

Chapter 5

Neuroscience-Informed Learning

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1. Introduction

Neuroscience occupies a central position in understanding the biological foundations of learning. The structure and functioning of the brain, as well as the interactions among neural networks, determine how information is acquired, processed, and transferred to long-term memory. Learning is no longer viewed solely as a pedagogical process but rather as the reorganization of dynamic connections among neurons. This perspective makes it possible to align educational practices with the brain's natural learning mechanisms (Chai et al., 2018). This biological framework demonstrates that learning is closely related not only to what is learned but also to how the brain regulates the learning process itself (Goldberg, 2022). At this point, higher-order cognitive mechanisms, such as executive functions that regulate the learning process, come to the forefront.

Executive functions encompass higher-order cognitive processes such as planning, goal setting, impulse control, cognitive flexibility, and decision-making. These functions are primarily associated with the prefrontal cortex and are among the key determinants of effective learning (Gravakmo et al., 2023). A learner's ability to regulate attention, develop strategies, and learn from errors depends on the healthy functioning of executive processes. For this reason, structuring learning environments in ways that support these skills is of critical importance. However, the effectiveness of executive functions is constrained by the capacity to temporarily hold and process information in the mind (Roitsch et al., 2022). This limitation brings working memory—an essential component of the cognitive infrastructure of learning—into focus.

Working memory is a cognitive system in which information is held for short periods and actively processed. Understanding a text, solving a problem, or following instructions during the learning process is directly related to the capacity of working memory (Willis, 2007). Due to its limited capacity, excessive cognitive load can hinder learning. Accordingly, designing instruction in ways that do not overload working memory constitutes one of the core principles of neuroscience-informed learning (Short et al., 2013). Nevertheless, the consolidation of information processed in working memory depends not only on momentary cognitive capacity but also on the brain's ability to undergo long-term change (Gokce et al., 2021). In this respect, the concept of neuroplasticity provides an explanatory framework.

Neuroplasticity refers to the brain's ability to undergo structural and functional changes in response to experience. Learning represents a concrete outcome of this plasticity; repetition, feedback, and meaningful interaction strengthen synaptic connections. Modern neuroscience has demonstrated that the brain remains open to change throughout the lifespan, not only during childhood (Battro et al., 2011). This finding indicates that learning is not limited by age and that cognitive development can be sustained across the lifespan when appropriate conditions are provided; however, for neuroplastic changes to occur, learning stimuli must be selected and processed by the brain (Ferreira et al., 2025). At the centre of this selective process lies attention.

Attention is a fundamental cognitive process that can be described as the gatekeeper of learning. The brain is capable of deeply processing only a limited portion of the numerous stimuli it receives

simultaneously. For this reason, attentional distraction constitutes one of the greatest barriers to learning. Neuroscientific research indicates that attention span is limited and must be deliberately directed. Effective learning becomes possible through meaningful and motivating learning experiences that support attentional processes (Lindsay, 2020).

2. Neuroscience and Learning: Conceptual Framework

The connections between neuroscience and education are increasingly evolving into an interdisciplinary field under the broad umbrella of neuroscience-informed learning (Dorsey, 2025). Closely related terms, including neuroscience-based learning, brain-based learning, educational neuroscience, and neuroeducation, are also used in the literature to describe the intersection of knowledge about the brain, learning, and educational practice (Ullman et al, 2014). Although these concepts overlap, they emphasize somewhat different dimensions of this interdisciplinary field. Educational neuroscience generally refers to the scientific investigation of the neural, cognitive, and developmental processes underlying learning and their implications for education, whereas neuroeducation emphasizes the integration of neuroscience, education, and related disciplines to bridge research and educational practice (Wang et al, 2025).

Brain-based learning is more commonly used to describe pedagogical approaches that seek to align teaching and learning practices with established knowledge about brain functioning. Neuroscience-based learning similarly emphasizes the application of neuroscientific evidence to understanding and supporting learning, whereas neuroscience-informed learning highlights the use of neuroscience evidence to inform educational thinking and practice without implying that educational approaches can be derived directly from neuroscientific findings (Schultz, 2018).

This interdisciplinary field aims to provide a more holistic framework for understanding how individuals learn by linking the neural foundations of learning with pedagogical theories and classroom practices. Neuroscientific concepts such as brain plasticity, attentional processes, memory systems, and executive functions offer new perspectives for instructional design, assessment and evaluation, and the structuring of learning environments (Funa et al., 2024).

In this way, education moves beyond traditional approaches that focus solely on behavioural outcomes and is repositioned on an evidence-informed foundation that takes cognitive and neurophysiological processes into account (Sortwell et al, 2026). Consequently, neuroscience-informed learning is taking shape as a forward-looking paradigm that creates a broad sphere of influence ranging from educational policies to teacher training, while providing a more nuanced understanding of individual differences in learning (Pradeep et al., 2024).

Neuroscience is a comprehensive scientific field that examines the physical, chemical, and biochemical properties of neurons; how the neural networks formed by these cells are organized in the brain; the mechanisms through which information is transmitted; and how these processes relate to behaviour, cognition, and emotion (Goldberg, 2022). It encompasses a multi-layered domain of

investigation, ranging from the molecular level to cellular structures, from neural circuits to whole-brain systems (Dipietro et al., 2023).

Data obtained through experimental methods, brain imaging techniques, electrophysiological measurements, and computational models aim to explain the biological foundations of complex mental processes such as perception, learning, memory, attention, language, and decision-making. In this context, neuroscience not only describes the structure and functioning of the nervous system but also constitutes an interdisciplinary research field that provides a holistic framework for understanding, explaining, and predicting human behaviour (Singh & Morkel, 2024). Within this broader framework, neuroscience-based learning focuses more specifically on how neuroscientific knowledge can contribute to understanding and supporting educational processes. It is an interdisciplinary field that investigates the relationships between education, learning, and the human brain (Parayangattu & Kishore, 2024).

Learning theories grounded in neuroscientific findings offer empirically supported perspectives for designing pedagogical strategies that are consistent with how the brain processes, stores, retrieves, and applies information (Febrialismanto, 2023). From this perspective, brain-based learning can be considered a practice-oriented approach that seeks to translate knowledge about brain functioning into instructional principles, while educational neuroscience provides the research-oriented foundation for examining how neural and cognitive processes interact with educational experiences. Neuroeducation, in turn, represents a broader interdisciplinary effort to connect these scientific insights with educational theory, practice, and policy (Funa et al, 2024).

Learning is the process through which knowledge, skills, or behaviours are acquired and made enduring. It begins with the perception, processing, and interpretation of stimuli from the environment. This process requires information to be processed, analysed, encoded into memory, and ultimately applied. Learning involves acquiring new information that is connected to an individual's existing knowledge and experiences and using this information to develop various skills (Dorsey, 2025). From a neuroscience-informed perspective, learning is therefore understood not merely as a change in observable behaviour but as a dynamic process involving interactions among neural activity, cognition, emotion, attention, memory, and prior experience (Dorsey, 2025). Taken together, these concepts can be understood as interconnected rather than competing perspectives within the neuroscience–education interface. Building on these foundations, neuroscience-based learning emphasizes the use of neuroscientific evidence to understand and support learning processes, whereas brain-based learning focuses more explicitly on translating knowledge about brain functioning into instructional strategies and learning environments (Funa et al, 2024).

Neuroscience-informed learning encompasses these complementary perspectives while maintaining a cautious distinction between scientific evidence and its educational application. Accordingly, neuroscience may explain the biological and cognitive mechanisms underlying learning; educational neuroscience investigates these mechanisms in relation to educational experiences; neuroeducation seeks to connect this knowledge with educational theory and practice; neuroscience-based learning applies relevant evidence to learning processes; and brain-based learning translates

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selected insights into pedagogical approaches (Ferreira et al., 2025). Viewing these concepts along this continuum helps establish conceptual coherence while avoiding the assumption that findings from neuroscience can be directly transferred into educational practice without appropriate theoretical, developmental, and empirical consideration.

Figure 1 presents a diagram that summarizes the conceptual framework of “neuroscience and learning,” illustrating how learner-centred, individualized, and inclusive instructional approaches are integrated with discovery-, interaction-, and creativity-based learning processes.

Figure 1.

Neuroscience and Learning: Conceptual Framework (Sortwell et al., 2026)

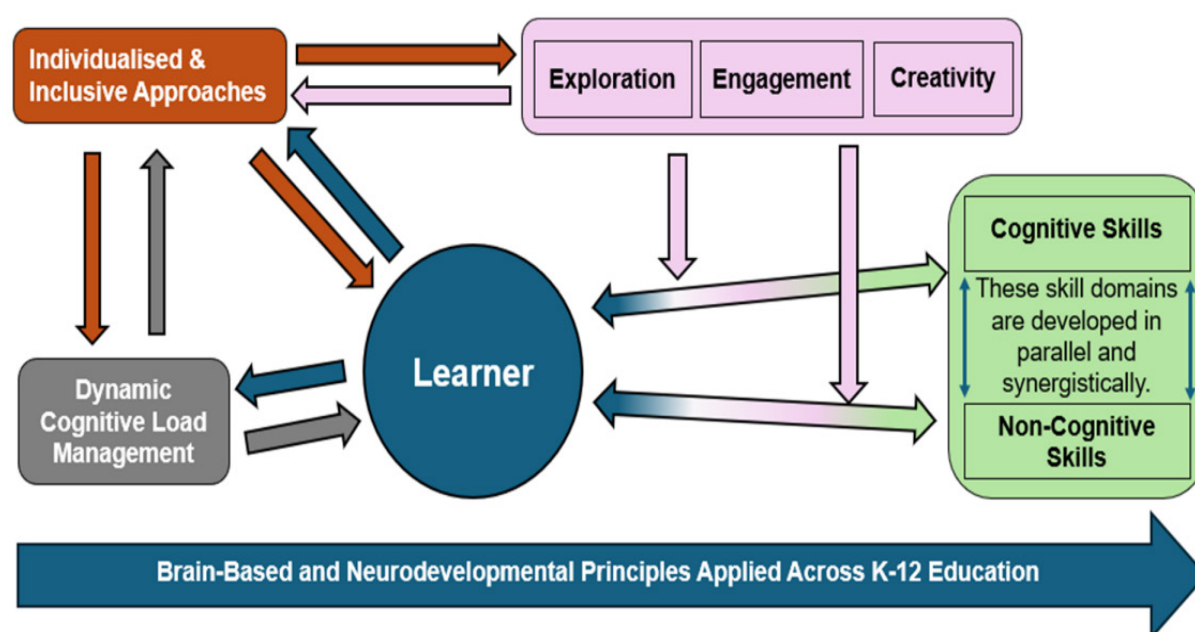


Figure 1 adapted from Sortwell et al, 2026

Figure 1 conceptualizes learning not as a unidirectional transmission process but as a multi-component learning ecosystem that continuously generates feedback. The “Learner,” positioned at the centre, is the active agent of the entire process. Rather than being treated as a passive recipient, the learner is conceptualized as a dynamic system in constant interaction with environmental arrangements, pedagogical approaches, and neurodevelopmental principles. “Personalized and Inclusive Approaches” refer to instructional design that is responsive to the learner’s cognitive capacity, developmental level, learning pace, and socio-emotional needs. The bidirectional arrows indicate that instructional approaches must be continuously adapted based on feedback from the learner. “Exploration, Interaction, and Creativity” constitute the pedagogical engine of learning. Exploration represents the learner’s active construction of knowledge; interaction strengthens the social and cognitive context; and creativity reflects the transfer and re-production of knowledge. The downward arrows from this domain indicate that these processes directly contribute to skill development.

For a long time, learning has been explained through pedagogical traditions, philosophical approaches, and behaviourist models. However, rapid advances in neuroscience over the past few decades have clearly demonstrated that learning is shaped not only by external stimuli and environmental arrangements but also directly by the biological, chemical, and structural dynamics of the brain (Singh & Morkel, 2024). Neuroscience-Informed Learning has emerged as an interdisciplinary approach that integrates this growing body of scientific knowledge with educational theory and practice (Willis, 2007). “Dynamic Cognitive Load Management” forms the neurocognitive backbone of the model. “Cognitive and Non-Cognitive Skills” represent the output dimension of the model. The bidirectional arrows between these skills and the learner indicate that skill development is both an outcome of the learning process and an input that further shapes learning. The phrase “Brain-Based and Neurodevelopmental Principles Applied in K–12 Education” represents the theoretical foundation that horizontally integrates all components of the model. Accordingly, Figure 1 represents a forward-looking instructional paradigm that redefines learning along the axes of personalization, cognitive balance, active engagement, and multidimensional skill development. The model strongly implies that pedagogical decisions should be grounded not only in the question of “what to teach” but also in “how the brain learns,” thereby explicating the conceptual framework of “Neuroscience and Learning.”

2.1. The Emergence of Educational Neuroscience

The emergence of the field of educational neuroscience is not the result of a sudden revolution but rather the outcome of an interdisciplinary necessity. The origins of educational neuroscience are closely associated with the recognition of the limitations of the cognitive revolution. Throughout the twentieth century, learning was explained through observable outcomes in behaviourist models and through mental representations in cognitive models. However, these approaches largely left the biological foundations of learning at the level of assumption. How the brain changes during learning, under which conditions plasticity increases, and the neurophysiological effects of stress, motivation, and emotional states on learning remained largely outside the scope of pedagogical theories for a long time (Guler et al., 2024).

The direct transfer of neurological research into educational science and policy represents a challenging task. Philosophical, political, and methodological differences between these two domains give rise to various issues of language and communication, particularly among researchers. At a superficial level, neurology focuses on the brain and the nervous system, whereas education branches into areas such as learning, teaching, assessment, educational policy, and sociology. While the subfields and concepts unique to each discipline are nourished by complex and distinct theories, it has become increasingly impossible to draw rigid boundaries between disciplines. The concept of learning, in particular, has moved beyond the exclusive domain of educational sciences and has attracted the attention of fields not traditionally associated with education, such as computer science, robotics, and artificial intelligence. Understanding, analysing, modelling, managing, and enhancing human learning—one of the most complex learning mechanisms—have become priority concerns within these domains (Dundar-Coecke, 2021).

During the 1990s, a period referred to as the “Decade of the Brain,” rapid advances in brain imaging technologies (fMRI, PET, EEG) made this gap increasingly visible. Learning could now be examined not only through behavioural performance but also through neural reorganization. At this point, a critical question emerged for educational research: “If learning takes place in the brain, why do educational theories not place the functioning of the brain at their core?” Educational neuroscience represents an interdisciplinary response to this question (Golkowski et al, 2017). The field seeks to bring neuroscience, cognitive psychology, and educational sciences together on a shared theoretical foundation. Its central claim is that effective instruction depends not only on the selection of content and methods but also on instructional design that aligns with the developmental and functional constraints of the brain (Luo et al., 2024).

Educational neuroscience draws on a range of neuroimaging and electrophysiological methods, each of which provides access to different aspects of brain structure and function. The selection of a particular method depends on the research question, developmental characteristics of the participants, ethical considerations, and the temporal or spatial characteristics of the neural process under investigation (Logothetis, 2002). Structural magnetic resonance imaging (MRI), for example, can provide detailed information about brain anatomy, including gray- and white-matter characteristics, whereas functional magnetic resonance imaging (fMRI) is primarily used to examine changes in blood oxygenation associated with neural activity through the Blood Oxygen Level-Dependent (BOLD) signal (Cai et al, 2013). Thus, fMRI provides relatively high spatial resolution for investigating patterns of brain activation, although the hemodynamic response is temporally slower than the underlying neural activity (Ashby, 2015). These characteristics make fMRI particularly useful for examining the neural systems associated with specific cognitive and learning processes, while also requiring careful interpretation of the relationship between the measured signal and neural activity (Golland et al., 2025).

Electrophysiological methods provide a complementary perspective by capturing neural activity with substantially greater temporal sensitivity. Electroencephalography (EEG) records electrical potentials at the scalp and can be used to examine rapid changes in neural activity and event-related responses. However, its ability to precisely localize the neural sources of these signals is constrained by the inverse problem and the effects of signal propagation through the tissues surrounding the brain (Khan et al, 2025). Magnetoencephalography (MEG), in contrast, records magnetic fields generated by neuronal activity and similarly provides high temporal sensitivity, while offering different spatial and source-localization characteristics from EEG (Ioannides, 2009). Neither technique should therefore be interpreted as providing a direct or complete representation of brain activity; rather, EEG and MEG offer complementary information about the temporal dynamics of neural processes (Golland et al., 2025). Other techniques, including positron emission tomography (PET), can provide information about metabolic or molecular aspects of brain function but involve the administration of radioactive tracers and therefore present additional practical and ethical considerations. Collectively, these methods should be viewed as complementary rather than interchangeable approaches, with their respective strengths and limitations taken into account when interpreting findings relevant to learning and education (Ashby, 2015).

A distinguishing feature of the educational neuroscience approach is its treatment of learning not as a static capacity but as a lifelong neurodevelopmental process. Concepts such as synaptic plasticity, the development of executive functions, sensory integration, attentional networks, and emotional regulation mechanisms have increasingly been linked to classroom practices (Khan et al, 2025). The recognition that the brain continues to develop throughout childhood and adolescence has rendered the notion of “one-size-fits-all instruction” scientifically questionable within K–12 education (Huang & Lajoie, 2023).

The emergence of educational neuroscience should also be understood as a response to neuromyths. Popular but scientifically weak claims such as “right-brain/left-brain learners,” “learning styles,” or the “10% brain usage” myth have long influenced educational practice. With the development of the field, the goal has not been to turn teachers into neuroscientists, but rather to prevent pedagogical decisions from being based on inaccurate neuro-information. In this sense, educational neuroscience provides a critical framework rather than a prescriptive set of instructional recipes (Bonomo, 2017).

Importantly, hemispheric specialization should be distinguished from the popular “left-brain/right-brain learner” concept. Neuroscientific evidence indicates that the two cerebral hemispheres are not functionally identical and that some cognitive processes show relative hemispheric specialization (Oner, 2024). For example, language processing is often more strongly associated with the left hemisphere, whereas certain aspects of visuospatial processing and attentional functions involve greater contributions from the right hemisphere. However, these functional asymmetries do not imply that individuals can be categorized as predominantly “left-brained” or “right-brained” learners. Most complex cognitive and learning processes depend on dynamic interactions between distributed neural networks across both hemispheres. Therefore, statements suggesting that left-brain individuals learn primarily through sequential, verbal, or text-based processing, whereas right-brain individuals learn primarily through holistic, non-linear, or spatial processing, should not be interpreted as stable learner characteristics (Parayangattuet & Kishore, 2024).

One of the most significant contributions of educational neuroscience to the field of education lies at the methodological level. This discipline aims to examine learning and teaching processes not only through theoretical frameworks but also through highly sensitive measurement and analysis tools (Gazzaniga, 2009). From this perspective, educational neuroscience enables the evaluation of pedagogical practices through biological and cognitive indicators rather than indirect inferences. Research in the field systematically employs experimental approaches designed to directly support learning processes, introducing techniques that were previously used only to a limited extent in educational research (Wang et al., 2025).

While brain structure and function in medical research are sometimes examined using invasive methods such as positron emission tomography (PET), which involve direct intervention in the brain, educational neuroscience primarily relies on non-invasive technologies due to ethical and practical constraints (Ullman et al, 2014). In this context, event-related potentials (ERPs) and magnetoencephalography (MEG) stand out as tools capable of measuring brain activity with

extremely high temporal resolution. In addition, magnetic resonance imaging (MRI) provides detailed visualization of the structural properties of gray and white matter, while functional magnetic resonance imaging (fMRI) offers data on the spatial distribution of brain activity through blood-flow-based measurements (Golland et al., 2025).

Neuroimaging and measurement methods serve multiple functions in educational research. First, they enable the reliable monitoring of typical and atypical neurodevelopmental processes. Moreover, they generate data on how the brain is organized during specific tasks and which functional networks are engaged. When compared with behavioural performance, these findings make it possible to understand not only the outcomes of learning processes but also the underlying cognitive and neurological mechanisms (Short et al, 2013). Consequently, these methods contribute to the development of a more comprehensive understanding of the biological foundations of human behaviour (Dundar-Coecke, 2021). Nevertheless, the limitations of these techniques must also be acknowledged. Current neuroimaging methods cannot directly explain how electrical or hemodynamic activity in the brain is transformed into subjective experience, nor can they fully account for the precise mechanisms through which learning occurs in the brain. Yet it is precisely this zone of uncertainty that constitutes the primary driving force of educational neuroscience research (Pradeep et al., 2024).

With the advancement of educational technologies, new research opportunities have emerged for scholars studying learning processes and learning difficulties. Leading research centres in the United Kingdom, Europe, and the United States have placed issues directly related to school contexts and curriculum-based learning at the centre of their research agendas (Chaengkit & Jansem, 2022). Studies focusing on reading and reading difficulties, the development of mathematical skills, and brain plasticity contribute both to theoretical knowledge production and to the establishment of a scientific foundation capable of informing educational practice (Redecker & Punie, 2013).

At the present stage, educational neuroscience deliberately avoids reductionist claims such as the “direct transfer from brain to classroom.” Instead, it proposes a multi-layered relationship. Neuroscience explains the biological possibilities and constraints of learning; cognitive psychology demonstrates how these processes are organized at the mental level; and educational sciences transform this knowledge into meaningful applications within ethical, cultural, and pedagogical contexts. Thus, the emergence of educational neuroscience represents not only the birth of a new field but also an epistemological repositioning of education itself (Dundar-Coecke, 2021).

Learning is no longer evaluated solely in terms of “how much information is transmitted,” but rather by considering the cognitive, emotional, social, and neurobiological conditions that support learning. This perspective is pushing future educational systems toward an orientation that prioritizes the optimization of learning conditions over content delivery (Arun & Singaravelu, 2018; Guler et al., 2024; Khanam, 2025; Sortwell et al., 2026).

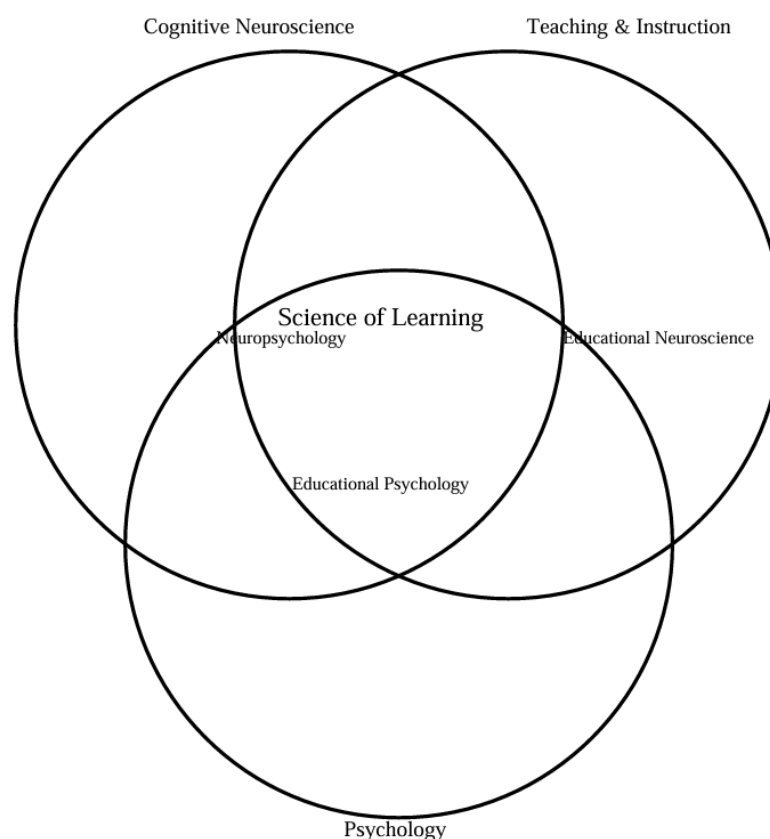
2.2. Neuroscience-Informed Learning Approach

The Neuroscience-Informed Learning approach conceptualizes learning not as an abstract mental activity, but as a comprehensive process involving the reorganization of neural networks, the strengthening or weakening of synaptic connections, and the brain's adaptive responses to environmental experiences. In other words, learning is no longer understood through the metaphor of "knowledge transmission," but rather through the concept of neuroplasticity. The brain's capacity to change across the lifespan provides strong biological evidence that learning is not limited by age, while simultaneously emphasizing the importance of appropriate learning conditions (Korkmaz, 2024).

The central premise of Neuroscience-Informed Learning is that effective learning should be designed in alignment with the brain's natural functioning. Processes such as attention, memory, emotion, motivation, and stress each possess neurobiological mechanisms that directly influence the quality of learning. For instance, emotionally meaningful experiences are known to leave more durable traces through amygdala–hippocampus interactions, whereas chronic stress suppresses prefrontal cortex functions and consequently weakens executive cognition (Bada & Jita, 2022). These findings indicate that learning environments must take into account not only cognitive but also emotional and physiological dimensions.

Within this context, Neuroscience-Informed Learning reframes traditional educational systems in light of biological realities. A critical re-evaluation of popular but scientifically weak concepts such as learning styles, along with the neuroscientific grounding of strategies such as repetition, feedback, spaced learning, and multisensory engagement, constitutes one of the distinguishing features of this approach (Roitsch et al, 2022). In this way, educational practices can be structured on the basis of empirical evidence rather than intuitive preferences. A conceptual diagram illustrating the disciplinary intersections from which the field of Neuroscience-Informed Learning has emerged is presented in Figure 2.

The diagram in Figure 2 explains that truly understanding learning and designing effective instruction cannot be achieved within the boundaries of a single discipline; rather, it requires the integration of cognitive, psychological, and pedagogical domains of knowledge. The Science of Learning represents a comprehensive framework that scientifically examines how learning occurs and under which conditions it becomes durable and transferable. Cognitive Neuroscience explains the biological and neurological foundations of learning. It addresses how the brain processes information, how memory is formed, and how processes such as attention, executive functions, and plasticity operate. In essence, it answers the question of "what happens in the brain during learning." For example, the effects of repetition on synaptic strengthening or the role of sleep in learning are examined within this context.

Figure 2.*The Science of Learning: An Interdisciplinary Framework*

Source: Original figure developed by the authors based on the relevant literature

Educational Neuroscience translates findings from cognitive neuroscience into educational contexts. It investigates how neuroscientific data obtained in laboratory settings can be reflected in classroom learning, instructional design, and assessment processes. Psychology examines how individuals and groups behave, become motivated, and learn. Teaching focuses on effective instructional practices, assessment methods, and learning outcomes, addressing the practical question of “what works in the classroom.” The areas of intersection constitute the true depth of the diagram. Neuropsychology lies at the intersection of cognitive neuroscience and psychology and examines the relationship between brain structures and behaviour. Learning difficulties, attention disorders, and memory problems are analysed from this perspective. Educational Psychology is situated at the intersection of psychology and teaching; it explores how learning theories can be adapted to classroom environments, how students can be motivated, and how instruction can be made responsive to individual differences. In conclusion, Figure 2 advances a forward-looking argument: effective and sustainable learning models can rely neither solely on brain-based explanations nor exclusively on pedagogical experience. The science of learning necessitates interdisciplinary thinking and aims to transform education through strong, evidence-based ideas rather than intuition. This approach constitutes the intellectual backbone of future educational systems.

2.3. Bridging Brain Research and Pedagogical Practice

Brain research represents one of the most critical—and simultaneously most problematic—domains of educational neuroscience. A central challenge lies in determining how scientific knowledge about the brain can be transformed into classroom teaching practices in ways that are meaningful, ethical, and effective (Goldberg, 2022). For many years, a clear distance existed between neuroscience and educational practice. Neuroscience has traditionally examined brain functioning in controlled laboratory settings, often through simplified tasks, whereas education unfolds within complex, context-sensitive, and highly variable classroom environments. The fundamental tension between these two domains arises from differences in scale and context: brain research focuses on neural mechanisms at the micro level, while pedagogical practice is embedded in macro-level social, cultural, and emotional factors (Funa et al., 2024; Sortwell et al., 2026). The need to “build a bridge” emerges precisely at this juncture.

An increasingly accepted view in the educational neuroscience literature is that direct translations from neuroscience to teaching practice are problematic from both scientific and pedagogical perspectives. For teachers, “knowing how the brain works” does not automatically legitimize a particular instructional method. Rather, the primary goal is to develop a conceptual framework that allows educators to evaluate whether the assumptions guiding instructional design are consistent with, or contradictory to, neuroscientific evidence (Bada & Jita, 2022).

Cognitive psychology plays a critical intermediary role in bridging neuroscience and learning. Findings derived from neuroscience cannot serve as a foundation for pedagogical decisions unless they are interpreted at the cognitive level. For example, neuroscientific evidence related to executive functions, attentional networks, or working memory capacity is translated—via cognitive psychology—into implications for learning tasks, instructional duration, and feedback structures. Pedagogy then transforms this knowledge into concrete classroom practices aligned with student profiles and learning objectives (Goldberg, 2022).

One of the domains in which the bridge between brain research and pedagogical practice is strongest concerns the optimization of learning conditions. Neuroscience has clearly demonstrated that the brain is sensitive to stress, motivation, emotional regulation, and reward systems. These findings support the view that learning is not solely a cognitive process but also an emotional and physiological one. Pedagogically, this provides a scientific foundation for the central role of safe learning environments, meaningful feedback, a sense of autonomy, and social interaction in learning (Pradeep et al., 2024).

In addition, “timing and developmental appropriateness” are crucial in bridging neuroscience and learning. Knowledge that different brain functions mature at different developmental stages offers powerful insights into when and how instructional content should be presented. In particular, the late maturation of executive functions and self-regulation skills suggests that rather than directly

“expecting” these abilities at early ages, they should be gradually constructed through supportive learning environments (Fontdevila et al., 2021). However, oversimplifying neuroscientific knowledge or detaching it from pedagogical context poses a significant risk. Neuromyths emerge precisely in this gap. One of the core missions of educational neuroscience is not to turn teachers into neuroscientists, but to equip them with a critical filter against inaccurate, superficial, or popularized brain-based claims. Thus, the process of building bridges involves not merely transferring knowledge, but understanding the limits of that knowledge (Dorsey, 2025).

Contemporary approaches propose a cyclical and interactive model rather than a linear relationship between brain research and pedagogical practice. In this model, pedagogical challenges inform neuroscientific research questions, while findings from neuroscience are reinterpreted at cognitive and pedagogical levels before being applied in the classroom. The bridge therefore becomes not a one-way transmission channel, but a mutually reinforcing knowledge ecosystem (Chaengkit & Jansem, 2022; Funa et al., 2024; Parayangattuet & Kishore, 2024).

In conclusion, Bridging Brain Research and Pedagogical Practice is less an attempt to make education more “scientific” and more an effort to make it more conscious, more cautious, and more human-centred. This perspective strengthens a pedagogical understanding that moves beyond teaching as a purely technical intervention, instead emphasizing respect for the brain’s learning capacities, sensitivity to developmental differences, and a learner-centred approach to education.

2.4. Brain-Based Learning Principles

Brain-based learning is an approach that places the structure, functioning, and developmental principles of the brain at the centre of understanding how learning occurs, with the aim of aligning instructional design, learning environments, and assessment processes with this scientific knowledge. This approach conceptualizes learning not merely as a pedagogical activity, but as a complex process encompassing biological, cognitive, emotional, and social dimensions (Bonomo, 2017).

Drawing on findings from neuroscience, cognitive psychology, and educational sciences, brain-based learning seeks to create instructional conditions that are consistent with the brain’s natural learning tendencies. Its core assumption is that instruction becomes more effective, durable, and meaningful when it takes into account how the brain learns. The goal is not to “teach directly to the brain,” but rather to design brain-friendly environments that support learning (Chaengkit & Jansem, 2022).

Understanding how the brain functions is important for all learning approaches; however, it constitutes a focal point for brain-based learning. This is because brain-based learning assumes that higher-level learning can be achieved when the mechanisms underlying brain function are better understood (Arun & Singaravelu, 2018). The scope of brain-based learning is broad and can be examined across three main dimensions.

The first dimension involves cognitive processes. Within this framework, attention, memory, executive functions, pattern recognition, meaning-making, and transfer are examined in terms of how they can be supported through instruction. Emphasis is placed on the role of multiple memory systems in learning and on the centrality of meaning. The second dimension is affective and motivational. The emotions on learning, the ways in which stress constrains cognitive performance, and the importance of safe learning environments constitute key concerns. Brain-based learning regards emotion not as a by-product of learning, but as a constitutive component of it. The third dimension concerns the bodily and social context. Movement, sleep, nutrition, social interaction, and collaborative learning processes are directly related to brain development. Accordingly, learning is addressed not solely as a mental activity, but within a holistic mind–body–environment framework (Khanam, 2025).

In classrooms where brain-based learning is implemented, the functions of the brain and its role in learning are explicitly taken into account throughout the teaching–learning process. Such environments emphasize the establishment of trust and the provision of rich stimuli. A balance is maintained between direct instruction and more challenging experiences, as well as between structured teaching and authentic learning opportunities (Korkmaz, 2024). This approach is learner-centred and supports the development of learners' cognitive structures while facilitating the learning process (Ginting & Tungka, 2025).

Each learner is unique and brings prior knowledge to the learning process. One of the key conditions for meaningful learning and optimal learning outcomes is establishing connections with existing knowledge and beginning instruction from what learners already know. To create an enriched environment that supports learning, it is necessary to incorporate physiological factors, social interaction, emotional connection, conscious and unconscious learning, individual styles and uniqueness, the ability to perceive both details and the broader picture, learning from environmental context alongside attentional capacities, and the capacity to learn both biographical events and context-independent memorization. In addition, such environments should acknowledge and validate learners' developmental stages and changes, reduce perceived threat, and enhance self-efficacy (Parayangattuet & Kishore, 2024).

Repetition alone is not sufficient for retention. For knowledge to become durable, it must be encoded, meaningfully organized, and connected with other knowledge structures. Research indicates that the stronger the connections between new information and prior knowledge, the more enduring the information becomes in memory (Redecker & Punie, 2013).

The human brain consists of left and right hemispheres. The notion that individuals with left-hemisphere dominance are logical while those with right-hemisphere dominance are creative is now considered outdated. Nevertheless, the left hemisphere generally tends to process information sequentially and in parts, with a preference for language- and text-based learning, whereas the right hemisphere tends to process information holistically, in a non-linear sequence, and within a spatial context (Hari & Demiralp, 2025). Although the hemispheres process information differently, learning is most effective when both hemispheres are engaged in the educational process (Schiller, 2010). An overview of brain-based learning is presented in Table 1.

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Table 1.*Brain-Based Learning Principles*

1. Every brain is uniquely organized	Each individual's brain develops distinctive neural networks shaped by genetics, early experiences, cultural context, and learning history. Consequently, learners differ in pace, strategies, and strengths. Effective instruction moves beyond one-size-fits-all assumptions and is responsive to individual differences
2. Emotions are central to learning.	Emotional processes directly influence attention, motivation, and memory formation. Positive emotional states support learning, whereas excessive anxiety and fear constrain cognitive resources. For this reason, learning environments must be built on emotional safety and meaningful engagement
3. Information is stored and retrieved through multiple memory systems	Learning does not rely on a single memory system; episodic, semantic, and procedural memory operate together. Instruction that employs multiple representations (visual, auditory, kinesthetic) strengthens connections across neural networks and promotes durable learning
4. Learning is often rich and non-conscious	Learners are not always aware of what they have learned. Pattern recognition, intuitive reasoning, and implicit learning processes operate beyond conscious awareness. This highlights that learning extends beyond explicit instruction alone
5. Patterns and mental schemas drive understanding	The brain processes information not as isolated units but as interconnected patterns and relational structures. New knowledge is more readily learned when it can be integrated with existing cognitive schemas. Establishing conceptual connections is therefore essential in instruction
6. Threatening environments and chronic stress	Prolonged stress elevates cortisol levels, negatively affecting memory and executive functions. Unsafe, punitive, or high-pressure learning environments trigger survival-oriented brain responses that inhibit learning
7. The brain is meaning-driven	The brain does not passively store information; it continuously seeks relevance and purpose. Learning becomes more enduring when knowledge is connected to real-life contexts, goals, and applications
8. Brain development proceeds through stages of readiness	Cognitive and emotional development is not linear; at certain periods the brain is more receptive to specific types of learning. Instruction that ignores learners' developmental readiness risks producing superficial or fragile learning outcomes
9. Neuroplasticity is lifelong	The brain is capable of forming new neural connections at any age. Learning capacity is not limited to childhood; with appropriate stimulation and experience, development continues throughout adulthood and later life. This principle provides the neuroscientific foundation for lifelong learning
10. The brain is a complex and adaptive system	Brain functioning is dynamic and non-linear. Small changes in experience or environment can lead to substantial learning effects. Learning processes should therefore be understood through an ecological rather than a mechanistic lens
11. The brain develops more effectively in interaction with other brains	Social interaction supports neural development related to language, empathy, and shared problem solving. Collaborative learning is not only pedagogically effective but also neurobiologically grounded
12. All learning is mind-body learning	Movement, nutrition, sleep, and attentional rhythms exert powerful on learning. The brain is not separate from the body; physical states are integral to cognitive performance. Learning environments should therefore not exclude bodily engagement

Source: Original table developed by the authors based on the relevant literature (Arun & Singaravelu, 2018; Battro et al, 2011; Funa et al, 2024; Gulet et al, 2024).

Today, brain-based learning is not considered a set of methods offering ready-made solutions, but rather a scientific framework of thinking that guides instructional design. Its strength lies in bringing instruction closer to the brain's natural functioning; its risk is the superficial application of scientific findings. Therefore, the approach reaches its true potential when considered not merely through pedagogical intuition, but through critical scientific literacy. From this perspective, brain-based learning is one of the most holistic answers to the question of “how do we teach?”, as well as “how do humans learn?”, in contemporary education.

2.4.1. Neuroplasticity and Learning Across Development

Neuroplasticity and learning across development provide a central conceptual framework for explaining how the brain's capacity for structural and functional change constitutes the biological foundation of learning. Neuroplasticity refers to the strengthening, weakening, or reorganization of synaptic connections in response to experience, environmental stimuli, and learning processes (Battro et al., 2011). This property demonstrates that learning is not a phenomenon confined to early childhood; rather, it is a dynamic process that continues throughout the lifespan.

During the early stages of development, neuroplasticity is particularly pronounced. In infancy and early childhood, the brain is highly receptive to sensory, motor, and social inputs from the environment. Learning during this period is shaped by intensive processes of synapse formation and synaptic pruning. While frequently used neural networks are strengthened, functionally ineffective connections are gradually eliminated. This mechanism explains why early experiences leave lasting cognitive and emotional traces. Language acquisition, foundational executive functions, and social-emotional skills are constructed during this period through robust neuroplastic processes (Ginting & Tungka, 2025).

Childhood and adolescence are critical periods during which neuroplasticity changes in form but continues to exert a strong influence. In adolescence in particular, the relatively late maturation of the prefrontal cortex extends the development of higher-order cognitive skills such as planning, impulse control, and self-regulation over time (Ferreira et al, 2025). This developmental trajectory indicates that learning difficulties or behavioural fluctuations have a biological basis, while also demonstrating that these skills can be strengthened through appropriate pedagogical support. The adolescent brain's heightened sensitivity to social feedback and emotional stimuli necessitates the design of learning environments that take this vulnerability into account (Galvan, 2025).

Table 2.*Neuroplasticity and Learning Across Development (Galvan, 2025)*

Developmental Stage	Characteristics of Neuroplasticity	Dominant Learning Types	Neural Mechanisms	Educational and Cognitive Implications
Prenatal Period	Extremely high plasticity; neural migration and organization are critical	Sensory priming, foundations of reflexive learning	Neuronal proliferation, synaptogenesis	Maternal health and environmental factors strongly shape brain architecture
Early Childhood (0–5)	Peak plasticity; presence of critical and sensitive periods	Language acquisition, motor learning, social learning	Intense synaptogenesis, experience-dependent strengthening	Enriched, multisensory learning environments yield long-term cognitive benefits
Middle Childhood (6–12)	Plasticity continues but becomes more selective	Academic skills, executive functions	Synaptic pruning, increased myelination	Structured instruction, feedback, and repetition are particularly effective
Adolescence	Plasticity increases again but is developmentally imbalanced	Abstract reasoning, emotion- and risk-related learning	Prefrontal cortex maturation, limbic system dominance	Emotional context strongly modulates learning; self-regulation should be supported
Early Adulthood	Relatively stable yet flexible plasticity	Skill specialization, complex problem solving	Long-term potentiation (LTP), network efficiency optimization	Deep learning and interdisciplinary skill development remain highly attainable
Middle to Late Adulthood	Gradually reduced but preserved plasticity	Experience-based learning, compensatory strategies	Synaptic reorganization, compensatory neural networks	Continuous cognitive engagement slows age-related cognitive decline
Older adulthood	Limited but functionally meaningful plasticity	Adaptive learning, relearning	Reduced neural efficiency, recruitment of alternative pathways	Learning is slower, yet meaningful and context-rich learning remains durable

Source: Original table developed by the authors based on the relevant literature (Battro et al, 2011; Oner, 2024).

Table 2 highlights that neuroplasticity is a lifelong process that changes in form rather than disappearing with age. From an advanced and future-oriented perspective, learning should not be conceptualized as a capacity confined to early developmental windows. Instead, it represents a dynamic biological and cognitive phenomenon that can be continuously reshaped through environmental enrichment, cognitive challenge, and sustained motivation (Battro et al, 2011). Such a framework provides a strong theoretical foundation for lifelong learning models, neuroeducation practices, and adaptive educational policies, emphasizing that the human brain retains the capacity for reorganization and growth across the entire lifespan (Pradeep et al, 2024).

The widespread belief that neuroplasticity disappears in adulthood has been refuted by contemporary neuroscientific evidence. Although synaptic flexibility tends to decline with age, the brain retains the capacity to acquire new knowledge and skills throughout adulthood (Ferreira et al., 2025). In particular, meaningful, goal-oriented, and repetitive learning experiences support the formation of new neural connections in the adult brain. This finding provides a strong biological foundation for lifelong learning approaches (Oner, 2024).

The relationship between neuroplasticity and learning is not limited to cognitive processes alone. Emotional states, stress levels, and motivation directly plasticity. Chronic stress negatively affects synaptic flexibility, whereas safe, supportive, and meaningful learning environments enhance it. Learning, therefore, should be understood not merely as the transmission of information but as an experience that renders the brain receptive to change (Dorsey, 2025; Guler et al., 2024).

In educational contexts, the concept of neuroplasticity offers a powerful alternative to fixed-ability beliefs. The idea that learning capacity is malleable supports more inclusive and developmental pedagogical approaches. However, misinterpretations of this concept also pose risks. Neuroplasticity does not imply that all learners can learn at the same pace or in the same way under all conditions. Individual differences, prior experiences, and environmental factors are key determinants of the direction and rate of plastic change. Neuroplasticity and learning across development require education to be conceptualized not around static goals but as a process that remains open to change and attentive to developmental continuity. This perspective supports a forward-looking educational approach that focuses not only on what is taught, but also on when, how, and under what conditions the brain is most receptive to learning (Battro et al., 2011; Galvan, 2025).

2.4.2. Attention and Learning Readiness

Attention has been defined by some researchers as the highest level of stimulation of the nervous system; in this context, it has been considered as a process in which the senses of sight, hearing, smell, taste, and touch are used selectively. Commodari et al (2025), on the other hand, explained attention as the state of focusing more clearly and distinctly on one of the objects or thoughts that appear simultaneously; he emphasized that the processes of focusing, concentration, and awareness are at the root of attention. In daily life, the fact that individuals pay more attention to some stimuli than others indicates that these stimuli are selected for advanced processing (lindsay, 2020).

Which stimuli are selected is largely related to the individual's repetitions and past experiences. For example, a football player who consistently practices certain exercises will notice mistakes in similar exercises more quickly, or an individual with refereeing experience will pay more attention to the referee's behaviour while watching a match. In the attention process, not all stimuli in the environment are completely eliminated; some are only kept in the background. This is particularly evident in auditory stimuli; for example, an individual listening to music while reading a book may occasionally direct their attention to the music and have difficulty remembering the content of the text they are reading, reflecting this selective process. Therefore, in order to better understand attention, it is necessary to examine its fundamental components (Yu & Smith, 2016).

Attention and learning readiness refer to the cognitive and neuropsychological state in which an individual is optimally prepared to engage with, process, and retain new information. Attention functions as a selective mechanism that prioritizes relevant stimuli while inhibiting distractions, whereas learning readiness reflects the alignment of cognitive capacity, emotional regulation, motivation, and prior knowledge necessary for effective learning. Together, these constructs describe not merely the ability to learn, but the preparedness of the learner to benefit from instruction (Lindsay, 2020).

Attention and learning readiness are foundational to meaningful learning outcomes. Without sufficient attentional engagement, instructional input fails to be encoded, regardless of its quality. High levels of learning readiness enhance cognitive efficiency, deepen conceptual understanding, and support transfer of knowledge across contexts. From an educational perspective, recognizing learning readiness shifts the focus from content delivery to learner-centred design, emphasizing timing, emotional safety, and cognitive load management. In a broader societal context, fostering attentional control and readiness is increasingly critical in an era characterized by digital distraction and information overload. Thus, attention and learning readiness are not peripheral variables but central determinants of educational effectiveness, cognitive development, and lifelong learning capacity (Commodari et al., 2025).

From a neuroscience-informed perspective, attention and learning readiness should be understood as dynamic and interacting processes rather than as fixed characteristics of the learner. Effective learning emerges when attentional systems selectively allocate cognitive resources to task-relevant information while executive and emotional regulatory processes support the maintenance of engagement (Lindsay, 2020). At the same time, prior knowledge, motivation, emotional state, arousal, and the demands of the learning environment can influence whether an individual is prepared to attend to and process new information (Singh & Morkel, 2024). Thus, learning readiness is not simply a prerequisite that exists before learning begins; it can also be shaped by the quality of instruction, the organization of the learning environment, and the learner's ongoing cognitive and emotional experience (Chaengkit & Jansem, 2022).

This dynamic interaction highlights the importance of considering attention within broader neural and cognitive networks rather than attributing learning outcomes to a single brain structure or isolated cognitive process (Commodari, Rosa & Foti, 2025). The following figures illustrate these

interconnected processes by presenting the functional organization of major brain systems and the interactions among sensory processing, attention, executive control, emotional evaluation, memory, and physiological regulation (Saragih & Azizah, 2025).

The functional roles of the brain's major structures and their reciprocal interactions are summarized in Figure 3 from a holistic network perspective. Figure 4 visualizes cognitive and physiological processes such as sensory processing, executive control, emotional evaluation, memory consolidation, and autonomic regulation, as well as the directions of information flow among these processes.

Figure 3.

Functional Brain Network Involved in Attention and Learning (Lindsay, 2020)

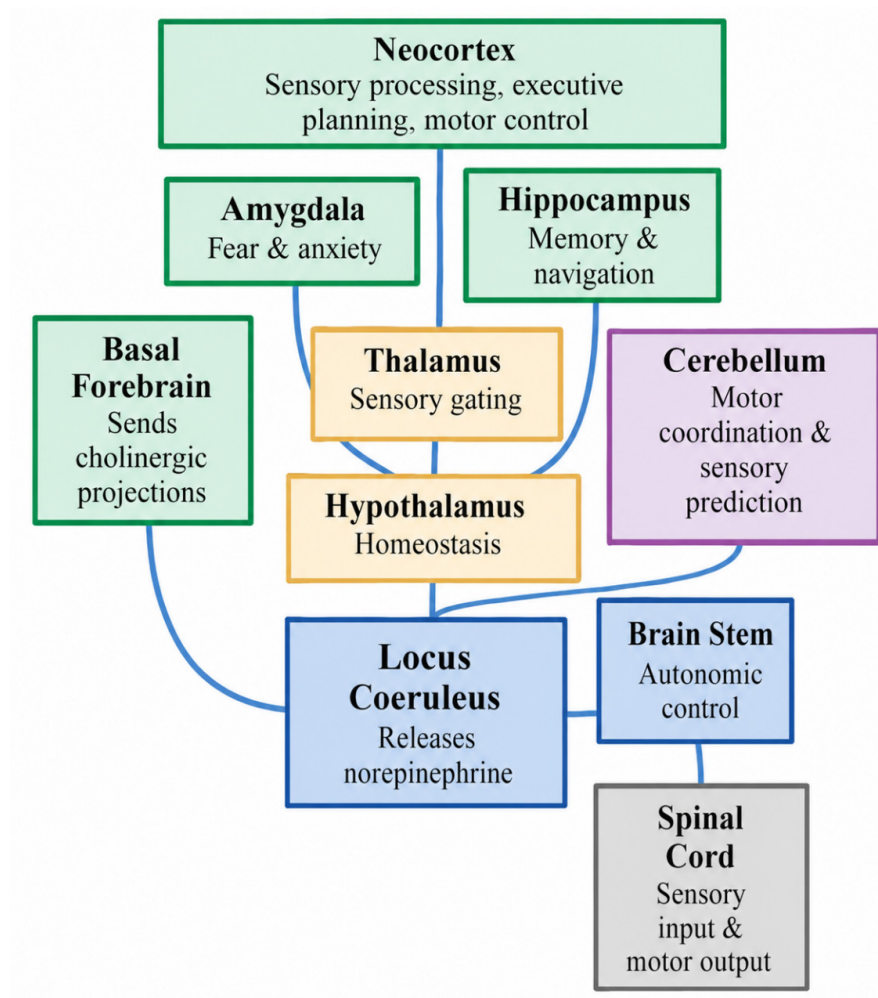


Figure 3 adapted from Lindsay, 2020

Figure 3 presents the functional anatomy of the brain as a modular yet densely interconnected network, illustrating how processes such as sensory processing, executive control, emotional appraisal, memory consolidation, and autonomic regulation interact through specific core structures.

Neocortex: Cortical areas are responsible for high-level processing of sensory data, the execution of executive functions, and the integration of motor planning; they play a central role in the transition from perception to action.

Thalamus: Defined as a “gateway” that filters sensory information and relays it to the cortex; sensory gating mechanisms constitute the neurobiological basis of attention and perceptual selectivity.

Hippocampus: Critical for the encoding of new memories and spatial navigation, it supports long-term memory consolidation through interactions with cortical networks.

Amygdala: A central nucleus in emotional appraisal, particularly in triggering rapid threat responses associated with fear and anxiety; activation of the amygdala modulates memory processes.

Cerebellum: Involved in motor coordination, timing, and sensory feedback-based predictive mechanisms; it interacts with cortical and brainstem loops to refine motor commands.

Basal Forebrain and Locus Coeruleus: These modulatory nuclei regulate cortical arousal, attention, and synaptic plasticity through cholinergic and noradrenergic projections, respectively.

Hypothalamus, Brainstem, and Spinal Cord: The primary functions of these structures include the homeostatic regulation of the internal environment, maintenance of autonomic functions, and execution of reflex pathways; they coordinate the physiological components of behavioural responses (Lindsay, 2020).

The scope of attention and learning readiness is inherently interdisciplinary, spanning cognitive psychology, neuroscience, educational sciences, and developmental studies. It encompasses multiple dimensions, including sustained, selective, and executive attention; arousal and alertness levels; emotional and motivational states; and contextual factors such as environmental structure and instructional design (Yu & Smith, 2016). Across development, learning readiness manifests differently—emerging in early childhood as behavioural regulation, evolving through adolescence with increasing executive control, and persisting into adulthood as self-directed attentional management. At the neural level, it is supported by distributed networks involving the prefrontal cortex, parietal regions, and neuromodulatory systems such as dopamine and norepinephrine, which regulate alertness and goal-directed behaviour (Saragih & Azizah, 2025).

2.4.3. Executive Functions and Cognitive Control

Executive functions are a general term used to describe the cognitive mechanisms of the prefrontal cortex that govern goal-directed behaviour (Cebioglu & Kafadar, 2024). Working memory, inhibitory control, and cognitive flexibility constitute the core components of executive functions. The preschool period is of critical importance for the development of children's executive function skills (Roitsch et al., 2022). Executive functions are higher-order neurocognitive skills that enable individuals to regulate their thoughts and actions and to direct their behaviour toward long-term goals (Hatoum et al., 2019).

Social skills, academic skills, and daily living skills are fundamental competencies that all individuals must possess in order to participate fully and independently in society. To be proficient in these skills, individuals need abilities such as planning, organization, prioritization, emotion regulation, behaviour regulation, attention, task initiation, and task persistence (Şengün et al., 2025). These abilities, referred to as executive function skills, are broadly defined as higher-order cognitive skills that individuals use to regulate their emotions and behaviours (Gravrakmo et al., 2023).

While the development of executive function skills largely depends on the maturation of the prefrontal cortex, environmental factors also play a highly significant role in this process. Cultural context, parenting practices, and family socioeconomic status are particularly influential in the development of children's executive function skills. Because poverty is associated with multiple risk factors, it constitutes a significant risk factor for the development of executive functions in children. Moreover, urban and rural poverty may affect children's development at different levels due to variations in living standards (Gravrakmo et al., 2023).

Figure 4 illustrates the components of executive functions, highlighting key cognitive processes essential for goal-directed behaviour. These functions include planning, attention, cognitive flexibility, inhibition, and memory (Roitsch et al., 2022). Each component encompasses specific abilities such as organizing and prioritizing tasks, maintaining focus, managing alertness and problem-solving, regulating emotions and controlling impulses, as well as holding, working with, and retrieving information. Together, these executive functions enable effective self-regulation and adaptive cognitive control necessary for learning and everyday functioning.

Figure 4.

Executive Functions (Neuro Trauma Training Reports, 2021)

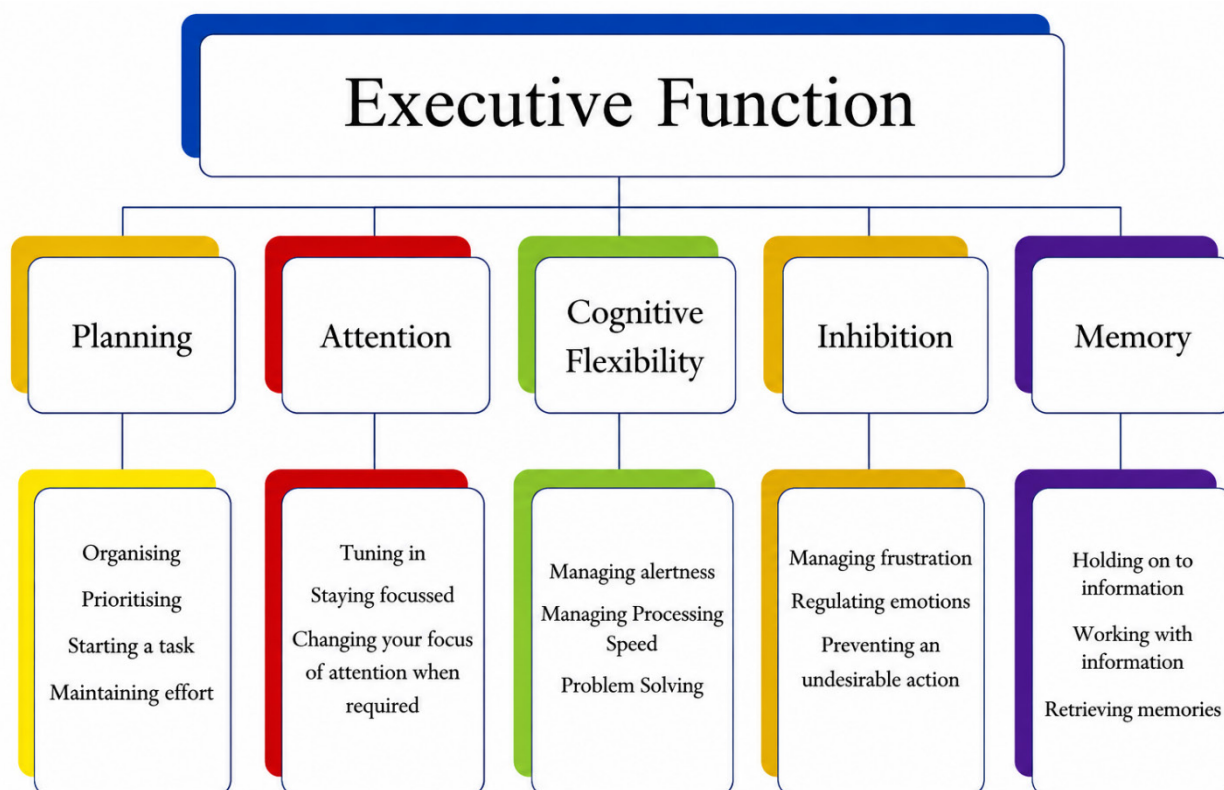


Figure 4 adapted from Neuro Trauma Training Reports, 2021

In Figure 4, the five main components within the framework of executive functions are summarized. These components represent the core skills that guide thinking and organize problem-solving processes in daily life. Planning involves setting goals and structuring steps to determine the sequence of actions; Attention enables focus on task demands, filters out distractions, and supports sustained concentration over time. Cognitive flexibility refers to the ability to adapt to changing situations, adopt different perspectives, and generate alternative solutions. Inhibition encompasses the capacity to suppress inappropriate impulses and select appropriate behaviours, enabling rapid yet controlled action. Memory includes the ability to store information and retrieve it when needed through short-term and working memory processes. Together, these five components enable planned action, focused attention, flexible thinking, impulse control, and information management; they support effective performance particularly in complex tasks, ambiguous situations, or multi-step problem-solving contexts.

Although the development of executive function skills begins in early childhood, it continues gradually throughout adolescence and young adulthood in parallel with the maturation of the prefrontal cortex (Şengün et al., 2025).

Longitudinal studies have shown that executive function skills acquired during the preschool period are associated with academic achievement, mathematical skills, and social competence in elementary school, as well as with educational attainment, impulse control, and the likelihood of college enrollment in adulthood (Hatoum et al., 2019). In this respect, executive function skills can be considered among the essential competencies that children need to develop.

It is important to note that the five-component framework presented in Figure 4 and the three-component model described below represent different levels of conceptualization rather than contradictory classifications of executive functions. Figure 4 adopts a broader functional framework that includes planning, attention, cognitive flexibility (Roitsch et al., 2022)inhibition, and memory-related processes, thereby emphasizing the range of cognitive and self-regulatory abilities involved in goal-directed behaviour. In contrast, the widely used framework proposed by Zelazo et al. (2016) identifies cognitive flexibility, working memory, and inhibitory control as the core executive functions from which more complex executive processes can develop. Accordingly, planning, attention, and other higher-order abilities may be understood as functions that depend on or emerge from the coordinated operation of these core components rather than as mutually exclusive categories. The two frameworks therefore provide complementary perspectives: the Figure 4 framework emphasizes the functional manifestations of executive functioning, whereas the three-component model emphasizes its foundational cognitive processes.

The core executive function skills are (1) cognitive flexibility, (2) working memory, and (3) inhibitory control (Zelazo et al., 2016). Cognitive flexibility, working memory, and inhibitory control constitute the fundamental components of the executive function system and operate in an integrated manner.

2.4.3.1. Executive Functions and Cognitive Flexibility

Cognitive flexibility refers to an individual's capacity to adapt to changing environmental conditions, rules, or goals. This skill involves the ability to shift between different perspectives, generate alternative strategies in response to a problem, and abandon a mental set that is no longer functional. At the neurobiological level, cognitive flexibility relies on interactions between the dorsolateral prefrontal cortex and the posterior parietal cortex, as well as dopaminergic modulation (Roitsch et al., 2022). In learning contexts, cognitive flexibility is a key determinant of the ability to learn from errors, update behavior based on feedback, and make effective decisions in complex and uncertain situations (Sortwell et al., 2026).

Taken together, these executive processes function as an integrated system rather than as isolated cognitive abilities. Their coordinated operation enables individuals to regulate attention and behavior, adapt to changing demands, and strategically use information during learning and problem-

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solving (Roitsch et al, 2022). Accordingly, the development of executive functions is closely associated with children's capacity to respond flexibly to novel situations, regulate their behavior, and sustain goal-directed learning. In educational settings, strengthening these interconnected skills may therefore support not only academic performance but also adaptive behavior and effective self-regulation (Gravrakmo et al, 2023).

Cognitive flexibility allows shifting perspectives and adapting to changing demands. These core components contribute to higher-level executive functions such as reasoning, problem-solving, and planning (Han et al, 2025). Additionally, the figure highlights the role of self-regulation, encompassing both effortful control and innate temperamental predispositions, which modulate emotional, motivational, and cognitive arousal essential for effective executive functioning (Zheng et al, 2023). Figure 5 depicts the complex structure of executive functions, illustrating the interplay between working memory, cognitive flexibility, and inhibitory control. Working memory involves maintaining and manipulating information, while inhibitory control includes managing interference and response inhibition to regulate thoughts, attention, and behavior (Golland et al, 2025; Wang et al, 2025).

Figure 5.

Cognitive Flexibility within the Scope of Executive Functions (Diamond, 2013)

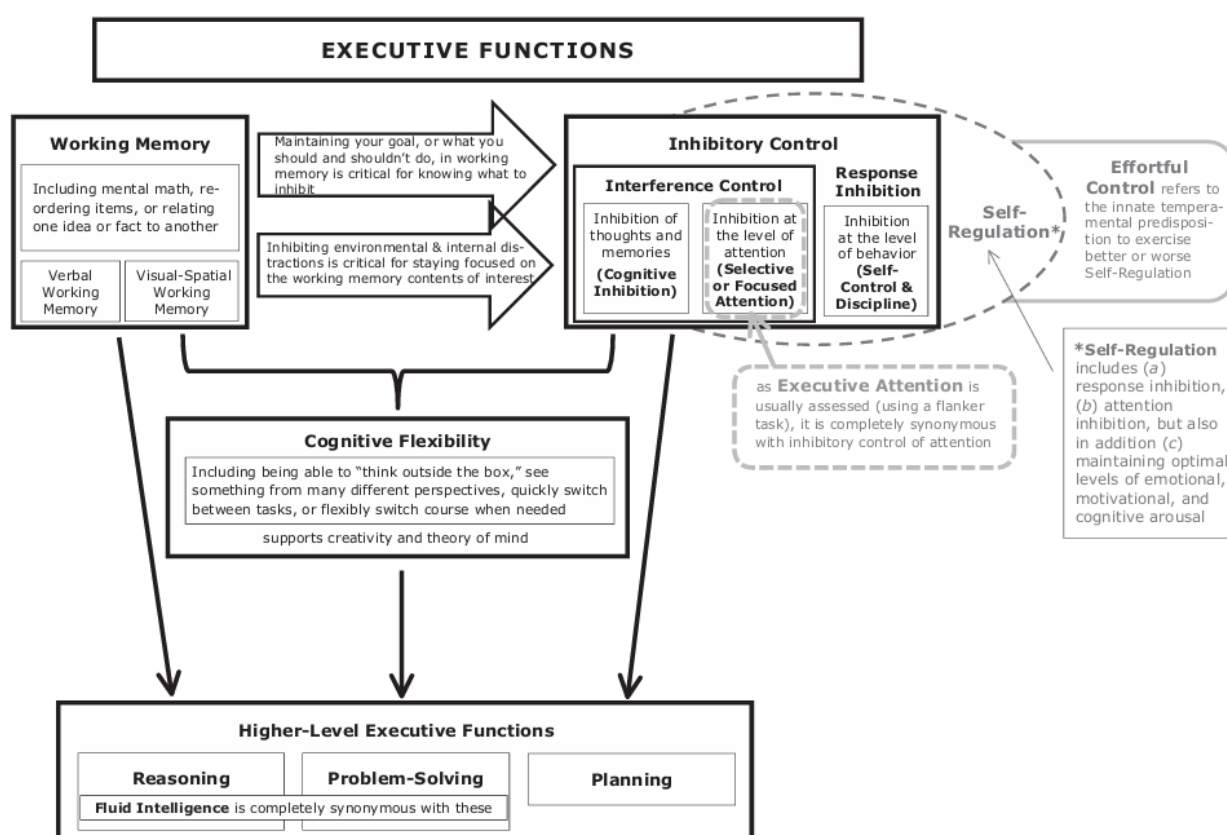


Figure 5 adapted from Diamond, 2013

In Figure 5, executive functions are conceptualized not as a linear sequence but as an interactive and hierarchical system: working memory and inhibitory control provide the core regulatory mechanisms, while cognitive flexibility builds upon this foundation to generate adaptation and creativity. The system as a whole, in turn, supports higher-order cognitive outcomes such as planning, problem solving, and reasoning. This perspective strongly demonstrates that executive functions lie at the centre of both cognitive performance and self-regulatory behaviours.

2.4.3.2. Executive Functions and Working Memory

Working memory is the ability to hold information in mind for a short period of time and to process that information simultaneously. It also refers to the cognitive system that keeps information in a highly accessible state for temporary use in ongoing information processing (Chai et al., 2018). The amount of information that can be stored mentally for quick and easy access is limited. For example, when performing a mental arithmetic task without using paper and pencil—such as multiplying two two-digit numbers—it is necessary to keep part of the intermediate results in mind. Similarly, when receiving verbal directions that involve multiple right and left turns without having a way to write them down, it becomes difficult to remember the route; if a phone call occurs during this process, almost all of the directions may be forgotten. In order to process information intellectually and socially, it must be held in mind. The limited cognitive space in which the numbers and directions described in these examples are maintained is defined as “working memory” (Gokce et al., 2021).

Rather than being a passive storage system, working memory functions as a dynamic mental workspace for cognitive operations such as problem solving, reasoning, and language comprehension. It is supported primarily by neural networks involving the prefrontal cortex in interaction with the hippocampus and the parietal cortex. From an educational and cognitive performance perspective, working memory plays a fundamental role in following instructions, maintaining multi-step tasks, and keeping goal-relevant information active despite distractions (Ullman et al., 2014).

Working memory capacity increases throughout childhood and adolescence. Examining the neural changes associated with this development provides insight into the mechanisms underlying working memory capacity. Studies conducted with 12-month-old infants have shown that structural connectivity in white matter, measured through magnetic resonance signals, is associated with working memory capacity during growth and development (Vogel & Machizawa, 2004; Short et al., 2013). Figure 6 illustrates the brain regions associated with the different components of working memory.

Figure 6.

Neurocognitive Architecture of Working Memory and Executive Attention Control (Chai et al., 2018)

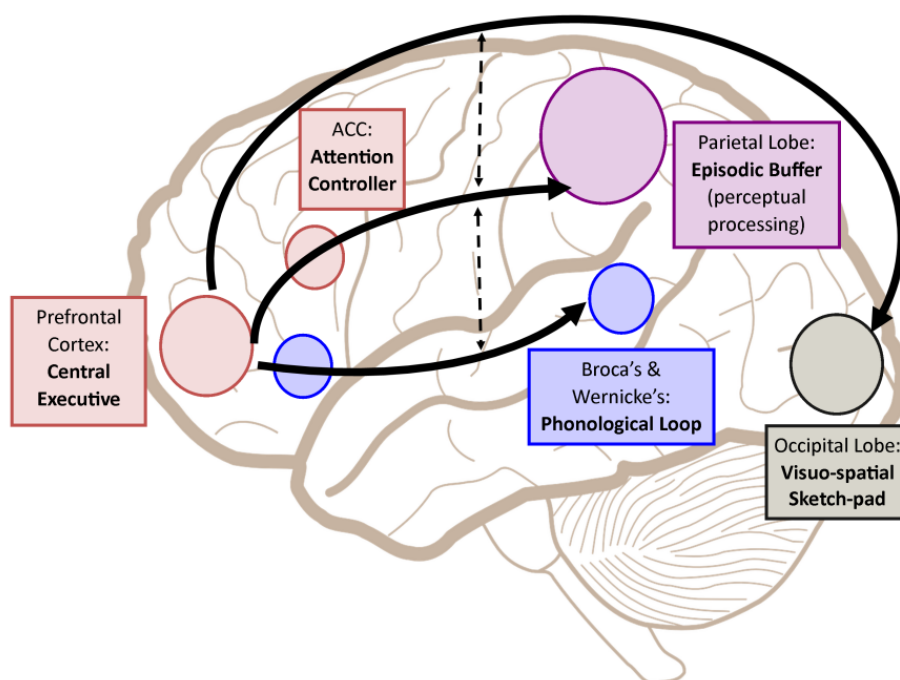


Figure 6 adapted from Chai et al., 2018

Figure 6 illustrates the functional organization of the Baddeley-based components of working memory within the brain and their interaction with executive attention systems. The prefrontal cortex assumes the role of the central executive by regulating information flow, while the anterior cingulate cortex plays a critical role in attention control and conflict monitoring processes. The episodic buffer, located in the parietal lobe, enables the integration of perceptual information, whereas the phonological loop—associated with Broca's and Wernicke's areas—is responsible for the temporary storage and processing of verbal information. The visuospatial sketchpad, situated in the occipital lobe, supports visual and spatial representations. The bidirectional connections indicated by arrows emphasize the dynamic exchange of information among these subsystems and the top-down control mechanisms modulated by attention. This integrated structure demonstrates that working memory is not merely a storage system but an active and regulatory cognitive system (Chai et al., 2018).

The figure should not be interpreted as a one-to-one anatomical mapping of each working memory component onto a single brain region. The central executive is associated with executive control processes involving the prefrontal cortex and broader frontoparietal networks, while attention control and conflict monitoring involve distributed networks that include the anterior cingulate cortex. The episodic buffer is a multimodal integration system that binds information from different sources and from long-term memory; although parietal regions have been implicated in episodic and multimodal processing, the episodic buffer itself should not be regarded as being anatomically localized to the parietal lobe (Baddeley, 2000; Chai et al., 2018). The visuospatial sketchpad likewise

involves distributed posterior cortical systems supporting visual and spatial processing and should not be equated exclusively with the occipital lobe. Thus, the anatomical labels and connections presented in Figure 6 are intended to illustrate functional associations and network-level contributions rather than discrete anatomical locations (Chai et al., 2018).

From a neurobiological perspective, working memory is primarily supported by fronto-parietal networks, particularly the interactions between the dorsolateral prefrontal cortex and the posterior parietal cortex. These networks operate through sustained patterns of neural activity that enable the active maintenance of information. The hippocampus serves as a bridge between working memory and long-term memory, while the dopaminergic system—especially within the prefrontal cortex—exerts a crucial neuromodulatory on working memory capacity and stability (Gokce et al., 2021). In the context of educational and cognitive performance, working memory is critical for maintaining multi-step tasks, keeping goal-relevant information active despite distracting stimuli, and reorganizing information in a contextual manner. Limitations in working memory capacity are closely associated with learning difficulties, attention problems, and declines in academic performance. For this reason, working memory is regarded not merely as a cognitive component but as the operational core of learning (Short et al., 2013). Taken holistically, working memory should be understood not as a “mental storage space” that temporarily holds information, but as a dynamic control system that regulates information flow in accordance with the moment-to-moment demands of the cognitive system. In this capacity, it occupies a central and regulatory position within executive functions (Chai et al., 2018).

2.4.3.3. Executive Functions and Inhibitory Control

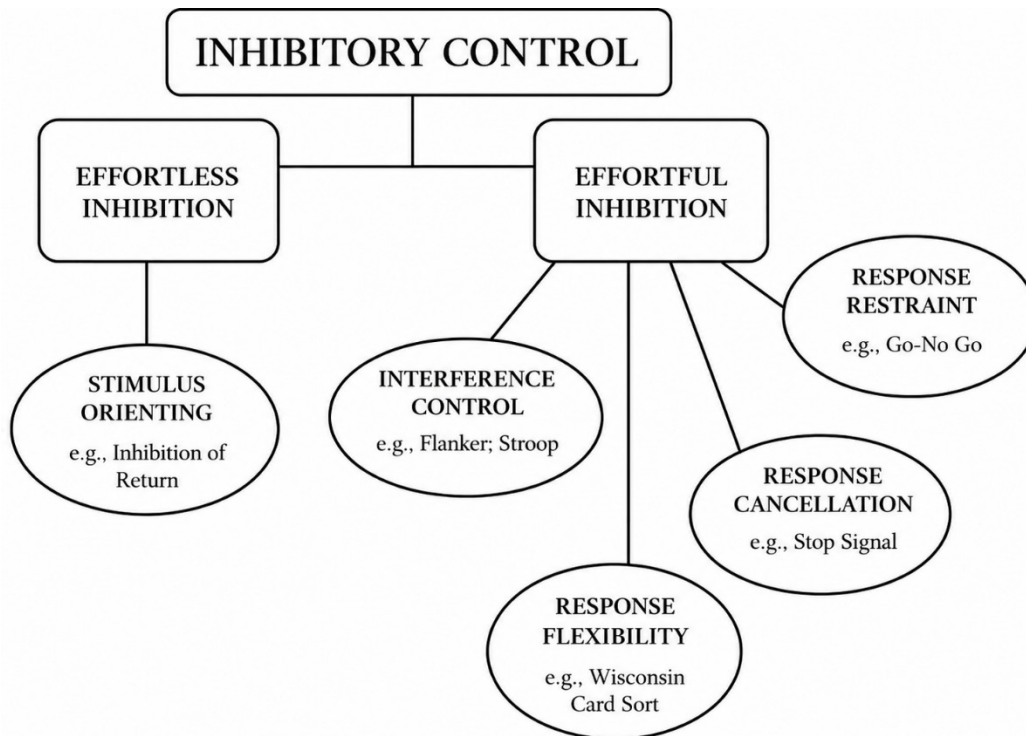
Inhibitory control is the capacity to consciously suppress automatic, dominant, or impulsive responses (Ananthavalli, 2024). This skill includes ignoring distracting stimuli, preventing inappropriate behaviours, and choosing delayed rewards over immediate gratification. The neural basis of inhibitory control primarily relies on circuits involving the orbitofrontal cortex, anterior cingulate cortex, and basal ganglia. This mechanism enables the regulation of thought flow at the cognitive level and the maintenance of self-control at the behavioural level (Pradeep et al., 2024).

Inhibitory control is a core component of executive functions that allows individuals to deliberately suppress dominant, automatic, or contextually inappropriate cognitive, behavioral, and emotional responses. It provides a selective regulatory mechanism at the levels of attention, thought, and action to sustain goal-directed behaviour (Battro et al., 2011). Inhibitory control is a multidimensional construct that encompasses not only the suppression of behavioural impulses but also the regulation of mental representations and cognitive processes (Febrialismanto, 2023). Within theoretical frameworks, inhibitory control is typically examined at two main levels: behavioural inhibition and cognitive inhibition. Behavioural inhibition involves stopping or delaying motor responses, whereas cognitive inhibition refers to the suppression of task-irrelevant thoughts, associations, or distracting stimuli. These two levels operate together during learning and problem-solving processes, enabling the efficient use of cognitive resources (Oner, 2024).

From a neurobiological perspective, inhibitory control is primarily regulated by a prefrontal cortex-centred network. In particular, the inferior frontal gyrus, anterior cingulate cortex, and orbitofrontal cortex play critical roles in detecting inappropriate responses, monitoring conflict, and implementing response inhibition. Through their reciprocal loops with the basal ganglia, these cortical structures exert inhibitory control over motor and cognitive outputs. Neuromodulatory systems such as dopamine and noradrenaline have a decisive influence on the timing and effectiveness of inhibitory control (Golland et al., 2025). From a developmental perspective, inhibitory control emerges in early childhood but continues to develop through adolescence and early adulthood in parallel with the structural and functional maturation of the prefrontal cortex. This developmental trajectory is associated with increases in self-regulation capacity, reductions in impulsivity, and stronger adherence to social norms. Individual differences in inhibitory control show strong associations with attention-deficit/hyperactivity disorder, impulse control disorders, and various forms of psychopathology (Sinopoli & Dennis, 2012).

In educational and academic contexts, inhibitory control plays a central role in maintaining attentional focus, suppressing task-irrelevant stimuli, and foregoing short-term impulses in pursuit of long-term goals. Insufficient inhibitory control is associated with distractibility, increased error rates, and declines in academic achievement during learning processes, whereas strong inhibitory control supports the development of metacognitive awareness and self-regulated learning skills (Pradeep et al., 2024).

Figure 7 divides the concept of inhibitory control into two main components: effortless inhibition and effortful inhibition. Effortless inhibition involves automatic and rapid stimulus orientation, for example, associated with the “Inhibition of Return” mechanism. Effortful inhibition, on the other hand, encompasses more conscious and controlled processes; these processes include interference control (e.g., Flanker and Stroop tests), response restriction (Go-No Go test), response cancellation (Stop Signal test), and response flexibility (Wisconsin Card Sort test). This distinction provides an important conceptual framework for understanding the dynamic and multidimensional nature of cognitive control processes. Figure 7 illustrates the multidimensional structure of inhibitory control, distinguishing between effortless and effortful inhibition. Effortful inhibition encompasses interference control, response flexibility, response restraint, and response cancellation, which collectively enable individuals to regulate attention, suppress inappropriate responses, and adapt behavior according to changing demands. These processes represent important components of executive functioning and contribute to effective self-regulation and goal-directed behavior (Sinopoli & Dennis, 2012).

Figure 7.*Inhibitory Control (Sinopoli & Dennis, 2012)**Figure 7 adapted from Sinopoli & Dennis, 2012)*

In academic and social contexts, inhibitory control plays a critical role in maintaining focus, adhering to rules, and regulating emotional responses (Sinopoli & Dennis, 2012). These three executive function components interact dynamically with one another. Effective learning and adaptive behaviour emerge through the maintenance of information in working memory, the regulation of attention and behaviour via inhibitory control, and the flexible restructuring of strategies when needed through cognitive flexibility. This integrated structure positions executive functions as the central regulatory system of human cognition (Ananthavalli, 2024). In conclusion, inhibitory control functions as a regulatory and protective mechanism within executive functions. By ensuring that the cognitive system operates in alignment with goals, it enables a flexible yet controlled capacity for adaptation at both learning and behavioural levels. In this respect, inhibitory control is regarded as one of the fundamental determinants of an individual's cognitive autonomy and academic functioning.

2.5. Application of Brain-Based Learning Principles in Education

The application of brain-based learning principles in education does not involve the mechanical use of specific techniques; rather, it entails the redesign of instruction in alignment with the biological and psychological nature of learning. Within the brain-based learning framework, the starting point of the process is the systematic construction of a learning environment in which learners feel emotionally and cognitively safe. Neuroscientific research clearly demonstrates that when the brain perceives threat, it allocates cognitive resources not to learning, but to survival and defence. Excessive competition,

constant evaluation, and high-performance pressure increase amygdala-based stress responses, thereby negatively affecting attention, working memory, and higher-order thinking processes (Fontdevila et al., 2021). For this reason, classroom environments should not be structured around avoiding mistakes, but around learning climates in which errors can be interpreted and transformed into learning opportunities.

In environments where mistakes are punished, learning remains superficial; by contrast, in classrooms where errors are accepted as a natural and inevitable part of the learning process, cognitive flexibility and durable learning are supported. At this point, the quality of feedback plays a decisive role. Judgmental and outcome-oriented feedback heightens students' perception of threat, whereas process-focused, guiding, and developmental feedback keeps the brain receptive to learning (Ginting & Tunga, 2025). Emotional safety does not merely signify the absence of negative stimuli; it also encompasses the presence of belonging, autonomy, and a sense of being valued. Learning environments in which students' perspectives are taken into account, where they have a voice in the learning process, and where individual differences are acknowledged activate, dopaminergic systems associated with motivation. This activation facilitates sustained attention and the transfer of information to long-term memory (Pradeep et al., 2024). A cognitively safe environment, in turn, requires learning tasks to be aligned with learners' developmental levels, cognitive load to be regulated in a balanced manner, and uncertainty to be structured in ways that support learning. Tasks that are either overly complex or overly simplified can disrupt the learning process, whereas an optimal level of challenge effectively engages the brain's problem-solving and meaning-making networks.

The brain processes information through meaningful patterns. Accordingly, content should be presented through conceptual relationships, big ideas, and contextual frameworks rather than fragmented and disconnected information. Activating prior knowledge, using analogies, employing visual organizers, and establishing real-life connections constitute core practices of brain-based instruction. Multisensory presentations (visual, auditory, and movement-based) enable information to be linked to multiple neural networks (Wang et al., 2025). Emotions are not a by-product of learning but a direct determinant of it. Within a brain-based educational approach, activities are designed to nurture curiosity, meaning, autonomy, and a sense of competence. Active participation in the learning process, clearly articulated goals, and visible progress provide neurobiological support for motivation (Pradeep et al., 2024). The assumption that every brain is unique necessitates flexibility in instruction. Allowing the same content to be learned through different pathways, accommodating variations in learning pace, and offering alternative forms of representation are practical reflections of this principle. Brain-based learning promotes adaptive instruction rather than standardized teaching (Parayangattuet & Kishore, 2024). Traditional assessment practices often measure short-term recall and generate stress. In a brain-based approach, assessment is treated not as the end of learning but as an integral part of it. Formative assessment, feedback, self-assessment, and performance-based tasks become tools that actively support learning. The aim is to make visible not only what has been learned, but also how learning has occurred (Khanam, 2025).

2.5.1. Cognitive Interventions in Educational Settings

In educational settings, cognitive interventions constitute a set of systematic and evidence-based practices aimed at strengthening learners' core cognitive processes, such as attention, memory, executive functions, and metacognitive regulation (Lindsay, 2020). These interventions seek not only to enhance academic outcomes but also to enable individuals to manage their learning processes in more effective, flexible, and sustainable ways. Positioned at the intersection of educational psychology, cognitive neuroscience, and developmental sciences, cognitive interventions directly address the mental mechanisms underlying learning (Golland et al, 2025).

From a theoretical perspective, cognitive interventions are grounded in information processing theory, executive function models, and self-regulated learning approaches. In particular, executive function components such as working memory, inhibitory control, and cognitive flexibility are widely regarded as strong predictors of academic performance. Accordingly, educational interventions extend beyond content instruction to focus on strengthening the cognitive infrastructure that supports learning (Chai et al., 2018; Parayangattuet & Kishore, 2024). At the level of practice, cognitive interventions include structured attention training programs, working memory-based exercises, problem-solving and reasoning strategies, and instructional designs aimed at enhancing metacognitive awareness. Such interventions support learners' ability to manage cognitive load by promoting more effective encoding, maintenance, and retrieval of information. Moreover, by suppressing task-irrelevant stimuli and strengthening goal-directed cognitive control, they increase levels of focus within learning environments (Zheng et al., 2023).

When developmental differences are taken into account, the effectiveness of cognitive interventions varies depending on age, cognitive maturity, and individual differences. Interventions implemented during early childhood and primary school tend to produce more enduring and generalizable effects, as executive functions are still undergoing active development during these periods. In contrast, cognitive strategy-based interventions applied during adolescence and adulthood yield significant gains in academic self-regulation and learning motivation (Han et al., 2025).

Empirical evidence indicates that cognitive interventions implemented in educational settings have positive effects on academic achievement, learning transfer, and problem-solving skills. However, the sustainability of these effects depends on the extent to which interventions are integrated into instructional curricula, incorporate contextually meaningful tasks, and are implemented consistently by teachers. Therefore, cognitive interventions should be conceptualized not as isolated practices but as integral components of comprehensive learning designs aligned with pedagogical objectives (Golland et al., 2025). In educational settings, cognitive interventions represent a forward-looking approach that emphasizes not only what is taught, but how learning occurs. By strengthening individuals' cognitive capacities, this approach contributes to the development of lifelong learning skills that extend beyond academic performance (Sortwell et al., 2026).

Table 3.*Cognitive Interventions in Educational Settings*

Type of Cognitive Intervention	Targeted Cognitive Processes	Example Practices	Expected Cognitive / Academic Outcomes
Attention-Based Interventions	Selective attention, sustained attention, inhibitory control	Focused attention exercises, attentional filtering tasks, mindfulness-based classroom practices	Increased attention span, greater resistance to off-task distractions, reduced error rates
Working Memory Interventions	Working memory capacity, information updating, cognitive load management	Digit-letter sequencing tasks, dual-task exercises, computer-based working memory training programs	Improved ability to follow instructions, enhanced problem-solving performance
Executive Function Training	Cognitive flexibility, planning, inhibitory control	Rule-switching tasks, strategy-based games, problem-based learning activities	Flexible thinking, improved strategy-shifting skills, enhanced self-regulation
Metacognitive Interventions	Metacognitive awareness, learning monitoring and evaluation	Self-assessment forms, think-aloud techniques, learning journals	Conscious use of learning strategies, increased learning retention
Cognitive Strategy Instruction	Encoding, retrieval, organization	Concept mapping, summarization techniques, keyword strategies	Improved information organization, enhanced long-term memory performance
Self-Regulated Learning Interventions	Goal setting, motivation, cognitive control	Goal-monitoring charts, time management training, feedback loops	Increased academic self-efficacy, higher learning motivation, improved task completion

Source: Original table developed by the authors based on the relevant literature (Gazzaniga, 2009; Sortwell, 2026).

Table 3 presents a systematic overview of cognitive interventions implemented in educational settings, organized according to the cognitive processes they target, representative instructional practices, and their expected cognitive and academic outcomes. The table highlights that cognitive interventions extend beyond content-focused instruction by directly addressing the underlying mechanisms that support learning, such as attention regulation, working memory capacity, executive control, and metacognitive monitoring. By aligning specific intervention types with clearly defined cognitive functions, the table illustrates how instructional designs can be intentionally structured to strengthen learners' self-regulatory capacities and academic performance. Overall, this classification underscores the importance of integrating cognitive interventions into educational practice as a means of fostering both immediate learning gains and long-term cognitive development.

2.6. Integrating Neuroscience into Educational Practice

Integrating neuroscience into educational practice involves the systematic translation of findings from cognitive and affective neuroscience into pedagogical frameworks, instructional design, and classroom implementation. This approach is grounded in the premise that learning is a biologically mediated process shaped by neural plasticity, developmental trajectories, and individual differences in brain organization. By aligning educational practices with empirically established principles of brain function, neuroscience-informed education seeks to enhance the effectiveness, equity, and adaptability of teaching and learning environments (Dipietro et al., 2023).

From a theoretical perspective, neuroscience contributes to education by elucidating the neural mechanisms underlying attention, memory, emotion, motivation, and executive functions. Insights into how neural networks support learning processes—such as the role of prefrontal–parietal circuits in executive control or hippocampal systems in memory consolidation—provide a scientific basis for instructional strategies that optimize cognitive load, promote active engagement, and support long-term retention (Singh & Morkel, 2024). In practical terms, neuroscience-informed educational practices emphasize developmentally appropriate instruction, sensitivity to individual variability, and the creation of learning environments that support self-regulation and cognitive flexibility. For example, understanding the protracted development of executive functions underscores the importance of scaffolding, feedback, and structured opportunities for practice, particularly in early and middle childhood (Lindsay, 2020).

At the systems level, integrating neuroscience into education encourages interdisciplinary collaboration among educators, psychologists, and neuroscientists. Such collaboration helps prevent neuromyths and promotes the responsible use of neuroscientific knowledge in educational decision-making. When grounded in robust empirical evidence and aligned with pedagogical goals, neuroscience-informed approaches have the potential to refine instructional practices, support diverse learners, and contribute to the development of adaptive, lifelong learning competencies (Parayangattuet & Kishore, 2024). Overall, the integration of neuroscience into educational practice represents a forward-looking framework that enriches educational theory and practice by situating learning within its biological context, while maintaining a critical and evidence-based stance toward application.

2.7. Limitations and Ethical Considerations in Neuroscience-Based Education

Limitations and ethical considerations in neuroscience-informed education constitute a critical counterbalance to the growing enthusiasm for applying brain research to educational contexts. (Lalancette & Campbell, 2012). While neuroscience-informed approaches offer valuable insights into learning processes, their use in education is constrained by conceptual, methodological, and ethical boundaries that must be explicitly acknowledged to avoid scientific overreach and pedagogical harm (Parayangattuet & Kishore, 2024).

A primary limitation lies in the problem of translation across levels of analysis. Neuroscience operates at the level of neural circuits, synaptic activity, and brain networks, whereas education unfolds within complex social, cultural, and institutional environments. Findings derived from controlled laboratory settings—often using simplified tasks and artificial stimuli—do not automatically generalize to real classrooms, where learning is shaped by motivation, peer interaction, prior knowledge, and contextual meaning. As a result, neuroscience can inform education only indirectly, typically through intermediate frameworks such as cognitive psychology, rather than serving as a direct guide for instructional design (Dundar-Coecke, 2021; Goldberg, 2022).

Methodological constraints further limit the explanatory power of neuroscience-informed education. Neuroimaging techniques such as fMRI, EEG, or MEG provide correlational data rather than causal explanations of learning. Observing activation in a particular brain region during a task does not imply that the region causes learning, nor does it prescribe how teaching should be structured (Rogers et al., 2007). Moreover, many neuroscientific findings are probabilistic and population-level, while educational decisions are made for individuals. This mismatch creates the risk of overgeneralization, particularly when group-level neural patterns are used to justify individual-level educational interventions (Neuro Trauma Training Reports, 2021). The limitations and ethical dimensions of neuroscience-informed education are summarized in Table 4.

Table 4 summarizes the main limitations and ethical issues encountered in the implementation of neuroscience-based education, from conceptual, methodological, and pedagogical perspectives. The framework presented in the table reveals the limitations of directly transferring findings from brain research to educational practices, while offering a critical perspective on how neuroscientific knowledge can be used more cautiously and contextually in pedagogical decision-making processes. Thus, without denying the possibilities of neuroscience-based education, the table emphasizes that this approach should be evaluated in accordance with the principles of scientific validity, ethical responsibility, and equality in education.

Table 4.*Limitations and Ethical Dimensions of Neuroscience-Based Education*

Dimensions	Key Problem	Area Description	Educational Implications
Conceptual Restrictions	Disconnect between levels of analysis	While neuroscience studies micro-level neural processes, education takes place at the macro level within social and cultural contexts.	Directly transferring brain findings to the classroom can be reductionist and misleading.
Methodological Limitations	Correlation-causality problem	Neuroimaging techniques produce relational data; they do not offer causal explanations.	Teaching prescriptions based on specific brain activations are not scientifically defensible.
	Generalization of group data to the individual	Neuroscientific findings are often based on group averages.	Individual learning differences may be ignored.
Developmental Limitations	Individual neuro-developmental differences	Although brain development follows age-related patterns, individual variation is high	There is a risk of students being labelled as "ready/not ready."
Ethical Risks	Neuro-essentialism	Brain-based explanations are often considered overly objective and definitive.	Pedagogical decisions become one-dimensional and exclusionary.
	Data privacy and consent	Neuroscientific and biometric data are collected from children.	Stigma, data misuse, and long-term privacy issues.
	Commercialization and neuromyths	Products presented as "brain-based" but lacking scientific basis.	Waste of resources and pedagogical misdirection.
Social Limitations	The issue of equality and access	Neuroscientific knowledge and technology are limited to certain countries and institutions.	Existing structural inequalities in education may deepen.
Pedagogical Balance	Excessive expectations and misuse	The assumption that neuroscience can replace pedagogy.	Devaluation of teacher expertise and contextual knowledge.

Source: Original table developed by the authors based on the relevant literature (Chai et al, 2018; Goldberg, 2022; Singh & Morkel, 2024).

Another significant limitation concerns developmental variability. Although neuroscience has demonstrated that brain development follows broad age-related trajectories, there is substantial individual variation influenced by genetics, environment, and experience. Neuroscience-informed education can unintentionally promote deterministic interpretations of ability—such as labelling students as neurologically “ready” or “not ready” to learn certain skills. Such interpretations conflict with evidence for brain plasticity and risk reinforcing fixed mindsets, particularly for learners already marginalized by socioeconomic or cultural factors (Bonomo, 2017; Fontdevila et al., 2021).

Ethical considerations become especially salient when neuroscientific data are introduced into educational decision-making. One major concern is neuroessentialism: the tendency to treat brain-based explanations as more objective, definitive, or truthful than behavioural or experiential evidence. This bias can lead educators and policymakers to privilege neuroscientific claims, even when they offer limited pedagogical relevance. In extreme cases, brain data may be used to legitimize exclusionary practices, such as tracking, labelling, or early intervention decisions that lack sufficient empirical justification (Schultz, 2018). Data privacy and informed consent also pose ethical challenges. Neuroscience-informed education increasingly intersects with neurotechnologies, cognitive assessments, and biometric data collection. When such data are gathered from children, ethical standards must be particularly stringent. Learners may not fully understand how their data are used, stored, or interpreted, raising concerns about long-term data ownership, stigmatization, and misuse. The potential for neuroscientific data to follow individuals across educational or institutional boundaries amplifies these risks neuro (Singh & Morkel, 2024).

A further ethical issue arises from the commercialization of neuroscience-based educational products. Programs, curricula, and interventions are often marketed as “brain-based” without rigorous scientific validation. This creates a fertile ground for neuromyths and pseudoscientific claims, which can mislead educators and divert resources away from evidence-based practices. From an ethical standpoint, presenting speculative or weakly supported neuroscientific claims as pedagogical solutions undermines professional integrity and informed decision-making (Jagusiak-Kocik & Janasik, 2023).

Importantly, neuroscience-informed education must also grapple with questions of equity and access. Advanced neuroscientific tools and expertise are concentrated in well-resourced institutions, primarily in high-income contexts. If neuroscience-based insights shape educational policy without consideration of local realities, they may exacerbate existing inequalities rather than reduce them. Ethical application therefore requires sensitivity to cultural, social, and economic contexts, as well as a commitment to inclusive educational goals. In light of these limitations and ethical concerns, a cautious and reflective stance is essential. Neuroscience-informed education should not aspire to replace pedagogical theory or professional judgment, but to complement them within a pluralistic evidence framework. Ethical responsibility in this field lies not in maximizing the use of brain data, but in recognizing when such data are informative, when they are silent, and when they risk distorting educational priorities.

3. Conclusion

This chapter has explored the emergence of educational neuroscience and its translation into pedagogical practice. Key principles of brain-based learning—such as neuroplasticity, attention, learning readiness, and executive functions—offer critical insights into the cognitive processes underlying learning. The subcomponents of executive functions, including cognitive flexibility, working memory, and inhibitory control, play a pivotal role in shaping learners' cognitive control and academic success. Furthermore, the application of these principles through cognitive interventions and the integration of neuroscience into educational settings present promising pathways for enhancing individualized learning experiences.

However, neuroscience-informed education should not be regarded as a replacement for pedagogical knowledge, educational theory, or teachers' professional judgment. Rather, neuroscience offers a complementary evidence framework that, when integrated with cognitive psychology and the educational sciences, can strengthen pedagogical decision-making and contribute to more informed and context-sensitive educational practices. Accordingly, the limitations and ethical implications of applying neuroscientific findings to education must be carefully considered to avoid overinterpretation, reductionism, and the inappropriate translation of laboratory findings into classroom practice. Overall, educational neuroscience is most valuable not as a stand-alone prescription for teaching, but as an interdisciplinary source of evidence that complements established pedagogical knowledge and supports more informed, adaptive, and learner-centered educational models.

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