reader to go far beyond word sequencing identification to make meaning out of what is read based on previous experience. What follows is that incoming information does not condition the brain. On the contrary, the brain translates what it gets by making meaning of its interaction with the world. Researchers postulate that this notion will advance comprehension of learning processes and human intelligence[326] as it gets better understood.

*The brain is not held captive by the information it receives. It translates the information it gets and uses it to make sense of interactions with the world.*

Although each brain is unique, individual brain characteristics do not define one's specific intelligence type. The multiple intelligences theory[327] formulated by Howard Gardner in 1983 enhances the variability of the human intellect. His theory proposes the development of abilities other than verbal and logical-mathematical traditionally favored in schools. And he does that by recognizing that characteristics of individual differences are due, in part, to genetics and interactions with the environment. Although the neural bases for distinct types of intelligence are not completely understood[328], some studies[329] tried to correlate characteristics of each intelligence to mental functions and their respective neural circuits. Of note is the finding that we need to provide each student with stimulating environments for ample and varied development of their potentialities.

## *Transforming principle two into action*

Neuroscientific evidence[330] confirms that our brains are as unique as our fingerprints and that learning is an individual process. Such evidence opposes the depersonalized teaching system still prevalent in several educational systems. A classroom full of same-aged students does not mean that all are equally ready to learn a new concept. Each student is special and has a personal life history reflected in a unique combination of

326 Bednarz, H. M. *et al.* (2017). "Decoding versus comprehension": Brain responses underlying reading comprehension in children with autism.

327 Gardner, H. (2020). Of human potential: A 40-year saga.

328 Waterhouse, L. (2006). Multiple intelligences, the Mozart effect, and emotional intelligence: A critical review.
Waterhouse, L. (2006) Inadequate evidence for multiple intelligences, Mozart effect, and emotional intelligence theories.

329 Cerruti, C. (2013). Building a functional multiple intelligences theory to advance educational neuroscience.
Shearer, C. B., & Karanian, J. M. (2017). Neuroscience of intelligence: Empirical support for the theory of multiple intelligences: Lessons learned from Neuroscience.
Shearer, B. (2018). Multiple intelligences in teaching and education: Lessons learned from Neuroscience.

330 Finn, E. *et al.* (2015). Functional connectome fingerprinting: Identifying individuals using patterns of brain connectivity.

competencies and needs that impact their learning. Each student in the classroom has a unique way of being with different preferences, talents, fears, and desires. And all deserve the opportunity to learn to their full potential[331] and overcome their weaknesses. Teachers in special should pay heed to this neuroscience principle as they design a curriculum, select strategies, and plan activities.

**Uncover students' interests.** The first step to personalize teaching is to find students' interest focus. It means discovering their favorite activities, motivation, talents, and dreams. In opening up room for discussions, teachers send students a message that their life experiences matter and will become part of teaching and learning processes. It is a powerful message to begin a school year. In getting to know students better, skilled teachers can connect previous curricular content to students' interests. This generates more motivation, autonomy, and student-led learning.

**Personalize teaching.** Stating that each learner's brain is wired[332] differently means saying that they learn in different ways. For this reason, the education process cannot offer a single learning pathway for all students. Diversifying pedagogical practices and teaching resources favors teaching and learning processes that enable different learners to recruit distinct learning pathways. In so doing, learners' brain structures may be recruited to the fullest, and development will soar. Personalizing teaching also means calibrating the difficulty level to varying learning rhythms. Some students will take longer to master a concept while others will need complementary activities, and some will benefit from challenging activities to advance and keep their motivation.

**Use adaptive platforms.** Teachers may get highly anxious in attending to each learner's needs, mainly when teaching large classes. Adaptive platforms may offer teachers some support and constitute an additional resource for personalized teaching. They propitiate a virtual learning environment that personalizes the learning process according to each student's progress. Artificial Intelligence lets algorithms analyze students' performance, identify their needs and difficulties, and suggest a customized learning trajectory with different resources (videos, games, exercises, texts, summaries, mental maps), tips, and feedback. The more students interact with the platform, the more it learns about each student. This allows for increasingly accurate suggestions. And for teachers in special, this kind of platform enables tools for crafting activities and tests while furnishing performance reports for each student. These features liberate teachers from repetitive chores, saving their time for more effective student-teacher interactions.

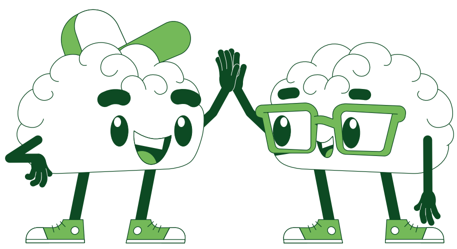
331 Stern, E. (2017). Individual differences in the learning potential of human beings

332 Bueno, D. (2019). Genetics and learning: How the genes influence educational attainment.

**Facilitate meaning-making.** The process of meaning-making is core to learning. A teacher gives the same content to all students, but the information is processed individually as each student uniquely encodes information. Learning is not the result of a passive knowledge absorption process where students automatically convert information into knowledge. If the information one gets does not make sense, generate reflection or impact, it is very likely to be forgotten and not consolidated in memory. And how can teachers facilitate meaning-making? By making room for motivation, inspiration, emotion, and students' involvement so that they can personalize information. Students understand new information when connected to their life experience, their set of values and beliefs, and their memory archive. Together, they get translated into meaning-making processes. Teachers need to promote activities that help students change far-off content into something of their own. The key to this change is creating opportunities for students to ask, question, reflect, confront ideas, build arguments, imagine possibilities, share thoughts, employ 'hands-on', generate and test hypotheses. Without such processes, students tend to copy, repeat and cram, getting further and further away from personalizing information. Involving students in what schools can offer is fundamental for making the education process effective. If such involvement – conducive to meaning-making – does not happen, learning becomes void; a formal activity that merely reproduces what teachers taught.

*Brains are different because of genes and changes brought about by interactions. Teachers provide the content while each brain in the classroom processes it singularly.*

## 6.3 SOCIAL INTERACTION IS CONDUCIVE TO LEARNING



The human **brain** has **neural circuits** that make us learners by design. We can learn just by simply observing others[333] which is not the same as learning from interacting with someone who is teaching us. Deliberate teaching seems to be a singular characteristic of human interactions not found among other primates[334]. Thus, teaching and learning processes become a social phenomenon[335]. In education contexts, teaching and learning processes happen via reciprocal, dynamic student-teacher interactions[336] in that one's actions exert an effect on another's brain processing. For this reason, a teacher may change a planned activity because a student's question showed that some concept has not been understood, for example. A student's performance may, in turn, be spurred by interacting with peers and teachers. In addition, a teacher's performance may be influenced by interacting with fellow teachers. Social interaction fosters social brain activity and brings about changes in teachers' and students' neural circuits, thus impacting teaching and learning processes[337].

Social neuroscience studies the neural basis of social cognition[338]. It seeks an understanding of how social interactions influence what we think and how we relate to one another[339]. Research focuses on the neural basis of trust, cooperation, justice, generosity, rejection, prejudice, bonding, and other aspects of human social interactions[340] geared towards an interdependence between social and individual worlds. Studies[341] show that the human brain has several brain areas specialized in recognizing and interpreting social signs like facial expression, body and eye movement, and tone of voice. These signs enable us to interpret emotions, mental states, and intentions belonging to other people. That interpretation guides our behavior towards them. The appraisal we make of others gets influenced by our mental state, memories, values, and beliefs[342].

333 Meltzoff, A. N., & Marshall, P. J. (2018). Human infant imitation as a social survival circuit.
334 Frith, U., & Frith, C. (2010). The social brain: Allowing humans to boldly go where no other species has been.
335 Yano, K. (2013). The science of human interaction and teaching.
336 Rodriguez, V. (2013). The human nervous system: A framework for teaching and the teaching brain.
337 Nelson, E. E. *et al.* (2016). Social re-orientation and brain development: An expanded and updated view.
338 Haase, V. G. *et al.* (2009). Um convite à neurociência cognitiva social.
339 Frith, C. D. (2007). The social brain?
340 Lieberman, M. D. (2010). Social cognitive neuroscience.
341 Adolphs, R. (2009). The social brain: Neural basis of social knowledge.
342 Bar, M. (2007). The proactive brain: Using analogies and associations to generate predictions.

Neuroscience has revealed that the brain has an in-built cooperation capability[343]. It has neural circuits that form the **mentalizing system** and the **mirror neurons system** activated during the processing of social interactions[344]. Besides, there are other neural circuits related to **executive functions**[345], stored memories[346], emotion regulation and the **reward system**[347]. These circuits all act in tandem to enable one's capacity and motivation[348] for social interactions and decisions[349] leading to a better adaptation to life. In sum, social interactions are fundamental for human development and culture[350].

A set of neuroscientific studies[351] verified that collaboration is motivating. Of note, motivation, an essential feature of effective learning, is a social construct. Neural circuits activated by social interactions have connections with the reward system[352] that triggers motivation[353]. Social interaction that stems from acting in cooperation motivates us to stay on task and keep cooperation going. For this reason, learning with peers is productive. When the brain plans for social cooperative interaction, it recruits the reward system even before interaction happens[354]. Cooperative learning generates positive feelings such as well-being, satisfaction, excitement, interest concerning future learning activities involving peers. Yet, negative emotions, like fear, shame, and insecurity must stay out of the equation, lest interactions get disrupted and avoided.

Different functional neuroimaging techniques[355] developed in the last 20 years enable measuring brain activity when one is observing another and when two or more people are interacting[356]. Thus, it is possible to check whether their brain activity is synchronized or not, that is, if they are devoted to and engaged in tandem in the same experience[357]. Such synchronization stems from social interactions and is defined by better perception,

343 Stallen, M., & Sanfey, A. G. (2013). The cooperative brain.
Frith C. D., & Frith, U. (2012). Mechanisms of social cognition.
Strang, S., & Park, S. Q. (2016). Human cooperation and its underlying mechanisms.

344 Vogeley, K. (2017). Two social brains: Neural mechanisms of intersubjectivity.

345 Wade, M. *et al.* (2018). On the relation between theory of mind and executive functioning: A developmental cognitive neuroscience perspective.

346 Brown, S. (2020). The "who" system of the human brain: A system for social cognition about the self and others.

347 Salamone, J. D., & Correa, M. (2012). The mysterious motivational functions of mesolimbic dopamine.

348 Rilling, J. K. *et al.* (2002). A neural basis for social cooperation.

349 Stallen, M., & Sanfey, A. G. (2015). Cooperation in the brain: Neuroscientific contributions to theory and policy.

350 Frith, U., & Frith, C. (2010). The social brain: Allowing humans to boldly go where no other species has been.

351 Clark, I., & Dumas, G. (2015). Toward a neural basis for peer-interaction: What makes peer-learning tick?
Krill, A. L., & Platek, S. M. (2012). Working together may be better: Activation of reward centers during a cooperative maze task.

352 Alkire, D. *et al.* (2018). Social interaction recruits mentalizing and reward systems in middle childhood.

353 Ruff, C. C., & Fehr, E. (2014). The neurobiology of rewards and values in social decision making.

354 Krach, S. *et al.* (2010). The rewarding nature of social interactions.

355 Babiloni, F., & Astolfi, L. (2014). Social neuroscience and hyperscanning techniques: Past, present and future.
Czeszumski, A. *et al.* (2020). Hyperscanning: A valid method to study neural inter-brain underpinnings of social interaction.

356 Hari, R. *et al.* (2015). Centrality of social interaction in human brain function.

357 Hasson, U. *et al.* (2012). Brain-to-brain coupling: A mechanism for creating and sharing a social world.
Dikker, S. *et al.* (2014). On the same wavelength: Predictable language enhances speaker–listener brain-to-brain synchrony in posterior superior temporal gyrus.

attention, and motivation to keep on interacting[358]. Studies show that brain activity during interactions with a person face-to-face enabling both participants to maintain visual contact[359] with signal and action reciprocity[360] is different from one triggered by interacting with a person via video (recorded) or when there is just observation and passive reception of their signaling. The face-to-face interaction in synch increases brain activity in areas related to social cognition and empathy in both participants to the conversations. Additionally, it improves their synchronization and communication quality in unparalleled ways[361].

Many studies[362] show that face-to-face interactions exert a considerable influence on what happens in teachers' and students' brains during the education process. And that becomes a social phenomenon. To that effect, these interactions must entail dynamic and reciprocal shifts in people's perceptions and reactions due to what each one says and does.

A joint study performed by American, Dutch, and German researchers[363] over 11 classes of a school term measured the brain activity of 12 high school students performing different activities during their biology classes: teacher's reading, video presentation, expository class, and group discussion. The researchers found that students' brain activity synchronization, reflected in the group's engagement, was higher for activities that students ranked as more interesting, like the video and group discussion. Synchronization was related to students getting the chance of establishing visual contact before or during the activity. Another interesting finding was that, concerning expository class, students who felt closer to the teacher showed better content retention[364].

Several research groups have confirmed that brain synchronization generated by face-to-face communication between teachers and students leads to effective learning. In the different studies, teacher-student interactions got set by previous knowledge

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358 Hari, R., & Kujala, M. V. (2009). Brain basis of human social interaction: From concepts to brain imaging.

359 Schilbach, L. (2015). Eye to eye, face to face and brain to brain: Novel approaches to study the behavioral dynamics and neural mechanisms of social interactions.
Kolke, T. *et al.* (2019). What makes eye contact special? Neural substrates of on-line mutual eye-gaze- A hyperscanning fMRI study.

360 Sakaiya, S. *et al.* (2013). Neural correlate of human reciprocity in social interactions.
Redcay, E., & Schilbach, L. (2019). Using second-person neuroscience to elucidate the mechanisms of social interactions.

361 Jiang, J. *et al.* (2012). Neural synchronization during face-to-face communication.
Yun, K. (2013). On the same wavelength: Face-to-face communication increases interpersonal neural synchronization.

362 Wass, S. V. *et al.* (2020). Interpersonal neural entrainment during early social interaction.
Brockington, G. *et al.* (2018). From the laboratory to the classroom: The potential of functional near-infrared spectroscopy in educational neuroscience.
Kostorz, K. *et al.* (2020). Synchronization between instructor and observer when learning a complex bimanual skill.

363 Dikker S. *et al.* (2017). Brain-to-brain synchrony tracks real-world dynamic group interactions in the classroom.

364 Bevilacqua, D. *et al.* (2018). Brain-to-brain synchrony and learning outcomes vary by student–teacher dynamics: Evidence from a real-world classroom electroencephalography study.

activation[365], by recruiting attention[366], by the teacher's monitoring of the student's learning stage[367] and by support activities created by teachers in asking guiding questions or in giving tips[368]. Interactions via dialogues also studied by researchers at the University of Buenos Aires and the University Hospital of Zurich[369] showed that participants' brain activity increased in mutual proportion during teaching and learning dialogic processes (questions and answers). The observed increase generated more effective learning. Case in point, dialogues facilitate previous memory retrieval and, for students that do not have such memories, they seem to stimulate new information processing[370].

Neuroscience then has shown that participatory teaching and learning activities[371] – which entail active social interaction between student-teacher, student-student, and whole groupings – have greater pedagogical effectiveness than passive activities. Group discussions, collaborative learning, and student-teacher or student-student dialogues are a few examples. The reason for effectiveness lies in combining attentional focus and motivation related to brain synchronization, that is, the collective engagement in the same objective or interest. Social interactions synchronize everyone in the education process towards a common goal – learning.

## *Transforming principle three into action*

The human brain is social[372]. That means bonding with other people is a basic human need. We need social interactions to learn and prosper as the human brain is not born ready. Human development does not get predetermined by a fixed or linear genetic programming[373]. Quite the opposite, as the brain is highly malleable and subject to changes during the life course. It is precisely the relationships and experiences in different social contexts that, via **neuroplasticity**, impact both brain architecture and functioning throughout development. The human brain gets shaped by connecting with other brains via social interactions. It happens in affective relationships, meaningful exchanges, confrontations, and challenges generated during these social interactions.

365 Liu, J. *et al.* (2019). Interplay between prior knowledge and communication mode on teaching effectiveness- Interpersonal neural synchronization as a neural marker.

366 Davidesco, I. *et al.* (2019). Brain-to-brain synchrony predicts long-term memory retention more accurately than individual brain measures.

367 Takeuchi, N. *et al.* (2017). Integration of teaching processes and learning assessment in the prefrontal cortex during a video game teaching–learning task.

368 Pan, Y. *et al.* (2020). Instructor-learner brain coupling discriminates between instructional approaches and predicts learning.

369 Holper, L. *et al.* (2013). The teaching and the learning brain: A cortical hemodynamic marker of teacher–student interactions in the Socratic dialog.
Battro, A.M. *et al.* (2013). The cognitive neuroscience of the teacher–student interaction.

370 Goldin, A.P. (2016). Meno, the whole experiment.

371 Lieberman, M. D. (2012). Education and the social brain.

372 Mercer, N. (2016). Education and the social brain: Linking language, thinking, teaching and learning.

373 Osher, D. *et al.* (2018). Drivers of human development: How relationships and context shape learning and development.

According to neuroscience, the social brain is a powerful learning mechanism. When we are in a group, the brain responds by activating neural mechanisms that propel action. There is robust scientific evidence that social interactions are an important learning catalyst[374]. Classroom contexts designed to potentialize social relationships boost motivation[375], self-efficacy perception[376], creativity[377], critical thinking, and problem-solving capacity[378]. Besides, research shows that when students have the chance to participate actively and equally in collaborative learning activities, they experience well-being, satisfaction, or even excitement[379]. Therefore, teaching methodologies that promote and value social interaction can significantly increase academic performance[380]. These methodologies facilitate student communication, sharing, and collaboration to analyze problems, explore ideas, and understand concepts. They make learning more social and attractive. The issue then lingers on how we can capitalize on social factors to teach better and instill in students interest and motivation for effective engagement in learning processes.

**Foster collaborative learning.** In this 21st century, collaboration is a key ability for group work or networks. Collaborative interactions have shared goals and a high level of negotiation, interactivity, and interdependence[381]. Collaborative learning proposals can get developed for different uses, in any subject and grade level[382]. They can happen in the classroom, online, in a laboratory, or a school court. In collaborative situations, students have to think critically and debate over logic and understanding of the topic. Collaborative activities enable students to contribute with their perspectives and participate in a group's diverse answers. These features broaden their scope on a problem. In facing different opinions or interpretations, students need to develop flexibility and their capacity for argumentation and communication. With a group's support, it is more likely that students take chances at being wrong and experience new ways of learning. Evidence shows that collaborative learning boosts time management abilities and enlarges responsibility as a result of fostering group commitment[383] with the added bonus of facilitating the sharing of references, resources, and ideas.

374 Meltzoff, A. N. *et al.* (2009). Foundations for a new science of learning.
375 Immordino-Yang, M., & Sylvan, L. (2010). Admiration for virtue: Neuroscientific perspectives on a motivating emotion.
376 Blazar, D., & Kraft, M. A. (2017). Teacher and teaching effects on students' attitudes and behaviors.
377 Xue, H. *et al.* (2018). Cooperation makes two less-creative individuals turn into a highly creative pair.
378 Hurst, B. *et al.* (2013). The impact of social interaction on student learning.
379 Clark, I., & Dumas, G. (2015). Toward a neural basis for peer-interaction: What makes peer-learning tick?
380 Chandra, R. (2015). Collaborative learning for educational achievement.
381 Lai, E. R. (2011). Collaboration: A literature review.
382 Slavin, R. E. (2014). Cooperative learning and academic achievement: Why does groupwork work?
383 Chandra, R. (2015). Collaborative learning for educational achievement.

Although research[384] shows that cooperative learning has considerable effects on learning, they are not automatic. Planning a successful collaborative learning activity is far from trivial[385]. There needs to be a careful design to safeguard elementary aspects. For example, teachers need to secure that learning tasks distributed to groups (problems, projects, etc.) are complex to avoid easy performance by any single student. They must be open-ended, discovery-type tasks that do not rely on a single answer or solution so that students interact and share resources (knowledge, solution strategies) for successful completion. The more complex the task, the greater likelihood that collaborative learning may lead to better results[386]. It also suggests that professionals should not have a single option choice between collaborative and individual learning. Alternatively, they should vary the approach depending on task complexity.

A key point from research[387] is that, even though teachers acknowledge the importance of developing collaborative abilities in students, their focus inevitably falls on evaluating task performance and acquired knowledge. The problem is that when teachers do not give much attention or value to collaboration, students tend to neglect social interaction. For effective results, teachers should structure tasks to include collaboration goals, and specify basic rules for interactions. Also, students should have equal opportunities for self-assessment of their social and collaborative abilities[388]. Constant teacher feedback is another essential feature[389] in monitoring and regulating student interactions. Teachers should actively walk around monitoring groups to confirm if they are advancing – or not – towards better goal achievement.

**Keep high expectations.** Anyone who has been in a classroom knows how a teacher can change learning into something memorable or an experience to be promptly forgotten. There is little doubt that bonding with a teacher and a teacher's stance in the classroom are crucial aspects of the social dimension of teaching and learning processes. A case in point is teachers' expectations towards students. The topic has been one for fruitful investigations in the last 50 years since the ground-breaking study[390] at Harvard University known as "the Pygmalion Effect". The study's central thesis, later confirmed by other studies,[391]

384 Warfa, A.-R. M. (2015). Using cooperative learning to teach chemistry: A meta-analytic review.
Kyndt, E. *et al.* (2013). A meta-analysis of the effects of face-to-face cooperative learning. Do recent studies falsify or verify earlier findings?

385 Willey, K., & Gardner, A. (2012). Collaborative learning frameworks to promote a positive learning culture.

386 Kirschner, F. *et al.* (2009). A cognitive load approach to collaborative learning: United brains for complex tasks.

387 Le, H. *et al.* (2018). Collaborative learning practices: Teacher and student perceived obstacles to effective student collaboration.

388 Falcione, S. *et al.* (2019). Emergence of different perspectives of success in collaborative learning.

389 Lai, E. R. (2011). Collaboration: A literature review.

390 Rosenthal, R., & Jacobson, L. (1968). *Pygmalion in the classroom: Teacher expectation and pupils' intellectual development.*

391 Hornstra, L. *et al.* (2018). Teacher expectation effects on need-supportive teaching, student motivation, and engagement: A self-determination perspective.
Li, Z., & Rubie-Davies, C. M. (2017). Teachers matter: Expectancy effects in Chinese university English-as-a-foreign-language classrooms.

is that teachers' expectations may affect students' sociopsychological, behavioral, and performance results. Scientific evidence suggests that teachers build expectations for students' performances based on their previous academic performance, their economic status, ethnicity, gender, physical appearance, and other personal attributes. Such expectations influence teacher-student interaction patterns and students' learning opportunities[392]. When teachers have high expectations for students, they believe that all can and will be successful. Accordingly, they set challenging goals, develop high-level activities for all, and give them motivating feedback to exponentiate learning. Also, they celebrate students' progress[393]. Research[394] on interventions designed to enhance novice and experienced teachers' awareness about the impact of their expectations points to positive effects. The moment teachers understand that their expectations can influence how students see themselves and their self-attainment perspectives, they become more careful with classroom interactions to offer equal learning opportunities and a positive environment for all[395]. In Brazil especially, teachers must learn to avoid the detrimental effects of low expectations. Data from teachers' questionnaires for the Basic Education Evaluation System (*Sistema de Avaliação da Educação Básica - Saeb*) show that public school teachers' low expectations start very early: only 16.3% among 5th-grade teachers believe their students will get a college education[396]. Opportunities are needed in teacher induction courses to learn how to deal with low expectations and find ways to overcome them. Creating such opportunities is an essential step for education to break the social inequity chain and become a feasible roadmap for equitable opportunities for every student.

**Develop dialogic classes.** The expository class model has been under heavy criticism, and rightfully so as it relies on a passive teacher-student interaction pattern. But we do not need to 'throw the baby out with the bathing water'. Some expository moments for concept presentations in class are important. The way class follows after concept presentation needs to change, though. First, classes need to include dialogue and active student engagement in knowledge building[397]. Besides, dialogic classes cannot be the only teaching strategy in a teacher's repertoire. These classes need to get articulated

392 Wang, S. *et al.* (2018). A systematic review of the teacher expectation literature over the past 30 years.

393 Rubie-Davies, C., & Rosenthal, R. (2016). Intervening in teachers' expectations: A random effects meta-analytic approach to examining the effectiveness of an intervention.

394 De Boer, H. *et al.* (2018). The effects of teacher expectation interventions on teachers' expectations and student achievement: Narrative review and meta-analysis.
Rubie-Davies, C. *et al.* (2015). A teacher expectation intervention: Modelling the practices of high expectation teachers.
Jones, J. N. *et al.* (2012). The Kalamazoo promise and perceived changes in teacher beliefs, expectations, and behaviors.
Timperley, H. S., & Phillips, G. (2003). Changing and sustaining teachers' expectations through professional development in literacy.

395 Wang, S. *et al.* (2018). A systematic review of the teacher expectation literature over the past 30 years.

396 Interdisciplinaridade e evidências no debate Educacional - IEDE. (2019). Como estão as escolas públicas do Brasil?

397 Howe, C., & Abedi, M. (2013). Classroom dialogue: A systematic review across four decades of research.

with other active learning methodologies that place the student at the center of the education process. A central feature of the dialogic class is a teacher's commitment to teaching students not only a new concept but also how to think about ideas, how to challenge allegations, and how to justify one's positions[398]. Research[399] reveals that the dialogic quality in the classroom correlates positively with students' academic performance and a deeper understanding of complex concepts. Scientific evidence[400] also corroborates the notion that students with low self-perception benefit from an environment conducive to free expression and self-elaboration of thoughts and ideas.

Researchers highlight that as students engage in new thinking and expression routines in constant dialogues with teachers and peers, they gradually internalize this dialogic pattern till it becomes part of their mental models[401]. Hence, after students internalize the pattern, they may use their debating and communication skills in other contexts. It is a high achievement as one's knowledge repertoire is just as valuable as one's capacity for reasoning, processing, interpreting, and eventually creating something new based on one's knowledge[402]. However, this is not a spontaneous or autonomous process. For successful dialogic classes, teachers need to state their expectations for students' participation. Also, they need to value students' reflections, comments, and doubts with positive feedback that strengthen students' belief in their reflective and communicative capacity. Teachers need to secure a classroom environment that is receptive and mutually supportive[403]. To that end, teachers need to have greater access to the evidence base on the real benefits that dialogic classes hold and on strategies to emulate interactions that use dialogue as a learning process catalyst[404]. Research[405] shows that teachers need to learn specific communication abilities designed to challenge students' cognitive and metacognitive thinking. When teachers employ a more challenging language, they can create a dynamic, dialogic atmosphere in the classroom that promotes students' productive participation.

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398 Goldin, A. P. *et al.* (2017). Producing or reproducing reasoning? Socratic dialog is very effective, but only for a few.

399 Muhonen, H. *et al.* (2018). Quality of educational dialogue and association with student's academic performance.
Topping, K. J., & Trickey, S. (2007). Collaborative philosophical inquiry for school children: Cognitive gains at a 2-year follow-up.

400 Pehmer, A.-K. *et al.* (2015). How teacher professional development regarding classroom dialogue affects students' higher-order learning.

401 Gillies, R. M. (2019). Promoting academically productive student dialogue during collaborative learning.

402 Resnick, L. B., & Schantz, F. (2015). Re-thinking intelligence: Schools that build the mind.

403 Reznitskaya, A. *et al.* (2009). Collaborative reasoning: A dialogic approach to group discussions.

404 Muhonen, H. *et al.* (2018) Quality of educational dialogue and association with students' academic performance.

405 Pehmer, A.-K. *et al.* (2015). How teacher professional development regarding classroom dialogue affects students' higher-order learning.
Gillies, R. M. (2004). The effects of communication training on teachers' and students' verbal behaviours during cooperative learning.

**Encourage teacher-student relationships.** During the last decades, a growing research body on education has analyzed students' belonging concerning school. It has evidenced that this feeling correlates positively with school performance, motivation, and dedication to studying, but correlated negatively with delinquency and school dropout[406]. Belongingness starts in the classroom with teacher-student relationships. Neuroscientific research confirms that when a teacher can involve students collectively, recruiting their attention and engagement on the same goal, there is synchronization in students' brain activity, and that generates better information assimilation[407]. A teacher who can manage emotions attains the essential element for class synchronization[408]. A teacher's tone of voice, their way of answering questions, and reacting towards students' behavior shapes the classroom environment and establish the basis for belongingness. Emotions and meaning-making processes about what happens in school may facilitate or hinder group synchronization. Another central element lies in how teachers organize classroom's architecture to promote 'teaching flow'[409] for better learning. Neuroscientific findings[410] show that face-to-face interaction has a crucial role in engagement, proactivity, productivity, creativity, and happiness. To add to that, it enhances brain synchronization more than indirect interactions without visual contact, for instance[411]. That indicates the traditional classroom design, with aligned desks, runs counter to research evidence. For a more effective social interaction, seating arrangements need to favor exchange, sharing, and higher synchronization between students and teachers[412] (T.N.).

*Teaching and learning processes are social phenomena. Social interactions capture the attentional focus and motivation leading to more effective learning.*

406 Trujillo, G., & Tanner, K. D. (2014). Considering the role of affect in learning: Monitoring students' self-efficacy, sense of belonging, and science identity.
Van Houtte, M., & Van Maele, D. (2012). Students' sense of belonging in technical/vocational schools versus academic schools: The mediating role of faculty trust in students.

407 Davidesco, I. *et al.* (2019). Brain-to-brain synchrony predicts long-term memory retention more accurately than individual brain measures.
Pan, Y. *et al.* (2020). Instructor-learner brain coupling discriminates between instructional approaches and predicts learning.

408 Kent, A. (2013). Synchronization as a classroom dynamic: A practitioner's perspective.

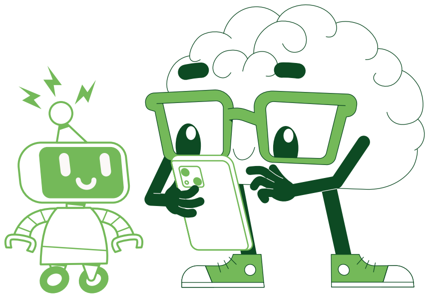
409 Rodriguez, V. (2013). The human nervous system: A framework for teaching and the teaching brain.

410 Yano, K. (2013). The science of human interaction and teaching.

411 Jiang, J. *et al.* (2012). Neural synchronization during face-to-face communication.

412 Park, E., & Choi, B. K. (2014). Transformation of classroom spaces: Traditional versus active learning classroom in colleges.
*Translator's Note: The box containing additional information on this topic in the English version was included for editing purposes.*

## 6.4 TECHNOLOGY USE INFLUENCES INFORMATION PROCESSING AND STORAGE



Humans create technology. And technology shapes humans[413]. Throughout evolution, alterations in **brain** structure and functioning enabled the creation of technology resources such as primitive tools, arithmetic systems, spoken and written language[414] that led to other changes in the human brain. About three decades ago, the technological scenario underwent a tremendous revolution with internet access and novel Information and Communication Technology (ICT). This revolution has completely changed human behavior. Although more research is needed, neuroscience has already unraveled brain and behavior changes caused by the use of new technologies that impact learning aspects such as information processing and storage, attention, and social cognition[415].

Neuroimaging studies[416] from a Chinese-American partnership showed that internet use is conducive to a more effective information search. In addition, it correlates with alterations in the **myelination** of **axon** bundles that interconnect **frontal, parietal**, **temporal**, and **occipital lobes**. However, they found evidence showing participants had less brain activation when trying to remember information from internet searches both in information processing areas and in long-term storage key areas. The decreased activation led to more difficulty in retrieving information later.

Findings from research at the University of California[417] show the internet has become something of an external transient memory. The research suggests that human memory processes adapt to new ICTs, and that humans are increasingly developing symbiotic relationships with digital tools. In a series of experiments, researchers demonstrated that people trusted the internet with knowledge recovery. Their behavior may be reducing the need for information processing and registration in memory. A different study[418] examined digital technology effects on memory and evidenced that taking

413 Osiurak, F. *et al.* (2018). How our cognition shapes and is shaped by technology: A common framework for understanding human tool-use interactions in the past, present, and future.

414 Loh, K. K., & Kanai, R. (2016). How has the internet reshaped human cognition?

415 Firth, J. *et al.* (2019). The "online brain": How the Internet may be changing our cognition.

416 Dong, G. *et al.* (2017) Short-term internet-search training is associated with increased fractional anisotropy in the superior longitudinal fasciculus in the parietal lobe.
Dong, G., & Potenza, M. N. (2015). Behavioural and brain responses related to Internet search and memory.

417 Sparrow, B. *et al.* (2011). Google effects on memory: Cognitive consequences of having information at our fingertips.

418 Henkel, L. A. (2014). Point-and-shoot memories: The influence of taking photos on memory for a museum tour.

photos of museum artifacts, as opposed to observing them, resulted in more difficulty in remembering them, their characteristics, and location in the museum. Participants in the study put less effort into processing and storing information about the artifacts once they knew they could easily access such information for the objects photographed.

Trusting technology as an external memory may result in less effort for learning and a superficial information processing[419]. On the internet, this can be attributed to hypertext environments which lead to screen overload and nonlinearity in information presentation. This generates cognitive overload[420] and prevents a deep, more elaborate information processing. For Naomi Baron[421], an American language researcher, the format of digital technologies is conducive to reading with a different mindset from the one we trained to employ for printed formats. She suggests that such fast and superficial behavior for reading and accessing information may also extend to reading purposes that demand concentration and immersion. According to Marianne Wolf, a neuroscientist and dyslexia researcher from the University of California in Los Angeles (UCLA), superficial information processing may prevent deep reading – an ability related to **neural circuitry** reorganization for reading that demands cognitive processes like attention, previous knowledge retrieval, inferential reasoning, critical thinking, insight, and reflection[422].

As digital technologies become more integrated into daily life, the internet gets more efficient in getting our attention and mobilizing multitasking. This phenomenon is especially noticeable in early adolescents[423]. Research[424] found that multitasking, which also includes social media use in learning contexts, may interfere with students' capacity for cognitive processing and negatively affect their academic performance. Due to a large number of studies, we present, later in this chapter, two principles[425] to explain the importance of attention and the impact of multitasking on the learning process.

*Multitasking may interfere with students' cognitive processing and negatively afffect their academic performance.*

419 Loh, K. K., & Kanai, R. (2016). How has the internet reshaped human cognition?

420 DeStefano, D., & LeFevre, J.-A. (2007). Cognitive load in hypertext reading: A review.

421 Baron, N. S. (2017). Reading in a digital age.

422 Wolf, M., & Barzillai, M. (2009). The importance of "deep reading" in a digital culture.

423 Baumgartener, S. E. *et al.* (2018). The relationship between media multitasking and attention problems in adolescents: Results of two longitudinal studies.
Crone, E. A., & Konijn, E. A. (2018). Media use and brain development during adolescence.

424 Cain, M. S. *et al.* (2016). Media multitasking in adolescence.
Demirbilek, M., & Talan, T. (2018). The effect of social media multitasking on classroom performance.

425 Principle 7: Attention is the gateway for learning
Principle 8: The brain does not multitask.

Another aspect studied in neuroscience is the relationship between social cognition and technology and its effects on brain functioning. Social media enable sharing, comparing, and giving feedback on information, messages, ideas, and opinions[426]. Neuroimaging studies show that **neural circuits** for offline social cognition also get recruited for online social cognition. Therefore, educational technologies that favor students' communication, discussion, and collaboration – irrespective of place and time – to analyze problems, explore ideas, and understand concepts may exponentiate individual learning potentials via social interaction[427].

However, there are some studies[428] showing the negative effect of social media, mainly for children and adolescents whose brain areas related to the **reward system** and inhibitory control are in development[429]. Examples cover cyberbullying, self-esteem and mental health alterations, and sleep deprivation. Also, there may be an empathy decrease due to fewer face-to-face interactions. Social media overuse and (or) dependence may restrict time for 'real world' social interactions. Taken together, they all may interfere with the development of students' social, emotional, and cognitive abilities and impact their learning process.

Possibilities for ICTs in education are varied and exponential. Neuroscientific research on this topic is still in the first steps. For this reason, scientific evidence on the influence of diverse technologies over **mental functions** for learning, such as emotion, motivation, attention, memory, and **executive functions** remain controversial[430]. Easy and fast access to a myriad of information and constant stimuli furnished by connectivity are still under debate in scientific arenas. Researchers suggest[431] more guidelines on technology use for learning. Education needs to develop students' abilities for concentration, self-control, critical thinking, creativity, and healthy social interaction so that they can make the best use of technology for learning. To that end, they need to be instructed for that lest some harm to cognitive functions, mental health, and social interactions due to over- or misuse of available technologies[432] may come forward.

426 Meshi, D. *et al.* (2015). The emerging neuroscience of social media.

427 Falk, E. B., & Bassett, D. S. (2017). Brain and social networks: Fundamental building blocks of human experience.

428 Yamamoto, J., & Ananou, S. (2015). Humanity in the digital age: Cognitive, social, emotional, and ethical implications.
Firth, J. *et al.* (2019). The "online brain": How the Internet may be changing our cognition.

429 Giedd, J. N. (2012). The digital revolution and adolescent brain evolution.

430 Wilmer, H. H. *et al.* (2017). Smartphones and cognition: A review of research exploring the links between mobile technology habits and cognitive functioning.
Choudhury, S., & McKinney, K. A. (2013). Digital media, the developing brain and the interpretive plasticity of neuroplasticity.
Lodge, J. M., & Harrison, W. J. (2019). The role of attention in learning in the digital age.

431 Hoehe, M. R., & Thibaut, F. (2020). Going digital: How technology use may influence human brains and behavior.

432 Small, G. W. *et al.* (2020). Brain health consequences of digital technology use.

## *Transforming principle four into action*

Although the digital revolution is over 50 years in the run, it was only in the last decade that education became more digitalized as schools sought to incorporate new technologies into teaching and learning processes. Many schools, mainly in the private sector, have adopted smartphones, laptops, and tablets as learning tools. Thus, children and adolescents are increasing their screen time during class. The question remains: what is technology's real contribution to the learning process? Is it the best way for students? Undoubtedly, technology has come to stay and is a fixture of modern life. However, the central issue is identifying benefits and mapping out losses to boost the benefits and minimize the harm technology brings to learning.

Veteran American class teachers Joe Clement e Matt Miles[433] noticed a change in classroom learning patterns over the last decade: a significant difference in children's and youngsters' capacity for concentration, social interactions, and critical thinking. Several teachers subscribe to that. They feel powerless to contain distractions caused by smartphones. They know that it is important to decrease multitasking but to demand effort and persistence to an ever-increasing immediatist generation is a tall order. A study[434] developed at Zayed University, in the United Arab Emirates, confirms that technology overuse may lead to a possible performance decline in reading and writing. Other researchers[435] endorse that and state that the digital revolution has reshaped the way students read, write, and access information.

But this is just one side of the story. Many studies highlight technology's positive aspects for teaching and learning processes[436]. Technology in the classroom has helped teachers personalize teaching (adaptive platforms). Stimuli diversity, such as images, podcasts, applications, has broadened students' perspectives, boosted autonomy in information search (Google) by connecting curriculum components to real life (Google Earth, videos), and involved students in projects (hands-on learning, fab labs, robotics) thus raising interest for learning.

It has also broadened students' perspectives via stimuli diversity (images, podcasts, applications), boosted their autonomy in information search (Google), connected curriculum components to real life (Google Earth, videos), and engaged students in projects (hands-on learning, fab labs, robotics) thus raising their interest in learning.

433 Clement, J., & Miles, M. (2017). *Screen schooled: Two veteran teachers expose how technology overuse is making our kids dumber.*

434 Alhumaid, K. (2019). Four ways technology has negatively changed education.

435 Baron, N. S. (2017). Reading in a digital age.
Wolf, M., & Barzillai, M. (2009). The importance of deep reading.
Greenfield, P. M. (2009). Technology and informal education: What is taught, what is learned.

436 Harper, B., & Milman, N. B. (2016). One-to-one technology in K–12 classrooms: A review of the literature from 2004 through 2014.

It is a fact that new technologies have enabled school innovation with new environments and teaching methodologies.

The problem is that we still do not know to what extent this innovation is indeed improving learning. OECD reports (2015)[437] show results that technological promise has yet to be seen in education[438]. Scientific evidence is a safe harbor, helping educators steer the course and choose the best route in using technology to benefit learning. Based on the current neuroscientific evidence previously discussed, the following indications may help achieve such benefits.

**Offer support and guidance. Use technology to tap into learning.** Digital natives have full command of technological tools and navigate the digital world much better than most of their teachers who belong to previous generations. However, it is a mistake to think that tech-savvy students are better prepared to deal with the cognitive challenges new technologies impose[439]. Successful learning results from a set of highly specialized cognitive processes that enables us to select, process, store, and retrieve information in efficient ways[440]. The neural basis for such processes is innate, but students only develop them via interaction. In school, teachers are instrumental to promote the cognitive processes necessary for learning. Information selection online imposes at least two major challenges: excess and trustworthiness. Students need guidance on using selection strategies and dealing with fake news. By employing self-monitoring strategies, they can improve their navigation in hypertext online environments. Success in information processing and storage depends on the quality of cognitive operations recruited. In giving activities and guidance, teachers should take students beyond face value, pushing them towards seeking multiple answers, deepening reflection, considering and assessing different perspectives, establishing connections, comparing ideas, and imagining possibilities. It urges students to take a proactive stance in exploring the web's potential and going beyond superficial information processing.

**Develop deep reading.** In an increasingly digital world, it is likely that readers gradually spend more time reading on different screens. Research in neuroscience already presented here shows that cognitive overload caused by internet environments may lead to superficial information processing. Other studies indicate that students score lower in text comprehension[441] when reading on screens (versus paper). What is more, they

437 OECD (2015). *Students, computers and learning: Making the connection.*
438 Lorenzo, M. F., & Trujillo, C. M. (2018). Cognitive processes, ICT, and education: A critical analysis.
439 Kirschner, P. A., & Bruyckere, P. D. (2017). The myths of the digital native and the multitasker.
440 Loh, K. K., & Kanai, R. (2016). How has the internet reshaped human cognition?
441 Ackerman, R., & Goldsmith, M. (2011). Metacognitive regulation of text learning: On screen versus on paper.

provide better answers to open questions that demand inferential reasoning[442] when reading on paper. What we read – and how deeply we do that – shapes our brain, but expert readers rarely get developed without guidance and instruction[443]. And here comes the major role of education. Students need cognitive strategies that enable deep reading, not only in print but also on screens.

Research[444] reveals printed texts are still a valuable tool for developing reading skills, both basic and complex, for school-aged children who are developing self-monitoring abilities. The reason lies in the limit to text size on mobile devices and challenges in the internet environment. For youngsters and adolescents, it is essential to raise awareness about how they read on-screen by developing their metacognition. Teachers can mediate reading by helping students to think about what they have understood from the text. Also, teachers must survey how much students have focused on the text, if they have analyzed it critically, if they have correlated it with other information, and if they have made inferences. Teachers can also stimulate actions, like notetaking and highlighting during reading. These are routine strategies in print but very scarcely used on screens. The core issue here is making sure that adolescents, who are used to reading fast and superficially, may exercise concentration and text immersion to benefit from the cognitive processes that reading offers.

**Boost motivation for reading.** In a non-stop, tech innovative context, using strategies is key to developing and holding students' interest in reading and for books, print or digital, as reading skills only get developed with practice. Research[445] done with an Australian sample of 8- to 11-year-old children showed that reading frequency decreased consistently when they had access to a greater variety of mobile devices. The motto 'learn for the future' is frequently associated with digital and technological skills. But scientific evidence gives us good reasons to believe that schools must double their efforts in motivating students for reading and rising deep reading time on par with digital and technological skills. Deep reading, then, is key for more productive web navigation and greater mastery of new technologies. Most importantly, deep reading safeguards fulfilling learning over the lifespan. Children and youngsters must acquire a love for reading and develop deep reading skills in a digital era.

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442 Kaufman, G. F., & Flanagan, M. (2016). High-low split: Divergent cognitive construal levels triggered by digital and non-digital platforms.

443 Wolf, M., & Barzillai, M. (2009). The importance of deep reading.

444 Delgado, P. *et al.* (2018). Don't throw away your printed books: A meta-analysis on the effects of reading media on reading comprehension.

445 Merga, M. K., & Roni, S. M. (2017). The influence of access to eReaders, computers, and mobile phones on children's book reading frequency.

**Foster authorship.** Since 2012, the research[446] *TIC kids online Brasil* shows that children and adolescents spend increasingly more time on several digital devices, a reality also found in other countries. A survey by Common Sense Media[447] detailed the habits and preferences for screen time of 8-18 aged Americans and found that, for the most time, they are involved with entertainment (music, videos, games), socializing (social media, chats), and information search (internet navigation). A conclusion is that adolescents use only around 3% of the time dedicated to technology to explore digital media to create their content. Technology may be a terrific tool for self-leadership and authorship. Teachers may contribute by guiding students not only to consume but also to create digital content. Currently, several applications and tools enable students to write, record, film, create, project, and code using digital media. Teachers can create challenges and opportunities to develop students' critical thinking and creativity in including activities that explore new technologies.

*New technologies have facilitated teaching personalization, collaborative learning, and student autonomy. However, if proper guidance fails, technology use may lead to multitasking with the fast, superficial information processing harmful to learning.*

446 Comitê Gestor da Internet no Brasil CGI.br. (2019). TIC Kids online Brasil: Pesquisa sobre o uso da internet por crianças e adolescentes no Brasil.

447 Common Sense. (2015). The Common Sense Media: Media use by tweens and teens.

## 6.5 EMOTION STEERS LEARNING

Research in neuroscience has challenged the idea of an opposition between cognition and emotion by revealing that this dualism cannot be found in the **brain**'s architecture[448]. Human mental functioning is not an oppositional battling field of deliberate reason versus impulsive, irrational emotion[449]. It is also not a simple reciprocal influence, but an interdependence for cooperative action for the brain to function.[450]. Such cooperation enables managing daily interactions in social and culturally specific contexts over the lifespan for better adaptation and well-being[451]. Emotion and cognition are inseparable processes that result from **neural network** activity with reciprocal connections and influences[452]. From a neuroscientific standpoint, it is impossible to build memories, do complex thinking, or make meaningful decisions without emotion. They are a crucial aspect of *how, what, and why* people think, remember and learn[453].

Neuroimaging and psychometric techniques[454] showed brain regions once considered purely 'emotional' (for example, the **amygdala**) or 'cognitive' (for example, the **prefrontal cortex**) interact in an intimate, dynamic way to enable complex processes such as learning. Emotions, also taken as experiences' 'affective filter' are generated by the joint activation of 'emotional' and 'cognitive' neural networks. This neural activity enables gauging the relevance and meaning-making of something one has experienced, like a math class. For that gauging, students' brains take in **mental representations** already stored related to needs, goals, values, well-being, social relationships, self-perception, and one's ability to deal with experience (Figure 5).

448 Pessoa, L. (2008). On the relationship between emotion and cognition.
Lindquist, K. A., & Barrett, L. F. (2012). A functional architecture of the human brain: Emerging insights from the science of emotion.

449 Brosch, T. *et al.* (2013). The impact of emotion on perception, attention, memory, and decision-making.

450 Duncan, S., & Barrett, L. F. (2007). Affect is a form of cognition: A neurobiological analysis.

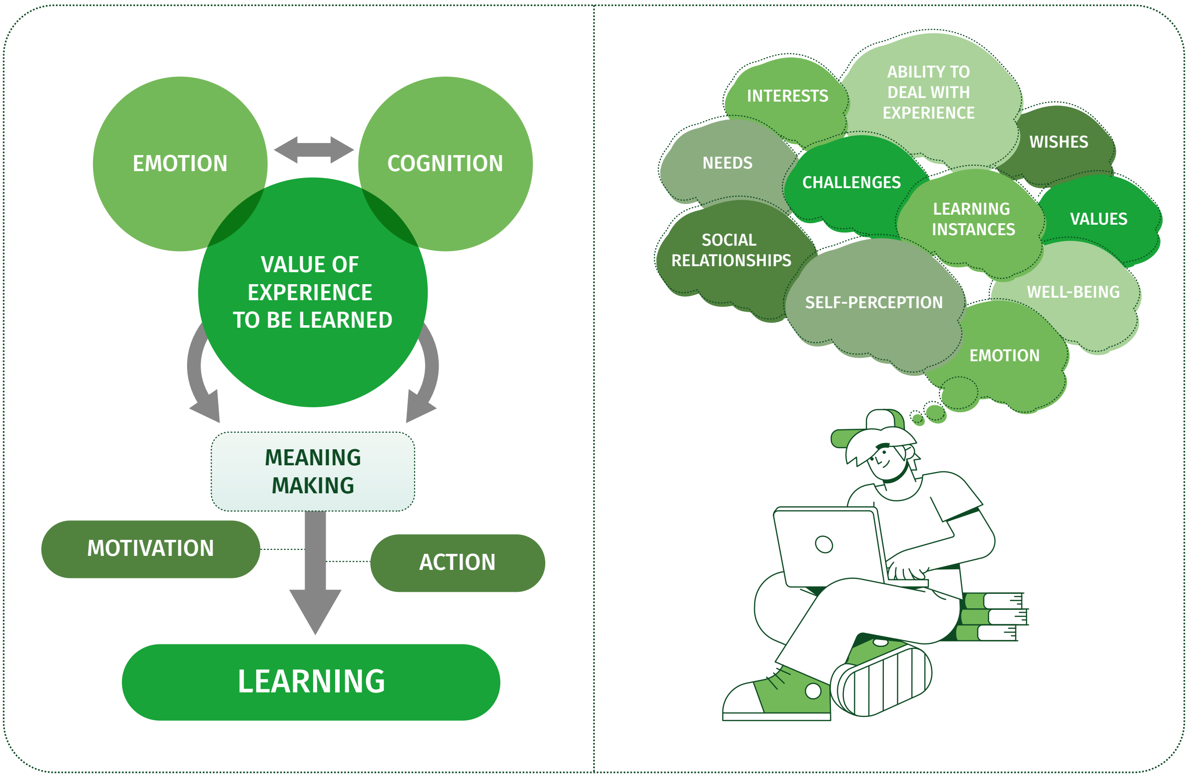
451 Immordino-Yang, M. H., & Damasio, A. (2007). We feel, therefore we learn: The relevance of affective and social neuroscience to education.
Immordino-Yang, M. H., & Gotlieb, R. (2017). Embodied brains, social minds, cultural meaning: Integrating neuroscientific and educational research on social-affective development.

452 Pessoa, L. (2017). A network model of the emotional brain.
Damasio, A., & Carvalho, G. B. (2013). The nature of feelings: Evolutionary and neurobiological origins.

453 Immordino-Yang, M. H. (2015). *Emotions, learning, and the brain: Exploring the educational implications of affective neuroscience.*

454 Barrett, L. F., & Satpute, A. B. (2013). Large-scale brain networks in affective and social neuroscience: Towards an integrative functional architecture of the brain.
Dolcos, F. *et al.* (2011). Neural correlates of emotion-cognition interactions: A review of evidence from brain imaging investigations.

**FIGURE 5 –** Meaning Making in Learning




The result from gauging equals the students' 'feeling' about the math class, for instance, that can lead to their interest or boredom, excitement or anxiety, pride or shame, ability or unpreparedness. Emotions thus generated are dependent on one's environment, life story, and personal characteristics[455]. How one feels influences *what, and how* effectively one learns. From this emotional response to experience, other neural **circuits** are get activated. Their activation may generate physiological responses, motor expressions, greater or lesser motivation, other **mental functions'** recruitment**,** and action planning and execution. These internal cognitive and emotional processes lead to reflection over one's learning[456] . This reflection, in turn, makes one reshape one's learning and impacts one's stance towards learning[457] leading to paying attention (or not) in class, making questions (or not), dedicating to study (or not). This mechanism shows how emotions steer learning.

455 Immordino-Yang, M. H. *et al.* (2018). *The brain basis for integrated social, emotional, and academic development: How emotions and social relationships drive learning.*

456 Fadel, C. *et al.* (2015). *Four-dimensional education: The competencies learners need to succeed.*

457 Immordino-Yang, M. H. (2009) Our bodies, our minds, our selves: Social neuroscience and its application to education.

Research groups in Malaysia[458] and Switzerland[459] in partnership with Israel and the USA[460] confirmed the interdependence between emotions and a set of crucial mental processes – like attention, memory, motivation, and **executive functions** – for a successful learning process. Emotions can mobilize and regulate these processes via reciprocal connections that the amygdala has with other areas in the nervous system[461]. When a processed stimulus is deemed relevant, the amygdala acts on **frontal** and **parietal circuits** that regulate attention, making one focus one's attention selectively on this stimulus while ignoring others. Attentional focus contributes to a better, more precise stimulus perception as the amygdala also acts on perception processing areas. Concerning memory capacity, experiences and information that trigger emotions tend to be better encoded, consolidated, and easily retrieved. Studies show that the amygdala influences the prefrontal cortex, central for encoding and forming memories, and the **hippocampus**, a key structure for long-term memory retention and successful learning. Of note, it is the relevance of the stimuli and experiences that generates these effects.

Emotions also influence motivation. Recent studies[462] in neuroscience show that these processes share neural circuits and are deeply intertwined. Although many aspects of the 'affective neural network' functioning need explaining, we already know such processes cooccur and guide one's behavior. As motivation is essential for the educational process[463], we elaborated a specific principle[464] to be presented next that explains the importance of motivation and the impact this mental function has on the learning process.

Our decisions are guided by emotions held when deciding or by the emotions that a decision will trigger[465]. The amygdala, which checks how threatening a situation is, connects to the **nucleus accumbens**, a structure that detects the reward likelihood for a given decision. The amygdala also harbors connections to different circuits in the prefrontal cortex, which elaborates behavior strategies. It is the joint activity of such circuitry that guides decision and motivation for action-dependent actions[466]. This mechanism demonstrates that if we change our emotions, we can change our decisions and, ultimately, our behavior.

458 Tyng, C. M. *et al.* (2017). The influences of emotion on learning and memory.

459 Brosch, T. *et al.* (2013) The impact of emotion on perception, attention, memory, and decision-making.

460 Okon-Singer, H. *et al.* (2015). The neurobiology of emotion–cognition interactions: Fundamental questions and strategies for future research.

461 Peterson, D. (2017). Looping circuits: Amygdalar function and interaction with other brain regions.

462 Cromwell, H. C. *et al.* (2020). Mapping the interconnected neural systems underlying motivation and emotion: A key step toward understanding the human affectome.

463 Headen S., & McKay, S. (2015). *Motivation matters: How new research can help* teachers *boost student engagement.*

464 Principle 6: "Motivation sets the brain into learning mode".

465 Phelps, E. A. *et al.* (2014). Emotion and decision making: Multiple modulatory neural circuits.
Brosch, T. *et al.* (2013) The impact of emotion on perception, attention, memory, and decision-making.

466 Cosenza, R. M. (2016). *Por que não somos racionais: Como o cérebro faz escolhas e toma decisões.*

Neuroscientific evidence has shown that reciprocal connections between the prefrontal cortex and amygdala also enable emotional regulation[467]. Cognitive control by the prefrontal cortex enables inhibition of negative emotional responses that interfere with social relationships and learning performance. A study at Columbia University[468], in the USA, explained how nervous system structures – the prefrontal cortex in specific- involved in emotional regulation mature later and conclude development at the end of adolescence. It means that children and pre-adolescents need support to deal with their emotions. That is why researchers underscore the benefits of investing in the development of socioemotional abilities, not only because of the reasons already explored here, but also because they may buffer students' mental health[469] and enhance their academic performance[470].

Of note, emotions triggered by situations that may cause stress and anxiety may negatively impact learning[471]. Cortisol, the main hormone released during stress, modifies both structure and function of neurons in the hippocampus, amygdala, and prefrontal cortex[472]. These structures, related respectively to memory, emotion, and executive functions, are essential for learning. Research conducted at the University of Hamburg in Germany[473] showed that exams, short deadlines, and interpersonal conflict trigger stress at school and influence memory consolidation and recovery. However, such effect on memory and learning varies according to stress type, moment, and duration. Anxiety may 'disorient' learning. A couple of studies[474] indicate that students who get math anxiety can indeed have difficulties and worse performance in math tasks. This finding correlates with brain structure alterations for emotion processing. However, other scientific evidence points towards decreasing anxiety and better performance due to tutoring interventions.

467 Morawetz, C. *et al.* (2017). Effective amygdala-prefrontal connectivity predicts individual differences in successful emotion regulation.
Ochsner, K. N. *et al.* (2012). Functional imaging studies of emotion regulation: A synthetic review and evolving model of the cognitive control of emotion.

468 Martin, R. E., & Ochsner, K. N. (2016). The neuroscience of emotion regulation development: Implications for education.

469 Ahmed, S. P. *et al.* (2015). Neurocognitive bases of emotion regulation development in adolescence.

470 Alzahrani, M. *et al.* (2019). The effect of social-emotional competence on children academic achievement and behavioral development.

471 Prokofieva, V. *et al.* (2019). Understanding emotion-related processes in classroom activities through functional measurements.

472 McEwen, B. S. *et al.* (2016). Stress effects on neuronal structure: Hippocampus, amygdala, and prefrontal cortex.

473 Vogel, S., & Schwabe, L. (2016). Learning and memory under stress: Implications for the classroom.
Schwabe, L., & Wolf, O. T. (2010). Learning under stress impairs memory formation.

474 Kucian, K. *et al.* (2018). Neurostructural correlate of math anxiety in the brain of children.
Dowker, A. *et al.* (2016). Mathematics anxiety: What have we learned in 60 years?

## *Transforming principle five into action*

Advances in neuroscience explain that emotion and cognition are closely interrelated in the human brain and contribute to the complexity of human behavior[475]. Of note, evidence suggests that mental functions recruited during the learning process, like attention, memory, language, and logical reasoning, are deeply interconnected to emotional and social processes[476]. Such evidence points towards a paradigm change – from one solely concerned to cognitive processes to another that recognizes emotional and social substrates of human cognition.

In teaching systems worldwide, there is growing recognition that socioemotional learning[477] needs factoring into a pedagogical practice based on holistic education[478], one that encompasses students in all their dimensions. Every committed teacher acknowledges that emotions affect students' performance[479]. What may not be so clear is what it means to work with emotions in the classroom and how teachers can do so.

For a comprehensive understanding, a first step is recognizing that emotions get in the way of how students access, process, consolidate and recover information and experiences[480]. And all that is related to meta-learning processes[481]; cognitive and emotional internal processes that enable reflection and shape learning. Working with emotions in the classroom means designing contexts and learning situations conducive to intentional management of emotional factors that regulate learning. It entails going beyond knowledge teaching. It means committing to the task of offering students opportunities that: (i) make sense and change learning into something personally relevant[482]; (ii) internalize a growth mindset that strengthens self-confidence[483]; and (iii) develop socioemotional abilities that enable students to face challenges outside schools. Some key elements for reaching these goals are the quality of student-teacher bonds and a positive classroom environment.

475 Okon-Singer, H. *et al.* (2015). The neurobiology of emotion–cognition interactions: Fundamental questions and strategies for future research.

476 Immordino-Yang, M. H., & Damasio, A. (2007). We feel, therefore we learn: The relevance of affective and social neuroscience to education.

477 Chernyshenko, O., Kankaraš, M., & Drasgow, F. (2018), Social and emotional skills for student success and well-being: Conceptual framework for the OECD study on social and emotional skills

478 Barros, R. P., *et al.* (2018). Desenvolvimento socioemocional: Do direito à educação à prática na escola.

479 Mega, C. *et al.* (2014). What makes a good student? How emotions, self-regulated learning, and motivation contribute to academic achievement.

480 Brosch, T. *et al.* (2013) The impact of emotion on perception, attention, memory, and decision-making.

481 Fadel, C. *et al.* (2015). *Four-dimensional education: The competencies learners need to succeed.*

482 Immordino-Yang, M. H. (2016). Emotion, sociality, and the brain's default mode network: Insights for educational practice and policy.

483 Mangels, J. A. *et al.* (2006). Why do beliefs about intelligence influence learning success? A social cognitive neuroscience model.

Many teachers believe investments in students' socioemotional development are desirable. However, they think this investment takes time and focus away from their core activity – teaching curricular components. Teachers need to see that investing in emotional development, far from disturbing their routine work, exponentiates students' outcomes and positively impacts academic performance[484]. The Brazilian National Common Core Curriculum (*Base Nacional Comum Curricular - BNCC*)[485] provides a set of ten general competencies that should be interrelated and reflected in teaching the different curriculum components. Developing such competencies is only possible once one is committed to integrating cognitive and emotional processes in the classroom.

Given such a far-reaching educational goal, teachers must broaden their understanding of learning's emotional dimension and its actionable factors. Current evidence on brain functioning[486] gives insights into the neuropsychological mechanisms for learning's emotional processing[487] and enables a set of suggestions that teachers may follow to align emotions for meaningful learning.

**Care for relationships with students.** Emotional language belongs to the body first and words later. That is why a teacher's body posture, attitudes, and behavior are crucial to student-teacher relationships and teaching and learning processes[488]. Teaching entails not only knowledge transmission, but also a set of feelings permeated by emotions. Teachers pass on to students whether they are passionate for the subject; whether they like being a teacher and having students around in the classroom; whether they believe in students' potential and in being able to help them; whether questions are forthcoming, and whether all have opportunity to speak up. It is the total sum of such feelings that teachers manifest in their practice and that directly impacts their teaching approach[489], classroom emotions[490] and relationship quality[491]. Learning happens if only there is trust and openness in student-teacher relationships permeated by an atmosphere of affection and personal commitment created by teachers. Caring for relationships with students is the first step for a teaching practice built on emotions.

484 Alzahrani, M. *et al.* (2019). The effect of social-emotional competence on children academic achievement and behavioral development.
Durlak, J. A. *et al.* (2011). The impact of enhancing students' social and emotional learning: A meta-analysis of school-based universal interventions.

485 BRASIL. Ministério da Educação (2017). Base Nacional Comum Curricular: Educação é a base.

486 Immordino-Yang, M. H., & Gotlieb, R. (2017). Embodied brains, social minds, cultural meaning: Integrating neuroscientific and educational research on social-affective development.

487 Immordino-Yang, M. H. (2016). Emotion, sociality, and the brain's default mode network: Insights for educational practice and policy.

488 Cosenza, R., & Guerra, L. (2011). *Neurociência e Educação: Como o cérebro aprende.*

489 Chen, J. (2019). Exploring the impact of teacher emotions on their approaches to teaching: A structural equation modelling approach.

490 Hosotani, R., & Imai-Matsumura, K. (2011). Emotional experience, expression, and regulation of high-quality Japanese elementary school teachers.

491 Lei, H. *et al.* (2018). The relationship between teacher support and students' academic emotions: A meta-analysis.

**Develop socioemotional abilities.** Given the rapid-changing current scenario and upcoming challenges, preparing students based on academic or technical skills will not be enough for a successful personal and professional life. Socioemotional skills such as openness, empathy, flexibility, and resilience are increasingly necessary. They regulate thoughts and behaviors as they mainly relate to how people manage their emotions, perceive themselves, and get involved with others[492].

Research advances on socioemotional abilities[493] led to their inclusion in curricula and educational practices and policies of teaching systems all over the world. In Brazil, socioemotional skills got terrain and visibility in the common core (*BNCC*)[494] and have been constantly debated in education. Although there is growing recognition of their importance, there is still little teachers' awareness about 'what works' in stimulating and evaluating them. There is a vast literature on the topic, and different programs are designed and used for such purposes. Given that socioemotional skills are part of an official normative document, expectations are for effective development in Brazilian schools.

**Create a positive classroom environment.** The classroom environment may exponentiate emotions – positive or negative. That is why teachers' ability to manage instances and social relationships is fundamental[495]. Teachers know well what may threaten a positive climate in the classroom: lack of students' motivation, problems at home, bullying, competition, indiscipline, test pressure are some. Although teachers may not control all these factors, they can use strategies[496] that reduce their negative effects. After all, evidence shows that emotions impact academic performance directly[497]. A strong feeling of belonging is fundamental to forge an environment where everyone can manifest one's self-worth and individuality. Teachers can create opportunities so that each student makes meaningful contributions to the group and show what s/he can achieve. Emotions mobilized by social values are powerful to strengthen self-image and group cohesion. To seize what a teacher is trying to convey, students need to feel safe, respected, and valued by those surrounding them. Teachers need to enable collaborative work opportunities for meaningful student interactions in a non-competitive environment. Being surrounded by a supportive community that

492 OECD. (2018). Social and emotional skills: Well-being, connectedness and success.

493 Osher, D. *et al.* (2016). Advancing the science and practice of social and emotional learning: Looking back and moving forward.

494 BRASIL. Ministério da Educação. (2017). Base Nacional Comum Curricular: Educação é a base.

495 Kashy-Rosenbaum, G. *et al* (2018). Predicting academic achievement by class-level emotions and perceived homeroom teachers' emotional support.

496 Pekrun, R. (2014). Emotions and learning.

497 Pekrun, R. *et al.* (2017). Achievement emotions and academic performance: Longitudinal models of reciprocal effects. Sainio, P. J. *et al.* (2019). The role of learning difficulties in adolescents' academic emotions and academic achievement. Villavicencio, F. T., & Bernardo, A. B. (2013). Positive academic emotions moderate the relationship between self-regulation and academic achievement.

allows for actual relationships among peers[498] generates motivation and engagement in students' learning processes. They have a greater sense of belonging and more positive emotions – what contributes to their academic success[499].

**Make a point of noticing negative emotions.** Neuroscientific evidence[500] reveals that stress and emotions - like anxiety, apathy, fear, frustration - may impact the capacity to pay attention and process information. Situations that are often conducive to negative emotions are those when students face unsurmountable difficulties, when they feel hopeless, get threats or derisive comments, feel overwhelmed by excessive discipline, or are pressed by exams[501]. Teachers must pay attention to such situations to help students overcome them with support and guidance. Negative emotions that get expressed in school may also be related to family or social issues. In this case, it is incumbent on teachers to discuss the problem with school leadership and family to better support the student.

*Emotion attributes value to the experience. It also generates meaning and motivation for learning. Therefore, emotion and cognition are indissociable. Without emotion, there can be no memories, complex thoughts, meaningful decision-making, and social interactions that lead to learning.*

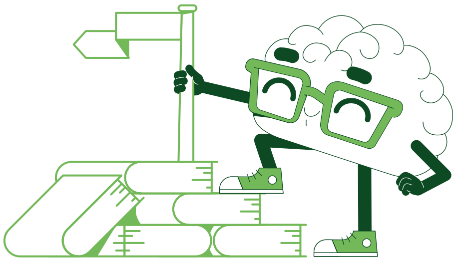
498 Reindl, M. *et al.* (2018). Associations between friends, academic emotions and achievement: Individual differences in enjoyment and boredom.

499 Lam, U. F. *et al.* (2015). It feels good to learn where I belong: School belonging, academic emotions, and academic achievement in adolescents.

500 Prokofieva, V. *et al.* (2019). Understanding emotion-related processes in classroom activities through functional measurements. Klein, E. *et al.* (2019). Anticipation of difficult tasks: Neural correlates of negative emotions and emotion regulation.

501 Cosenza, R., & Guerra, L. (2011). *Neurociência e Educação: Como o cérebro aprende.*

## 6.6 MOTIVATION SETS THE BRAIN INTO LEARNING MODE



Intrinsic motivation is the spontaneous mobilization for action even without rewards or incentives[502]. Such intrinsically motivated behaviors generate satisfaction and pleasure that mobilize voluntary engagement in current or future activities[503]. In psychology, there is a robust research body on intrinsic motivation based on behavioral methods and self-report experiences[504] indicative of a positive correlation between intrinsically motivated students and their learning performance[505]. Neuroscience has unraveled the neurobiological substrates of motivation with assessments of electrical brain activity (electroencephalography), neuroimaging studies (**fNIRS**), and computational models[506]. Results show that motivation is associated with brain activity in areas that gauge the value of experiences – if it is gratifying or rewarding enough to be repeated and maintained over time.

Neuroscientific studies reveal intrinsic motivation may be triggered by a pleasant stimulus, but pleasure alone does not sustain it[507]. Good grades or fun classes may be significant to generate motivation, but they are not sufficient to keep the flow demanded by the learning process. Intrinsic motivation has to do with the satisfaction triggered by activity engagement[508] and with consubstantiated senses that lead to a personal interest in learning.

When we experience something, the **reward system** and emotion regulating structures get activated and yield greater or lesser satisfaction, or even a disagreeable sensation – that makes the brain attribute 'value' to the experience. And we build memories of this experience so that next time around, we can predict the satisfaction it can offer us. It is this capacity for predicting satisfaction for a given experience that generates motivation[509].

502 Domenico, S., & Ryan, R. (2017). The emerging neuroscience of intrinsic motivation: A new frontier in self-determination research.

503 Reeve, J. (2019). Neuroscience of intrinsic motivation.

504 Kruglanski, A. W. *et al.* (2015). Motivation science.
Cook, D., & Artino, A. (2016). Motivation to learn: An overview of contemporary theories.

505 Cerasoli, C. P. *et al.* (2014). Intrinsic motivation and extrinsic incentives jointly predict performance: A 40-year meta-analysis.
Taylor, G. *et al.* (2014). A self-determination theory approach to predicting school achievement over time: The unique role of intrinsic motivation.

506 Murayama, K. (2018). The science of motivation.

507 Berridge, K. C. *et al.* (2009). Dissecting components of reward: 'Liking', 'wanting', and learning.

508 Lee, W. *et al.* (2012). Neural differences between intrinsic reasons for doing versus extrinsic reasons for doing: An fMRI study.

509 Kim, S.-i. (2013). Neuroscientific model of motivational process.

To keep motivation, signals from the reward system and brain areas that process emotion, physiological states, and affective perceptions integrate with the **prefrontal area**, specifically in the **orbitofrontal cortex**. This brain area analyzes the value of an experience gauging the effort needed to have it, the satisfaction it generates, and the perception we have of ourselves together with the memories of past experiences and their value. This is how we form preferences, which may change with each new experience, that influence our choices[510].

The chance of making a personal choice is regarded as a biological and psychological need[511] and a relevant factor in the motivational process[512]. When we make a choice based on the value of an experience, the orbitofrontal cortex activates the **dorsolateral** cortex involved with **executive functions** and jointly set an action course that keeps us engaged in an activity, such as a learning process. A study conducted by Japanese and American researchers[513] showed that choice making contributes to better task performance. The chance to make choices is a core aspect of motivation as it enables selecting higher-value experiences.

The process of regulating motivation takes place when we commit to an experience for longer. This regulation enables cognitive control over goal-set behavior[514]. When we set a goal, we predict future outcomes and the satisfaction they generate. In addition, we need to refrain from urges, needs, impulses, and emotions that compete with the goal we had set. The self-regulation of motivation is related to brain areas that act to keep goals as a high priority, recruiting executive functions for strategic planning, attention maintenance, error detection, performance monitoring, and flexibility to select other strategies[515].

This self-regulation[516] is characteristic of growth-mindset students that believe their capacities and talents may be developed by constant effort and persistence. Studies in psychology[517] show that they have more motivation, self-confidence, and self-regulation for learning than those students who have a fixed mindset and do not acknowledge that

510 Kim, S.-i. *et al.* (2017). Introduction to motivational neuroscience.
511 Leotti, L. A. *et al.* (2010). Born to choose: The origins and value of the need for control.
512 Lee, W., & Reeve, J. (2013). Self-determined, but not non-self-determined, motivation predicts activations in the anterior insular cortex: An fMRI study of personal agency.
Meng, L., & Ma, Q. (2015). Live as we choose: The role of autonomy support in facilitating intrinsic motivation.
513 Murayama, K. *et al.* (2015). How self-determined choice facilitates performance: A key role of the ventromedial prefrontal cortex.
514 Kim, S-i. *et al.* (2017). Introduction to motivational neuroscience.
515 Kim, S-i. (2013). Neuroscientific model of motivational process.
516 Duckworth, A., & Gross, J. (2014). Self-control and grit: Related but separable determinants of success.
517 Mangels, J. *et al.* (2006). Why do beliefs about intelligence influence learning success? A social cognitive neuroscience model.
Zeng, G. *et al.* (2016). Effect of growth mindset on school engagement and psychological well-being of Chinese primary and middle school students: The mediating role of resilience.

their talents can grow. North American researchers[518] using electroencephalography to measure brain activity confirmed that a growth mindset influences activity in areas related to cognitive control. Additionally, neuroimaging studies[519] revealed that such brain areas, which are typically more activated in growth-mindset subjects, also take part in the motivational process thus indicating a probable correlation between growth mindset and motivation.

Neuroscientific studies[520] show a strong relationship between curiosity and intrinsic motivation. Research conducted at the University of California[521] showed that novelty and curiosity-generating situations activate the reward system and its connections with the **hippocampus**. This activation enables higher memory retrieval for such stimuli. Thus, curiosity leads to intrinsic motivation that, in turn, influences memory processing and may contribute to more effective learning.

Although neuroscience has been making important discoveries about motivation[522], there is still a lot to uncover because of the need for investigations into learning and the school environment.

## *Transforming principle six into action*

We cannot foresee the future, but we can rest assured that learning is a lifelong need. The learning cycle will not end in high school or even at the university as we are under constant pressure to learn in this fast-changing world. It justifies the importance of understanding neuroscientific evidence on fostering and keeping the motivation to learn in all stages of human development.

Motivation is the driving force for students to seek information, commit to a task, engage in challenging projects, get interested in research, try out new situations, and mainly, keep wishing to learn. The neuroscientific model[523] of the motivational process reveals that motivation is complex and involves three intrinsically related subprocesses: the first is about generation, the second, maintenance, and the third, regulation. The model indicates that mobilizing motivation for learning is not subsumed to a set of pleasurable

518 Schroder, H. S. *et al.* (2014). Mindset induction effects on cognitive control: A neurobehavioral investigation. Schroder, H. S. *et al.* (2017). Neural evidence for enhanced attention to mistakes among school-aged children with a growth mindset.

519 Wang, S. *et al.* (2018). Neuroanatomical correlates of grit: Growth mindset mediates the association between gray matter structure and trait grit in late adolescence.

520 Oudeyer, P-Y *et al.* (2016). Intrinsic motivation, curiosity, and learning: Theory and applications in educational technologies. Siddique, N. *et al.* (2017). A review of the relationship between novelty, intrinsic motivation and reinforcement learning.

521 Gruber, M. *et al.* (2014). States of curiosity modulate hippocampus-dependent learning via the dopaminergic circuit.

522 Murayama, K. (2018). The science of motivation.

523 Kim, S-I. (2013). Neuroscientific model of motivational process.

and fun activities; it requires a pedagogical practice aligned with several aspects to optimize brain functions related to motivation. Schools, in general, have not traditionally achieved success in intrinsically motivating students to engage them personally with learning. Consequently, many students respond to learning automatically and show interest only in getting a passing grade. How can we change this scenario? Research in neuroscience offers some routes.

**Foster intrinsic motivation.** Literature shows that intrinsically motivated students have a better academic performance[524]. Intrinsic motivation refers to a behavior propelled by self-satisfaction[525] and personal engagement with learning[526]. It is felt when students seek learning because it is meaningful, i.e., it makes meaning for each student, and they find value and relevance in the learning situations. Intrinsically motivated students enjoy activities or see them as opportunities to explore, learn and realize their potential. Their motivation derives from self-actualization rather than external rewards like getting a good grade, approval, or compliment. This does not mean that intrinsically motivated behaviors do not come with rewards. Rather, it means that they do not drive students' behavior. Indeed, teachers have often tried to motivate students by underscoring what is important to learn to get a passing grade, into university, or even a job later on. However, it is crucial that students find relevance in what they are doing in the here and now – as opposed to the future – to feel motivated and engaged in school. To motivate students, the learning process has to be gratifying and interesting[527]. And this is where the problem arises: schools usually place 'rewards' at the end of the process: grades, compliments, approval. To effect, students get driven by these end-goals. The learning process per se is not valued, and students do not get a chance to generate intrinsic motivation throughout the process. This mechanism makes real engagement hard to achieve. Scientific evidence reveals a set of effective strategies to mobilize intrinsic motivation for learning: stimulate a growth mindset, generate self-efficacy, promote autonomy, make room for choice and cultivate curiosity. These strategies are explained below.

**Stimulate a growth mindset.** Neuroscientific evidence[528] reveals the mental model each one builds about their capacities becomes a critical point for regulating and keeping intrinsic motivation over time. Trusting or not one's capacity for development impacts

524 Pascoe, L. *et al.* (2018). Intrinsic motivation and academic performance in school-age children born extremely preterm: The contribution of working memory.

525 Lee, W., & Reeve, J. (2017). Identifying the neural substrates of intrinsic motivation during task performance

526 Mega, C. *et al.* (2014). What makes a good student? How emotions, self-regulated learning, and motivation contribute to academic achievement.

527 Kim, S-I. (2013). Neuroscientific model of motivational process.

528 Ng, B. (2018). The neuroscience of growth mindset and intrinsic motivation.
Schroder, H. *et al.* (2017). Neural evidence for enhanced attention to mistakes among school-aged children with a growth mindset.

students' stance towards their learning and ultimately, their academic performance[529]. Across development, students absorb a composite of messages from family, community, and society about their rights and wrongs, talents and weaknesses, possibilities and limitations. For the American researcher Carol Dweck[530], the way an individual processes these messages emotionally is in tandem with a mental model that guides learning behavior. Students with a growth mindset believe that they can develop, embrace challenges, persist over obstacles, understand that effort is necessary for learning success, deal with criticism better, and learn from their mistakes. Students with a fixed mindset tend to work pushed by teachers, avoid challenges, give up easily, see effort as something negative, ignore feedback, and consequently, fall down on their potential.

A body of research[531] shows teachers have a central role in forming and changing students' mental models. The key lies in the quality of their bond and the kind of feedback[532] they offer. Although common sense may suggest that demotivated students or those that lack confidence may benefit from compliments on their capacity and intelligence, research findings[533] point to recognition of dedication and effort as propellers for students to invest in studying and overcoming a challenge. In addition, teachers need to show confidence in students and offer activities that promote self-efficacy[534] so that they can strengthen the belief that their efforts in school are worthwhile. Whereas some research[535] shows that when a student develops self-efficacy with achievements and successful experiences, s/he gets a motivational boost to keep learning and moving forward, other research also shows that feelings of failure and lack of support undermine intrinsic motivation[536]. Taken together, they underscore the need for students to develop a sense of competence – a feeling that they are well equipped to deal with challenges and evaluations. Most importantly, they must believe that their potential can grow with commitment, practice, persistence, and constant learning.

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529 Blackwell, L. S. *et al.* (2007). Implicit theories of intelligence predict achievement across an adolescent transition: A longitudinal study and an intervention.

530 Dweck, C. S. (2017). *Mindset: a nova psicologia do sucesso.*

531 Boaler, J. (2013). Ability and mathematics: The mindset revolution that is reshaping education.
Zeng, G. *et al.* (2016). Effect of growth mindset on school engagement and psychological well-being of Chinese primary and middle school students: The mediating role of resilience.

532 Bondarenko, I. (2017). The role of positive emotions and type of feedback in self-regulation of learning goals achievement: Experimental research.

533 Dweck, C. S. (2008). *Mindsets and Math/Science achievement.*

534 Komarraju, M., & Nadler, D. (2013). Self-efficacy and academic achievement: Why do implicit beliefs, goals, and effort regulation matter?

535 Joet, G. *et al.* (2011). Sources of self-efficacy: An investigation of elementary school students in France.

536 Au, R. C. P. *et al.* (2010). Academic risk factors and deficits of learned hopelessness: A longitudinal study of Hong Kong secondary school students.

**Make room for choice.** Autonomous movement in learning involves the possibility of making choices. Recent neuroimaging studies show that making choices mobilizes neural circuits involved with motivation processing[537]. This explains why volitive activities generate interest and satisfaction that, in turn, propel voluntary engagement with the activity or context[538]. Therefore, making room for choice has a critical role in promoting intrinsic motivation[539]. It allows for interweaving students' interests with school curricula. In traditional settings, students have not had choices in the classroom. In general, students have got activities that are not personalized. They have not been invited to seek topics of interest or choose books to read and, most often, they have got essays pre-defined by teachers. In promoting choice, teachers make room for students to be responsible for their learning, commit to self-directed activities and find value in their learning. To effect, that arouses intrinsic motivation for what gets processed in the classroom[540].

**Arouse curiosity.** Research[541] shows that when curiosity gets aroused, brain regions associated with motivation and memory activate. In other words, curiosity may be a great motivator that makes the brain want to learn. And questions may be excellent tools for learning. A good question can *open up the mind,* change paradigms, mobilize connections and generate new ideas. For a long time in education, giving answers has received higher value than making questions. But, regarding curiosity, questions, rather than answers, triggers student involvement. Neuroscientific evidence shows that arousing students' curiosity and developing their capacity in making questions should be an educational objective. To attract students, teachers can make open-ended questions that encourage topic exploration – questions not answered with a yes or a no but that require investigation, exploration, and perspective-taking for an answer. However, the other way round is also valid; before a new topic, teachers can ask students to search for some trivia and to elaborate their questions.

Of note in this process is the capacity for teachers to listen. When this capacity is coupled with attention, two important messages remain. First, questions have a place in the classroom. Second, curious students are valued. And this latter point is crucial in a school culture where questioning is still taken to mean that one is 'dumb' or that 'did not understand the message'. By placing value on questions, teachers break away from such stigma and strengthen the idea that those who question are intelligent and interested

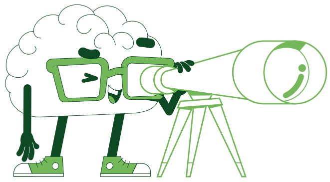
537 Leotti, L. A. *et al.* (2010). Born to choose: The origins and value of the need for control.
538 Reeve, J. (2019). Neuroscience of intrinsic motivation.
539 Meng, L., & Ma, Q. (2015). Live as we choose: The role of autonomy support in facilitating intrinsic motivation.
540 Patall, E. *et al.* (2008). The effects of choice on intrinsic motivation and related outcomes: A meta-analysis of research findings.
541 Gruber, M. J. *et al.* (2014). States of curiosity modulate hippocampus: Dependent learning via the dopaminergic circuit.

in knowing more. Last, it is worth mentioning a meta-analysis by researchers in England and Switzerland[542] that put together data from around 200 studies and over 50,000 students. They found that curiosity has as large an effect on academic performance as intelligence because it propels learning. According to them, stimulating a 'hungry mind' is a cornerstone for individual differences in academic performance (T.N.).

*Motivation gets regulated by emotions, self-perception, and meaning-making. It activates executive functions and gears the brain towards learning.*

542 von Stumm, S. *et al.* (2011). The hungry mind: Intellectual curiosity is the third pillar of academic performance.
*Translator's Note: The box containing additional information on this topic in the English version was included for editing purposes.*

## 6.7 ATTENTION IS THE GATEWAY FOR LEARNING



Stimuli are all around us. They continuously expose our sensory organs to an astounding variety. Even counting billions of **neurons,** our **brain** cannot examine everything simultaneously. Attention enables selecting the stimulus to be processed, filtered by relevance, and maintained in focus. All of that makes attention the gateway for learning. Attention grants access to information processing and storage. If we do not pay attention, our brain does not register any information. Thus, it is not stored nor learned.

Once a stimulus goes through the attention 'gateway', the challenge lies in keeping concentration, that is, sustaining attention on a single stimulus for longer. A study from the Neuroscience Institute at Princeton University showed that the brain has attentional cycles, alternating greater or lesser attention every three seconds[543]. But the widely spread notion that we can sustain attention for a few minutes – 10 to 15 minutes – lacks scientific evidence. What studies have shown[544] is that the longer the time of exposure, the more frequent the distractions generated by other stimuli or even by one's thinking. Thus, information processing and retention may suffer (T.N.).

Neuroscience has evidenced that attention gets modulated by emotion. Areas that process emotions act on the **prefrontal cortex** region responsible for sustained attention. Attentional focus, dependent on prefrontal and parietal circuits, is also regulated by other neural circuits related to areas that process emotion and motivation. American researchers[545] in employing electrophysiological techniques noticed that when adolescents ranked the stimuli presented to them as more 'interesting', areas related to selective attention received some influence from brain areas related to motivation. This finding showed that attentional focus gets heightened for interesting stimuli. In another investigation[546], Swiss and Italian researchers showed that stimuli that activate emotions (involving the **amygdala**) and motivation (involving the **reward system** and **dopamine** release) may guide attention and modify our perception despite our conscious awareness. Neuroimaging showed that brain structures related to motricity, such as the **cerebellum** and **basal ganglia** that have connections with the prefrontal cortex, take part

543 Fiebelkorn, I. C. *et al.* (2018). A dynamic interplay within the frontoparietal network underlies rhythmic spatial attention.

544 Farley, J. *et al.* (2013). Everyday attention and lecture retention: The effects of time, fidgeting, and mind wandering. *Translator's Note: The box containing additional information on this topic in the original version had its content incorporated into the text in the English version for editing purposes.*

545 Banerjee, S. *et al.* (2015). Interests shape how adolescents pay attention: The interaction of motivation and top-down attentional processes in biasing sensory activations to anticipated events.

546 Bourgeois, A. *et al.* (2016). How motivation and reward learning modulate selective attention.

in cognitive functions[547] like attention regulation. Several studies have also evidenced that physical activity that generates movement and keeps students active in class may enhance selective attention[548]. Beyond exerting a direct impact on attentional focus, physical activity and movement also contribute to self-control development and greater academic engagement[549].

## *Transforming principle seven into action*

The first challenge for any educator is to make students 'pay attention'. The capacity to maintain focus is a prerequisite for classroom management and learning success. In current times, this becomes a great challenge as information overload coupled with distractions and difficulty in keeping memory registrations grow bigger. Indeed, in our fast-paced culture, lack of attention has become endemic. Neuroscientific discoveries on how the brain processes attention enable a group of strategies to enhance students' focus on learning.

**Be receptive.** How do you start your class? If you answered 'by roll calling', you would be doing the opposite of what neuroscience recommends for good attentional management. You need to put students in a mental state conducive to the upcoming content. Just as our body needs physical energy to run, our brain needs a good reason to channel mental energy or thinking. To listen to someone or do something, learners need greater mental activation. To 'recharge students' batteries', it is worthwhile thinking about something more dynamic to start a class. Researchers at the San Francisco State University[550] showed that beginning class with something new, unexpected – like a poem, game, or jigsaw puzzle – that arouses the wish to learn upcoming content has a greater chance of recruiting learners' attention.

**Foster engagement.** The brain has a natural inclination towards paying attention. It comes from evolutionary transformations that led to structural and functional characteristics suitable for noticing surrounding stimuli. Teachers have the challenge of opening students' 'attention gateway' to what is relevant in the learning process, and motivation is the key. A student would rarely pay attention to information that s/he does not understand, that is not meaningful nor holds some relationship with their previous experiences or their daily life. Therefore, the most effective path to motivate students is to put them at the center of this process and develop strategies for making meaning out of what they are learning. Thus, teachers should offer room for choice and

547 Leisman, G. *et al.* (2016). Thinking, walking, talking: Integratory motor and cognitive brain function.

548 Mazzoli, E. *et al.* (2019). Associations of class-time sitting, stepping, and sit-to-stand transitions with cognitive functions and brain activity in children.

549 McClelland, E. *et al.* (2015). Enhanced academic performance using a novel classroom physical activity intervention to increase awareness, attention and self-control: Putting embodied cognition into practice.

550 Rosegard, E., & Wilson, J. (2013). Capturing students' attention: An empirical study.

stimulate curiosity by presenting unusual topic features. Also, they would do well in placing challenges that raise students' interest and spur their engagement in projects that draw on curriculum content close to their lives. Studies[551] reveal that students have fewer attention lapses when engaged in a task. Teachers should also promote such engagement by providing students with roles that are indeed active instead of just observational. Students need a good reason to talk, express themselves, give opinions. And student-led initiatives fosters engagement and increase attention. Also, teachers should make a point of stimulating students to pose problems, design projects, imagine solutions, and set goals. Such strategies are compatible with attentional processing as they enhance students' engagement and their ability to keep focused.

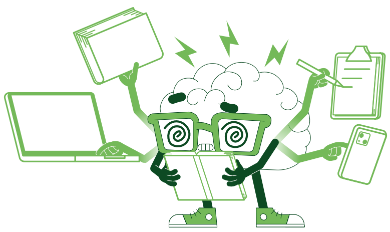
**Secure contexts conducive to learning.** The brain responds to stimuli. However, it is not so much quantity, but rather quality that matters. Whereas this means selecting more suitable stimuli, it also means decreasing distractors. Excessive or unsuitable stimuli – like inadequate acoustics, light, and temperature; hard seats; too many classroom posters and realia – may generate distractions and hamper attention focus[552]. Another fundamental point concerns keeping students seated for a whole session - not a good idea. Simple movements may furnish the necessary stimuli to help them sustain attention. Group activities in different places at school, games, or dynamics that entail getting up for a while may relax them and reengage their attention[553].

**Adjust time of exposure.** The capacity to sustain attention for a longer period requires specific **neural circuitry**[554]. After a while, distraction caused by external or internal stimuli[555] mounts. Teachers should avoid long expositions and prefer a composite of activities that includes rest periods or even fun breaks for venting out[556]. In truth, humans get habituated to contexts fast. When something in our surroundings changes, we reengage our attention. That is why generating new stimuli from time to time may bring students back to class.

*It is by paying attention that we select information. Attention is also crucial for memory formation. If we do not pay attention, our brain does not process the information.*

551 Bunce, D. M. *et al.* (2010). How long can students pay attention in class? A study of student attention decline using clickers.
552 Barrett, P. S. *et al.* (2015). Clever classrooms: Summary report of the HEAD project.
553 Lengel, T. *et al.* (2010*). The kinesthetic classroom: Teaching and learning through movement.*
554 Posner, M. I., & Rothbart, M. K. (2014). Attention to learning of school subjects.
555 Szpunar, K. K. *et al.* (2013). Mind wandering and education: From the classroom to online learning
556 Rosegard, E., & Wilson. J. (2013). Capturing students' attention: An empirical study.

## 6.8 THE BRAIN DOES NOT MULTITASK



Multitasking seems to be a modern-world need. In times of massive internet, technologies, and media exposure, the capacity to do many things at a time and assimilate competing stimuli simultaneously gets increasingly more valued. However, contrary to common belief, neuroscience has shown that the **brain** can only concentrate and efficiently perform one task at a time. Even something seemingly simple like listening to music while doing homework may cause students to lose attentional focus. The fact is that the brain does not process two stimuli concomitantly; it alternates attention between them, losing part of the information and compromising memory.

A recent study[557] by researchers at Stanford University and the University of California revealed that multitaskers fare worse in attention and working memory tests. It seems connected to their decreased capacity to keep focus and ignore distractions resulting in less retention of learning material. When we perform two tasks simultaneously, like listening to a talk and texting, we will not fully remember what we have heard. Both activities are very taxing on mental functioning and use up resources from the same brain regions, like the **prefrontal cortex,** responsible for working memory. Thus, all that is essential for effective learning, like reading comprehension, note-taking, and self-regulation, gets compromised in switching between media during a class or study sessions (T.N.).

The belief that multitasking makes us more productive is a myth. Instead of saving time, multitaskers take longer to finish tasks and make more mistakes than those that concentrate on one task at a time. Research from Stanford University[558] confirmed that multitaskers cannot filter out irrelevant information. For this reason, they become slower in carrying out cognitive tasks.

Neuroscientific breakthrough about multitasking being harmful to cognitive performance stands against what many youngsters do in class today. A survey from Common Sense Media[559] with American adolescents found that, while doing homework, 50% watch TV or use social media whereas 60% text and 76% listen to music. Another finding is that two-thirds of these students do not believe that multitasking while doing homework impacts their academic performance. The challenge is up to parents and teachers.

557 Uncapher, M. R., & Wagner, A. D. (2018). Minds and brains of media multitaskers: Current findings and future directions. *Translator's Note: The box containing additional information on this topic in the original version had its content incorporated into the text in the English version for editing purposes.*

558 Ophir, E. *et al.* (2009). Cognitive control in media multitaskers.

559 Common Sense. (2015). The Common Sense Media: Media use by tweens and teens.

## *Transforming principle eight into action*

Parents and teachers can confirm children's and adolescents' brains face a never-ending battle for attention-competing stimuli. With such overload in external stimulation, concentration for academic tasks turns into a formidable task. Scientific evidence[560] shows that children and youngsters are paying a high 'mental price' in this new context and reveal some detrimental effects of multitasking behavior over the learning process:

- Difficulty to prioritize and keep focus leads to a greater susceptibility to peripheral stimuli interference.
- Distractions taxes time for task completion.
- Mental tiredness leads to more mistakes.
- Working memory gets taxed due to cognitive overload.
- Superficial learning (less elaborate information comprehension).
- Retention difficulty for content studied due to divided attention.
- Negative impact on academic performance.

Children and youngsters are in their developmental prime. The more they reinforce multitasking behavior, the less capacity they build for deep thinking. And there is a risk of developing a mental model for regarding as boring activities that fail in offering fast alternation of tasks and novel stimuli. The good news is the capacity to resist technological urges may be developed intentionally. Next, we present some suggestions that may help teachers reach such goals.

**Amplify awareness.** Students must understand the harmful consequences of multitasking on the learning brain. But this needs guidance. Teachers may raise students' awareness that doing too many things at a time may not be for the best. That is because sharing attention leads to distraction, and it often means (re)starting from scratch, thus increasing time spent on a task. Put simply, it means making students aware that mixing Facebook and math is not a good idea. Being aware of multitasking consequences on learning may help students choose a different path that distributes better the time allotted to technology and to learning instead of doing both at the same time. If students do not amplify awareness of this process, they will probably face roadblocks to developing the self-regulation needed to deal with the persistent temptation of new media.

560 Foerde, K. *et al.* (2006). Modulation of competing memory systems by distraction.
Demirbilek, M., & Talan, T. (2018). The effect of social media multitasking on classroom performance.
Junco, R. (2012). In-class multitasking and academic performance.
Bellur, S. *et al.* (2015). Make it our time: In class multitaskers have lower academic performance.
Lee, J. *et al.* (2011). The impact of media multitasking on learning.

**Stimulate technology breaks.** Researchers[561] underscore the importance of teaching students to make balanced use of technological resources. It is crucial to enable 'technology breaks' for students to address their need for digital communication for a set time after uninterrupted work on academic tasks. The idea is to give students opportunities to send or check messages and posts to decrease their FOB (fear of missing out). Creating such 'technology breaks' means, for instance, allowing students to start class by briefly checking their social media and then silencing their devices while on-task. Mobiles on silent mode may prevent students from being interrupted by sound and visual alerts and yet provide a stimulus for connection over the next 'technology break'. Studies[562] reveal that such strategies increase attention and focus and enhance learning.

**Map out priorities.** Multitasking behavior often leads to distractions. Losing focus impacts task execution and increases time for task completion. Teachers can help students map out priorities and organize their time schedules so that deadlines – and the time to fulfill them – become clear. This may contribute to being aware that we need to optimize available time and adjust social media time.

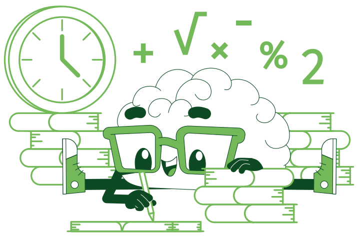
**Assess degree of motivation.** Another clear indication lies in observing students' engagement in assigned tasks to assess their degree of motivation. Multitasking can be a way out of activities that do not motivate students because of their unaddressed interests. In such instances, rerouting is necessary to find new ways to engage students and foster student-led learning.

*Brains do not process simultaneous stimuli adequately. Multitasking impoverishes attention and working memory leading to a loss of focus. There is less efficient reading comprehension and note-taking. Overall, learning gets compromised.*

561 Rosen, L. D. *et al.* (2011). An empirical examination of the educational impact of text message-induced task switching in the classroom: Educational implications and strategies to enhance learning.

562 Rosen, L. D. *et al.* (2013). Facebook and texting made me do it: Media-induced task-switching while studying.

## 6.9 LEARNING REQUIRES ELABORATION AND TIME TO GET CONSOLIDATED IN MEMORY



Scientific evidence shows that learning changes the brain's functional architecture[563]. For such changes to happen and resist for longer, learners' **neural circuits** should get repeated activation by exposure to diversified, increasingly complex stimuli that recruit several distinct **neural networks**[564]. To that end, active learning is crucial for lasting memories as it leads students to more robust cognitive and emotional engagement compared to passive learning processes. Researchers[565] have systematically noticed that students who employ active strategies for planning, monitoring, and evaluating their learning progress fare better than those who do not.

In effect, active learning requires a set of factors addressed in many of the principles already presented in this chapter such as selective attention, emotional engagement, motivation, self-regulation, metacognition, social relationship, and creativity. And for principle nine, in particular, we make explicit how active learning contributes more effectively with information elaboration and consolidation in long-term memory.

Memory is a **mental function** essential for learning[566]. It enables making **mental representations** of experiences lived more permanently. Such internal mental registrations grant us access to a personal background encompassing all the knowledge we built, and the abilities we developed. They, in turn, enable remembering, understanding, applying, analyzing, evaluating, and creating information, situations, problems, and ideas[567].

Neuroscience has explained the mechanisms and factors that influence memory formation, highlighting the differences between memories that last for a short time and those stored more permanently in the brain and that support learning[568]. Memory formation begins when new information gets processed by the **hippocampus**,

563 Owens, M. T., & Tanner, K. D. (2017). Teaching as brain changing: Exploring connections between neuroscience and innovative teaching.
Zatorre, R. J. *et al.* (2012) Plasticity in gray and white: Neuroimaging changes in brain structure during learning.

564 Eichenbaum, H. (2017). Memory: Organization and control.

565 Freeman, S. *et al.* (2014). Active learning increases student performance in science, engineering, and mathematics.
Markant, D. *et al.* (2016). Enhanced memory as a common effect of active learning.
Theobald, E. *et al.* (2020). Active learning narrows achievement gaps for underrepresented students in undergraduate science, technology, engineering, and math.

566 Fandakova, Y., & Bunge, S. (2016). What connections can we draw between research on long-term memory and student learning?

567 Stern, E. (2017). Individual differences in the learning potential of human beings.

568 Roediger, H. L., & McDermott, K. B. (2018). Remembering what we learn.
Soderstrom, N.C., & Bjork, R. A (2015). Learning versus performance: An integrative review.

which manages its storage as memory in neural networks in the **cerebral cortex**[569]. The brain builds memories by repeating, elaborating, and remembering information. Consequently, they get consolidated via synapse reorganization and reinforcement. This process makes them more permanent[570]. Research employing behavioral and brain activity measures show that stimuli diversity[571] contributes with memory formation and learning performance[572]. There lies the importance of repetition, in varied ways[573], for memory elaboration and consolidation of information and experiences[574]. Neuroscientific evidence shows that activating different neural circuits that process sensory input such as visual, olfactory, shape, and taste results in a larger number of mental representations of experiences encompassing their several aspects[575]. All of this contributes to a more robust memory network[576].

A study conducted by American researchers[577] with undergraduates learning physics concepts has evidenced that concrete experience, such as using a bicycle wheel, enabled students to experience the forces associated with the wheel's movement and contributed to their learning of scientific concepts of torque and angular momentum. The students' improved understanding had to do with the activation of sensorimotor brain regions when they reasoned later about angular momentum. Having a concrete experience with the object added details and kinesthetic meaning to students' thinking. The study made clear how multisensory learning contributes to improved concept encoding, understanding, and consolidation.

A body of evidence[578] shows that new information elaboration happens when it relates to previously registered information in memory[579]. In a neural perspective, new information activates neurons of neural circuits preestablished as memory[580] facilitating an understanding of the new information by making it meaningful. This, in turn, favors registration[581] and broadens information representations already in

569 Sekeres, M. J. *et al.* (2018). The hippocampus and related neocortical structures in memory transformation.

570 van Kesteren, M. T. R., & Meeter, M. (2020). How to optimize knowledge construction in the brain.
Squire, L. *et al.* (2015). Memory consolidation.

571 Thelen, A., & Murray, M. (2013). The efficacy of single-trial multisensory memories.
Shams, L., & Seitz, A. (2008). Benefits of multisensory learning.

572 Denervaud, S. *et al.* (2020). Multisensory gains in simple detection predict global cognition in schoolchildren.

573 Chi, M.T. (2009). Active-constructive-interactive: A conceptual framework for differentiating learning activities.

574 Clewett, D. *et al.* (2019). Transcending time in the brain: How event memories are constructed from experience.

575 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e Educação: Como o cérebro aprende.*

576 Van Atteveldt, N. *et al.* (2014). Multisensory integration: Flexible use of general operations.

577 Kontra, C. *et al.* (2015). Physical experience enhances science learning.

578 Brod, G. *et al.* (2013). The influence of prior knowledge on memory: A developmental cognitive neuroscience perspective.

579 Schlichting, M. L., & Preston, A. R. (2015). Memory integration: Neural mechanisms and implications for behavior.

580 Brod, G. *et al.* (2015). Differences in the neural signature of remembering schema-congruent and schema-incongruent events.

581 Danker, J. F., & Anderson, J. R. (2010). The ghosts of brain states past: Remembering reactivates the brain regions engaged during encoding.

store[582]. It is thus that we swiftly incorporate new information when they are related to previous knowledge[583]. A study elaborated by researchers in the Netherlands, France, and the USA[584] indicated that brain areas that process memory (hippocampus) and previous knowledge (**prefrontal cortex**) get activated when a new stimulus related to previous knowledge is presented. Several studies underscore participation of previous knowledge in new memory formation[585] and in previous memory consolidation[586] as well as their role in educational contexts[587]. They show that knowledge building happens when there is a reintegration of previous knowledge during new learning[588], weaving what students are learning with what they learned before.

Elaboration generates new mental representations from stored ones. This set of mental representations that gets formed and reorganized results in learning across the lifespan and is essential for complex mental processes such as concept learning[589] – a crucial aspect of cognition. Neuroscientific evidence[590] combining neural measures and computational models reveals that concept learning relies on the integrated activity of several neural circuits, not only for memory but also for attention, perception, and motivation.

Evidence in neuroscience shows that one's active participation in processing information influences its memory registration[591]. Researchers at the University of Illinois[592] demonstrated how memorization of visuals presented on a computer screen was greater when participants used the moused to make it appear than when it was on autorun. Neuroimaging data showed that this more effective learning instance under participants' voluntary control involves coordinated hippocampal activity with other distinct brain areas related to registered memories, attention control, and strategic planning[593]. This coordinated activity enables active exploration of what is to be learned by steering attention to information to be obtained from previously stored data. During this more active learning, the brain also registers mental strategies most in demand.

582 Gilboa, A., & Marlatt, H. (2017). Neurobiology of schemas and schema-mediated memory.

583 Greve, A. *et al.* (2019). Knowledge is power: Prior knowledge aids memory for both congruent and incongruent events, but in different ways.

584 van Kesteren, M. T. R. *et al.* (2020). Congruency and reactivation aid memory integration through reinstatement of prior knowledge.

585 van Kesteren, M. T. R. *et al.* (2016). Interactions between memory and new learning: Insights from fMRI multivoxel pattern analysis.

586 McKenzie, S., & Eichenbaum, H. (2011). Consolidation and reconsolidation: Two lives of memories?

587 Shing, Y. L, & Brod, G. (2016). Effects of prior knowledge on memory: Implications for education.

588 van Kesteren, M. T. R. *et al.* (2018). Integrating educational knowledge: Reactivation of prior knowledge during educational learning enhances memory integration.

589 Cetron, J. *et al.* (2020). Using the force: STEM knowledge and experience construct shared neural representations of engineering concepts.

590 Zeithamova, D. *et al.* (2019). Brain mechanisms of concept learning.

591 Markant, D. B, & Gureckis, T. M. (2014). Is it better to select or to receive? Learning via active and passive hypothesis testing. Ruggeri, A., *et al.* (2019). Memory enhancements from active control of learning emerge across development.

592 Voss, J. L. *et al.* (2011). Hippocampal brain-network coordination during volitional exploratory behavior enhances learning.

593 Voss, J. L. *et al.* (2011). Cortical regions recruited for complex active-learning strategies and action planning exhibit rapid reactivation during memory retrieval.

This optimizes learning. In short, this means stating that active learning is synonymous with an active brain.

Beyond connecting new information with previous knowledge, an effective elaboration requires that the brain use mental representations in different ways[594] engaging more complex cognitive processes such as analyzing, evaluating, and creating. American researchers[595] examined some university students working out physics problems that demanded complex reasoning. They noticed activated brain areas not only for physics concepts previously stored, but also for those related to visual motion perception, attention, and executive functions. Joint activation of these areas enabled successful problem-solving. During complex cognitive processes, mental representation for information establishes associations with other neural circuits resulting in new mental representations. These associations generate different ideas and reasoning skills[596]. Such new associations strengthen information registering.

For new mental representations to get consolidated in long-term memory, there needs to be neuroplasticity for reorganization and strengthening of neuronal connections[597]. That is why learning takes time[598]. Students need time to encode information and repeat them actively in diversified situations. And they also need to elaborate on them via different cognitive processes. Besides, students must have the chance to recover the information[599]. Remembering corresponds to the recovery of information from memory. This process reactivates the neural circuits related to that mental representation[600]. Every time some information goes through exposure and recovery, there is new elaboration. This cycle further consolidates it in memory. Memories that do not get reactivated in the long term are forgotten[601]. That is why we must bear recovery in mind when thinking about long-term learning. A body of neuroscientific studies[602] underscores the benefits of information recovery[603] and the resulting improvement in registration[604]. Encoding, repetition, elaboration, and recovering rely on cellular mechanisms[605] triggered by reactivating neural circuits and influenced by

594 Rosner, Z. A. *et al.* (2013). The generation effect: Activating broad neural circuits during memory encoding.

595 Bartley, J. E. *et al.* (2019). Brain activity links performance in science reasoning with conceptual approach.

596 Guerra-Carillo, B., & Bunge, S. (2018). Eye gaze patterns reveal how reasoning skills improve with experience.

597 Schaefer, N. *et al.* (2017). The malleable brain: Plasticity of neural circuits and behavior – A review from students to students.

598 San Martin, A. *et al.* (2017). The spacing effect for structural synaptic plasticity provides specificity and precision in plastic changes.

599 Buhry, L. *et al.* (2011). Reactivation, replay, and preplay: How it might all fit together.

600 Robertson, E. M. & Genzel, L. (2020). Memories replayed: Reactivating past successes and new dilemmas.

601 MacLeod, S. *et al.* (2018). The mitigating effect of repeated memory reactivations on forgetting.

602 Feng, K. *et al.* (2019). Spaced learning enhances episodic memory by increasing neural pattern similarity across repetitions.
Zhao, X. *et al.* (2015). Neural mechanisms of the spacing effect in episodic memory: A parallel EEG and fMRI study.

603 Roediger, H., & Butler, A. (2011). The critical role of retrieval practice in long-term retention.

604 Tambini, A., & Davachi, L. (2019). Awake reactivation of prior experiences consolidates memories and biases cognition.

605 Korte, M., & Schmitz, D. (2016). Cellular and system biology of memory: Timing, molecules, and beyond.
Sekeres, M. *et al.* (2017). Mechanisms of memory consolidation and transformation.

several factors – sleeping periods especially[606]. It is during sleep that we consolidate what we learned throughout the day[607]. That is why sleeping is crucial for learning[608].

Our memory trove makes us who we are, shapes our ideas, impacts how we feel and relate. Memories are like pieces in a kaleidoscope; depending on the mental functions we use, they can be reorganized and generate new patterns of knowledge, abilities, and attitudes. Students get to add, change or repaint their kaleidoscope pieces in infinite novel combinations with every learning opportunity.

## *Transforming principle nine into action*

Active learning has been a constant source for scientific research in Cognitive Psychology and Education. Neuroscience explains that active learning recruits neural circuits for several distinct cognitive and emotional processing concerning brain functioning. This recruitment leads to significant long-term physical changes in the brain[609]. In the classroom, this means teaching methodologies and activity designs that foster effective student engagement via motivation and meaning-making processes during learning, as previously discussed.

Memory is core to learning but should not be confused with it. Neuroscience reveals that while learning has to do with acquiring new knowledge, abilities, and attitudes, memory has to do with their permanence level as registrations in the nervous system[610]. Some registrations do not get consolidated in long-term memory and do not become effective learning. These registrations are fast forgotten[611]. Learning that stands the test of time relies on the formation and stabilization of new synapse connections. To that end, learning requires repetition with variation and time for elaboration, recovery, and consolidation in long-term memory[612].

Traditional pedagogy has focused excessively on memorization processes. This focus led to memory being 'condemned'. However, education debates cannot be a dichotomy

606 Lewis, P., & Durrant, S. (2011). Overlapping memory replay during sleep builds cognitive schemata.

607 Ribeiro, S., & Stickgold, R. (2014). Sleep and school education.

608 Okano, K. *et al.* (2019). Sleep quality, duration, and consistency are associated with better academic performance in college students.

609 Owens, M. T., & Tanner, K. D. (2017). Teaching as brain changing: Exploring connections between neuroscience and innovative teaching.
Markant, D. *et al.* (2016). Enhanced memory as a common effect of active learning.
Voss, J. L. *et al.* (2011). Cortical regions recruited for complex active-learning strategies and action planning exhibit rapid reactivation during memory retrieval.

610 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende.*

611 Cowan, N. (2008). What are the differences between long-term, short-term, and working memory?
Richards, B. A., & Frankland, P. W. (2017). The persistence and transience of memory.

612 van Kesteren, M. T. R., & Meeter, M. (2020). How to optimize knowledge construction in the brain.
Eichenbaum, H. (2017). Memory: Organization and control.

of 'memorizing versus not memorizing' as the importance of memory for learning is beyond any doubt. The epicenter of 21st-century education lies in how to promote long-term memory processes for effective learning without recurring to repetitive, dull, meaningless pedagogical strategies based on passive transmission methodologies. Advances in neuroscience[613] enable a current understanding of factors for an innovative education that has overcome rote learning in favor of lasting, meaningful learning – one that becomes a robust personal repertoire of knowledge and abilities.

Next, we present a set of suggestions that favor active learning, especially concerning cognitive processing of information and consolidation in long-term memory.

**Boost repetition with variation.** Scientific evidence reveals that learning starts when the brain processes information and not when it has access to it[614]. Students may access loads of daily information by surfing the internet, reading a book, or teacher transmission. However, access to these sources does not mean learning from them. For persistent registration in the brain, information needs extra work. After going through the attention filter, it must go through repetition, elaboration, retrieval, and consolidation to become long-term memory. Insofar as repetition goes, variation[615] and relevance are critical. That is why the education process needs diversity. Teachers must create opportunities for the same content to be worked in different, increasingly complex, meaningful ways. Using distinct sensory channels to enable brain access for information processing is indeed crucial[616]. To that effect, activities like listening and writing, watching videos many times, reading and discussing, hypothesizing, asking questions, taking notes, making mistakes and seeking different ways, peer teaching, mind mapping, and sensorial experiencing can all contribute to synapse formation and strengthening besides granting frequent chances to activate related neural circuits for a more robust memory network[617]. On the contrary, going over some topic superficially, skipping to the next, and only recovering it for the test does not enable the necessary neural processing for effective learning. Therefore, information that gets repeated in different and relevant ways result in new neural connections becoming established in the brain[618]. These will turn into robust, time-resistant registrations.

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613 Mayer, R. E. (2017). How can brain research inform academic learning and instruction?
Dubinsky, J. *et al.* (2019). Contributions of neuroscience knowledge to teachers and their practice.

614 Clark, R. C., & Mayer, R. E. (2008). Learning by viewing versus learning by doing: Evidence-based guidelines for principled learning environments.

615 Denervaud, S. *et al.* (2020). Multisensory gains in simple detection predict global cognition in schoolchildren.
Chi, M. T. (2009). Active-constructive-interactive: A conceptual framework for differentiating learning activities

616 Shams, L., & Seitz, A. R. (2008). Benefits of multisensory learning.
Broadbent, H. *et al.* (2018). Withstanding the test of time: Multisensory cues improve the delayed retention of incidental learning.

617 Van Atteveldt, N. *et al.* (2014). Multisensory integration: Flexible use of general operations.

618 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende.*

**Foster elaboration.** Research[619] suggests that information recovery is dependent on how it was encoded. When students cram and accumulate vast amounts of information without much elaboration, fast forgetting is the outcome. Elaboration has to do with the exponential process of understanding information that implicates a set of cognitive processes and meaning-making specially. The first step for elaboration is associating new information to previously encoded brain registrations[620]. In accordance, neuroscientific discoveries coincide with the ideas postulated by the American psychologist David Ausubel about meaningful learning being the connection between new information and prior knowledge[621]. The more associations or 'hooks' students establish with previously encoded knowledge[622], the better it will be as they will be able to understand well what was just learned based on their world knowledge[623]. Connections students thus make can bind new information to their memory trove and contribute to making meaning out of what they are learning. Making meaning means going beyond information meaning as it is universally shared. It entails a unique, individual process that is part of one's personal history[624].

Elaboration also happens when the brain works on new information with a different repertoire of cognitive processes. The complexity level of elaboration processes[625] contribute to the exponential stabilization of new information in the brain. That is why students need to process new information employing a variety of cognitive processes such as those proposed in Bloom's Taxonomy[626] (remembering, understanding, applying, analyzing, evaluating, and creating). The first three processes (remembering, understanding, applying) describe cognitive processes for memory retrieval and focus on what is known and understood. The other three processes (analyzing, evaluating, and creating) entails students' recruitment of cognitive processes that generate new relationships, discoveries, or ideas not contained in the original information[627]. Teachers must boost active learning by making questions, generating problem-solving activities, and recruiting imagination to engage all these cognitive processes. It is when students

619 Klein-Flügge, M. *et al.* (2019). Multiple associative structures created by reinforcement and incidental statistical learning mechanisms.

620 van Kesteren, M. T. R. *et al.* (2018). Integrating educational knowledge: Reactivation of prior knowledge during educational learning enhances memory integration.
Shing, Y. L., & Brod, G. (2016). Effects of prior knowledge on memory: Implications for education.

621 Agra, G. *et al.* (2019). Analysis of the concept of meaningful learning in light of the Ausubel's theory.

622 van Kesteren, M. T. R. *et al.* (2020). Congruency and reactivation aid memory integration through reinstatement of prior knowledge.
Tambini, A., & Davachi, L. (2019). Awake reactivation of prior experiences consolidates memories and biases cognition.

623 Watagodakumbura, C. (2015). Some useful pedagogical practices: Educational Neuroscience perspective.

624 Vygotsky, L. V. (2001). *A construção do pensamento e da linguagem*.

625 Bartley, J. *et al.* (2019). Brain activity links performance in science reasoning with conceptual approach.

626 Agarwal, P. K. (2019). Retrieval practice & Bloom's taxonomy: Do students need fact knowledge before higher order learning?

627 Watagodakumbura, C. (2015). Some useful pedagogical practices: Educational Neuroscience perspective.

have the chance to remember and elaborate information of a higher cognitive complexity that they get to strengthen long-term registration[628].

**Give the brain time.** We do not learn overnight. It takes time, effort, and cognitive and emotional investment. That is why schools should contribute to this investment by defining the curriculum and choosing methodologies. These are definitive steps towards learning success. Encyclopedic curricula do not allow time for diversified repetition and complex elaboration of academic content. Students browse through the information. They memorize facts, dates, and formulae but cannot go beyond that as they are stuck with repeating such information. Passive methodologies, in turn, do not foster meaningful, lasting learning as they draw students away from the center of the education process. Students need time and teacher incentive to think, connect information and make meaning out of what they are learning. Some practice and spaced repetition facilitate information consolidation in long-term memory. Brain changes that enable learning also demand sleeping periods[629]. While we are sleeping, our brain goes over experiences and information we got during the day to consolidate those more meaningful. Because of that, students and parents need to be made aware of the importance of sleep for learning[630]. The brain also needs rest and leisure time for mental hygiene so that it can return to tasks anew[631].

**Use active learning.** Active methodologies enable active construction of one's learning as they build on the development of students' cognitive and socioemotional abilities rather than passive knowledge transmission[632]. These methodologies demand cognitive and emotional engagement as they place students at the center. This fosters exploration of their ideas, experiences, attitudes, and values. Active learning often entails group work which boosts collaborative learning through peer interaction[633]. These strategies are ideally suitable to enlarge students' motivation and autonomy and to stimulate them to think critically and creatively[634]. Evidence shows that active learning helps students learn more effectively[635] because they allow for autonomy and accountability over the

628 MacLeod, S. *et al.* (2018). The mitigating effect of repeated memory reactivations on forgetting.
Roediger, H., L. & Butler, A. C. (2011). The critical role of retrieval practice in long-term retention.

629 Abel, T. *et al.* (2013). Sleep, plasticity and memory from molecules to whole-brain networks.
Acosta, M. T. (2019). Sueño, memoria y aprendizaje.
Lemos, N. *et al.* (2014). Naps in school can enhance the duration of declarative memories learned by adolescents.

630 Ribeiro, S., & Stickgold, R. (2014). Sleep and school education.

631 Cosenza, R. M., & Guerra, L. B. (2011). *Neurociência e educação: Como o cérebro aprende.*

632 Konopka, C. *et al.* (2015). Active teaching and learning methodologies: Some considerations.

633 Prince, M. (2004). Does active learning work? A review of the research.

634 Coil, D. *et al.* (2010). Teaching the process of science: Faculty perceptions and an effective methodology.

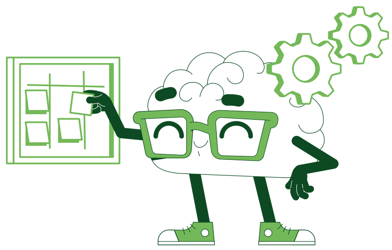
635 Freeman, S. *et al.* (2014). Active learning increases students' performance in science, engineering, and mathematics.
Michael, J. (2006). Where's the evidence that active learning works?
Beichner, R. J. (2014). History and evolution of active learning spaces.
Ruiz-Primo, M. *et al.* (2011). Impact of undergraduate science course innovations on learning.

learning process. It encompasses a series of activities and propositions. It can range from something simple and time-savvy (e.g., class breaks to allow students to clear up ideas and organize them through peer discussion) to something more complex (e.g., problem-solving) that takes time to develop. Current favored active methodologies are problem-based learning, project-based learning, flipped class, case studies, peer learning, and class rotation. We do not intend to exhaust the topic here as it falls outside this study's scope, but there is vast literature on each of them[636].

*Going over loads of information in a superficial way, or cramming for tests, results in fast forgetting. For information to be more permanent in the brain, we need repetition, elaboration, retrieval, and consolidation. This process takes time and demands active methodologies.*

636 Paiva, M. *et al.* (2016). Metodologias ativas de ensino-aprendizagem: Revisão integrativa.

# 6.10 SELF-REGULATION AND METACOGNITION BOOST LEARNING



The inherent complexity of modern life increasingly demands the ability to self-guide one's learning. It applies not only during formal schooling for academic achievement but also for professional development and lifelong learning[637]. Scientific evidence attests that productive studying and learning lead to effective, gratifying learning experiences. To that end, it is crucial to learn how to channel time and energy. Once successful experiences are enacted, self-efficacy and motivation levels soar[638]. The key is to learn how to monitor and reflect on one's learning process. Yet, that does not grow naturally for most. And here is where teachers can make a difference.

The first step for teachers' success in this arena is understanding which processes relate to self-regulated learning. Then, they can design strategies to help students develop learning routines that generate better results. Self-regulated learning means applying metacognition and self-regulation to learning[639]. Self-regulation[640] refers to the ability to self-monitor and control emotions and behaviors. It modulates emotional expressions (both positive and negative) and enables socially acceptable complex interactions. It is also related to the ability to steer behaviors for task completion and to orient actions for goal achievement. Metacognition refers to the process of becoming aware of and monitoring thinking processes[641]. Of note, from a neuroscientific perspective, self-regulation and metacognition[642] are integrated as they are intrinsically interrelated[643] and engage overlapping, interdependent neural substrates in the **brain**.

**Executive functions** are the cornerstone of self-regulation[644]. From a brain perspective, executive functions are essential for self-regulated learning. For task performance, executive functions enable students to monitor intrusive thoughts and inhibit interfering behaviors while making decisions and managing time. For task execution, executive

637 Wride, M. (2017). Guide to self-assessment.
638 Education Endowment Foundation (2018). *Metacognition and self-regulated learning.*
639 Mannion J. (2018) *Metacognition, self-regulation, oracy: A mixed methods case study of a complex, whole-school learning to learn intervention.*
640 Kelley, W. M. *et al.* (2015). In search of a human self-regulation system.
641 Metcalfe, J., & Schwartz, B. L. (2016). *The ghost in the machine: Self-reflective* consciousness *and the neuroscience of metacognition.*
642 Ardila, A. (2016). Is "self-consciousness" equivalent to "executive function"?
643 Roebers, C. M. (2017) Executive function and metacognition: Towards a unifying framework of cognitive self-regulation.
644 Heatherton, T. F. (2011). Neuroscience of self and self-regulation.
Hofmann, W. *et al.* (2012) Executive functions and self-regulation.

functions allow for storing and manipulating necessary information over a short period while detecting and adjusting 'errors' and alternating flexibly between ideas[645]. The role that executive functions play is not bound just to cognitive aspects. The **prefrontal cortex** has connections with brain areas that process emotion and motivation, therefore it also monitors and regulates emotions[646] that students experience while facilitating socioemotional adjustment[647].

Once supported by executive functions[648], metacognition[649] allows students to monitor ongoing information processing[650] (*"Am I moving forward in this task?"*); evaluate actual mastery over task and strategy use (*"Is there a better way to solve this task?"*); experience and relate different levels for (un-)certainty (*"I'm not sure I'll remember that later"*). Such monitoring relies on the brain's ability to become aware and reflect on the learning experience, considering the emotions, memories, and beliefs built over one's life course[651].

One of the most relevant metacognitive processes is analyzing and learning from mistakes. Neuroscience reveals that mistakes made during the learning process may become opportunities for a more effective performance[652]. American researchers developed a study[653] with students around age 7 and showed that they increased their brain activity in an error-monitoring area when they realized they had made a mistake on a task. This increase in activation made children pay more attention to the mistake and contributed to better task performance next time around.

Neuroimaging studies confirmed that neural circuits related to metacognition and executive functions are present at birth[654] but only get developed from interactions fostered by experiences[655] in a learning environment, be it the school, family, or community[656]. Since infancy, children have already manifested these functions[657] which

645 Zelazo, P. D. *et al.* (2016*). Executive function: Implications for education.*
Roebers, C. M., & Feurer, E. (2016). Linking executive functions and procedural metacognition.

646 Moriguchi, Y. (2014). The early development of executive function and its relation to social interaction: A brief review.

647 Liew, J. (2012). Effortful control, executive functions, and education: Bringing self-regulatory and social-emotional competencies to the table.

648 Kim, N. Y. *et al.* (2017). Behavioral and neural correlates of executive function: Interplay between inhibition and updating processes.

649 Vaccaro, A. G., & Fleming, S. M. (2018). Thinking about thinking: A coordinate-based meta-analysis of neuroimaging studies of metacognitive judgements.

650 Lyons, K. E., & Zelazo, P. D. (2011). Monitoring, metacognition, and executive function: Elucidating the role of self-reflection in the development of self-regulation.

651 Metcalfe, J., & Schwartz, B. L. (2016). *The ghost in the machine: Self-reflective consciousness and the neuroscience of metacognition.*

652 Metcalfe, J. (2017). Learning from errors.

653 Schroder, H. S. *et al.* (2017). Neural evidence for enhanced attention to mistakes among school-aged children with a growth mindset.

654 Fiske, A., & Holmboe, K. (2019). Neural substrates of early executive function development.
Engelhardt, L. E. *et al.* (2019). The neural architecture of executive functions is established by middle childhood.

655 Diamond, A. (2014). Want to optimize executive functions and academic outcomes? Simple, just nourish the human spirit.

656 Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not.

657 Roebers, C. M. (2017). Executive function and metacognition: Towards a unifying framework of cognitive self-regulation.

can – and should - be developed over the years[658]. Thus, the abilities of monitoring behavior, planning strategies, and solving problems gradually increase to enable self-regulated learning since early schooling and to enhance such learning over the coming years[659].

A study carried out by researchers from Max Planck Institute in Germany and the University of California in the USA[660] monitored 5-6-year-olds throughout a school year. The study revealed the school environment contributed to neural network development in brain regions subserving executive functions that accounted for self-regulated learning. This happened by fostering children to perform cognitively demanding tasks. Such findings confer heightened importance to teachers developing strategies that boost metacognitive and self-regulation processes for learning[661].

## *Transforming principle ten into action*

For students to develop metacognition and self-regulation processes, teachers need to create opportunities for active, systematic student engagement in planning and organizing their task execution, while monitoring their performance and reflecting on outcomes[662]. Research shows that there is a positive correlation between self-regulated learning and academic performance[663]. It is a good reminder for more teachers' efforts in this arena. To effect, the topic of emotional self-regulation got covered in this chapter under principle five – *emotion steers learning*. Now, we highlight pedagogical strategies geared towards other aspects of self-regulated learning like developing autonomy and metacognition.

**Develop autonomy.** Self-regulated learning is related to students' ability to self-guide their learning process, manage time, develop study strategies, seek information independently, solve problems proactively, and make choices that are consistent with their life projects. Taken together, they translate into autonomy – a slow-developing capacity that starts with early schooling but requires specific stimuli given individual potential and developmental characteristics. To move forward in developing autonomy, students need opportunities to incorporate the idea that learning is not bound to following assigned tasks, doing exercises, and taking exams. To change this idea, schools

658 Zelazo, P. D., & Carlson, S. M. (2012). Hot and cool executive function in childhood and adolescence: development and plasticity.
659 Blair, C. (2016). Executive function and early childhood education.
660 Brod, G. *et al.* (2017). Does one year of schooling improve children's cognitive control and alter associated brain activation?
661 Son, L. K. *et al.* (2020). *Metacognition: How to improve students' reflections on learning.*
662 Zimmerman, B. (2002). Becoming a self-regulated learner: An overview.
663 Mega, C. *et al.* (2014). What makes a good student? How emotions, self-regulated learning, and motivation contribute to academic achievement.
Dent, A. L., & Koenka, A. C. (2016). The relation between self-regulated learning and academic achievement across childhood and adolescence: A meta-analysis.

need to recruit active learning because it places students at the center of the education process. Active learning also allows students to exercise their autonomy by making choices between topics, thinking critically, generating independent ideas, developing self-interest projects, reflecting, and self-evaluating their learning. Research[664] reveals that a teacher's role is crucial for developing autonomy. This goal should be uppermost in pedagogical practices as self-regulation in learning predicts greater motivation and self-confidence[665].

**Guide metacognition.** In education, metacognition has been known as 'thinking about thinking', 'learning to learn', and 'learning to study'. Research shows that metacognition is a powerful propeller for self-regulated learning[666] that can get developed since preschool[667], even though this process gets little stimulation at any education segment[668]. In the learning context, metacognition refers to students' capacity for planning, monitoring, and evaluating their academic progress[669]. Most students do not spontaneously develop metacognitive strategies. Thus, teachers must provide explicit instructions on how students can develop the ability to manage their learning independently. Teachers can create a reflective class culture by boosting dialogues, making challenging questions, and guiding students via constant feedback so that they can recognize their strengths and weaknesses, identify knowledge gaps, and most importantly, recognize their own mistakes as learning opportunities[670]. The essential lies in creating a habit of making students ask themselves: *'did I get the expected outcomes?', 'is there something I still do not understand?', 'where do I need to move forward?', 'which study strategies are more efficient?', 'did I find the most relevant concepts?', 'have I made enough effort ?', 'how much time do I need to complete this task?', 'did I review my mistakes?', 'what can I do differently next time around for better results?'*. These questions are necessary reflections for students to self-guide their learning and build autonomy to overcome complex or unexpected problems. Next, we highlight two key strategies to facilitate metacognition in the learning process: enabling visible thinking and promoting self-evaluation.

664 Nguyen, C. T. (2012). The roles of teachers in fostering autonomous learning at the university level.
Sierens, E. *et al.* (2008). The synergistic relationship of perceived autonomy support and structure in the prediction of self-regulated learning.

665 Guay, F. *et al.* (2010). Academic self-concept, autonomous academic motivation, and academic achievement: Mediating and additive effects.

666 Zepeda, C. *et al.* (2015). Direct instruction of metacognition benefits adolescent science learning, transfer, and motivation: An in vivo study.

667 Destan, N. *et al.* (2014). Early metacognitive abilities: The interplay of monitoring and control processes in 5- to 7-year-old children.

668 Watkins, C. *et al.* (2001). Learning about learning enhances performance.

669 Quigley, A., Muijs, D., & Stringer, E. (2018). Metacognition and self-regulated learning..

670 Metcalfe, J. (2017). Learning from errors.

**Enable visible thinking.** An important metacognitive strategy is enabling one's thinking to become visible. Even though students may suppose they know how they have finalized a process, the possibility of registering or communicating what they think fosters their comprehension and strengthens their learning. To effect, when students speak, write or draw their ideas, they enhance their cognition[671]. Project Zero[672] at Harvard University spurred an initiative called *Visible Thinking*[673] that develops methodologies to turn students into better thinkers. The initiative developed over 100 Thinking Routines for the different subjects in collaboration with elementary and high school teachers in the USA, the Netherlands, Sweden, Belgium, and Australia. The goal was to foster and guide students' thinking processes to become visible. This boosts active learning. The main idea is for teachers to stimulate students' thinking patterns to become habitual and be used outside school contexts. Teachers can do that by introducing and practicing thinking routines. Thinking routines for every school subject can be found for free at Project Zero's website[674].

Another strategy that helps students to make thinking visible is graphic elaborations of concepts and ideas with mind maps[675] or concept maps[676]. Mind maps can visually organize concepts and ideas. Concepts in a map stem from a core idea that stands in the middle of the diagram from where related notions branch out. To that end, keywords, images, drawings, and different colors highlight information. Mind maps allow for personalization. Students organize information and branches compatible with their understanding of the content. It thus facilitates understanding and learning. Each keyword and (or) image generate specific memories, stimulates new reflections and ideas, and fosters creativity and association with previous knowledge. To the same effect but slightly different from mind maps, concept maps are diagrams for interconnected concepts placed in boxes and connected by arrows to indicate their relationship. Concept maps favor learning as they enable students to summarize or specify constructs, analyze complex problems, and identify solutions.

**Promote self-evaluation.** Self-evaluation is a process that recruits both metacognition and self-regulation of emotions and behaviors as it takes students to reflect on their learning[677]. When teachers promote self-evaluations, they raise students' interest and

671 Ritchhart, R., & Perkins, D. (2008). Making thinking visible.
672 http://www.pz.harvard.edu/
673 https://pz.harvard.edu/projects/visible-thinking
674 https://pz.harvard.edu/thinking-routines#CoreThinkingRoutines
675 Edwards, S., & Cooper, N. (2010). Mind mapping as a teaching resource.
676 Schroeder, N. L. *et al.* (2018). Studying and constructing concept maps: A meta-analysis.
677 Sharma, R. *et al.* (2016). Impact of self-assessment by students on their learning.

engagement, leading to better academic performance[678]. Teachers can understand students' possibilities and difficulties and identify strategies that foster their learning. Research on the topic[679] proposes self-evaluation as formative and embedded throughout the learning process. Such qualities allow students to change strategies or their behavior in search of better results[680]. Teachers can foster self-evaluation by designing tools and systematically scaffolding their use. It is also crucial that, before implementing a self-evaluation approach, teachers give explicit instructions so that students understand what to do and also allow for joint decisions on self-evaluation criteria[681] (T.N.).

*Metacognition and self-regulation rely on executive functions. They are crucial for the ability to guide one's own learning so that students can manage their lifelong learning independently without constant teacher supervision.*

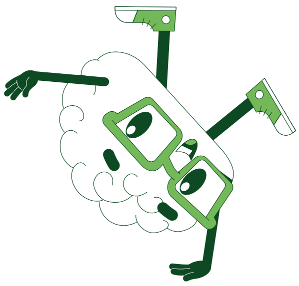
678 Yan, Z. (2020). Self-assessment in the process of self-regulated learning and its relationship with academic achievement. Chen, P. *et al* (2017). Strategic resource use for learning: A self-administered intervention that guides self-reflection on effective resource use enhances academic performance.

679 Andrade, H., & Valtcheva, A. (2009). Promoting learning and achievement through self-assessment.

680 Pandero, E. *et al.* (2017). Effects of self-assessment on self-regulated learning and self-efficacy: Four meta-analyses.

681 Wride, M. (2017). *Guide to self-assessment.*
*Translator's Note: The box containing additional information on this topic in the English version was included for editing purposes.*

## 6.11 WHEN THE BODY TAKES PART, LEARNING BECOMES MORE EFFECTIVE



The **brain** is part of the body. While it can control the body, several bodily parts are responsible for activating it. Learners experiment, process, and register experiences that change their brains through the whole body. That generates neural connections via **neuroplasticity**. Besides, the body is a stage for our emotions. In acting and interacting, we experience emotions that are central to attentional, motivational, and memory processes[682]. Neuroscientific research[683] shows that learning relies on mutual exchanges between the brain and our bodily parts. Such evidence stands in stark contrast to students' passiveness in most education systems.

Researchers at the University of Cambridge[684] explain that no complex **mental representation** may get mapped out to a single brain region. Indeed, complex processes get encoded via the interactions of interconnected **neural circuits**[685]. Neuroscience reveals[686] complex learning processes (e.g., reasoning, decision making, language, reading, and mathematical thinking) operate in tandem with emotions, sensations, and movement, that is, with the whole body. Learning emerges from dynamic interactions between body and environment that are modified bidirectionally.

Movement impacts brain structure and function and goes way beyond physical conditioning and motor development. It promotes brain health by increasing blood flow, oxygen, glucose, and nutrient levels. This increase enhances neuronal activity. Movement produces gene activation and **neurotrophic factors**, involved with neuroplasticity. It also contributes to the production of **neurotransmitters**, like **dopamine**, which is associated with motivation, greater attentional focus, and learning; **serotonin**, which improves humor; and **noradrenaline**, which boosts attention, perception, and motivation[687]. Besides, some of the neural circuits activated during planning and execution of movement, like some in the **cerebellum**, **basal ganglia**, and in the frontal

682 Immordino-Yang, M. H., & Damasio, A. (2007). We feel, therefore we learn: The relevance of affective and social neuroscience to education.

683 Shapiro, L., & Stolz, S. A. (2019). Embodied cognition and its significance for education.

684 Szucs, D., & Goswami, U. (2007). Educational Neuroscience: Defining a new discipline for the study of mental representations.

685 Pessoa, L. (2014). Understanding brain networks and brain organization.

686 Dijkerman, C., & Lenggenhager, B. (2018). The body and cognition: The relation between body representations and higher level cognitive and social processes.

687 Basso, J. C., & Suzuki, W. A. (2017). The effects of acute exercise on mood, cognition, neurophysiology, and neurochemical pathways: A review.

part of the brain are also related to important **mental functions** for learning[688] such as attention and **executive functions**[689].

Several studies have shown that movement has a high positive impact on cognition[690] and learning overall[691]. Researchers in Australia, the Netherlands, Switzerland[692], and Germany[693] underscore that integrating movement with cognitive tasks influences learning. For example, when one learns the word 'dance' in a foreign language while performing a dance[694], one temporarily integrates the cognitive activity into the movement. This gives relevance and meaning to one's learning. Extracurricular activity[695] may influence learning but it does not necessarily allow for the same integration and concomitant relevance for learning. Handwriting, in turn, may facilitate reading acquisition according to American researchers[696]. When preliterate children at 5 years of age, who had written, typed or drawn a given traced letter got exposed to that letter image, their brain areas for letter recognition reactivated for such letter when it had been written (not typed or drawn). Thus, their hand movement in drawing the letter contributed to the activation of brain areas necessary for reading development.

However, the body's role in learning stretches further than the effects related to movement. Studies[697] in embodied cognition reinforce the growing understanding that movement, emotion, and cognition are intrinsically interrelated and exert mutual impact and activation. This research body shows cognition as based on bodily interactions with context and culture. It also shows abstract concepts are built concomitantly with sensorimotor[698], emotional[699] and social[700] representations derived from concrete experiences. Therefore, the richer and more diversified the bodily experience in the

688 Leisman, G. *et al.* (2016). Thinking, walking, talking: Integratory motor and cognitive brain function.

689 de Greeff, J. W. *et al.* (2018). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: A meta-analysis.

690 Bidzam-Bluma, I., & Lipowska, M. (2018). Physical activity and cognitive functioning of children: A systematic review.
Esteban-Cornejo, I. *et al.* (2015). Physical activity and cognition in adolescents: A systematic review.

691 Meeusen, R. *et al.* (2017). *Physical activity and educational achievement: Insights from exercise neuroscience.*
Donnelly, J. E., *et al.* (2016). Physical activity, fitness, cognitive function, and academic achievement in children: A systematic review.
Savina, E. *et al.* (2016). The benefits of movement for youth: A whole child approach.

692 Mavilidi, M. F. *et al.* (2018). A narrative review of school-based physical activity for enhancing cognition and learning: The importance of relevancy and integration.

693 Skulmowski, A., & Rey, G. D. (2018). Embodied learning: Introducing a taxonomy based on bodily engagement and task integration.

694 Mavilidi, M. F. *et al.* (2015). Effects of integrated physical exercises and gestures on preschool children's foreign language vocabulary learning.

695 Coe, D. P., *et al.* (2006). Effect of physical education and activity levels on academic achievement in children.

696 James, K. H. (2017). The importance of handwriting experience on the development of the literate brain.
James, K. H., & Berninger, V. (2019). Brain research shows why handwriting should be taught in the computer age.

697 Kiverstein, J., & Miller, M. (2015). The embodied brain: Towards a radical embodied cognitive neuroscience.
Cardona, J. F. (2017). Embodied cognition: A challenging road for clinical neuropsychology.

698 Kiefer, M., & Trumpp, N. M. (2012). Embodiment theory and education: The foundations of cognition in perception and action.

699 Price, T. F. *et al.* (2012). The emotive neuroscience of embodiment.

700 Leung, A. K. Y. *et al.* (2011). Embodied cultural cognition: Situating the study of embodied cognition in socio-cultural contexts.

learning process, the greater and more varied the information encoding and its later retrieval[701]. Embodied cognition holds relevance in educational contexts for effective learning[702]. Several studies have shown how important it is to integrate multisensory stimuli, motor activity, emotion, and social interaction in projects and activities for students' cognitive processing[703]. This integration contributes to learning in several subjects like science, technology, math[704] and language[705].

## *Transforming principle eleven into action*

Sitting, seeing, hearing for over four hours – such has been the imposed *modus operandi* for students' classroom behavior since school got invented as if learning happened 'from the neck up' and the rest of the body had nothing to account for. Current neuroscience research confirms the ideas of great education thinkers, like John Dewey and Maria Montessori, who advocated for thinking as inseparable from action. Both acknowledged the importance of body and practice for wholesome learning. Based on these theories and neuroscientific evidence on the importance of putting students' bodies in motion, teachers can use strategies such as the following.

**Promote hands-on learning.** Proposals for hands-on learning or makerspaces[706] regard the body as key for cognitive-affective processing. By experimenting, students understand the inextricable relationship between theory and practice. Learning then gets a new meaning. Maker culture furnishes students with time and space for releasing their curiosity, raising problems, developing critical thinking and creativity in searching for solutions for activities and projects[707]. Maker movement boosts students' engagement. It also develops executive functions (like planning and cognitive flexibility) while bridging the gap between scientific knowledge and the real world. This coupling facilitates concept learning.

**Foster concrete learning.** Making one's learning concrete is an experience that sets the body into motion, recruits different senses, improves learning, and makes it meaningful. It can happen in simple ways, like making a cell using playdough, building a model, or a

701 Macedonia, M. (2019). Embodied learning: Why at school the mind needs the body.

702 Shapiro, L., & Stolz, S. A. (2019). Embodied cognition and its significance for education.

703 Fugate, J. M. B. *et al.* (2018). The role of embodied cognition for transforming learning.

704 Weisberg, S. N., & Newscombe, N. S. (2017). Embodied cognition and STEM learning: Overview of a topical collection in CR-PI.
Kontra, C. *et al.* (2015). Physical experience enhances science learning.
Bahnmueller, J. *et al.* (2014). NIRS in motion: Unraveling the neurocognitive underpinnings of embodied numerical cognition.

705 Kosmas, P., Ioannou, A., & Zaphiris, P. (2018). Implementing embodied learning in the classroom: Effects on children's memory and language skills.
Schmidt, M. *et al.* (2019). Embodied learning in the classroom: Effects on primary school children's attention and foreign language vocabulary learning.

706 Roffey, T. *et al.* (2016). The making of a makerspace: Pedagogical and physical transformations of teaching and learning.

707 Halverson, E. R., & Sheridan, K. (2014). The maker movement in education.

fossil out of clay. It can also happen by using elaborate tools and materials in complex ways. The essence is to offer students the chance to use other sensory channels to make concrete curriculum concepts. Students organize their different representations for the same learning object by using their senses and movements. This process broadens their understanding of the object.

**Develop whole body activities.** Neuroscientific research in the last 10 years yielded relevant findings for the deeply intricate relationship between movement and cognition[708]. When we keep students active, their alertness and attention levels are up. Movement provides the brain with oxygen-rich blood, necessary for the mental functions essential for learning. Teachers are not furnishing ideal learning conditions if they insist on keeping students seated throughout class. Reducing recess, breaks or dropping out of physical education is not a good idea. Movement, thus, must become part of the learning context via whole-body activities[709] – projects, workshops, theater, dance, music, games, dynamics – that potentially foster positive humor states, decrease stress, and boost learning and memory[710]. Several studies[711] are currently underway about activities that involve movement integrated into cognitive tasks to boost the learning process (embodied cognition[712]). Empirical evidence[713] shows that the body – via actions and gesture[714] – is a powerful tool for understanding and learning curriculum subjects like math[715] and science[716].

**Stimulate handwriting.** Neuroscientific studies show that handwriting, that is the physical, tactile act of moving a pen or pencil, furnishes more stimuli and precision for the brain to capture and retrieve information than digital writing, which involves only pressing keys (in computers, tablets, or mobiles)[717]. When compared to typing, handwriting demands a larger set of movements. Such demand generates more brain activation and makes students more committed and attentive. It, in turn, improves their written communication and later reading comprehension[718]. Underscoring the importance of handwriting at tech-savvy times brings a lot of questions. We still do not hold all the answers, and more research is coming to help us understand technological impacts.

708 Doherty, A., & Miravalles, A. F. (2019). Physical activity and cognition: Inseparable in the classroom.
709 Yoo, J., & Loch, S. (2016). Learning bodies: What do teachers learn from embodied practice?
710 Montes, J. L. (2012). *El cerebro y la educación. Neurobiología del aprendizaje.*
711 Kamp, J. V. D.*et al.* (2019). On the education about/of radical embodied cognition.
712 Kosmas, P., & Zaphiris, P. (2018). Embodied cognition and its implications in education: An overview of recent literature.
713 Macedonia, M. (2019). Embodied Learning: Why at school the mind needs the body.
714 Goldin-Meadow, S. (2017). Using our hands to change our minds
715 Abrahamson, D., & Bakker, A. (2016). Making sense of movement in embodied design for mathematics learning.
716 Kontra, C. *et al.* (2015). Physical experience enhances science learning.
717 Mueller, P. A., & Oppenheimer, D. M. (2014). The pen is mightier than the keyboard: Advantages of longhand over laptop note taking.
718 Santangelo, T., & Graham, S. (2016). A comprehensive meta-analysis of handwriting instruction.

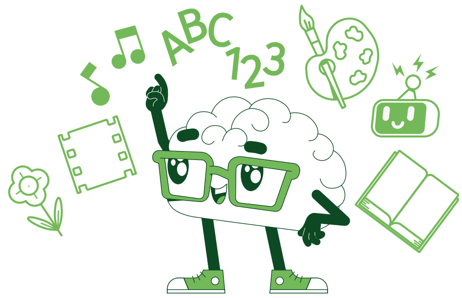
However, we already have scientific evidence[719] to support handwriting and reinstate penmanship's glory for now. Some states in the USA that have abandoned handwriting after the initial grades are returning it to their curricula[720].

*Movement and cognition are highly related. Practical activities that furnish movement in learning contexts allow students to live, process, and register experiences that change the brain more effectively. Keeping students seated and passive is not conducive to ideal learning conditions.*

719 van der Meer, A. L. H., & Van der Weel, F. R. (2017). Only three fingers write, but the whole brain works: A high-density EEG study showing advantages of drawing over typing for learning.

720 Hochman, J., & MacDermott-Duffy, B. (2015). Effective writing instruction: Time for a revolution.

## 6.12 CREATIVITY REORGANIZES MULTIPLE NEURONAL CONNECTIONS AND EXERCISES THE LEARNING BRAIN




Creativity means generating original ideas and finding new ways to act by combining and recombining information. It is an intrinsically human process and enables astounding innovations in every field – from science to technology, art, and culture[721] – generating social and economic prosperity[722]. Humans' large capacity for creativity can be recognized in practically every aspect of our lives, as in when we generate unexpected ideas, develop new solutions for problems or express ourselves in unique ways[723]. Despite the complexity of studying creativity[724], the fields of neuroscience[725] and cognitive psychology[726] have systematically advanced our understanding of the fundamental mental process that makes us creative.

Researchers understand that creativity is not an innate, hereditary characteristic but an ability that can[727] and should be developed[728] in view of the **brain**'s potential[729] and the individual characteristics that make us unique[730]. It results from activity in several **neural circuits,** modulated by **neurotransmitters**[731] that get reorganized and changed[732] via social interactions and experiences[733]. Thus, at birth, we have creative potential that we need to develop to have an ability. Saying that creativity needs developing means that education has a critical role in this process[734]. Creativity is essential to learning as it enables students to go beyond 'rote learning' to formulate original questions, solve problems in different ways, develop innovative projects, and write reflections and

721 Zaidel, D. W. (2014). Creativity, brain, and art: Biological and neurological considerations.
722 Abraham, A. (2013). The promises and perils of the neuroscience of creativity.
723 Fogarty, L. *et al.* (2015). Cultural evolutionary perspectives on creativity and human innovation.
724 Dietrich, A., & Haider, H. (2017). A neurocognitive framework for human creative though.
725 Raymond, S. (2017). Neural foundations of creativity: A systematic review.
726 Abrahan, V. D., & Justel, N. (2019). Creatividad. Una revisión descriptiva sobre nuestra capacidad de invención e innovación.
727 Ritter, S. M. *et al.* (2020). Fostering students' creative thinking skills by means of a one-year creativity training program.
728 Runco, M. A. (2003). Education for creative potential.
729 Saggar, M. *et al.* (2019). Creativity slumps and bumps: Examining the neurobehavioral basis of creativity development during middle childhood.
730 Ren, Z. *et al.* (2018). Neural and genetic mechanisms of creative potential.
731 Zabelina, D. L. *et al.* (2016). Dopamine and the creative mind: Individual differences in creativity are predicted by interactions between dopamine genes DAT and COMT.
732 Sun, J. *et al.* (2016). Training your brain to be more creative: Brain functional and structural changes induced by divergent thinking training.
733 Barbot, B. *et al.* (2015) Creative potential in educational settings: Its nature, measure, and nurture.
734 Bloom, L., & Dole, S. (2018). Creativity in education: A global concern.
Zhou, Z. (2018). What cognitive neuroscience tells us about creativity education: A literature review.

creative essays. In exercising their creativity, students personalize knowledge to create new forms of expression and action.

Where do creative ideas come from, that is, original ideas that fit a purpose? How can one write a book on an adventure that never happened or a song never heard? Or solve a problem never faced? Or even invent new recipes or a method to test a hypothesis? How does the creative brain work[735]?

In the last 10 years, several studies[736] have contributed to explaining the neural bases of creative thinking using neuroimaging[737], brain activation measures[738] and psychometric tests[739] that evaluate originality, ideational fluency, and diversity, for instance. Such findings enable an understanding of how creative a research participant is. Neuroscience revealed that creativity is the remarkable product of joint activation of distinct brain areas which subserve other **mental functions** such as memory, attention, and **executive functions**[740]. It does not rely on a single mental process or brain area[741] and is not associated to the right side of the brain specifically either, nor is it inherently bound to mind wandering, dreams, relaxing states, chance, or sudden inspiration[742]. Evidence is mounting on creativity involvement of the whole brain, recruiting some areas more than others depending on the creative activity in development (e.g., verbal, visual, musical, or scientific[743]). Creativity is a complex, dynamic phenomenon related to distinct mental processes constantly recruited and influenced by social interactions, emotions, discoveries, problems, and real-world challenges posed to our minds[744].

To have a creative idea, the brain seeks different stored memories, makes different combinations with them, imagines new possibilities, checks whether they fit the set goal, and selects the most creative. This process demands that the brain alternates attention between stored memories and novel incoming, external information. The brain needs to access ideas in store, process incoming information, and form new combinations while keeping it all in working memory. At the same time, the brain is imagining possibilities and analyzing whether they make sense or not. Thus, it has to be flexible to let go of

735 Beaty, R. E. (2020). The creative brain.

736 Khalil, R. *et al.* (2019). The link between creativity, cognition, and creative drives and underlying neural mechanisms.

737 Boccia, M. *et al.* (2015). Where do bright ideas occur in our brain? Meta-analytic evidence from neuroimaging studies of domain-specific creativity.

738 Zabelina, D. L., & Ganis, G. (2018). Creativity and cognitive control: Behavioral and ERP evidence that divergent thinking, but not real-life creative achievement, relates to better cognitive control.

739 Fink, A. *et al.* (2007). Creativity meets neuroscience: Experimental tasks for the neuroscientific study of creative thinking.

740 Benedek, M., & Fink, A. (2019). Toward a neurocognitive framework of creative cognition: The role of memory, attention, and cognitive control.

741 Sawyer, K. (2011). The cognitive neuroscience of creativity: A critical review.

742 Kounios, J., & Beeman. M. (2014). The cognitive neuroscience of insight.
Ritter, S. M., & Dijksterhuis, A. (2014). Creativity: The unconscious foundations of the incubation period.

743 Feng, Q. *et al.* (2019). Verbal creativity is correlated with the dynamic reconfiguration of brain networks in the resting state.

744 Chakravarty, A. (2010). The creative brain: Revisiting concepts.

ideas in store and consider the novel ones and the combinations that come forward. Also, it needs to check whether combinations fit the purpose.

To process creativity, the brain recruits neural circuits of distinct regions – **frontal**, **prefrontal**, **parietal**, and **temporal** (**hippocampus**) **cortices**, anterior and posterior regions of the **cingulate gyrus** and **insula** – forming three **neural networks**: (i) **cognitive control** (**executive**) **network**[745] ; (ii) **default network**[746]; and (iii) **salience network**[747]. The first is involved in several aspects of executive functions and stored memories[748], the second has to do with imagining new possibilities[749], and the third with checking the sense and validity of new ideas. It is the dynamic interactions of these three neural networks[750] that generates, evaluates[751], and expresses creative ideas.

However, 'creative cognition' is not enough for creativity to manifest itself. It also relies on a 'creative impulse' related to a set of factors – emotions, motivation, humor states, rewards, social interactions – that may facilitate or hamper the creative process[752]. Brain areas that process emotions and motivation as well as the neurotransmitters that regulate humor states and aspects of executive functions jointly influence neural networks for creative cognition[753]. In general, intrinsic motivation, emotions, and positive mood states such as optimism, joy, excitement, relaxation, tranquility boost creativity. On the contrary, fear, anger, anxiety, sadness, depression, and stress may hamper it. Nonetheless, such effects on creativity are context-dependent and vary according to individual characteristics[754].

The myth that the left side of the brain is purely rational and logical and that the right side is just emotional and creative has been debunked by neuroscience[755]. Neuroimaging shows that tasks and creative thinking recruit both **brain hemispheres**, activating distinct neural circuits with creativity relying on interhemispheric communication[756]. Greater left or right hemispheric recruitment[757] also varies according to the creative

745 Beaty, R. *et al.* (2015). Default and executive network coupling supports creative idea production.
746 Buckner, R. L. *et al.* (2008). The brain's default network: Anatomy, function, and relevance to disease.
747 Seeley, W. W. (2019). The salience network: A neural system for perceiving and responding to homeostatic demands.
748 Madore, K. P. *et al.* (2019). Neural mechanisms of episodic retrieval support divergent creative thinking.
749 Beaty, R. E. *et al.* (2014). Creativity and the default network: A functional connectivity analysis of the creative brain at rest.
750 Beaty, R.E. *et al.* (2018). Robust prediction of individual creative ability from brain functional connectivity.
751 Ellamil, M. *et al.* (2012). Evaluative and generative modes of thought during the creative process.
752 Khalil, R. *et al.* (2019). The link between creativity, cognition, and creative drives and underlying neural mechanisms.
753 Gu, S. *et al.* (2018). The neural mechanism underlying cognitive and emotional processes in creativity.
754 Khalil, R. *et al.* (2019). The link between creativity, cognition, and creative drives and underlying neural mechanisms.
755 Corballis, M. C., & Häberling, I. S. (2017). The many sides of hemispheric asymmetry: A selective review and outlook. Wang, D. *et al.* (2014). Functional specialization in the human brain estimated by intrinsic hemispheric interaction.
756 Lindell, A. K. (2011). Lateral thinkers are not so laterally minded: Hemispheric asymmetry, interaction, and creativity.
757 Aberg, K. C. *et al.* (2017). The "creative right brain" revisited: Individual creativity and associative priming in the right hemisphere relate to hemispheric asymmetries in reward brain function.

activity[758]. Creativity then results from the brain's effective integration of different mental functions subserved by distinct regions that come to operate in tandem. This joint operation generates creative responses that stand apart from the ones that each function can isolatedly provide[759].

The human brain has evolved to enable and sustain creative thinking[760]. However, creativity will only manifest itself if those neural circuits get activated. Many studies[761] have shown that interventions that stimulate participants to think 'outside the box' by (i) proposing alternative, original uses for ordinary objects, (ii) forming sentences using words that are not associated, (iii) relating explanations and consequences for situations, and (iv) improving products cause brain changes and increase creativity. Adolescence is an especially susceptible period for such interventions as there is more prominent development of the prefrontal cortex and executive functions[762].

Imagination also recruits neural circuits for creativity[763], but it derives from remembering the past. To imagine what can happen or is yet to become, the brain recruits the hippocampus via default network and guide the retrieval and recollection of past experiences – people, places, objects, actions – to reconstruct past and possible future events[764]. The brain regions recruited while we remember past experiences are the same as those activated when we imagine a future experience[765]. For researchers, imagination furnishes the seed of creativity but is not enough – socio-cultural context and personality traits (for example, openness and flexibility) are the fertile soil that determines the number of fruits the creativity tree may bear[766].

Neuroscience helps explain why sharing ideas may help us be more creative. A group of Austrian and Swiss researchers[767] showed that reflecting over other people's ideas activates brain regions involved with attention, integration for word meanings (semantics), and memory retrieval. In effect, participants processed other people's ideas and integrated them with their memories. Interestingly, it led to new associations, that is, to more original and innovative ideas. When new ideas are not interspersed with interacting with other people or with new knowledge, the creative process is limited to what got

758 Blazhenkova, O., & Kozhevnikov, M. (2016). Types of creativity and visualization in teams of different educational specialization.

759 Beaty, R. E. *et al.* (2016). Creative cognition and brain network dynamics.

760 Baas, M. *et al.* (2015). Editorial: The cognitive, emotional and neural correlates of creativity.

761 Fink, A. *et al.* (2018). Modulation of resting-state network connectivity by verbal divergent thinking training.
Kleibeuker, S. W. *et al.* (2017). Training in the adolescent brain: An fMRI training study on divergent thinking.

762 Stevenson, C. E. *et al.* (2014). Training creative cognition: Adolescence as a flexible period for improving creativity.

763 Beaty, R. E. *et al.* (2018). Core network contributions to remembering the past, imagining the future, and thinking creatively.

764 Beaty, R. E. *et al.* (2018). Brain networks of the imaginative mind: Dynamic functional connectivity of default and cognitive control networks relates to openness to experience.

765 Schacter, D. L. (2012). The future of memory: Remembering, imagining, and the brain.

766 Gotlieb, R. J. M. *et al.* (2018). Imagination is the seed of creativity.

767 Fink, A. *et al.* (2010). Enhancing creativity by means of cognitive stimulation: Evidence from an fMRI study.

registered in our memory. We expand our horizons beyond what we already know by interacting with people and exchanging ideas.

Researchers in China[768] also confirmed that social interactions exponentiate creativity. They compared paired performances – formed by pairs of less creative undergraduate students and highly creative ones – in creative problem solving while monitoring their brain activity in the cooperative task. Findings show that less creative participants in peer work were more cooperative and presented solutions as creative as those presented by the pairs of highly creative participants. Their cooperation led to synchronization and higher brain activity in regions related to social interaction. To effect, social abilities seem necessary for better integration of one's cognitive resources and may generate new ideas. Effective cooperation boosts creative performance.

Creativity exercises the learning brain. Being creative reactivates memories and thus reorganizes and reinforces multiple neural connections. Also, it recruits attention and executive functions. It requires reflection and evaluation of new ideas. In sum, it is a byproduct of emotions and mood states that propel such brain activation. Imagining, learning different things, facing new experiences and challenges are processes that activate the creative brain and make us discover how much greater we may become.

## *Transforming principle twelve into action*

Learning and creativity are processes that make us different from other animals. We have evolved throughout time because we can learn from previous generations' legacies. We can create and transform what we learn in astounding innovations[769]. Neuroscience confirms that creativity is not a gift. Rather, it is an ability open for development[770]. This relevant scientific evidence underscores that creativity then is open for teaching. It thus reinforces the role that learning institutions have in fomenting creative thinking and expression. Stimulating creativity in the school context goes beyond developing this crucial 21st-century ability. First, creativity needs to be in the classroom so that students can learn creatively, that is, they can use their creative capacity to move past rote learning of concepts and formulae[771]. As such, creativity cannot be supplementary to the education process. It must be intrinsic and defining and permeate teaching and learning processes.

768 Xue, H. *et al.* (2018). Cooperation makes two less-creative individuals turn into a highly-creative pair.
769 Abraham, A. (2013). The promises and perils of the neuroscience of creativity.
770 Ritter, S. M. *et al.* (2020). Fostering students' creative thinking skills by means of a one-year creativity training program.
771 Amaral, A. L. (2011). A constituição da aprendizagem criativa no processo de desenvolvimento da subjetividade.

Neuroscience research shows that creativity relies on the integrated activation of distinct neural networks related to cognition and emotion[772]. It means that cognitive abilities per se do not safeguard thinking and creative expression in learning. To that end, motivation, engagement, initiative, and openness to novelty need inclusion as the true propeller for creativity is thriving in discovery and being passionate for one's work. For Einstein, 'creativity is intelligence having fun'. Transferring this into classroom language means teachers should stimulate students to use creativity. They must push students towards establishing connections between contents, elaborating unusual questions, integrating practice with theory, discovering different solutions for the same problem, imagining possibilities, solving challenges, and sharing ideas. In other words, teaching creatively means using student-led methodologies in learning contexts to stimulate exchange and collaboration.

In that direction, all the principles and indications previously discussed in this chapter are essential to boost creativity in the classroom, such as recruiting attention, working with emotions, generating motivation, promoting autonomy, stimulating curiosity, stimulating social interactions, putting the body into action, guiding metacognition and self-regulation. In this principle twelve, we highlight four complementary suggestions that have not been addressed before but are central to boosting creativity.

**Ignite imagination.** According to neuroscience, imagination is the seed of creativity[773], but it has been underdeveloped in education. This may be due to imagination being commonly associated with 'fantasy' or 'make believe', thus leading teachers to understand it as the sole realm of preschool or arts. In truth, who has time to give free room to imagination with such challenging curriculum requirements? But the notion that developing imagination lies in contrast to reality and knowledge building is a huge mistake[774]. Knowledge propels imagination. Great thinkers and inventors testify to the relevance of imagination, of thinking from different perspectives, and imagining what still does not exist. Imagination is a mental process that enables expanding possibilities of a situation or problem from a different perspective by considering other alternatives, by combining and recombining ideas. For this reason, Lev Vygotsky[775] postulated that imagination and thinking processes form a singular unity that helps us make sense of the world. Additionally, this unity gives us the possibility of understanding the world from a unique angle. It uniquely recombines the knowledge trove we gather throughout life.

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772 Khalil, R. (2019). The link between creativity, cognition, and creative drives and underlying neural mechanisms.

773 Gotlieb, R. J. M. *et al.* (2018). Imagination is the seed of creativity.

774 Lindqvist, G. (2003). Vygotsky's theory of creativity.

775 Gajdamaschko, N. (2005). Vygotsky on imagination: Why an understanding of the imagination is an important issue for schoolteachers.

Teachers can effectively incorporate imagination in the learning process by generating situations that compel students to shake up their knowledge and experience. Students need to connect content from different subjects, come up with ideas, create new research problems, find creative solutions for projects, and present work in unusual forms.

**Foster interdisciplinarity.** According to neuroscience, creativity results from the functional integration of different neural circuits related to several mental processes that are influenced by social interactions and by incoming information about the world[776]. It means that creativity's core lies in making new associations, combining images, crossing knowledge and data. However, schools are delivering a message that is far from close. Instead of inviting students to establish relationships between elements, schools have fostered siloed thinking. This mechanism is a major roadblock for expressing creativity in learning[777]. In working with subjects in silos, schools block students' access to more encompassing meanings of life and knowledge. As a result, students run the risk of not building an interconnected knowledge network that enables transferring and application of knowledge in different realms[778]. To effect, researchers understand that pedagogical practices based on interdisciplinarity work as catalysts for creative thinking[779]. There is evidence that an interdisciplinary approach values diversity, boosts creative problem solving, fosters cognitive flexibility, and improves metacognition processes[780]. Besides, information acquired holistically is easier to connect with previous knowledge and may also be retrieved faster[781]. Because of what literature suggests, if a school wants to invest in students' creative development, it needs to design a curriculum and teaching methodologies that boost interdisciplinarity and combine students' knowledge and experience.

**Combine practice with theory.** Theory and practice are two sides of the same coin: knowledge. The new Brazilian Common Core (*Base Nacional Comum Curricular -BNCC*) proposes an integral scholastic formation that goes beyond theoretical knowledge and prepares students to face modern world's challenges. According to the *BNCC*[782], the competency curriculum is based on knowledge mobilization built to solve daily problems, practice citizenship and get into the labor market. In this perspective, teachers cannot favor theory over practice. Being creative cannot be only 'out of the box' ideas and rampant imagination. It also involves refining, testing, evaluating, and rearranging

776 Sawyer, K. (2011). The cognitive neuroscience of creativity: A critical review.
777 Amaral, A. L. (2011). A constituição da aprendizagem criativa no processo de desenvolvimento da subjetividade.
778 Sicherl-Kafola, B., & Denacb, O. (2010). The importance of interdisciplinary planning of the learning process.
779 Darbellay, F. *et al.* (2017). *Creativity, design thinking and interdisciplinarity.*
780 Plucker, J., & Zabelina, D. (2009). Creativity and interdisciplinarity: One creativity or many creativities?
781 Sicherl-Kafol, B., & Denac, O. (2010). The importance of interdisciplinary planning of the learning process.
782 BRASIL. Ministério da Educação. (2017). Base Nacional Comum Curricular: Educação é a base.

ideas based on practical experience. Creativity comes out of the possibility of putting knowledge, abilities, attitudes, and values into practice. In practicing students find room for meaning-making and expression[783]. Learning based on practice, with hands-on activities, enables integration of different cognitive and socioemotional abilities and promotes a deeper understanding of theoretical concepts. Moving beyond activities that boost 'learning by doing', teachers may integrate practice with theory when they use examples and establish relationships with daily situations. Examples and relationships contribute to creativity in bridging the gap between theoretical concepts and students' experiences.

**Acknowledge individual talents.** Creativity has a motivational basis. It gets expressed in the activities that arouse our interest and propels our creativity. Each child and youngster has singular talents and interests that need noticing and nurturing for development in school and in life. Some are naturally athletic; others excel in math or poetry. Some others are prone to music, painting, or drama while others are passionate about scientific experiments. There are also those especially good in leadership roles and social interactions. Many people grow up without a clear idea of their talents and spend their whole lives working in areas that do not match their talents and do not give them pleasure[784]. Consequently, they go into autopilot, without any creative expression. A fundamental task of education is to help students discover their creative juices. Once they do that, they renew their interest in studies and increase their self-confidence. A renewed interest propels them to devise a life project and put effort into that. However, identifying talents and interests does not happen in a single observation. It takes continuity instead. Teachers need to be attentive to students' signals and offer constant feedback. And this needs to be part of students' records together with their academic performance. These observations need to be forwarded to the following teachers. It is also fundamental that teachers structure learning activities to offer students some possibilities to showcase their talents. Another important initiative is sharing their observations with students' parents who may nurture their children's talents and offer substantial support for their development. Most often, human talents are like the natural world's resources; they are buried deep in the ground, and we do not know they are there until there is active search and development[785]. Figure 6 presents in consolidated form the 48 guidelines for teachers to transform neuroscience principles into action in the classroom.

783 Raravi, P., & Madhusudan H. K. (2017). *Enhancing constructive learning by integrating theory and practice.*

784 Robinson, K., & Aronica, L. (2013). *Finding your element: How to discover your talents and passions and transform your life.*

785 Robinson, K., & Aronica, L. (2013). *Finding your element: How to discover your talents and passions and transform your life.*

**FIGURE 6 –** Transforming 12 Neuroscience principles into action

### 1. LEARNING CHANGES THE BRAIN

- Tell students that intelligence is malleable
- Make a point of noticing stimuli quality
- Secure full literacy
- Foster early second language learning

### 2. HOW WE LEARN IS UNIQUE

- Uncover students' interests
- Personalize teaching
- Use adaptive platforms
- Facilitate meaning making

### 3. SOCIAL INTERACTION IS CONDUCIVE TO LEARNING

- Foster collaborative learning
- Keep high expectations
- Develop dialogic classes
- Encourage teacher-student relationships

### 4. TECHNOLOGY USE INFLUENCES INFORMATION PROCESSING AND STORAGE

- Offer support and guidance. Use technology to tap into learning
- Develop deep reading
- Boost motivation for reading
- Foster authorship

### 5. EMOTION STEERS LEARNING

- Care for relationships with students
- Develop socioemotional abilities
- Create positive classroom environment
- Make a point of noticing negative emotions

### 6. MOTIVATION SETS THE BRAIN INTO LEARNING MODE

- Foster intrinsic motivation
- Stimulate a growth mindset
- Make room for choice
- Arouse curiosity

## 7. ATTENTION IS THE GATEWAY FOR LEARNING

- Be receptive
- Foster engagement
- Secure contexts conducive to learning
- Adjust time of exposure

## 8. THE BRAIN DOES NOT MULTITASK

- Amplify awareness
- Stimulate technology breaks
- Map out priorities
- Assess degree of motivation

## 9. LEARNING REQUIRES ELABORATION AND TIME TO GET CONSOLIDATED IN MEMORY

- Boost repetition with variation
- Foster elaboration
- Give the brain time
- Use active learning

## 10. SELF-REGULATION AND METACOGNITION BOOST LEARNING

- Develop autonomy
- Guide metacognition
- Enable visible thinking
- Promote self-evaluation

## 11. WHEN THE BODY TAKES PART, LEARNING BECOMES MORE EFFECTIVE

- Promote hands-on learning
- Foster concrete learning
- Develop whole body activities
- Stimulate handwriting

## 12. CREATIVITY REORGANIZES MULTIPLE NEURONAL CONNECTIONS AND EXERCISES THE LEARNING BRAIN

- Ignite imagination
- Foster interdisciplinarity
- Combine practice with theory
- Acknowledge individual talents

# 7 LOOKING OUT FOR THE FUTURE OF LEARNING

*In this chapter, we rescue the past, analyze the present and look forward to the future of learning to highlight main trends in education interwoven with findings in neuroscience.*

In the 19th century, the needs of a world revolved by industrialization dictated the cornerstones of our current educational system. New, faster, and mechanized production lines that were time – and task-sensitive generated a novel idea for work – one that underscored education. In that context, there was a need for universal access to education as work organizations still kept a divide between conception and execution where most in the labor force did well without any knowledge beyond task routine. Schools were invested in a rational dimension characterized by strong discipline and standardized behavior based on a teaching model that was hierarchical, homogenous, and focused on the passive transmission of information[786].

Since then, the world has evolved. Yet, schools remained impervious to society's novel requests. Since the early 20th century, great thinkers and researchers exposed the extent of school's outdatedness. In many countries, Brazil included, many education manifestations and pedagogical trends, such as *The New School*[787] demanded new principles for education. Advances in psychology, in turn, strengthened the movement and brought countless contributions to developmental and learning processes that disputed traditional pedagogical practices. Despite contributions from several pedagogical[788] and psychological[789] approaches, transformations that reshaped education across the 20th century were more incremental than radical. Some specific changes did happen, but schools' principles, structure, organization, and operation remained the same. In truth, schools have never been at the forefront of change to foresee and respond to society's needs.

786 Bittar, M. (2009). *História da educação: Da antiguidade à época contemporânea.*

787 Dewey, J. (2002). *A escola e a sociedade. A criança e o currículo.*
Teixeira, A. (1969). *A educação e o mundo moderno.*

788 Freire, P. (1996). *Pedagogia da autonomia: saberes necessários à prática educativa.*
Montessori, M. (2003). *Para educar o potencial humano.*

789 Piaget, J., & Inhelder, B. (1990). *A psicologia da criança.*
Vygotsky, L. (2003). *Psicologia pedagógica.*

Why did schools not take in educational progressive thinking and scientific findings? Why did they perpetuate an archaic structure that was not addressing society's demands? Here we raise two hypotheses. First, there were no converging forces addressing education goals, no social convergence over the type of formation schools needed to offer. Not all companies and governments wanted citizens that could reflect and lead. Education had to keep reproducing patterns. Second, school, for most of the 20th century, remained the sole knowledge diffusor. It held power and center stage in educating new generations, thus regarded as necessary. We needed a revolution to change schools' *status quo* concerning knowledge. And it came with technology, fraying schools' fabric, and propelling innovation. Schools finally surrendered to reinvention.

In the current scenario, stronger convergence pushes for an emancipated education. One that boosts critical and creative thinking and develops the socioemotional abilities for full-blown participation in 21st-century society. History has shown that quality, accessible education changes a nation's path. Governments believe that there is no progress without education as the human factor is the competitive edge for technological and scientific progress – the current exchange in our innovation society. Companies, in turn, started to search for new production patterns given technological changes and starker competitiveness. This search demanded a complex set of knowledge and abilities beyond the traditional repertoire required by manual, rote tasks. The emerging 4.0 industry technologies are creating new occupations, phasing others out, and strongly impacting our relationship with knowledge[790]. The world of work will increasingly rely on education and formation for people who can create and manage fast-evolving technologies. The work profiles on-demand today greatly contrast with the expectations of a century ago.

This current technological revolution has significantly changed the way humans access knowledge, think, learn, communicate, and use their memories and brain. This change means schools' audiences are radically different. Every child and youngster who is in school today was born in the 21st century and is part of the tech-savvy world. Educating this new generation with past-century formats is inconceivable. Motivation is lacking and dropout rates are rising[791], mainly in high school, indicating that schools got disconnected from the universe and students' expectations.

790 AfDB, ADB, BID, & EBRD. (2018). *El futuro del trabajo: perspectivas regionales.*
791 Neri, M. C. (2009). *O tempo de permanência na escola e as motivações dos Sem-Escola.*

However, the revolution in course far transcends the technology issue. Our world has *turned upside down* and the upheaval is not just digital. It involves other areas as well. Challenges for the world's sustainability are mounting[792]; world hunger affects around 800 million[793]; religious conflicts spur wars and terrorism across borders[794]; refugees are all over the world; youth unemployment keep many out of the job market[795]. As if those challenges were not enough, other issues wait for humankind's response. And they restate the need for creative and ethical people capable of dealing with our current world's typically complex, evolving situations. Our world needs people that can lead and generate changes for a better life.

That is why a change in education is paramount. Schools have remained the same for over 200 years. Now, though, change is unstoppable because schools' audiences are no longer the same, expectations from companies and governments have also changed, and social challenges got increasingly complex. In this scenario, we are all called to act. The whole world is rethinking education's future, but the future is now and there is no time to lose.

When we speak of the future, what is the scenario we invoke? The answer is: one full of uncertainties that reflect fast-paced, unpredictable changes – the 'liquid modernity'[796] according to sociologist Zygmunt Bauman. To him, the only certainty in such scenario is that learning should be continuous and ongoing[797]. The speed and magnitude of change in almost every knowledge area signal that lifelong learning is not an option, but rather an absolute necessity. And it is because, even with quality compulsory elementary education and a college degree, getting into the labor market generates challenges indicative of a gap between learning and recent discoveries. According to the World Economic Forum[798], 65% of school children will get novel occupations, ones not known today, with a great chance of having different ones across life. A single job till retirement is no longer a variable in this scenario.

Indeed, formation and career have become less linear. This disruption turns education's commitment to including new generations in society more complex as it needs to furnish tools for personal development, successful labor market access, and full-blown citizenship. All, by the way, social rights by law[799].

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792 Tortell, P. D. (2020). Earth 2020: Science, society, and sustainability in the Anthropocene.
793 FAO, IFAD, UNICEF, WFP, & WHO. (2019). *The state of food security and nutrition in the world.*
794 Pew Research Center. (2014). *Religious hostilities reached a six-year high.*
795 International Labour Office. (2013). *Global employment trends for youth 2013: A generation at risk.*
796 Bauman, Z. (2001). *Modernidade líquida.*
797 Porcheddu, A. (2009). Zygmunt Bauman: Entrevista sobre a educação. Desafios pedagógicos e modernidade líquida.
798 World Economic Forum (2018*). The future of jobs report.*
799 Brasil (1988). *Constituição da República Federativa do Brasil.*

To that end, education faces the challenge of overcoming classic antagonisms that have for long prevailed in educational debates. Antagonisms generate deadlocks that lack any meaning in the current scenario. They range from forming for citizenship or the workforce, teaching knowledge or abilities, prioritizing theory or practice, offering in-person or online teaching, promoting individual or group learning, underscoring arts or sciences, stimulating critical thinking or creativity, cognitive or affection, mind or body.

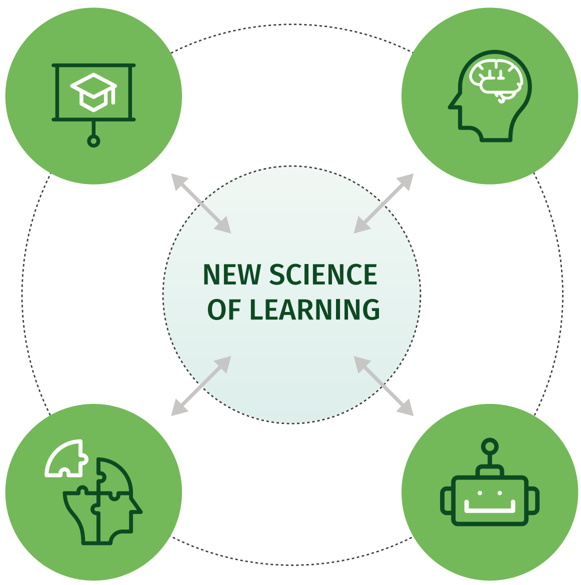
In future education, there should be no antagonisms or pedagogy of dichotomies. Complexity defines 21st-century education, and it entails breaking away from a single-lens perspective to advance towards a 'what else', 'this and that'. And why?

- The reason lies in full-blown citizenship being connected to a critical formation and successful inclusion in the labor market.
- It also means that knowledge integrated with abilities and values is the basis for wholesome education.
- A theoretical-practical consistency generates knowledge mastery and its applications.
- And while in-person education connects, going online opens a world of possibilities.
- Learning should be personalized with customized itineraries for each student. And it can happen in a network via platforms and workgroups.
- While creativity gives us wings, critical thinking enables landing and innovating.
- The connections between sciences and arts bring together sense and sensibility and confer meaning to the knowledge-building process via interdisciplinarity.
- In sum, as Aristotle once said, 'educating the mind without educating the heart is no education at all.'

The challenge is considerable, but future education anchored on a new science of learning[800] has four pillars that sustain the changes needed. Converging discoveries in education, developmental psychology, neuroscience, and artificial intelligence form the basis and will furnish the concepts and insights for redesigning future educational practices and learning environments (Figure 7).

800 Meltzoff, A. N. *et al.* (2009). Foundations for a new science of learning.

**FIGURE 7 –** New Science of Learning




**Source:** Authors' adaptation based on Meltzoff, A. N. *et al.* (2009). Foundations for a new science of learning.

In respect to learning, a synergistic partnership among these areas offers a more profound discussion coupled with a diverse body of scientific evidence for a better understanding of how the brain learns and of how education can potentialize it. Discoveries in neuroscience offer a solid basis for a body of discrete theoretical concepts in education and developmental psychology which, in turn, furnish neuroscientific research with new data on learning, cognition, emotions, and social interaction processes. In addition, artificial intelligence uses constructs from neuroscience and psychology to track big data and analyze learning patterns which enable personalized itineraries for students and contributions to educational management processes[801]. Advances in brain functioning research may contribute to new machine-learning models[802] while artificial intelligence may favor studies on human cognition[803]. Neuroscience, psychology, and education may use data from artificial intelligence to open up research questions and develop new studies that innovate the educational arena.

801 Blanco, I. F., & Carvalho, A. P. L. C. (2017). Máquinas que aprendem: o que nos ensinam?
802 Ullman, S. (2019). Using neuroscience to develop artificial intelligence.
803 Van der Velde, F. (2010). Where artificial intelligence and neuroscience meet: The search for grounded architectures of cognition.

Given such arguments, the neuroscience principles presented in the previous chapter, and the literature review on the future of education, we now introduce and explain 22 trends reshaping education. Figure 8 at the end of this chapter consolidates this information.

## COMPETENCE DEVELOPMENT

Till recently, schools were intent on knowledge transmission. But there is a growing understanding that knowledge is more of a start point than a finish line. Building a strong knowledge repertoire is the first step as power is no longer with those that hold knowledge. It lies with those able to apply such knowledge critically and creatively. In other words, in a world shaped by artificial intelligence, **learning is not holding knowledge but developing competencies that safeguard knowledge applicability and constant motivation to keep learning across one's lifespan.**

## SELF-DIRECTED LEARNING

To seize learning opportunities over the life course, we need to develop self-regulation. Despite great courses and library content being one click away, many people cannot make the best out of such opportunities because they have not developed the capacity to self-guide their learning process. This capacity includes planning their time, developing study strategies, searching information on their own, solving problems proactively, making decisions and choices - irrespective of teachers' support or constant supervision. All of the above is under the umbrella of self-regulation for learning. And this ability is built slowly and steadily throughout schooling. It means that lifelong learning does not begin when students leave school for work, but much earlier. Therefore, **future education must commit to developing self-directed learning so that children and youngsters grow up capable of managing their learning independently.**

## EDUCATIONAL ECOSYSTEMS

Self-regulation for learning is conducive to a non-linear, knowledge-building process via multiple entry points that reach beyond educational institutions. **Future education will increasingly happen via educational ecosystems**[804] that offer a wide array of learning opportunities connected to educational platforms, online video channels, social networks, cultural and community experiences, research centers, companies, and interactive

804 Gipple, J. (2020). *The learning ecosystem.*
Hannon, V. *et al.* (2011). *Developing an innovation ecosystem for education.*

museums. Some countries like Japan[805] have invested in science centers that work like informal learning stations offering authentic experiences, lectures, and meetings with scientists to enhance motivation for learning and interest in scientific research. Attending formal teaching institutions becomes another possibility within an array of educational experiences that enable personalized pathways for lifelong learning[806].

## NEW ARCHITECTURES

In this new reality where learning is unlimited by either time or space and gets exponentiated by ongoing, 'here-and-now'[807] learning ecosystems, learning institutions will forcefully break away from the hermetic classroom structure. Learning contexts will extend over multiple spaces within the school such as labs, theater, maker spaces, library, court, and spaces beyond schools' walls like communities, local companies, and virtual environments. **Classrooms will get a new architecture[808] with different workstations and flexible furnishings for greater mobility, more student interaction (happening outside the outdated seating rows), and total integration with technology tools[809].**

Time organization will also get flexible. The rigid, sequential structuring of 50-minute classes distributed over terms will give way to a more fluid design for developing and integrating multiple activities and projects. The flipped classroom[810] is an approach designed to connect students with content before class. It is a viable alternative to find more pedagogical time for active work – one that enables the development of abilities and greater depth in curricular components. According to neuroscience[811], learning needs time plus cognitive and emotional investment. Future education should offer the time necessary for students to think, elaborate information, and make sense of what they are learning.

## CURRICULUM DIVERSIFICATION

Undoubtedly, one of the most relevant characteristics of ecosystems for lifelong learning is personalizing learning tracks. To that end, we need to overcome the unified-curriculum paradigm and acknowledge that not every student needs to learn the same

805 Sakata, S., & Kumano, Y. (2018). Attempting STEM education in informal Japanese educational facilities through the theme of "sand".
806 Tawil, S. (2013). *Two roads ahead for education: Which one should we take?*
807 Northey, G. *et al.* (2018). The effect of "here and now" learning on student engagement and academic achievement.
808 Hod, Y. (2017). Future learning spaces in schools: Concepts and designs from the learning sciences.
809 Galán, J. G. (2017). Educational architecture and emerging technologies: Innovative classroom models.
810 Strelan, P. *et al.* (2020). The flipped classroom: A meta-analysis of effects on student performance across disciplines and education levels.
811 Korte, M., & Schmitz, D. (2016). Cellular and system biology of memory: Timing, molecules, and beyond.

thing, at the same time, in the same way[812]. Thus, setting personal learning goals in tandem with whole group learning goals should be a cornerstone of future education. **In parallel with the common curriculum, students should pursue individual tracks based on electives**. These will encompass varied topics, widen students' perspectives, and foster acknowledgment of talents and abilities.

## DIGITAL COMPETENCIES

It is hard to think about learning and development in the 21st century without acknowledging technology's role[813]. About 92% of future jobs worldwide will demand digital competencies[814] and, in this new work configuration, competence development ceases to be an advantage to become students' rights. A trend in some countries[815] is to **incorporate computational thinking, programming, and general competencies related to Information and Communication Technology (ICT) into the school curriculum.** In Finland[816], for example, there are goals for such competencies with different complexity levels from the first to the last years of elementary education. Another growing trend is in STEM[817] which integrates Science, Technology, Engineering, and Math with real problem-based teaching. Both trends have been gaining curriculum terrain in countries that believe in the best possible early start to prepare students for future challenges[818].

## EMERGING TECHNOLOGIES IN CLASSROOMS

Some countries have already incorporated robotics, gamification, and emerging technologies like virtual[819] and augmented[820] reality in classrooms to innovate teaching methods. To illustrate, augmented reality is great for creating 3D multimedia models for animals, plants, and landscapes. Also, it is instrumental to visualize things that are not seen by the naked eye such as magnetic fields, atoms, microorganisms, and cellular division[821]. In chemistry classes, augmented reality has been used to show 3D molecules that interact to form connections. Tridimensional images are more realistic, and students

812 Chiappe, A. *et al.* (2020). Rethinking 21st-century schools: The quest for lifelong learning ecosystems.
813 Ching, Y.-H. *et al.* (2018). Developing computational thinking with educational technologies for young learners.
814 Australian Government. (2017). *Australia 2030: Prosperity through innovation,*
815 European Education and Culture Executive Agency, Eurydice. (2019). *Digital education eurydice report at school in Europe.*
816 NCCA. (2018). *Investigation of curriculum policy on coding in six jurisdictions.*
817 Kong, S.-C., Abelson, H., & Lai, M. (2019). Introduction to computational thinking education.
818 García-Peñalvo, F. J., & Mendes, A. J. (2018). Exploring the computational thinking effects in pre-university education.
819 Al-Azawi, R. *et al.* (2019). Exploring the potential of using augmented reality and virtual reality for STEM education.
820 Hsu, H.-P. *et al.* (2018). Developing elementary students' digital literacy through Augmented Reality Creation: Insights from a longitudinal analysis of questionnaires, interviews, and projects.
821 Richardson, J. (2018). *Augmented Reality could rule the classrooms of the future.*

can rotate them for different perspectives. Interactivity and tactile learning stimulate the senses and generate motivation and engagement. **Emerging technologies will be increasingly used in future education**.

## DIGITAL LEARNING SET

Paradigm changes and technological innovations in education impacted the classroom. Such impacts have revamped teaching methodologies and led to different needs and challenges for teachers and students. More diverse learning materials, with the adoption of a digital learning kit, will come in installments to adequately support the technological revolution in teaching and learning processes.

Schools will need to secure devices as much as access to good, quality broadband and cloud storage. They will also need to cater to software and apps for text and spreadsheet editing, digital content (video classes, educational games, and the like), materials, and technologies (robot kits, physical computation, 3D printers, programming tools, virtual labs, creation tools). Taken together, they will allow students to perform experiments and build physical and virtual objects.

However, school premises and resources are not the only investment in need. Teachers will need the training to safeguard that new technologies become innovations in education.

## DIGITAL ETHICS AND CITIZENSHIP

We have made incredible strides in science, innovation, and technology but for humanity to benefit from them, reflection and ethics must steer progress. Ethics have always been in educational agendas but has become critical in a new scenario where questions greatly surpass our ability to find answers. A large part of current facts and information are absorbed by children and youngsters without a robust discussion on the values and attitudes that should be bound to them. **Future education must make room for ethical reflection to boost consciousness and expression of humanitarian attitudes and values.** The reason derives from a lack of any evidence, despite all the progress made in artificial intelligence, that we are anywhere near an ‘artificial consciousness’. Robots will solve problems, but feelings, emotions, empathy, sympathy, justice, altruism, generosity, and compassion remain inherently human.

In a scenario where children will get in touch with technologies and the internet much earlier[822], future education should go beyond literacy and digital inclusion. It must commit to helping students develop a healthy relationship with technology by exploring – in safe and trustful contexts – the digital word[823]. Research[824] shows that including 'digital citizenship' in the school curriculum is crucial to help children and youngsters become responsible technology users who can: (i) keep their personal information safe, (ii) fight harmful content, (iii) balance online and offline agendas, and (iv) be aware of copyrights. In some countries, like the United Kingdom and Italy, government education policies are evolving to turn digital citizenship compulsory in schools. This move underscores that responsible technology use will be increasingly necessary for a constructive and engaging citizenship[825].

Despite the slogan 'learn for the future' being associated with digital and technology skills, scientific evidence[826] weigh in towards deep reading skills[827] as an arena where future schools should double their efforts. Deep reading goes beyond text information. In the digital era, it is likely that readers gradually increase their screen reading mileage. Also, the cognitive overload generated by internet contexts may lead to superficial information processing[828]. What and how deeply we read shape our brains, but readers rarely get developed without guidance and instruction. And this is where education shows its true colors. Research[829] carried out with an Australian sample of 8-11 aged children shows that reading frequency dropped systematically when they had access to several mobile devices. Children and adolescents need safeguards for proper reading development and upkeeping, either in digital or printed means, together with the possibility to concentrate and immerse themselves in the text to reach the cognitive and emotional benefits that deep reading yields.

## CRITICAL THINKING

Educating people in the 21st century cannot be reduced to teaching them something. It corresponds to teaching them to think about something, thereby conducting them to learn. Education has always revolved around the 'what' to be learned (Maths, Science,

822 UNICEF. (2017). *Children in a digital world.*
823 Jones, L. M., & Mitchell, K. J. (2016). Defining and measuring youth digital citizenship.
824 Middaugh, E. *et al.* (2017). Digital media, participatory politics, and positive youth development.
825 Google for Education. (2020). *O futuro da sala de aula.*
826 Baron, N. S. (2017). Reading in a digital age.
827 Wolf, M., & Barzillai, M. (2009). The importance of deep reading.
828 Loh, K. K., & Kanai, R. (2016). How has the internet reshaped human cognition?
829 Merga, M. K., & Roni, S. M. (2017). The influence of access to eReaders, computers, and mobile phones on children's book reading frequency.

History), the 'how' (using metacognition, critical thinking, and autonomy to think independently) was never in the equation. New generations have had access to unlimited amounts of information. Nonetheless, scientific evidence shows that learning does not happen when we are granted access to information but rather when we process it [830]. Thinking critically involves moving past the 'what' to reach the 'why'. It involves considering different perspectives, breaking away from prejudice and stereotypes, overcoming the obvious, and embracing the complexities to build solid arguments and make sound decisions. In a rapid-changing scenario, students will not always count on someone by their side translating what is happening, explaining consequences, and finding solutions. Students who grow up with state-of-the-art smartphones, but low schooling will face real risks[831]. New generations' frailty is noticeable in surveys that show, for instance, that only 1 out of 10 adolescents can distinguish true information from fake news[832]. **Future education needs to develop critical thinking to confer autonomy to children and youngsters. They can use that to analyze and discriminate what happens in their contexts. This will enable a more responsible decision- and choice-making, one aligned with a better world.**

## CREATIVITY

In tandem with critical thinking, creativity is another essential 21st-century ability. Neuroscience confirms that creativity is not a heritable gift but an ability that can be developed[833]. This paramount scientific evidence underscores the notion that creativity can be taught and further reinforces the roles that learning institutions have in fomenting creative thinking and its expression in learning[834]. To reshape our country's future, we need to form creative people that enrich our present with open-mindedness, explore curiosity, use imagination, bring a fresh look on old problems. We need people who are not afraid of making mistakes, who keep their confidence in generating new ideas to transform reality. **In future education**, **creativity cannot be an add-on to the education process. It has to be intrinsic, defining, and constantly integrated with learning and teaching processes.**

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830 Clark, R. C., & Mayer, R. E. (2008). Learning by viewing versus learning by doing: Evidence-based guidelines for principled learning environments.

831 Schleicher, A. (2019). *PISA 2018: Insights and interpretations.*

832 OCDE. (2019). *PISA 2018 Results: What students know and can do.*

833 Chen, Q. *et al.* (2016). Longitudinal alterations of frontoparietal and frontotemporal networks predict future creative cognitive ability.

834 Ritter, S. M. *et al.* (2020). Fostering students' creative thinking skills by means of a one-year creativity training program.

## INTERDISCIPLINARITY

For critical thinking and creativity to come together in teaching, 21st-century pedagogy must move past the dichotomy between sciences and arts that places emotions and intuitions in opposition to rational thinking. Research in neuroscience reveals that human mental functioning is not a battlefield of reason versus impulsive, irrational emotion[835]. Much to the contrary. From a neuroscientific perspective, it is impossible to make memories, complex thinking, or meaningful decisions without mixing reason with emotions[836]. A study revealed that Nobel laureates, far from being restricted to a single area of focus, were more prone than other scientists to have broad interests or artistic skills[837]. This stands to reason as science that is limited to facts and apart from culture does not favor the necessary connections to spur new ideas[838]. Scientific innovations and breakthroughs would not have happened solely on critical thinking. It is precisely the integration of cognition with emotion that enables knowledge construction and renovation. In the last years, there has been an innovative spurt in many countries towards a STEAM curriculum, one that incorporates Arts to Science, Technology, Engineering, and Math[839]. In reality, this means advancing towards **interdisciplinary work that catalyzes critical and creative thinking to foster a dialogue among sciences, arts, and humanities.** In future education, poetry, music, design, fashion, cinema, theater, painting, and drawing cannot be part only of recess or end-of-term presentations. They need to be on the school agenda on par with math and other subjects. This will give students the chance to build a knowledge network that makes sense and meaning, one applicable to different contexts[840]. In quoting the Russian poet and writer Vladimir Nabokov (1899-1977), "there is no science without fancy and no art without facts."

## CHANGES IN STUDENTS' ROLE

Reports[841] showing potential education trends point towards a change in students' role from knowledge consumers to content producers. Translating this in the classroom requires a **paradigm change for students that move from a supporting role to a center-stage one in teaching and learning processes.** Schools have traditionally determined students' trajectories. And students had to follow them passively. Students

835 Broscha, T. *et al.* (2013). The impact of emotion on perception, attention, memory, and decision-making.
836 Duncan, S., & Barrett, L. F. (2007). Affect is a form of cognition: A neurobiological analysis.
837 Root-Bernstein, R. *et al.* (2008). Arts foster scientific success: Avocations of Nobel, National Academy, Royal Society, and Sigma Xi members.
838 Braund, M., & Reiss, M. J. (2019). The 'great divide': How the arts contribute to science and science education.
839 Harris, A., & Bruin, L. R. (2018). Secondary school creativity, teacher practice and STEAM education: An international study.
840 Sicherl-Kafol, B. & Denac, O. (2010). The importance of interdisciplinary planning of the learning process.
841 Becker, S. A. *et al.* (2016). *Horizon Report: 2016 K-12 Edition.*
Scott, C. L. (2015). *The future of learning 1: Why must learning content and methods change in the 21st century?*

are called to act beyond listening and repeating content to overcome encyclopedic teaching focused on information consumerism. They need to produce something new from what they learned – authorship needs enticing.

## PERSONALIZED LEARNING

Students need to build their path as content developers rather than knowledge reproducers. Research in neuroscience[842] shows that our brains are as unique as our fingerprints and that learning is an individualized process. **To be aligned with scientific evidence, future education needs personalization.** Of note, at the beginning of education, nobility's children were educated by tutors in a personalized teaching model[843]. With the Industrial Revolution, the school needed to expand, and individualized, small-group education ceased to be an option. Necessity bred a new pedagogy of knowledge transmission for much larger audiences of children, youngsters, and adults. That was when blackboards found a place in the classroom, and the teacher became the center of the education process incumbent with teaching the same content to everyone regardless of individual rhythms, abilities, and interests. Currently, education has tools to personalize learning for a larger student body backed up by new technologies. Adaptive platforms may offer teachers the support they need with virtual learning environments that personalize the learning process and progress. Artificial intelligence[844] algorithms analyze students' performance, identify their needs and difficulties, and suggest a customized learning track. For teachers in special, performance reports on individual students can be generated to facilitate understanding of individual trajectories.

## TEACHERS' NEW PROFILE

Technology can be a powerful tool to personalize learning. However, this process can only be enabled when teachers effectively change their roles and develop relationships with students. Teachers must do away with the lecture model and diversify pedagogical practices and resources for student-tailored learning pathways. **In 21st-century education, teachers will gradually become less of a content provider and more of a learning guardian[845].** This means that teachers are committed to mediating students' relationship with knowledge by searching for the best pathways to safeguard an individual's full learning potential. In truth, teachers got a chance to innovate and reshape their roles.

842 Miller, G. (2012). Why are you and your brain unique?

843 Kamecka, M. (2007). Educating and passing knowledge: The role of private tutors in the formation of polish youth of noble origins in the sixteenth to eighteenth centuries.

844 Tuomi, I. (2018). *The impact of artificial intelligence on learning, teaching, and education.*

845 USP: Cátedra de Educação Básica da Universidade de São Paulo. (2019). *Ciclo Ação e Formação do Professor.*

Far from being substituted by new technologies, teachers will become increasingly necessary in the 21st century[846]. This trend reinforces the need to invest in formation, wages, careers, work conditions, and social worth to attract more qualified and talented people for teaching careers. For teachers to act based on the pillars of future education, their initial and ongoing formation should go beyond adding new knowledge and technical skills to their repertoires. It needs to boost a paradigm change that enables teachers to rebuild their role and objectives[847].

## SOCIAL INTERACTION AND NETWORK LEARNING

Of note, personalized teaching is not the same as individualized teaching. Personalized learning caters for the unique needs of each learner while individualized learning caters for one single individual at a time. According to neuroscience, social interaction is a crucial catalyst for learning[848]. Educational contexts designed to potentialize social relationships boost motivation[849], self-efficacy awareness[850], creativity[851], and problem-solving[852]. That is why, in future education, learning must be personalized with customized itineraries while also happening **in networks, platforms, and workgroups in the classroom.**

In collaborative contexts, students must think critically and confront their thinking logic and accuracy to understand a topic. Collaborative tasks also enable students to develop their communication skills and learn how to expose and defend their points of view[853]. Thus, social interactions in education contexts are essential to prepare students for real social and work exchanges[854]. Teachers' interactions and exchange are critical for better outcomes as effective teachers work in tandem with peers and are constantly learning, thereby improving their practices and their students' learning as a result[855].

## INNOVATIVE PEDAGOGY WITH ACTIVE LEARNING

Preparing students for challenges, present and future, means adopting innovative teaching methodologies. To that end, teachers need to understand the reason for

846 UNESCO. (2015). *Rethinking education: Towards a global common good?*

847 Bull, A., & Gilbert, J. (2012). *Swimming out of our depth: Leading learning in 21st century schools.*
Kuhlmann, J. (2019). *Role of the teacher in a personalized, competency-based classroom.*

848 Yano, K. (2013). The science of human interaction and teaching.

849 Immordino-Yang, M.-H., & Sylvan, L. (2010). Admiration for virtue: Neuroscientific perspectives on a motivating emotion.

850 Blazar, D., & Kraft, M. A. (2017). Teacher and teaching effects on students' attitudes and behaviors.

851 Xue, H. *et al.* (2018). Cooperation makes two less-creative individuals turn into a highly-creative pair.

852 Hurst, B. *et al.* (2013). The impact of social interaction on student learning.

853 Official Norwegian Reports. (2015). *The school of the future: Renewal of subjects and competences.*

854 Scott, C. L. (2015). *The future of learning: What kind of pedagogies for the 21st century?*

855 Schleicher, A. (2012). *Preparing teachers and developing school leaders for the 21st century: lessons from around the world.*

different methodologies and be prepared to choose the most appropriate for the learning goals of each situation. Education in the 20th century got hallmarked by a homogeneous pedagogy where methodologies were the same. The single way of 'expository class' stifled teaching and learning processes and did not require teachers to reflect on how they should be teaching. **Future education will latch onto innovative pedagogy reflected in several teaching methodologies.** Teachers need upskilling as learning designers that steadfastly decide what methodology to use at any given moment and know what to select for successful end-goals[856].

Teaching methodologies have a crucial role as the way people get taught affect 'what' and 'how' they learn[857]. Besides, methodologies shape teacher-student relationships. And evidence points towards relationships exerting an effect on students'[858] academic performance. Students need to incorporate the notion that learning is not limited to following teachers' lessons, doing exercises, and taking exams. And to put that into effect, future schools need to adopt active learning and place the student at the center of the education process. Schools need to enable students to self-guide their learning by making choices of topics and activities, exploring their curiosity, making questions, generating ideas independently, working with problem situations, developing self-interest projects, and reflecting and self-evaluating their learning. Evidence suggests that active methodologies help students to learn more effectively as they foster autonomy and responsibility for the learning process[859].

## SOCIOEMOTIONAL ABILITIES

Active methodologies are the ideal scenario for developing socioemotional abilities which are much in demand – at present and in the future. In a fast-paced, automation process where robots gain more space, developing the abilities that define our humanity like empathy, leadership, responsibility, collaboration, flexibility, resilience, and emotional stability are increasingly relevant[860]. However, work-life challenges are not the only argument in favor of a future education that integrates socioemotional abilities. Studies reveal that they modulate adult-life outcomes like income, health, and social integration[861].

856 Jensen, B. *et al.* (2016). Beyond PD: *Teacher professional learning in high-performing systems beyond PD: Teacher professional learning in high-performing systems.*

857 Peterson, A. *et al.* (2018). *Understanding innovative pedagogies: Key themes to analyze new approaches to teaching and learning.*

858 Roorda, D. L. *et al.* (2017). Affective teacher, student relationships and students' engagement and achievement: A meta-analytic update and test of the mediating role of engagement.

859 Konopka, C. L. *et al.* (2015). Active teaching and learning methodologies: Some considerations.

860 Börner, K. *et al.* (2018). Skill discrepancies between research, education, and jobs reveal the critical need to supply soft skills for the data economy.

861 Chernyshenko, O. S. *et al.* (2018). *Social and emotional skills: Well-being, connectedness, and success.*
Lechner, C. *et al.* (2019). Socio-emotional skills in education and beyond: Recent evidence and future research avenues.

Such narrative – coupled with neuroscientific evidence[862] that emotions affect how students access, process, and consolidate information and experiences – strengthens the need for an educational paradigm change from one solely based on cognitive processes to another that acknowledges emotional and social human factors. **Future education will integrate socioemotional abilities with academic development for a more apt studentship today and better prepared citizenship tomorrow.** In following that, education will tend to students' expectations for greater importance of socioemotional abilities in the future[863].

Across schooling, students absorb a mixed set of messages about their rights and wrongs, talents and frailties, possibilities and limitations. The way each one emotionally processes these messages shapes one's mindset[864] and guides one's behavior toward future achievements. Students who develop a growth mindset believe that they can grow; they embrace challenges, stay firm when facing setbacks, understand that learning success demands efforts, deal better with criticism, and learn from mistakes. Conversely, students who have a fixed mindset tend to function only when pushed by teachers; they avoid challenges, give up easily, see effort as something negative, ignore feedback, and consequently, fall short of their potential. Research[865] shows that when students experience success at school, they get motivated to keep learning and moving ahead. Studies also show that those harmed by negative school experiences develop a fear of failure. This fear makes them doubt their capacity for success throughout life[866]. Future education should stimulate a mindset that fosters students' trust in their ability to develop their potential, face challenges and succeed. Encouraging a growth mindset for teachers should also become a priority[867]. Those with a fixed mindset tend to get stuck on their practice and resist new ideas.

## DIVERSIFIED EVALUATIONS

Several reconfigurations involving aspects of the educational process addressed before – redesigning the curriculum, innovating teaching methodologies, and restructuring teachers' formation – are necessary to broaden education goals towards a holistic perspective that transcends academic performance. For these reconfigurations to work,

862 Immordino-Yang, M.-H., & Damasio, A. (2007). We feel, therefore we learn: The relevance of affective and social neuroscience to education.

863 Pearson. (2019). *The global learner survey.*

864 Dweck, C. S. (2017). *Mindset: A nova psicologia do sucesso.*

865 Dweck, C. S. (2017). Growth mindset and the future of our children.

866 Au, R. C. P. *et al.* (2010). Academic risk factors and deficits of learned hopelessness: A longitudinal study of Hong Kong secondary school students.

867 Seaton, F. S. (2017). Empowering teachers to implement a growth mindset.

aspects should be part of the evaluation process. Evaluation systems draw teachers' and students' expectations and thus become the cornerstone of the educational system. As such, evaluations have always happened by standard processes focused on grades as endpoints and do not get used as an effective feedback tool for students. This leads to a huge gap between this evaluation model and the new pillars of education[868]. There is a call for innovative approaches that encompass evaluation of socioemotional abilities and students' mindset – both complex constructs not easily measurable[869]. **In future education, greater use of multiple, innovative assessment tools will facilitate evaluating the learning processes more broadly and in a personalized fashion throughout formation**.

## BIG DATA AS A SCHOOL LEADERSHIP TOOL TO IMPROVE RESULTS

Evaluation is vital for the educational process[870], not only as a compass to steer students' progress, but also as a diagnostic tool for assessing the broad educational perspective, and thus necessary for learning management and public policy. Education generates a huge data set. To effect, **big data analysis via artificial intelligence will be increasingly present and favor in-depth data interpretation that can signal routes for better outcomes in learning, school leadership, and public policymaking.**

## NEW CERTIFICATIONS

Another trend in evaluation lies with the certification process for the work environment. As learning ecosystems get developed, possibilities for knowledge building and ability development abound. These will no longer be tied to formal learning institutions. **New certifications will gradually reconceptualize the value given to official certificates and diplomas. There will be an ample acknowledgment of learning as a set of competencies and experiences gathered throughout life. Alternative forms of certification will be increasingly coupled with official certificates and get progressively valued by companies.** People will use ability-tracking technologies like the Learning Record Store (LRS)[871] and micro-credentials[872] coupled with portfolios and

868 Siarova, H. *et al.* (2017). *Assessment practices for 21st century learning: Review of evidence.*

869 Soland, J. *et al.* (2013). *Measuring 21st century competencies: Guidance for educators.*

870 Gordon Commission. (2013). *To assess, to teach, to learn: A vision for the future of assessment.*

871 *Learning Record Store* (LRS) is a server capable of receiving and processing Web requests. It can receive, store, and grant access to learning records.

872 Micro-credentials represent specific abilities or knowledge that students acquire at a granular level. They often take the form of digital badges (digital learning indicators that certify one's competence in a given topic).

extracurricular activities, like volunteering, to showcase their out-of-bounds (classroom and curriculum) learning[873].

## COLLABORATIONS AMONG MULTIPLE STAKEHOLDERS

Education in the 20th century remained shut-in, ensconced in high walls that prevented a more thorough social participation. Such enclosure left many stakeholders out who could have contributed with new perspectives and innovations despite not being directly connected to the learning process. Today, schools are expanding their connections with the outside world[874], establishing partnerships and coalitions with third-sector organizations, startups, technology providers, and telecommunications networks, to name a few. Together with governments, families, and the local community, they can boost innovations in education. **The trend is that such collaborative efforts encompass an even wider array of stakeholders who can interact and jointly work for education.** This falls in line with the constitutional principle that education should be a society's responsibility not restricted to governments and families[875].

The historical review and research we carried out in this chapter show that education and society demands have been out of synch for too long. This collapse in synchronization derives from the cumulative experience of teaching systems structured since pre-elementary education. And it reflects on the failure of recent professional formation. In reality, this means two things. First, the problem – and its solution – begins early. Second, there is no time to lose. Future education begins now.

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875 Brasil (1988). *Constituição da República Federativa do Brasil.*

**FIGURE 8 –** 22 Global Trends In Education

ORGANIZATION OF THE EDUCATION PROCESS

1. **NEW ARCHITECTURES**
Classrooms will get a new architecture with different workstations and flexible furnishings for greater mobility, more student interaction and total integration with technology tools.

2. **INNOVATIVE PEDAGOGY WITH ACTIVE LEARNING**
Innovative pedagogy with multiple active learning modes will drive education. These will overtake lectures and place the student at the center of the educational process.

3. **CURRICULUM DIVERSIFICATION**
Curriculum will get progressively diversified. This will give students the opportunity to pursue individual tracks based on electives. These will encompass varied topics, widen students' perspectives and foster acknowledgement of talents and abilities.

4. **CHANGES IN STUDENTS' ROLE**
Students will increasingly take a more active role in their learning by being more autonomous and exercising authorship in developing their competencies.

5. **TEACHERS' NEW PROFILE**
Teachers' role will get gradually reshaped from being less of a content provider and more of a mediator and learning guardian.

6. **PERSONALIZED LEARNING**
Teaching will get more personalized with tutorship and mediation backed up by new technologies to foster student-tailored learning pathways.

7. **INTERDISCIPLINARITY**
The pedagogical process will become increasingly interdisciplinary, fostering integration of STEM with arts and humanities.

8. **SOCIAL INTERACTION AND NETWORK LEARNING**
Students' social interaction will get a boost. Learning will be fueled by group work, in classrooms and in platforms. Squads – small, multidisciplinary groupings – focused on project development will replace fixed classes.

9. **DIVERSIFIED EVALUATIONS**
Greater use of multiple, innovative assessment tools will largely facilitate evaluation of the learning process and of socioemotional development throughout formation.

10. **NEW CERTIFICATIONS**
New certifications will gradually reconceptualize value given to official certificates and diplomas. There will be an ample acknowledgment of learning as a set of competencies and experiences gathered throughout life in different learning ecosystems.

11. **COLLABORATIONS AMONG MULTIPLE STAKEHOLDERS**
There will be more participation and collaboration among different stakeholders (third sector, startups, tech companies). These will foster education.

## ABILITIES AND COMPETENCIES

**12 COMPETENCE DEVELOPMENT**

Teaching will be increasingly geared towards developing competencies. This will safeguard knowledge use instead of passive content transmission.

**13 SELF-DIRECTED LEARNING**

There will be greater support for the development of self-directed learning for children and youngsters so that they grow up capable of managing their own learning independently and without constant teacher supervision.

**14 DIGITAL COMPETENCIES**

Digital competencies (programming, computational thinking, and general competencies related to Information and Communication Technology - ICT) will populate curricula and be developed in tiers throughout basic formation. Educational robotics will become a constant in the education process.

**15 SOCIOEMOTIONAL ABILITIES**

Development of socioemotional abilities will be a cornerstone of any learning process. This will make students more apt in learning and better prepared for future citizenship.

**16 CRITICAL THINKING**

Greater focus on critical thinking development will confer autonomy to children and youngsters . They can use that to analyze and discriminate what happens in their contexts. This will enable a more responsible decision- and choice-making, one aligned with a better world.

**17 CREATIVITY**

Greater focus on creativity development will tap into students' curiosity and engage their imagination for innovative problem solving.

**18 DIGITAL ETHICS AND CITIZENSHIP**

Digital ethics and citizenship will grow in curricula so that students can express attitudes and values for the common good and make responsible use of new technologies.

## TECHNOLOGY

**19 EDUCATIONAL ECOSYSTEMS**

Future education will not be restricted to formal educational institutions. It will progressively become part of educational ecosystems that foster ongoing 'here and now' learning. This will happen via multiple entry points connected to educational platforms, online streaming, social networks, cultural and community experiences, research centers, companies, and interactive museums.

**20 BIG DATA AS A SCHOOL LEADERSHIP TOOL TO IMPROVE RESULTS**

Big data analysis via artificial intelligence will be increasingly present favoring in-depth data interpretation that can signal routes for better outcomes in learning, school leadership, and public policy making. It will also contribute to realigning education systems with the workplace.

**21 EMERGING TECHNOLOGIES IN CLASSROOMS**

Emerging technologies will be increasingly used. Learning contexts will encompass intelligent tutoring and chatbots, virtual technologies such as VR, remote labs, digital simulators and interactive virtual environments. These will congregate students from different classrooms worldwide.

**22 DIGITAL LEARNING SET**

Digital learning resources sets (digital books, mobile apps, internet packages) will become part of traditional teaching materials.

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## CHAPTER 5 – LEARNING MAKES US HUMAN

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## CHAPTER 6 – HOW DO WE LEARN?

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## CHAPTER 7 – NEUROSCIENCE PRINCIPLES THAT MAY ENHANCE LEARNING

### *PRINCIPLE 1: LEARNING CHANGES THE BRAIN*

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## CHAPTER 8 – LOOKING OUT FOR THE FUTURE OF LEARNING

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# GLOSSARY

**Amygdala**. Cluster of neurons located in the anterior part of the temporal lobe. It processes emotions, confers positive or negative value to stimuli, and detects threats.

**Ascending Reticular Activating System (ARAS)**. Cluster of neurons located in the brain stem involved in the regulation of sleep and awake states.

**Axon**. Neuron extension that carries the nerve impulse from the neuronal cell body to the synapse where it is transmitted to other neurons or to effector organs (muscles and glands).

**Axonal and dendritic processes**. Extensions emerging from the neuronal cell body. *See* **Neuron**, **Axon** and **Dendrite**.

**Basal ganglia**. Set of structures located within the brain bearing reciprocal connections with the cerebral cortex. They are involved in the regulation of motor control and behavioral strategies.

**Brain Ventricules**. Spaces within the encephalon filled by a liquid (liquor).

**Brain**. Set of nervous system structures – brain stem, cerebellum, and cerebrum – located in the skull. It corresponds to the encephalon. In general, the term "brain" is used to refer to cerebrum. *See* **Encephalon.**

**Brain stem**. Structure in the central nervous system situated between the spinal cord and the brain. It contains neural circuits related to vegetative functions such as breathing, cardiac functioning, digestion, and brain activity regulation including sleep and awake cycles.

**Cerebellum**. Structure located at the back of the brain involved with balance, muscular tone, posture, motor coordination, and also with cognitive functions, like perception, attention, memory, planning, and action execution.

**Cerebral cortex**. Most external brain (cerebrum) layer where neuronal cell bodies are located (gray matter). The cortex is named after the brain lobe where it is located or according to its function. For example: occipital, parietal, temporoparietal, occipito-temporal (for location), and visual, auditory, motor (for function).

**Cerebrum.** Structure in the central nervous system and the largest part of the brain (brain stem, cerebellum, and cerebrum). It is involved with perception, language, memory, abstract reasoning, action planning, movement, logical mathematical reasoning, imagination, emotions, and more. It is usually referred as brain.

**Corpus callosum.** A thick bundle of axons that connect the left and right cerebral hemispheres located in the center of the cerebrum (brain).

**Cingulate gyrus**. Located above the corpus callosum in the medial portion of each brain hemisphere. It takes part in emotional and cognitive processes such as attention, error detection, decision making, memory, and motor control. Its anterior portion is also termed anterior cingulate cortex.

**Cognitive/Executive control network**. Neural network regulating thoughts and behaviors needed for achieving a goal. It involves neural circuitry in frontal and parietal lobes. *See* **Neural network** and **Executive functions**.

**Cortex**. Most external brain layer. *See* **Cerebral cortex.**

**Cortical areas**. Several regions of the cerebral cortex. *See* **Cerebral cortex**.

**Default network**. Neural network activated when one is more focused on internal (rather than external) stimuli, remembering the past and planning the future. *See* **Neural network**.

**Dendrites**. Specialized expansions of the neuronal cell body that receive information from other neurons. This is where synapses are formed.

**Dopamine**. Neurotransmitter involved in motor regulation, emotions, and motivation. *See* **Neurotransmitter.**

**Dorsolateral cortex**. Located in the superior lateral region of the prefrontal area. *See* **Prefrontal area**.

**Electrochemical language**. *See* **Nerve impulse**.

**Encephalon**. Set of nervous system structures – brain stem, cerebellum, and cerebrum – located in the skull. Colloquially, the encephalon is referred to as brain.

**Epigenetic factors.** Environmental factors that may modify gene expression.

**Executive functions.** Set of mental functions related to action planning, execution, and monitoring necessary for reaching goals and solving problems.

**fNIRS**. Neuroimaging technique that employs near-infrared spectroscopy to assess cerebral blood flow.

**Frontal lobe**. Anterior region of the brain.

**Frontoparietal neural network**. *See* **Cognitive/Executive control network**.

**Glial cells**. Cells (neuroglia) surrounding neurons and essential for several aspects involving their functioning, like information transmission, structural support, nutrition, defense against microorganisms, and myelination.

**Gray matter**. Group of neuronal cell bodies. *See* **Neuron**.

**Hippocampus**. Structure located in the temporal lobe involved with memory.

**Insula**. Brain lobe hidden by temporal, frontal and parietal lobes. It is involved with processing visceral sensations and emotions.

**Left and Right Hemisphere**. Each one of the two sides of the brain.

**Limbic system**. Set of brain structures involved with processing emotions and memory.

**Mental function**. Functions that emerge from brain activity.

**Mental representation**. Neural registration of an experience. It is a set of neural circuits activated during a certain experience which mentally reproduces that same experience – even if it is absent – when activated.

**Mentalizing system**. Set of neural circuits involved with the capacity to infer internal states of other people based on their actions and on what is known about them.

**Mirror neurons system**. Set of neural circuits specially related to learning by imitation and to empathy.

**Mirror Neurons**. *See* **Mirror neurons system**.

**Myelination**. Myelin sheath formation process covering axons. It speeds up nerve impulse conduction.

**Nerve impulse**. Chemical and electrical alteration produced by a stimulus or a neurotransmitter that characterizes neuron activation.

**Nerve**. Bundle of axons.

**Nervous system**. Set of structures composed by neurons (nerve cells) situated inside the skull (brain stem, cerebellum, and cerebrum) and the vertebral column (spinal cord), that together form the central nervous system. The other structures – nerves and ganglia – are distributed in the body forming the peripheral nervous system.

**Neural circuit**. Set of interconnected neurons, a.k.a. neuronal circuit. The denomination of neural circuits is related to its localization in the different brain regions (lobes) (e.g., frontal, parietal, occipital circuits).

**Neural circuitry**. Set of different neural circuits functionally related. *See* **Neural circuit**.

**Neural network**. Set of interconnected neural circuits located in different brain areas. When activated, specific cognitive functions are produced. Neural networks are named according to their location in the brain, for example, frontoparietal neural network involving circuits of the frontal and parietal lobes, or according to their function, for example, cognitive control network. *See* **Neural circuit**.

**Neuron**. Basic functional unit of the nervous system. It is formed by a cell body – where proteins and energy – essential for neuron functioning – are produced, and by dendrites and axons. *See* **Axon** and **Dendrite**.

**Neuron doctrine**. Proposed in the late 19th century, it is a historical cornerstone in neuroscience. It proposes that the nervous system is formed by interconnecting neurons.

**Neuronal circuit**. *See* **Neural circuit**.

**Neuroplasticity**. Nervous system capacity to modify itself, a.k.a. brain plasticity or neural plasticity. It entails connecting and disconnecting neurons due to environmental interactions.

**Neurotransmitter**. Chemical substance released at the synapse. It enables information transmission from one neuron to another. *See* **Dopamine**, **Noradrenaline**, **Serotonin**.

**Neurotrophic factors.** Important substances for neurons' survival, development, structure, and function.

**Noradrenaline**. Neurotransmitter related to anxiety, learning, and memory. It regulates viscera, attention, alertness, and mood. *See* **Neurotransmitter**.

**Nucleus accumbens**. Cluster of neurons located deep in the brain. It is also referred to as ventral striatum and is involved with pleasure, satisfaction, reward, and motivation.

**Occipital lobe**. Most posterior region of the brain.

**Occipito-temporal cortex**. *See* **Cerebral cortex**.

**Optic nerves**. Transmit visual information from the retina to the brain.

**Orbitofrontal cortex**. Located in the prefrontal area. *See* **Prefrontal area**.

**Parietal cortex**. *See* **Cerebral cortex**.

**Parietal lobe**. Posterior region of the brain behind the frontal lobe and above the temporal lobe.

**Postsynaptic membrane**. Neuronal membrane awaiting activation by another neuron. It is the site for neurotransmitter action. *See* **Synapse**.

**Prefrontal area**. Most anterior portion of the frontal lobe involved in selecting and planning behavior, decision making, and memory. *See* **Prefrontal cortex.**

**Prefrontal cortex**. Most anterior portion of the frontal lobe involved in selecting and planning behavior, decision making, and memory. *See* **Cerebral cortex** and **Prefrontal area.**

**Proprioception**. Sensation that gives information about limb muscle contraction, joint movement and joint position. Kinesthesia.

**Reward system**. Set of structures in the encephalon that, once activated, enable feelings of satisfaction and well-being. It fosters motivation.

**Salience network**. Neural network that selects attention-worthy stimuli by gauging the bodily information sent to the brain, our physiological needs, emotions, and memories. *See* **Neural network**.

**Sensorial receptors**. Structures located in the sensory organs that detect environmental stimuli.

**Serotonin**. Neurotransmitter involved in the regulation of pain, sleep and awake cycles, and mood. *See* **Neurotransmitter**.

**Spinal cord**. Structure located inside the vertebral column containing neurons and their axons. It sends motor commands from the brain to the body and sensory information from the body to the brain and coordinate reflexes. *See* **Encephalon**.

**Subcortical areas**. All the brain structures containing neurons that are not in the cerebral cortex. *See* **Thalamus**, **Basal Ganglia, Cerebellum, Cerebral Cortex.**

**Sympathetic autonomic nervous system.** Set of structures in the nervous system that regulates viscera.

**Synapses**. Structure that connects two neurons. It enables transmission of a nerve impulse by releasing neurotransmitters from one neuron to another. *See* **Neurotransmitter** and **Postsynaptic membrane**.

**Synaptic pruning**. Synapse elimination.

**Synaptogenesis**. Synapse formation.

**Temporal lobe**. Lateral region of the brain, anterior to the occipital lobe and posterior to the frontal lobe.

**Temporoparietal cortex**. *See* **Cerebral cortex**.

**Thalamus**. Structure located inside the brain bearing reciprocal connections with the cerebral cortex. It processes stimuli before they reach the cortex. It is involved with the regulation of consciousness and pain, sensory (except for smell), motor, cognitive and emotional processing.

**Tractography**. Magnetic resonance technique enabling identification of axon fibers that form the white matter in the central nervous system. *See* **White matter**.

**Translational research**. Research that integrates the findings of basic (research) science more quickly and efficiently into evidence-based practices.

**White matter**. Set of axons extending from neuronal cell bodies (gray matter) distributed in the central nervous system. Axons from neurons located in the cerebral cortex form the most central part of the brain. *See* **Axon**.

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