10.24193/ed21.2026.33.02

Neuroeducation and Biology Learning Through the Lens of Cognitive Principles and Pedagogical Implications

Isac Maria Crina

Educatia 21 Journal 33 (2026)

ISSN online: 2247-8671

Educatia 21 Journal, (33) 2026, Art. 02
doi: 10.24193/ed21.2026.33.02
Theoretical article

Neuroeducation and Biology Learning Through the Lens of Cognitive Principles and Pedagogical Implications

Isac Maria Crina [a*]

[a] *Department of Educational Sciences, Faculty of Psychology and Educational Sciences, Alexandru Ioan Cuza University, Iași, Romania*

*Corresponding author: *isacmariacrina@yahoo.com*

Abstract

Keywords:
neuroeducation, biology learning, cognitive principles, motivation, emotions

Neuroeducation integrates findings from cognitive neuroscience and psychology to inform effective teaching practices, offering a valuable framework for biology education. Contemporary research demonstrates that learning is not purely cognitive but is strongly influenced by emotions, motivation, and attentional processes. Emotional engagement, mediated by the limbic system, modulates memory consolidation, attention, and cognitive resource allocation, enhancing retention of complex biological concepts. Intrinsic motivation further supports persistence, metacognitive strategies, and active exploration, particularly in abstract or counterintuitive topics such as genetics, cellular processes, and ecological systems. Biology instruction can leverage these principles through narrative-based teaching, problem-solving tasks, inquiry-oriented activities, and real-life contextualization that connects scientific content to students' experiences. However, translating neuroscience findings into classroom practice faces challenges, including methodological limitations, differences in levels of analysis, and the persistence of neuromyths. Teacher training, ethical considerations, and evidence-based curricular design are essential to ensure responsible application. Integrating neuroeducational principles promotes multisystemic learning, fostering attention, memory, emotional engagement, and curiosity-driven exploration. By aligning teaching strategies with the brain's natural learning mechanisms, neuroeducation enhances conceptual understanding, engagement, and positive attitudes toward science. It provides educators with a scientifically grounded guide for designing biology lessons that are both effective and meaningful.

1. Introduction

In recent decades, the field of education has undergone a profound transformation, marked by the integration of neuroscience research results into pedagogical theories and practices. This orientation, known as neuroeducation or brain-based education, proposes an interdisciplinary approach to the educational act, based on the understanding of the neurocognitive mechanisms that support the learning process (Sousa, 2016; Tokuhama-Espinosa, 2020). In essence, neuroeducation does not aim to simply apply neuroscience data in school, but to build an epistemological bridge between brain biology, cognitive psychology and educational sciences, in order to optimize student performance and motivation (Immordino-Yang, 2015).

In the context of scientific disciplines, biology occupies a central place in the formation of scientific thinking and logical reasoning skills. However, numerous studies highlight students' cognitive difficulties in learning complex biological concepts, such as cellular structure, molecular processes, or genetic mechanisms (Gilbert & Justi, 2016). These concepts involve operating with abstract levels of representation, often difficult to internalize through traditional teaching methods. This results in the need to identify scientifically grounded teaching strategies that facilitate the construction of coherent and sustainable mental models.

Neuroeducation offers a promising framework for responding to this challenge. By understanding how working memory, attention, emotions, and brain plasticity work, teachers can adapt biology teaching methods to actively stimulate students' cognitive processes (Neacşu, 2019). Recent studies show that effective learning involves not only reason, but also emotion, social context, and multisensory experiences, all integrated into the neural architecture of the brain (Caine & Caine, 1991).

This article aims to conduct a critical review of the literature on the application of neuroeducation principles in the learning of biology. The theoretical foundations of neuroeducation, the correlations between neurocognitive processes and teaching strategies, as well as the implications for teaching practice and teacher training are discussed. The main goal of the study is to highlight the potential of

Published by Educational Sciences Department, Babeș-Bolyai University

neuroeducation to transform biology learning into an active, reflective and evidence-based approach to the functioning of the human brain.

2. Theoretical foundations of neuroeducation

Neuroeducation is an emerging interdisciplinary discipline, located at the intersection of neuroscience, cognitive psychology and pedagogy, which aims to translate research findings on brain function into effective teaching strategies. The aim of this approach is to base teaching and learning on empirical knowledge about neural plasticity, attention, memory, emotions and executive processes, so that learning is optimized and adapted to the cognitive needs of students (Sousa, 2016; Tokuhama-Espinosa, 2020). Neuroeducation is not limited to the simple application of scientific data, but involves a systematic integration of cognitive and affective principles in the design of educational activities and the assessment of learning outcomes (Jolles & Jolles, 2021).

One of the central concepts in neuroeducation is brain plasticity, that is, the ability of the brain to form and reorganize neural connections in response to experience and learning. This allows information to be transformed and consolidated into long-term memory and supports the idea that didactic interventions can have a significant impact on cognitive development at all ages (Zull, 2023). In parallel, working memory has a limited capacity, which means that new information must be presented in a structured and sequential manner, avoiding cognitive overload. Studies show that materials presented in multisensory contexts, correlated with prior knowledge, are processed more efficiently and retained longer (Barutchu et al., 2020; Sweller, 1988).

Attention is another essential factor in neuroeducation, being considered the “gateway” to the learning process. Research indicates that attention decreases after short intervals, which is why educational activities must include task switching, cognitive breaks, and challenges that stimulate active student engagement (Scherer & Mason, 2019). At the same time, the role of emotions and motivation cannot be underestimated. Positive emotions facilitate the encoding and consolidation of information, and affective engagement increases the retention capacity and application of knowledge. In contrast, stress or negative emotions can inhibit executive functions and learning (Immordino-Yang, 2015).

Neuroeducation also supports contextual and multisensory learning. Activities that simultaneously involve multiple sensory channels—visual, auditory, and kinesthetic—and that link new concepts to relevant experiences activate multiple neural circuits, facilitating the processing and memorization of information. In addition, the development of metacognition and self-regulation in learning, i.e. the ability of students to reflect on their own cognitive processes and adjust their learning strategies, is supported by the executive functions of the brain and has significant effects on academic performance (Follmer & Sperling, 2016).

However, the implementation of neuroeducation in practice must be done with caution. There are numerous “neuromyths” in education, such as the left/right hemisphere theory or rigid learning styles, which can deviate the correct application of scientific discoveries. Also, the translation of mechanisms observed in the laboratory into real school contexts is complex and requires the adaptation of activities to the specificities of students and the educational environment (Dekker et al., 2012; Howard-Jones, 2014). Socio-educational factors, such as sleep, nutrition and family context, also influence the learning process and must be integrated into the pedagogical analysis.

Thus, neuroeducation provides a robust theoretical framework for understanding how students learn, laying the foundation for innovative and effective teaching strategies in biology teaching. By integrating cognitive and affective principles, teachers can design lessons that not only convey information, but also stimulate critical thinking, motivation, and active engagement of students, thus maximizing the results of the educational process.

3. Applying neuroeducation principles in biology teaching

Applying neuroeducation principles in biology teaching involves translating neurocognitive concepts such as synaptic plasticity, working memory, attention, motivation, emotion, and executive functions into concrete teaching strategies that are adapted to the complex nature of the subject (dynamic processes, invisible patterns, multiple levels of biological organization). The main goal is to build accurate mental models, consolidate knowledge, and facilitate long-term transfer and retention, while reducing cognitive overload and preventing misconceptions through active exposure to evidence and conceptual modeling (Sweller, 1988; Tokuhama-Espinosa, 2010). This translation must take into account both experimental evidence and the real limitations of the classroom, space, time, resources, and cognitive diversity of students (Howard-Jones, 2014).

3.1. Multisensory learning and the development of mental representations

Biology teaching can be substantially enhanced by the deliberate integration of multisensory learning experiences, as neuroscientific literature demonstrates that the simultaneous processing of information from visual, auditory, tactile, and kinesthetic sources leads to the activation of distributed neural networks, favoring both synaptic consolidation and the formation of more coherent and stable cognitive structures (Baddeley, 2012; Shams & Seitz, 2008). In the context of biology, a discipline that often involves processes inaccessible to direct perception, such as the translocation of ions through membrane channels, the transcription and translation of genetic material, or the dynamics of biogeochemical cycles, multisensory stimulation functions as a conceptual anchoring mechanism, facilitating the mental representation of abstract phenomena.

Thus, effective teaching strategies include combining verbal presentations with animations, graphic representations, digital simulations, 3D models and micro-experiments, elements that amplify useful information redundancy and reduce the risk of forming erroneous concepts. By overlapping these processing channels, a mutual reinforcement of perceptual codes is achieved, a phenomenon supported by working memory theories and research on multisensory integration in the associative cortex (Baddeley, 2012). Also, comparative studies consistently emphasize the superiority of multisensory training programs over unisensory ones, especially in terms of long-term retention, cross-contextual transfer and resistance to conceptual interference (Shams & Seitz, 2008).

The practical application of these principles involves structuring lessons in short temporal sequences, according to the “chunking” model, to optimize cognitive load: a concise introduction to the concept (3–7 minutes), followed by a visual-interactive stage (e.g., viewing an animation or manipulating a three-dimensional model), complemented by a kinesthetic activity (mini-experiment, molecular model reconstruction) and concluded by a moment of metacognitive reflection (learning journal, written analysis, self-explanation). This alternation between modalities not only respects the operational limits of working memory, but also facilitates spaced repetition and varied encoding, two mechanisms empirically demonstrated to be fundamental for the sustainability of learning (Baddeley, 2012; Sweller, 1988).

Therefore, integrating multisensory learning into biology teaching is not limited to diversifying activities, but involves intentional instructional design that aims to balance cognitive tasks, maintain attentional activation, stimulate semantic elaboration, and consolidate long-term memory through coordinated activation of neural networks involved in perception, representation, and scientific reasoning.

3.2. Scientific storytelling, analogies and conceptual modeling

Biology, by its nature, involves describing and understanding complex processes and transformations at the molecular, cellular, and ecosystem levels, making it well-suited for the use of educational storytelling. Scientific narrative allows students to organize information sequentially, build coherent mental models, and anticipate causal relationships between elements (Bruner, 1991; Green, 2006). For example, presenting the trajectory of a glucose molecule from ingestion to ATP generation stimulates both planning and attention systems, as well as circuits responsible for temporal integration and event prediction (Immordino-Yang & Damasio, 2008). Introducing the narrative component reduces conceptual ambiguity and facilitates the transfer of knowledge between varied contexts, by creating a meaningful and memorable learning framework (Mayer, 2014).

Conceptual analogies, such as “ribosomes as factories,” “enzymes as keys to locks,” or “membranes as dynamic semipermeable filters,” are powerful cognitive scaffolding tools. However, the literature warns that using analogies without metacognitive guidance can lead to unwarranted extension of analogies and the formation of erroneous representations (Duit, 1991; Glynn, 2012). To prevent these effects, students should be actively involved in analyzing the limits of analogies and comparing them with empirical evidence.

Conceptual modeling is another central tool in biology teaching, including concept maps, diagrams, dynamic models, and interactive simulations. The process of building, testing, and revising models involves executive functions, planning, inhibition, cognitive flexibility, and progress monitoring, and promotes the detection of conceptual dissonance, the correction of misconceptions, and the consolidation of deep and transferable understanding (Gobert &

Buckley, 2000; Hmelo-Silver et al., 2007). Thus, students do not simply memorize facts, but learn to relate and integrate different levels of biological organization, from the molecular to the organismic, developing critical thinking and cognitive self-regulation skills.

Therefore, the combination of storytelling, well-guided analogies, and conceptual modeling provides an integrated framework that optimizes cognitive and affective activation, stimulates working memory and executive functions, and contributes to the development of robust and sustainable scientific understanding (Sweller, 1988; Tokuhama-Espinosa, 2010).

3.3. Learning through inquiry and interactive activities

Inquiry-based learning methodologies, complemented by structured collaborative activities, are powerful pedagogical tools for stimulating executive functions, planning, inhibition, cognitive flexibility, and developing metacognition, essential components of self-regulated learning (Hmelo-Silver et al., 2007; Tokuhama-Espinosa, 2010). By asking students to formulate hypotheses, design experiments, and collect and analyze data, these methodologies encourage active application of knowledge and continuous monitoring of progress, which leads to deliberate adjustment of cognitive strategies in real time (Hmelo-Silver et al., 2007).

In biology, problem-focused activities allow students to explore simulated ecosystems, test the effect of abiotic factors on communities of organisms, or investigate cellular processes through virtual experiments and micro-laboratories. By directly engaging in data generation and verification, students develop critical thinking skills, problem-solving skills, and the ability to construct explanations based on empirical evidence (Gobert & Buckley, 2000; Hmelo-Silver et al., 2007).

Systematic reviews and longitudinal studies indicate that inquiry-based approaches lead to improved conceptual transfer, deeper understanding, and higher academic performance compared to traditional methods based solely on theoretical exposure (Furtak et al., 2012; Lazonder & Harmsen, 2016). These effects are more pronounced when activities are designed to integrate both cognitive and affective components, with motivation, curiosity, and emotional engagement significantly influencing information encoding and retention (Immordino-Yang & Damasio, 2007).

Therefore, inquiry-based learning and interactive activities not only allow the construction of solid scientific knowledge, but also the development of flexible, self-regulated thinking capable of transferring concepts to new contexts, thus strengthening sustainable learning in biology (Hmelo-Silver et al., 2007; Tokuhama-Espinosa, 2010).

3.4. Educational technologies: VR/AR, simulations and formative assessments

The integration of emerging technologies, such as virtual reality (VR), augmented reality (AR), and interactive simulations, constitutes an advanced instructional strategy in biology teaching, facilitating the exploration of microscopic phenomena or invisible processes, inaccessible to direct observation in the context of the traditional classroom (Radianti, Majchrzak, Fromm & Wohlgenannt, 2020). These technological environments allow the construction of immersive experiences, which simultaneously stimulate multiple sensory channels, activating integrated neural networks and favoring the sustainable encoding of knowledge (Baddeley, 2012; Shams & Seitz, 2008).

The effectiveness of VR/AR in science education depends largely on the instructional design, which must be deliberate and oriented towards cognitive activation. Interventions based on guided integration, reflective tasks, and iv-formatted feedback promote active learning and avoid turning technology into a passive tool (Sweller, 1988; Tokuhama-Espinosa, 2010). Furthermore, VR/AR allows for real-time manipulation of variables, hypothesis testing, and visualization of dynamic models of biological systems, providing opportunities for deep conceptual understanding and contextual transfer (Mayer, 2014; Radianti et al., 2020). In addition, the use of interactive technologies can facilitate personalization of learning, adjusting the pace and level of complexity for each student, helping to reduce cognitive overload and optimize affective and motivational engagement. Studies suggest that the deliberate integration of VR/AR, in combination with other multisensory and inquiry-based learning methods, maximizes the benefits of instruction and stimulates the development of executive functions and critical thinking (Immordino-Yang & Damasio, 2007; Tokuhama-Espinosa, 2010).

Therefore, VR/AR should not be viewed solely as a technological innovation, but as a strategic pedagogical tool, designed to extend the learning experience, facilitate the encoding and retention of complex information, and enable the exploration of invisible biological phenomena in an interactive, meaningful, and cognitively challenging way (Radianti et al., 2020; Shams & Seitz, 2008).

3.5. Implications for motivation, attention, and performance

The integration of multisensory strategies, educational storytelling, and investigative activities has profound effects on students' affective and cognitive engagement. The literature emphasizes that stimulating curiosity, satisfaction, and intrinsic motivation favors the efficient encoding of information in memory and facilitates the transfer of knowledge to new and complex contexts (Immordino-Yang & Damasio, 2007; Tokuhama-Espinosa, 2010).

Deliberate alternation of activity types, combining visual exposure, practical manipulation, and metacognitive reflection, along with planned cognitive breaks, helps prevent working memory overload and maintain attention throughout the lesson (Baddeley, 2012; Sweller, 1988). These interventions also allow the strengthening of neural networks involved in focused attention, emotional regulation, and multisensory information processing, which leads to optimized academic performance and a greater ability to apply knowledge in new situations (Immordino-Yang & Damasio, 2007; Mayer, 2014).

Continuous formative feedback, implemented in parallel with interactive activities, amplifies the learning process by monitoring progress, adjusting individual strategies, and stimulating cognitive self-regulation. Thus, students not only accumulate information, but also develop metacognitive skills, cognitive flexibility, and problem-solving skills, all fundamental elements for sustainable understanding and conceptual transfer in biology (Hmelo-Silver et al., 2007; Tokuhama-Espinosa, 2010).

Therefore, the careful combination of multisensory elements, educational narratives and investigative activities constitutes a robust pedagogical framework, which simultaneously optimizes attention, motivation, affective involvement and cognitive performance, respecting the principles of neuroeducation and promoting deep and sustainable learning (Baddeley, 2012; Immordino-Yang & Damasio, 2007; Sweller, 1988).

3.6. Practical recommendations for biology teachers

Implementing neuroeducation principles in the teaching of biology requires a deliberate, evidence-based instructional design that aligns cognitive mechanisms with pedagogically validated strategies. Central to this approach is the structuring of lessons into short, coherent instructional segments (chunking), which reduces cognitive load and supports the efficient transfer of information into long-term memory (Baddeley, 2012; Sweller, 1988). Instruction should integrate verbal explanations with visual representations, diagrams, animations, and manipulable three-dimensional models, following the cognitive theory of multimedia learning, which demonstrates that dual-channel processing enhances comprehension and retention (Mayer, 2009; Shams & Seitz, 2008). Alternating these modalities with reflective pauses and brief metacognitive prompts encourages students to monitor their own understanding and regulate their cognitive strategies.

A critical component of effective biology instruction involves the responsible use of analogies and conceptual models. Teachers must systematically guide students in identifying both the strengths and limitations of analogies, contrasting intuitive explanations with empirical evidence in order to prevent the formation of robust misconceptions—a recurrent challenge in biological education (Duit, 1991; Glynn, 1991). This process not only strengthens conceptual accuracy but also cultivates scientific reasoning. Laboratory investigations, mini-experiments, and other forms of hands-on inquiry play a pivotal role in developing students' executive functions and higher-order reasoning skills. Such activities give learners opportunities to formulate hypotheses, design experimental procedures, interpret data, and evaluate their cognitive strategies, thereby consolidating metacognition and critical thinking within authentic scientific contexts (Hmelo-Silver et al., 2007; Tokuhama-Espinosa, 2010).

Educational technologies, including virtual reality (VR) and augmented reality (AR), can further support conceptual understanding when integrated purposefully. Their pedagogical value lies not in passive immersion but in enabling students to visualize complex biological structures, manipulate variables safely, test predictions, and engage in guided inquiry. Effectiveness depends on structured teacher mediation, reflective tasks, and feedback mechanisms that ensure cognitive activation rather than superficial engagement (Radianti et al., 2020; Tokuhama-Espinosa, 2010). Continuous formative assessment—implemented through short quizzes, reflective writing tasks, peer feedback, and teacher observations—supports the monitoring of students' cognitive progress in real time, facilitates adaptive instructional decisions, and promotes the development of self-regulated learning (Black & Wiliam, 1998; Hmelo-Silver et al., 2007). Beyond instructional techniques, the successful application of neuroeducation depends on teachers' ongoing professional development, particularly in understanding neuroscientific evidence and identifying neuromyths that could distort educational practice. Training that strengthens teachers' scientific literacy and capacity for critical evaluation ensures that neuroeducation is applied rigorously and ethically in the classroom (Howard-Jones, 2014; Tokuhama-Espinosa, 2010).

3.7. Limits and precautions

Despite significant advances in neuroeducation, the application of neuroscientific findings in the school context must be done with methodological caution. Many experimental results from laboratory studies — often conducted in controlled environments, on small populations — do not automatically transfer to effective pedagogical practices in real classrooms, where cognitive, emotional, and socio-economic variability is considerably greater (Bruer, 1997; Rogers & Thomas, 2022).

In addition, the literature indicates the persistence of some extremely widespread neuromyths in education, such as the idea of hemispheric dominance (left/right), the myth of fixed learning styles, or the overvaluation of strictly visual or auditory-kinesthetic processes. These erroneous conceptions, although popular, contradict the scientific consensus and can lead to counterproductive didactic implementations (Dekker et al., 2012; Howard-Jones, 2014). Therefore, teachers must base their decisions on empirically validated data, not on simplified or overly extrapolated statements.

Another critical element is the complexity of translating neural mechanisms into applicable pedagogical recommendations. Processes such as synaptic plasticity, working memory, or attention are phenomena dependent on numerous biological, contextual, and psychological variables, and the literature warns that reducing them to rigid didactic "recipes" risks ignoring individual differences and learning group dynamics (Rogers & Thomas, 2022; Tokuhama-Espinosa, 2010). Therefore, educational interventions must be validated through classroom studies, using experimental or quasi-experimental designs, before being implemented on a large scale.

Also, socio-educational factors such as sleep quality, nutrition, stress level, emotional stability, family support and environmental security strongly influence the learning process and can modulate the effectiveness of any neuroeducational intervention (Immordino-Yang & Damasio, 2007; Taras & Potts-Datema, 2005). Ignoring these variables can lead to overestimation of the impact of teaching strategies, since academic performance is the result of the interaction between biology, psychology and the socio-cultural context.

Consequently, the implementation of neuroeducation principles must be an iterative process, based on piloting, continuous monitoring and progressive adaptation to the needs of students. A systematic evaluation of the effects, using valid instruments and clear criteria, is necessary to determine whether the intervention produces real, stable and replicable improvements. Only in this way can neuroeducation be avoided from becoming a set of pseudo-scientific practices and a rigorous, evidence-based pedagogical approach be ensured (Howard-Jones, 2014; Tokuhama-Espinosa, 2010).

4. The role of emotions and motivation in learning biology

Over the past two decades, the literature in cognitive neuroscience, educational psychology, and neuroeducation has converged on the idea that learning cannot be conceptualized as a purely cognitive process; on the contrary, it is inseparable from the emotional states and motivational dynamics of the subject (Immordino-Yang & Damasio, 2007; Pekrun, 2017). This perspective represents an epistemological break with traditional paradigms that considered emotions as disruptive factors of reasoning. Modern neurobiological research demonstrates that emotions constitute the functional background architecture of higher cognitive processes: they modulate attention, influence the depth of processing, reorganize neural networks involved in memory consolidation, and determine the energetic availability of the prefrontal cortex in complex learning tasks (Pessoa, 2008; Tyng et al., 2017).

Biology teaching highlights this interdependence in a privileged way, because the discipline requires not only a conceptual understanding of abstract processes such as DNA replication, homeostasis, photosynthesis, gene expression, and population dynamics, but also the ability to relate these processes to personal, social, emotional, and ethical realities. The invisible processes, the multiple levels of organization (molecular, cellular, tissue, organismic, ecosystemic), and the interdisciplinary nature of biology imply a high cognitive load, which makes emotions and motivation become fundamental resources for supporting attention and persistence in the task (Mayer, 2014; Sweller et al., 2011).

From a neurobiological point of view, emotions influence biology learning by activating the limbic system, especially the amygdala, which facilitates the selection of relevant stimuli and the signaling of their biological importance (Phelps, 2006). The interaction between the basolateral amygdala and the hippocampus, which has been extensively documented in recent years, plays a key role in consolidating episodic and semantic memory, leading to enhanced retention of information associated with emotional stimulation (McGaugh, 2018). This relationship explains why students more easily retain biological concepts presented through personal, clinical, or narrative examples, such as the story of a patient with a genetic disorder or the evolution of an ecosystem after a catastrophe. Moderate activation of the limbic system has been shown to enhance synaptic plasticity in cortical regions associated with conceptual learning (Shohamy & Adcock, 2010), which has major implications for teaching difficult biological concepts, especially counterintuitive ones.

In parallel, emotions directly influence the availability of cognitive resources by modulating attentional networks oriented towards key stimuli. The salience network, located in the anterior insula and anterior cingulate cortex, detects relevant changes in the learning environment and switches between the executive and implicit networks (Seeley et al., 2007). Thus, positive emotional states of interest, admiration, “epistemic curiosity” optimize attentional orientation and increase the student’s ability to follow complex biological explanations, such as metabolic fluxes or immunological mechanisms (Gruber & Ranganath, 2019; Kang et al., 2009).

Motivation, especially intrinsic motivation, contributes to biology learning by enhancing persistence, managing cognitive effort, and promoting the use of advanced metacognitive strategies. According to Self-Determination Theory, students are profoundly influenced by the extent to which learning activities satisfy psychological needs for autonomy, competence, and relatedness (Ryan & Deci, 2024). Biology has a unique potential to generate intrinsic motivation because it provides authentic and relevant contexts, from explaining the functions of one’s own body to understanding climate change or the pandemic. Students perceive biology as having a direct impact on their identity and lives, and this perception translates into increased cognitive engagement and a tendency for self-explanation and autonomous investigation (Hidi & Renninger, 2015; Vansteenkiste et al., 2006).

The role of negative emotions, although often presented in popular literature as purely destructive, is much more nuanced in current research. Moderate stress can increase alertness and focused attention, but high levels of anxiety, especially evaluative anxiety, reduce the functioning of the dorsolateral prefrontal cortex, directly affecting working memory and the ability to integrate information, skills essential in biological tasks that involve complex reasoning, such as solving genetic problems or analyzing experimental data (Owens et al., 2012). In the context of biology, certain topics can provoke emotional rejection, anxiety, shame, or cultural resistance: lessons on reproduction, anatomy, evolution, or communicable diseases can activate cognitive defense mechanisms that prevent deep information processing (Nadelson & Southerland, 2012). Sensitive management of these topics requires, according to pedagogical research, a safe socio-emotional climate and a non-evaluative didactic discourse that reduces perceived threat and facilitates conceptual exploration.

Curiosity, recently recognized as an affective-motivational component with a high impact on science learning, is a strong predictor of long-term memory and conceptual transfer (Gruber & Ranganath, 2019). In biology, natural paradoxes, uncertainties, and mysteries—the emergence of bacterial resistance, emerging animal behaviors, symbioses, genetic mutations, and microbiome interactions—trigger neural exploration mechanisms associated with activation of the hippocampus and mesocorticolimbic dopaminergic circuits (Kang et al., 2009). This neurobiological combination explains why problem-focused and inquiry-based instructional structures significantly increase student performance. Integrating emotions and motivation into biology instructional design is essential for maximizing learning. Scientific narrative, the use of realistic scenarios, ethical framing of content, and connecting concepts to personal experiences generate positive emotional states and increase the sense of relevance (Dahlstrom, 2014). In parallel, formative feedback oriented towards progress rather than performance stimulates intrinsic motivation and reduces evaluative anxiety (Hattie & Timperley, 2007). Also, emotional regulation strategies such as cognitive reappraisal, controlled breathing or error normalization contribute to maintaining a beneficial learning climate, especially in lessons with high emotional load (Gross, 2015). In conclusion, emotions and motivation are not peripheral factors in learning biology, but constitute the functional foundation of cognitive processes that allow the development of scientific understanding. Teaching biology requires an integrated, neuroscientifically informed approach, in which the curriculum design, didactic strategies and classroom atmosphere are calibrated to activate positive emotions, to stimulate intrinsic motivation and to diminish affective barriers. Such an approach not only optimizes current performance, but also contributes to the formation of a sustainable, positive and reflective relationship of students with life science.

5. Discussions and challenges

Despite the considerable progress of neuroeducation and the growing enthusiasm for integrating neuroscientific knowledge into pedagogical practice, the application of these discoveries in the school environment remains marked by multiple epistemological, methodological and institutional difficulties. Although numerous studies suggest that a thorough understanding of neurocognitive mechanisms can contribute to the optimization of didactic strategies, their direct transposition into didactic activity is far from being a linear or unambiguous process. The limitations result both from the complexity of neuronal organization and from the conceptual distance between the levels of analysis specific to neuroscience and those specific to pedagogy.

The first major challenge concerns the fundamental difference between the neurobiological and educational levels. Neuroscience operates with microscopic measurements, at the level of synapses, neurotransmitters or neural networks, while education deals with macrosocial phenomena, such as the development of skills, motivation, classroom interactions and instructional processes. However, this structural difference makes it difficult to directly infer pedagogical recommendations based exclusively on neuroscientific data. The epistemological equivalent of this problem is the "level error" the tendency to extrapolate mechanisms identified at the neuronal level to complex behaviors, without an intermediate stage of psychological and educational validation. Therefore, the scientific community warns that neuroeducation should not be viewed as a set of immediately applicable solutions, but as a source of general principles that require translation and adjustment at the pedagogical level. In the absence of this mediation process, there is a risk of generating reductive or even erroneous interpretations of brain functioning.

This difficulty directly contributes to the emergence of neuromyths – overly simplified, scientifically unvalidated or even counterfactual conceptions that frequently circulate in the educational environment. These include the idea that students learn predominantly through the left or right hemisphere, the theory that individuals have rigid learning styles ("visual," "auditory," "kinesthetic"), or the belief that exposure to classical music automatically stimulates cognitive development. These concepts, although popular, have been repeatedly refuted by the specialized literature, which shows that brain functioning is deeply integrated and dynamic, and sensory preferences do not, in themselves, determine academic performance. The persistence of these neuromyths is supported by three main factors: teachers' limited access to reliable scientific sources, the difficulty of interpreting the results of neurobiological studies, and the attractive rhetoric of these ideas, which promise quick solutions to complex problems. As a result, without the critical filter of continuing professional development, teachers may adopt unvalidated practices that are not only ineffective, but can also consume time and resources to the detriment of empirically based pedagogical strategies.

These challenges highlight the urgent need for teacher training in neurodidactics. For teachers to be able to use neuroscience information responsibly and effectively, it is essential that they acquire a minimal neuroeducational literacy that allows them to distinguish between solid results and speculative interpretations. Initial training in pedagogical institutions rarely includes courses in applied cognitive neuroscience, and in-service training programs are often fragmentary or theoretical. In the absence of formal education, teachers remain vulnerable to pseudoscientific discourses, which highlights the need for an institutional infrastructure capable of offering rigorous, interdisciplinary programs focused on the synthesis of neuroscience, psychology, and pedagogy. In addition, training must integrate practical aspects, such as critical interpretation of data, design of didactic interventions, and evaluation of their impact on learning.

In parallel, current discussions in neuroeducation focus on future research directions, which must address the methodological limitations of the field. A major challenge is the difficulty of constructing longitudinal empirical studies that track the effects of brain-based instructional strategies in real-world learning contexts. Much neuroscience research is conducted in laboratory settings, using small samples or simplified tasks, which raises issues of external validity. For neuroeducation to become a robust field, closer alignment between laboratory research and situated educational research is needed, using hybrid methodologies such as design-based research, naturalistic neuroimaging, or field studies integrated with physiological measurements. It is also necessary to develop standardized instruments for evaluating neuroeducational interventions, so that the impact on school performance, student motivation, and executive functioning can be accurately determined.

Last but not least, ethical challenges are an emerging area of discussion. The use of neural monitoring technologies or biometric data in educational contexts raises sensitive questions regarding privacy, informed consent and the risk of pathologizing natural cognitive differences. Any application of neuroeducation principles must respect a rigorous ethical framework, aimed at protecting students, avoiding premature labeling and promoting an inclusive vision of cognitive diversity. Overall, the discussions and challenges that accompany the application of neuroeducation in schools should not be interpreted as insurmountable obstacles, but as opportunities for conceptual and methodological refinement. Neuroeducation does not promise miraculous solutions, but offers a theoretical framework capable of enriching traditional pedagogy by understanding the neurocognitive mechanisms that support learning. To fully benefit from its potential, genuine interdisciplinary collaboration, rigorous professional training of teachers and a critical, evidence-based approach to the proposed strategies are necessary. Only under these conditions can neuroeducation evolve from an emerging field to a mature one, capable of substantially contributing to the transformation of contemporary education.

6. Conclusions

The conclusions of this paper reveal that neuroeducation represents a solid and increasingly influential conceptual framework for optimizing the teaching and learning processes of biology, a discipline that, by its very nature, requires a constant articulation between different levels of abstraction: molecular, cellular, organismic and ecosystemic. To the extent that it describes the neurocognitive mechanisms underlying perception, attention, memory and motivation, neuroeducation offers a scientific foundation that can guide teachers in designing learning experiences adapted to the functioning of the human brain. This perspective does not promise simplified solutions, but rather requires a complex approach, based on a critical understanding of experimental data and their responsible transposition into pedagogical practice. The integration of neuroeducation principles in biology teaching indicates that learning processes are essentially multisystemic: they depend simultaneously on attentional structures, working memory, long-term consolidation mechanisms and emotional networks that modulate student engagement. From this perspective, the scientific understanding of synaptic plasticity, reconsolidation processes or the role of emotional charge in the formation of memories becomes a fundamental tool for building effective teaching sequences. In addition, current research shows that learning is optimally achieved when the student is placed in situations of active exploration, problem solving or conceptual modeling, practices that support the development of executive functions and favor the transfer of knowledge to new contexts. On the other hand, the conclusions also highlight the essential need for epistemological prudence. The field of neuroeducation is crossed by numerous conceptual vulnerabilities, in particular the tendency to over-simplify neuronal phenomena or to uncritically extrapolate laboratory data to classroom activities. The persistence of neuromyths demonstrates that, in the absence of solid training, teachers can adopt practices that superficially claim to be from neuroscience, without having a real empirical basis. Thus, the fundamental responsibility of researchers, trainers and educational institutions is to build solid bridges between neuroscientific discoveries and pedagogy, through rigorous, accessible and constantly updated training programs.

The results of the analyzed studies suggest that biology teachers can particularly benefit from understanding the principles of neuroeducation, because this discipline requires a complex operationalization of theoretical concepts, explanatory models and visual tools. In the context of biology, students' difficulties often stem from excessive abstraction, the complexity of invisible processes or high cognitive load. Precisely for this reason, knowledge of the limits of working memory, how multisensory coding is achieved or the role of sustained attention becomes essential to design lessons that facilitate the construction of stable mental models.

Reflecting on future directions, the paper highlights the need for interdisciplinary research that links neuroimaging, cognitive psychology, and pedagogy to systematically assess the impact of instructional interventions on real-world learning in the classroom. Longitudinal studies, experimental designs adapted to authentic teaching situations, and standardized instruments capable of measuring changes in performance, motivation, and executive function are needed. Only by strengthening the empirical base can neuroeducation evolve from a promising field to a scientifically established one. Overall, the conclusions of this paper emphasize that neuroeducation should not be viewed as a panacea or a speculative field, but as a space for dialogue between neuroscience and education. Its power derives not from magic formulas, but from its ability to provide teachers with a deeper understanding of how the brain learns, so that the instructional process becomes more efficient, more flexible, and more adapted to the cognitive diversity of students. Biology teaching, by its complex nature, is among the areas that can benefit most from this integrative perspective.

Authors note:

Isac Maria Crina is currently a final-year student in the Master's program in Didactic Biology at the Faculty of Psychology and Educational Sciences, Alexandru Ioan Cuza University of Iași, Romania. She is also enrolled in the Master's program in Medical Laboratory Science at the Faculty of Biology. Her academic and research interests include science education, neuroeducation, cognitive processes in learning, and the integration of biological and pedagogical perspectives in instructional design.

References

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual review of psychology, 63*(1), 1-29.

Barutchu, A., Fifer, J. M., Shivdasani, M. N., Crewther, S. G., & Paolini, A. G. (2020). The interplay between multisensory associative learning and IQ in children. *Child development, 91*(2), 620-637.

Black, P., & Wiliam, D. (1998). Assessment and classroom learning. *Assessment in Education: principles, policy & practice, 5*(1), 7-74.

Bruer, J. T. (1997). Education and the brain: A bridge too far. *Educational researcher, 26*(8), 4-16.

Bruner, J. (1991). The narrative construction of reality. *Critical inquiry, 18*(1), 1-21.

Caine, R. N., & Caine, G. (1991). *Making connections: Teaching and the human brain*.

Dahlstrom, M. F. (2014). Using narratives and storytelling to communicate science with nonexpert audiences. *Proceedings of the national academy of sciences, 111(supplement_4)*, 13614-13620.

Dekker, S., Lee, N. C., Howard-Jones, P., & Jolles, J. (2012). Neuromyths in education: Prevalence and predictors of misconceptions among teachers. *Frontiers in psychology, 3*, 33784.

Dekker, S., Lee, N. C., Howard-Jones, P., & Jolles, J. (2012). Neuromyths in education: Prevalence and predictors of misconceptions among teachers. *Frontiers in psychology, 3*, 33784.

Duit, R. (1991). On the role of analogies and metaphors in learning science. *Science education, 75*(6), 649-672.

Follmer, D. J., & Sperling, R. A. (2016). The mediating role of metacognition in the relationship between executive function and self-regulated learning. British *Journal of Educational Psychology, 86*(4), 559-575.

Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. *Review of educational research, 82*(3), 300-329.

Glynn, S. M. (2012). Explaining science concepts: A teaching-with-analogies model. *In The psychology of learning science* (pp. 219-240). Routledge.

Gobert, J. D., & Buckley, B. C. (2000). Introduction to model-based teaching and learning in science education. *International Journal of Science Education, 22*(9), 891-894.

Green, M. C. (2006). Narratives and the mind. In B. H. Ross (Ed.), *The psychology of learning and motivation* (Vol. 46, pp. 167–192). Academic Press.

Gross, J. J. (2015). Emotion regulation: Current status and future prospects. *Psychological inquiry, 26*(1), 1-26.

Gruber, M. J., & Ranganath, C. (2019). How curiosity enhances hippocampus-dependent memory: The prediction, appraisal, curiosity, and exploration (PACE) framework. *Trends in Cognitive Sciences, 23*(12), 1014–1025.

Hattie, J., & Timperley, H. (2007). The power of feedback. *Review of educational research, 77*(1), 81-112.

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: a response to Kirschner, Sweller, and. *Educational psychologist, 42*(2), 99-107.

Howard-Jones, P. A. (2014). Neuroscience and education: myths and messages. *Nature reviews neuroscience, 15*(12), 817-824.

Immordino-Yang, M. H. (2015). *Emotions, learning, and the brain: Exploring the educational implications of affective neuroscience* (the Norton series on the social neuroscience of education). WW Norton & Company.

Immordino-Yang, M. H., & Damasio, A. (2008). *We Feel, Therefore we Learn*' (pp. 183-198). The Jossey-Bass reader on the brain and learning.

Jolles, J., & Jolles, D. D. (2021). On neuroeducation: Why and how to improve neuroscientific literacy in educational professionals. *Frontiers in psychology, 12*, 752151.

Justi, R., & Gilbert, J. K. (2016). *Modelling-based teaching in science education*.

Kang, M. J., Hsu, M., Krajbich, I. M., Loewenstein, G., McClure, S. M., Wang, J. T. Y., & Camerer, C. F. (2009). The wick in the candle of learning: Epistemic curiosity activates reward circuitry and enhances memory. *Psychological science, 20*(8), 963-973.

Lazonder, A. W., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. *Review of educational research, 86*(3), 681-718.

Mayer, R. E. (2014). Incorporating motivation into multimedia learning. *Learning and instruction, 29*, 171-173.

McGaugh, J. L. (2018). Emotional arousal regulation of memory consolidation. *Current opinion in behavioral sciences, 19*, 55-60.

Nadelson, L. S., & Southerland, S. (2012). A more fine-grained measure of students' acceptance of evolution: development of the Inventory of Student Evolution Acceptance—I-SEA. *International Journal of Science Education, 34*(11), 1637-1666.

Neacşu, I. (2019). *Neurodidactica învăţării şi psihologia cognitivă: ipoteze, conexiuni, mecanisme* [Neurodidactics of learning and cognitive psychology: hypotheses, connections, mechanisms]. Polirom.

Owens, M., Stevenson, J., Hadwin, J. A., & Norgate, R. (2012). Anxiety and depression in academic performance: An exploration of the mediating factors of worry and working memory. *School psychology international, 33*(4), 433-449.

Pekrun, R. (2017). Emotion and achievement during adolescence. *Child Development Perspectives, 11*(3), 215-221.

Pessoa, L. (2008). On the relationship between emotion and cognition. *Nature reviews neuroscience, 9*(2), 148-158.

Phelps, E. A. (2006). Emotion and cognition: insights from studies of the human amygdala. *Annu. Rev. Psychol., 57*(1), 27-53.

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & education, 147*, 103778.

Renninger, K. A., & Hidi, S. (2015). *The power of interest for motivation and engagement*. Routledge.

Rogers, C., & Thomas, M. S. (2022). *Educational neuroscience: The basics*. Routledge.

Ryan, R. M., & Deci, E. L. (2024). Self-determination theory. In *Encyclopedia of quality of life and well-being research* (pp. 6229-6235). Cham: Springer International Publishing.

Seeley, W. W., Menon, V., Schatzberg, A. F., Keller, J., Glover, G. H., Kenna, H., ... & Greicius, M. D. (2007). Dissociable intrinsic connectivity networks for salience processing and executive control. *Journal of neuroscience, 27*(9), 2349-2356.

Shams, L., & Seitz, A. R. (2008). Benefits of multisensory learning. *Trends in cognitive sciences, 12*(11), 411-417.

Shohamy, D., & Adcock, R. A. (2010). Dopamine and adaptive memory. *Trends in cognitive sciences, 14*(10), 464-472.

Sousa, D. A. (2016). How the brain learns (5th ed.). Corwin. ISBN: 9781506346328.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive science, 12*(2), 257-285.

Sweller, J. (1988). load during problem solving: 职 On/earn/ng. *Cognitive Science*, *12*(2).

Sweller, J., Ayres, P., & Kalyuga, S. (2011). Altering element interactivity and intrinsic cognitive load. In *Cognitive load theory* (pp. 203-218). New York, NY: Springer New York.

Taras, H., & Potts-Datema, W. (2005). Sleep and student performance at school. *Journal of School Health, 75*(7), 248–261.

Tokuhama-Espinosa, T. (2010). *Mind, brain, and education science: A comprehensive guide to the new brain-based teaching*. WW Norton & Company.

Tokuhama-Espinosa, T., & Nouri, A. (2020). Evaluating what mind, brain, and education has taught us about teaching and learning. *Contemporary Issues in Education, 40*(1), 63-71.

Tyng, C. M., Amin, H. U., Saad, M. N., & Malik, A. S. (2017). The influences of emotion on learning and memory. *Frontiers in psychology, 8*, 235933.

Vansteenkiste, M., Lens, W., & Deci, E. L. (2006). Intrinsic versus extrinsic goal contents in self-determination theory: Another look at the quality of academic motivation. *Educational psychologist, 41*(1), 19-31.

Zull, J. E. (2023). *The art of changing the brain: Enriching the practice of teaching by exploring the biology of learning*. Routledge.