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Neuroscientific Discoveries and Their Implications for Early Childhood Language Education

Mukhabbat Khakimova, Shaturaev Jakhongir *, Nilyufar Fayzullayeva, Shavkat Mamarajabov, Gulnoza Ochilova, Gulnora Musakhanova, Roman Pantin, Sayyora Akbarova, Mekhribonu Kayumova, Iroda Khojiyeva

Department of Economic Theory, Tashkent State University of Economics, Tashkent 100066, Uzbekistan

ABSTRACT

Recent advancements in neuroscience have provided valuable insights into how the brain functions, offering significant potential for enhancing educational practices. Despite this, current neuroscientific findings on how the brain learns - particularly in early childhood language acquisition - are not fully utilized in educational settings. This article investigates the foundational principles of educational neuroscience as an interdisciplinary field, situated at the intersection of neurobiology, pedagogy, and cognitive science. It emphasizes the integration of neuroscientific research into educational practices, specifically focusing on language development during early childhood and assessing the reciprocal influence of education on brain function. The paper traces the origins and progress of neuroscience in education while addressing the terminological ambiguity in modern scientific literature concerning the relationship between neuroscience and education. It also highlights promising pathways for collaboration among psychology, pedagogy, and neuroscience, with special attention to early language learning. A scientometric analysis of key research trends in the neuroscience-education nexus, based on the Scopus scientific literature database, is presented. This study seeks to enhance the dialogue between neuroscientific discoveries and educational applications, advocating for a more integrated approach to improve learning outcomes. It underscores the necessity of interdisciplinary collaboration to bridge the gap between theoretical insights from neuroscience and the practical needs of educational environments, particularly in fostering early childhood language development.

Keywords: Educational Neuroscience; Early Childhood Language Acquisition; Language Development; Pedagogy;

*CORRESPONDING AUTHOR:

Shaturaev Jakhongir, Department of Economic Theory, Tashkent State University of Economics, Tashkent 100066, Uzbekistan; Email: jakhongirshaturaev@tsue.uz

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Psychology; Neuroimaging; Cognitive Neuroscience

1. Introduction

Neuroscience in education represents an interdisciplinary field at the intersection of neurobiology, pedagogy, and cognitive science. It primarily aims to integrate insights into the neural mechanisms of learning into educational practice, emphasizing how these mechanisms shape cognitive and linguistic development, particularly during early childhood. The neural basis of language learning has emerged as a critical focus, with research highlighting the brain's sensitivity to language input during formative years. This understanding underscores the importance of creating evidence-based educational strategies that align with the brain's developmental processes and promote optimal learning outcomes [1].

Early childhood is a critical period for language acquisition and development, driven by the brain's extraordinary plasticity. Neuroscientific research has identified neural pathways and regions, such as Broca's and Wernicke's areas, that play central roles in processing and producing language [2]. Studies reveal that enriched environments, interactive communication, and multimodal linguistic stimuli during this period can significantly influence structural and functional brain development, laying the foundation for lifelong learning and communication [3]. These findings underscore the potential of neuroscience to transform educational practices, particularly in early language learning contexts.

Neuroscience in education also investigates how education influences brain function and the neurobiological mechanisms underlying behavior transformation through learning. While some question the feasibility of applying neuroscience findings in teaching [4], the growing body of research suggests that these insights can refine pedagogical methods and interventions. For instance, understanding the neural basis of literacy acquisition and multilingualism has practical implications for developing targeted teaching strategies to address individual differences in language learning [5].

A useful analogy for this evolving field is the historical development of medicine. Two centuries ago, medicine relied on fragmented empirical knowledge and lacked a scientific foundation. The application of the scientific method transformed medicine into a rigorous applied science, enabling breakthroughs that significantly improved human health. Similarly, education can benefit from neuroscience by incorporating experimentally validated data to enhance teaching and learning. Just as biology underpins medical science, neuroscience provides the foundation for understanding how education influences the brain, enabling educators to make informed decisions grounded in evidence. This article provides a comprehensive review of the interdisciplinary dialogue between neuroscience, psychology, and pedagogy. It aims to highlight the contributions of neuroscience to education, particularly in the context of early childhood language acquisition, and to explore challenges and opportunities in applying these findings to educational practice.

The article is organized as follows: the first section addresses terminological ambiguities in language research on neuroscience in education. The second section traces the historical development of neuroscientific studies in education, with a particular emphasis on language learning. The third section explores the intersection of neuroscience, psychology, and pedagogy, while the fourth section discusses challenges in implementing neuroscientific findings in practical teaching. The fifth section identifies key neuroscientific research directions relevant to educational practice, including early childhood language development. The sixth section provides an overview of significant studies from 2000–2022. Finally, the conclusion summarizes the analysis and presents recommendations for advancing neuroscience-informed educational research.

1.1. Terminological Ambiguity

In the academic context, research on the intersection of neuroscience and education faces significant terminological uncertainty. This ambiguity is not unusual for a nascent field and reflects ongoing efforts to conceptualize its scope and focus. Broadly, three approaches to defining this area of study can be identified: "translational," populist, and substantive. Internationally, terms such as *educational neuroscience* and *neuroscience in education* describe the application of cognitive neuroscience to education. In literature, equivalents such as "neurosciences in education," "educational neuroscience," and "neuroeducation" are used, though without consensus on a clear definition. These terms generally align with the study of the neurobiological mechanisms underlying learning processes [6].

A "translational" approach to defining the field emphasizes bridging basic neuroscience research with its practical applications, though this view may narrow the discipline's potential by privileging neurobiological perspectives over pedagogical and psychological insights. The "populist" approach highlights the proliferation of the prefix "neuro" in educational discourse. Terms such as *neuropsychology*, *neurodidactics*, and *neuroeducation* have gained popularity, often without substantive advancements in content. This trend, driven by commercial interests or the desire to appear more "scientific," risks diluting the field's credibility.

The "substantive" approach, however, is gaining traction as researchers refine terminology and clarify distinctions between overlapping fields. Efforts are underway to differentiate neurodidactics from neuropsychology, explore the connections between neuropsychology and neuroeducation, and delineate the neurodidactic approach [7]. Similarly, researchers are examining the basis for classifying educational technologies as "neurotechnologies" [8]. These developments suggest that the field is evolving toward a more rigorous and well-defined framework.

1.2. Historical Development of Neuroscientific Research in Education

The integration of neuroscience into education has a historical foundation, with early contributions by figures such as E.L. Thorndike, who emphasized the relevance of understanding the neurobiological foundations of learning in the early 20th century [9]. However, it was not until the 21st century that technological advancements, particularly in neuroimaging, enabled significant progress. Portable and relatively inexpensive devices using electroencephalography (EEG) [10] and functional near-infrared spectroscopy (fNIRS) [11] have allowed researchers to study the brain in real-world cognitive tasks [12]. Neuroimaging now encompasses a suite of methods for visualizing brain structure, function, and biochemical processes [13].

Neuroscience has increasingly been applied to address educational challenges, including those arising from the shift to distance learning [14]. International initiatives have supported this integration. For example, the International Mind, Brain, and Education Society (IMBES) was established in 2004, followed by the European Association for Research on Learning and Instruction's (EARLI) thematic group on "Neuroscience and Education" in 2009. Specialized journals such as *Trends in Neuroscience and Education*, launched in 2012, and *Mind, Brain, and Education*, published since 2007, have further legitimized the field. These publications rank highly in both educational and cognitive neuroscience categories, signaling their influence. Related articles also appear in leading journals such as *Cognitive Development*, *Brain and Cognition*, and *Developmental Cognitive Neuroscience*.Master's programs in neuroeducation and neuropsychology are flourishing globally, including at renowned institutions such as Harvard University, Teachers College at Columbia University, and the University of Edinburgh. Universities in developing countries, such as the International University of La Rioja (Mexico) and the University Center of Assunção (Brazil), are also offering advanced training in this field. Institutions including the Immanuel Kant Baltic Federal University and the Ural Federal University are leading efforts to incorporate neuroscience into pedagogical education, including specialized master's courses at the Higher School of Economics.

Despite these advances, the integration of neuroscience with education remains contentious. In 1997, Prof. John Bruer famously critiqued the feasibility of bridging neuroscience and education in his work "*Education and the Brain: A Bridge Too Far"* [15]. Twenty-five years later, Prof. Gerry Leisman echoed this sentiment, noting that while progress has been made, the "bridge" is far from complete [16]. A key challenge lies in the methodological disconnect between neuroscience and educational practice. Neuroscience research often relies on controlled paradigms that exclude variables prevalent in real-world educational settings, limiting its direct applicability [17]. Furthermore, there is a risk of creating educational technologies based on misinterpreted or inaccurate neurophysiological data [18]. The prevalence of "neuromyths", misconceptions about brain function, can lead to misguided applications of neuroscience in education. This issue is compounded by commercial interests eager to market unverified "neuro" products to schools and universities [19].

The interaction between neuroscience, psychology, and pedagogy is often marked by competition rather than collaboration. This tension fuels skepticism among educators, who perceive neuroscience as offering more theoretical promise than actionable insights. Critics argue that the field currently emphasizes programmatic aspirations over experimental evidence that can inform practical teaching strategies. Psychology and education have historically enjoyed a productive interplay, with some scholars asserting that psychological research alone provides a sufficient foundation for developing scientific pedagogical frameworks [20]. However, relying exclusively on psychology may not adequately address the complexities of modern educational theories. Through teaching and upbringing, pedagogy directly influences behaviors of learners. Psychological theories, which explain and predict behavior, are rooted in experimentally identified mechanisms of cause-and-effect relationships. Since the pioneering work of Vygotsky, educational psychology has analyzed the development of higher mental functions such as imagination, memory, thinking, and attention [21]. While psychology focuses on behavior, neuroscience investigates the underlying brain mechanisms, offering deeper insights into how learners process and retain information [22]. Advancements in neuroscience have opened new avenues for enriching pedagogy with data derived from direct research on brain mechanisms. Psychological theories that disregard the biophysical or biochemical nature of learning processes risk inaccuracies by positing mechanisms that may be biologically implausible [23].Educational practice often raises questions that psychology alone cannot fully answer. For instance:

- Why is factual information, such as the capital of Guatemala, easily forgotten, while phobias remain deeply ingrained?
- Why does sleep enhance the retention of new material?
- Why is language acquisition more efficient at ten years old than at fifty?

To answer these questions, integrating neuroscience research with psychological and pedagogical theories is imperative. Contemporary psychological theories of learning often fail to accommodate findings from neuroscience.

a. Complexity of skill transfer: The transfer of skills is far more complex than suggested by traditional cognitive theories. Contrary to the assumption of universal cognitive mechanisms (e.g., working memory or cognitive control), neuroscience reveals that skill transfer is highly specific. Training in one task may enhance performance in similar tasks but rarely results in general improvements across unrelated domains [24]. For instance, a child with memory impairments may struggle with tasks involving sequential recall, such as instructions or number sequences. While teachers can adapt learning environments to support these difficulties, neuroscience underscores the limited generalizability of working memory training.

b. Age-Related Learning Variability: Behavioral responses and learning capacities change with age, a phenomenon not fully explained by psychological theories. Neuroscience provides insights into why these changes occur, such as age-related differences in brain plasticity and memory consolidation.

c. Impact of Daily Routines and Physical Activity: Factors such as sleep, physical activity, and class schedules significantly affect learning effectiveness. For example, restricting adolescents' sleep to six hours markedly impairs cognitive functions such as attention and memory. Such findings highlight the need to integrate neuroscience into educational planning and policy.

d. Functional Brain Networks: The concept of functional brain networks has transformed cognitive science and has direct implications for pedagogy [25]. Functional networks describe dynamic connections between brain regions that enable cognitive functions. Unlike traditional models associating specific brain regions with specific cognitive processes, neuroscience reveals "many-to-one" and "one-to-many" relationships. For example, attention—a critical cognitive process—does not stem from a single brain region but emerges from interactions among multiple overlapping mechanisms, including orientation to action, information processing, and sustained task maintenance [26].

This nuanced understanding challenges educators to reconsider how attention is taught and assessed. Misconceptions, such as treating attention as a singular process, may lead to unrealistic expectations about student behavior and uneven learning outcomes. **Figure 1** illustrates three potential modes of interaction between neuroscience, psychology, and education:

a. Direct Influence (Upper Arrow): Neuroscience directly informs educational practices by elucidating basic brain functioning patterns during learning.

b. Two-Step Influence (Lower Arrow): Neuroscience reshapes psychological theories, which, in turn, guide pedagogical paradigms and methodologies. This pathway ensures that neuroscience data not only "validate" existing psychological theories but also transform them, thereby driving innovation in education.

c. Interactive Integration (Middle Arrow): Neurotechnology, such as brain-computer interfaces, facilitates individualized educational trajectories. This approach represents the most advanced and synergistic interaction, rapidly incorporating neuroscientific insights into teaching and learning.

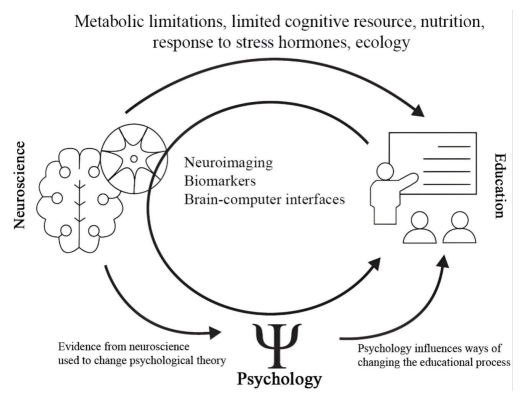

Figure 1. Interaction of neuroscience, psychology and education.

For meaningful progress, the integration of neuroscience and education must move beyond demonstrating how the brain implements cognitive theories. Instead, neuroscience should inform and refine psychological theories, which can then translate into practical pedagogical strategies. This iterative approach ensures that education remains both scientifically grounded and responsive to the needs of learners [27].

The brain, as a highly complex "electrochemical machine," operates within certain metabolic constraints. Factors such as nutrition, stress hormone levels, and environmental pollution significantly influence brain function, including learning, through neuroglial interactions. These factors underscore the importance of considering non-psychological influences on learning outcomes, including rest and sleep patterns, and physical activity such as sports training [28]. Such insights contribute to the emerging field of educational neuroscience, which aims to optimize learning by adjusting educational conditions based on brain function patterns (upper arrow in **Figure 1**) [29]. Traditional models of interaction between neuroscience and education often depict education as passive, where psychology and neuroscience shape pedagogical processes without reciprocal influence. However, advancements in neurotechnologies now enable educational systems to incorporate various feedback mechanisms, including those utilizing neurointerfaces [30].

A neurointerface is a sophisticated hardware-software system that facilitates functional connectivity between the brain and a computer. This direct connection between computational intelligent control systems and the nervous system allows for real-time interaction and adjustment of educational processes [31]. Such technologies are no longer theoretical but are actively being developed to enhance educational practices.

2. Methodological Rationale and Empirical Support

The integration of neuroscience into educational practice represents a dynamic and rapidly evolving area of research. However, the methodologies used to investigate this intersection must be rigorously justified to ensure the validity and applicability of the findings to real-world educational settings. The current manuscript explores the neural underpinnings of early childhood language acquisition, utilizing a variety of neurobiological models and frameworks. However, it is crucial to provide a clearer explanation of the methodological choices underpinning this exploration to enhance transparency and foster critical engagement with the research.

Neuroimaging techniques, such as EEG and fNIRS, offer valuable insights into brain activity during language acquisition processes. However, while these techniques have demonstrated efficacy in controlled experimental settings, their application in real-world educational environments warrants further scrutiny. Studies in laboratory contexts often simplify the complexity of cognitive and educational processes by isolating variables, a methodological limitation that challenges the generalizability of findings to the classroom [32]. For example, research involving EEG typically occurs in environments where participants are stationary, and stimuli are controlled, which contrasts with the dynamic, interactive learning environments found in schools [33]. As such, the paper must engage more thoroughly with these limitations by exploring the challenges of translating laboratory-based findings into applicable educational strategies. Furthermore, considering alternative methodologies such as observational research or action research, which are more ecologically valid in classroom settings, could strengthen the manuscript's methodological approach and provide a more comprehensive perspective on the real-world applicability of neuroscience in education.

A critical concern raised by the reviewers is the reliance on older, generalized studies that may no longer reflect the current state of the field. While seminal research on the roles of Broca's and Wernicke's areas in language processing remains fundamental, advances in neuroplasticity and the integration of multimodal linguistic stimuli provide an opportunity to update the theoretical framework. Recent findings suggest that language learning during early childhood is not solely dependent on specific cortical regions but is influenced by a network of interacting brain areas and modalities [34]. For example, the impact of environmental enrichment and interactive, multimodal language input on neural development has been highlighted in more recent studies [35]. Incorporating such contemporary research would present a more nuanced understanding of early language acquisition and better align the manuscript with the latest developments in the field.

In addressing the theoretical promise of emerging neurotechnologies, such as brain-computer interfaces for personalized learning, the paper currently emphasizes speculative applications that lack substantial empirical support. While the potential of these innovations is notable, they remain at the experimental stage, and their practical feasibility in educational contexts has not been adequately tested [36]. Given the nascent nature of these technologies, a more balanced discussion is needed that critically evaluates both their promise and their limitations. For example, challenges related to the accessibility, reliability, and ethical considerations of real-time neuroimaging technologies in educational settings must be discussed to provide a more grounded and realistic perspective. A review of the existing experimental work on neurotechnologies in education (e.g., studies on the use of EEG for cognitive state monitoring in students) would offer a more robust empirical foundation for the claims made regarding the future of personalized learning.

Additionally, while the manuscript presents a broad exploration of various neurobiological frameworks, the structure and flow of the paper could benefit from greater clarity and coherence. In some instances, sections of the manuscript reiterate similar points, leading to redundancy, while others provide important insights without sufficient depth. Streamlining the paper by condensing overlapping sections and ensuring that each part contributes distinctly to the overarching narrative would enhance the manuscript's readability and scholarly impact. Specifically, focusing on the most salient aspects of the research - particularly the ways in which neuroscience can inform pedagogical approaches to early childhood language acquisition - would create a more cohesive and focused discussion.

To address these issues, the manuscript must engage more explicitly with the methodological choices that inform the research, particularly in relation to the limitations of existing neuroimaging techniques and the challenges of applying laboratory findings to educational practice. Incorporating more recent, relevant studies will ensure that the manuscript reflects the most up-to-date research in the field of educational neuroscience. Furthermore, the paper would benefit from a more balanced treatment of speculative technologies, emphasizing their theoretical potential while acknowledging the practical challenges that remain to be addressed. Finally, streamlining the paper's structure and ensuring that each section provides a meaningful contribution to the discussion will enhance the clarity and impact of the manuscript.

2.1. Implementing Neurotechnology for Personalized Learning

To explore the potential of neurotechnology in education, we developed an intelligent system for monitoring and adjusting the learning process of elementary school students using a brain-computer interface. This system consists of three main components (**Figure 2**) [37]:

a. Portable Electroencephalograph: A device that records electrical brain activity signals from the surface of a student's head during cognitive tasks. This element is critical for obtaining real-time information about brain activity.

b. Electronic Educational Environment (EEE): An interactive, gamified interface designed for use on a tablet. The EEE facilitates student interaction with the intelligent system by offering tasks, presenting educational material, and providing supplementary information.

c. Control Computer: A laptop equipped with software for processing EEG data and managing the learning process. The software includes a management system module that analyzes incoming data, monitors learning efficiency, and develops corrective strategies.

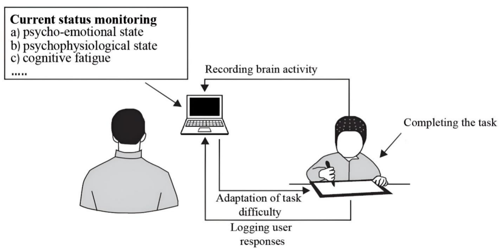

Figure 2. General diagram of a system for monitoring and adjusting the learning process of junior schoolchildren based on the brain-computer neural interface.

This system represents a significant step toward the practical application of neuroscience in education. By integrating neurophysiological and psychological data, it becomes possible to personalize learning experiences, adapt educational materials to individual needs, and optimize cognitive outcomes. Neurotechnologies and AI-driven solutions provide a foundation for innovative educational practices, enabling a reciprocal relationship between neuroscience and pedagogy.

The control system, depicted in **Figure 2**, operates through three primary information streams:

a. EEG Data Transmission: EEG data are wirelessly transmitted to the control computer. These signals are processed through the EEG data-reading software module and subsequently analyzed in the system management software module. This analysis identifies key EEG biomarkers such as attention concentration, stress levels, and task completion success.

b. Student Test Results: Test results generated on the student's tablet, which hosts the EEE, are wirelessly sent to the control computer. These results include data on the correctness and speed of task solutions, reaction times, error counts, and other behavioral metrics.

c. Feedback Loop for Task Adjustment: A feedback loop is established as control commands are transmitted wirelessly from the system management software module to the tablet. These commands dynamically adjust task parameters - difficulty, types, rest intervals, and other settings—based on the analysis of EEG biomarkers and behavioral data.

This system exemplifies the integration of neurointerfaces into education, enabling real-time monitoring of brain activity alongside psychological and behavioral assessments. The managed feedback loop supports the individualization of the educational process, as shown in **Figure 1**.

The neural basis of language learning holds a pivotal role in shaping effective educational practices. By understanding the mechanisms underlying language acquisition and cognitive development, educators can design interventions that align with how the brain processes and internalizes information. Recent advances in neuroscience emphasize the need for an evidence-based approach to integrate these findings into teaching methodologies. Neuroscience has significantly contributed to understanding language acquisition in early childhood. This period is marked by heightened neuroplasticity, enabling rapid development of linguistic abilities. Insights into neural processes such as the role of the prefrontal cortex, mirror neurons, and auditory pathways in language comprehension and production underscore the importance of early, targeted educational strategies.

2.2. Challenges in Neuroscience and Education Integration

The application of neuroscience in education faces several challenges. On the one hand, the learning process is highly complex from a neurobiological perspective, with many mechanisms still to be understood. On the other hand, the scope of education encompasses not just learning but also upbringing, complicating the direct application of neuroscientific insights. Psychological and pedagogical theories often fail to explain the efficacy of certain teaching methods, leading to persistent use of outdated or ineffective practices. For example, highlighting text or repeated rereading, despite evidence of ineffectiveness [38, 39], is still commonplace. Addressing these gaps requires a systematic and collaborative approach. Critics argue that neuroscience may not directly inform educational methods. For example, Professor Derek Bowers of the University of Bristol posits that neural mechanisms are irrelevant to education, which he views solely in terms of behavioral outcomes. However, this perspective overlooks the potential of neuroscience to uncover the underpinnings of learning processes, thereby enriching pedagogical practices. Indeed, the content of the concept of "learning" differs significantly for educators and researchers in the field of neuroscience. From the perspective of neuroscience, the learning process is reduced to several variants of its implementation in the brain. There is a system for memorizing specific events, involving episodic or autobiographical memory [40]. Learning involves multiple neural systems, each contributing to different aspects of skill acquisition and knowledge retention:

- **Episodic Memory**: Mediated by the hippocampus, facilitating the formation of event-specific memories.
- **Sensorimotor Integration**: Managed by the somatosensory and motor cortex, enabling association between sensory input and motor responses.
- **Reward-Based Learning**: Engaged in goal-oriented behaviors via the basal ganglia and limbic structures.
- **Procedural Learning**: Involving repetitive actions that become automated through practice, supported by basal ganglia and cerebellum loops.
- **Higher Cognitive Functions**: Developed through observation, modeling, and conceptual learning, often mediated by mirror neurons and language networks.

These systems operate in complex interdependence, influenced by motivation, emotional states, and frequency of practice. Effective educational strategies must account for these dynamics to foster long-term retention and skill mastery. Despite high expectations, the translation of neuroscientific findings into classroom practices has been slow. Challenges include the controlled conditions required for neuroimaging studies and the lack of empirical data connecting neuroscience to practical pedagogy. For example, as Willingham notes, discussions on neuroscience in education often outnumber empirical studies in the field. In Russia, the rise in publications on neuroeducation reflects growing interest but highlights issues such as factual inaccuracies and insufficient experimental evidence. Progress requires interdisciplinary collaboration between educators, psychologists, and neuroscientists to develop and test research-based educational practices. The prevalence of neuromyths, such as the effectiveness of a "growth mindset" or tailoring education to individual learning styles, underscores the need for neuroscience-informed teacher training. Empirical studies have debunked many such claims, emphasizing the importance of grounding pedagogical practices in validated research. Educational neuroscience can flourish only through methodical research and empirical validation, fostering scientifically informed approaches to teaching and learning.

A bibliographic analysis of publications from 2000 to 2022 highlights the evolution of neuroscientific research in education. Using scientometric tools, key trends, methodologies, and research directions were identified. The study focused on articles published in leading journals such as Cognitive Development, Brain and Cognition, and Developmental Cognitive Neuroscience, among others. Higher cognitive functions are also trainable. Functional brain networks are formed during the perception and understanding of others, so skills can be acquired simply by observing other people, so-called modeling [41]. Results indicate a steady increase in publications, with six primary research directions emerging. These include neuroimaging applications, cognitive development, and technology-enhanced learning. **Figures 3** and **4** detail publication dynamics and research trends, respectively, offering insights into the trajectory of neuroeducation as a field.

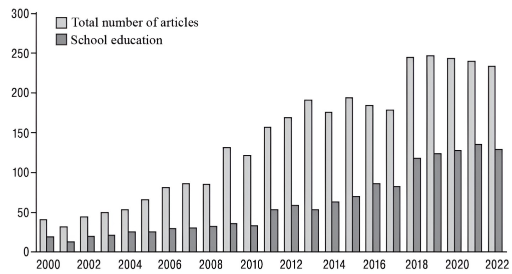

Figure 3. Annual number of published articles devoted to the study of brain mechanisms of learning and, in particular, schoolchildren's learning, for 2000–2022 (according to the international database Scopus).

The neural underpinnings of language learning are integral to understanding how students acquire and develop linguistic skills. This understanding has the potential to inform and enhance educational practices by providing insights into how the brain processes language acquisition. Neuroscience highlights that early intervention and targeted strategies can significantly influence outcomes, particularly during critical developmental windows when neuroplasticity is at its peak [42].

2.3. Early Childhood Language Acquisition and Development

Advances in neuroscience have illuminated the mechanisms underlying early childhood language acquisition. Studies reveal how neural circuits responsible for phonological, semantic, and syntactic processing evolve during this stage and are shaped by environmental stimuli and interactions. Such insights emphasize the need for age-appropriate pedagogical approaches that harness the plasticity of the developing brain. We identified research employing neuroimaging techniques to examine the brain activity of school-aged children during learning as particularly relevant. These studies offer unique opportunities to apply neuroscience in education, as children's brains are highly plastic and receptive to influences during this developmental stage [43]. A scientometric analysis of studies incorporating keywords such as "school," "child," and "children" revealed 1,358 works, with 1,122 classified into six primary research directions:

a. Measurement of cognitive abilities.

b. Comparison of cognitive function indicators across age groups.

c. Advancement of neuroimaging methodologies and technologies.

d. Assessment of factors (e.g., stress, errors, physical activity) affecting learning outcomes.

e. Application of neuroimaging in solving educational tasks.

f. Investigation of brain activity in students with developmental disorders.

Figure 4 illustrates the relative proportions of works across these directions, normalized to the total studies analyzed.

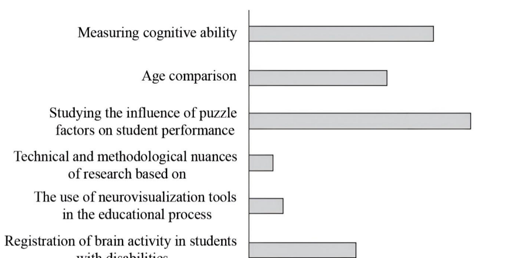

Figure 4. Relative share of works in each of the main areas of research for 2000–2022, % (according to the Scopus international database).

The predominant focus is on understanding how external and internal factors influence cognitive abilities and age-related differences in cognitive development. However, practical applications of these findings in pedagogy remain underexplored [44]. Methodological limitations and technological constraints hinder the integration of neuroscientific practices into education. Despite the growing body of research, studies specifically addressing the direct application of neuroscientific findings in classroom settings remain scarce. Developmental cognitive neuroscience investigates how the brain forms associations between sensory inputs and behavioral responses. Such research informs the design of educational activities aimed at improving learning outcomes. Neural mechanisms linked to inhibitory control, long-term memory, and reward-based learning play critical roles in skill acquisition, such as literacy and arithmetic.

Studies using neuroimaging techniques (e.g., fMRI, EEG) have identified brain regions involved in numerical cognition (e.g., fusiform gyrus, intraparietal sulcus) and spatial abilities, offering insights into targeted interventions. For example, training the "approximate number system" associated with the parietal lobe enhances rapid quantity estimation and spatial information processing.

Neurolinguistics research has identified neural mechanisms underlying visual, semantic, and phonological processing during foreign language acquisition. Differences in brain activation between learners of varying proficiency levels highlight the neural correlates of linguistic errors and guide personalized learning interventions. While research in linguistics and mathematics is well-established, other academic disciplines, aside from music, remain in the early stages of neuroscientific exploration.

Portable EEG and fNIRS technologies have emerged as promising tools for educational neuroscience. These devices are cost-effective, user-friendly, and suitable for real-world educational settings. For example, portable EEG systems have been used to monitor attention phases during learning tasks. Although these systems offer advantages over traditional setups, small sample sizes and methodological inconsistencies limit the generalizability of findings. fNIRS combines the portability of EEG with the spatial resolution of fMRI, making it a valuable tool for studying cognitive processes in children. However, hemodynamic lag remains a limitation for recording rapid neural processes. Neuroscientific tools hold promise for personalized education, particularly for children with developmental disorders. For example, preparatory measures, such as familiarization with EEG procedures, have improved data quality in children with autism spectrum disorders (ASD). Similarly, studies on dyslexia have shown that rhythm-based auditory training can enhance phonological processing, offering a complementary approach to traditional phonology interventions. Transcranial magnetic stimulation (TMS) has demonstrated potential in modulating functional brain networks. While primarily used in clinical settings (e.g., depression treatment), TMS could be adapted to enhance executive functioning in children with attention deficit-hyperactivity disorder (ADHD) or other learning challenges. Advances in neuroscience provide valuable insights into the neural mechanisms underpinning learning and cognition. However, the practical application of these insights in educational contexts requires further exploration. Future research should focus on scaling studies, improving methodological rigor, and bridging the gap between neuroscientific findings and pedagogical practices. By addressing these challenges, neuroscientific approaches can revolutionize education, making it more effective and inclusive for all learners.

2.4. Limitations in Implementing the Neurointerface System for Early Childhood Language Education

While the proposed neurointerface system offers a dynamic and individualized learning environment, its application to early childhood language education presents several challenges. A key limitation in this context is the complexity of differentiated instruction, particularly in literacy and reading comprehension at an early age. Differentiated instruction refers to the tailoring of teaching strategies to accommodate diverse learning needs, cognitive abilities, and language proficiencies among students. This pedagogical approach is essential in early education, where learners exhibit significant variability in language acquisition rates and reading comprehension skills.

Despite the potential of neurointerfaces to monitor cognitive engagement and adapt instruction in real time, implementing these technologies within differentiated instructional frameworks remains challenging. One major difficulty lies in aligning neurointerface data with pedagogical strategies that address individual learning styles, prior knowledge, and developmental differences. Early literacy development involves complex neural processes, including phonological awareness, orthographic processing, and semantic integration, which may not be fully captured by current neurointerface technologies. Furthermore, practical considerations such as classroom integration, teacher training, and ethical concerns regarding data privacy pose additional barriers to widespread adoption.

Moreover, while neurointerface systems can provide insights into cognitive load and engagement levels, they do not replace the need for comprehensive pedagogical strategies that include multimodal instruction, scaffolding techniques, and social interaction - all crucial for literacy acquisition. Differentiated instruction strategies, such as guided reading, adaptive text complexity, and phonics-based interventions, have been widely recognized for their effectiveness in literacy education. However, the challenge remains in designing neurointerface-supported systems that complement these established methods rather than merely providing biometric feedback without clear pedagogical application.

Future research should explore how neurointerface systems can be seamlessly integrated into differentiated instruction models to enhance literacy education. Investigating how real-time neurophysiological data can inform adaptive learning pathways while ensuring accessibility for diverse learners is critical. Additionally, collaboration between educators, cognitive scientists, and technology developers is essential to refine these systems to meet the specific needs of early language learners. By addressing these limitations, neuroscience-driven educational technologies can contribute more effectively to personalized and inclusive literacy instruction.

3. Conclusions

Brain research stands as a cornerstone of contemporary interdisciplinary science, merging neuroscience, neurotechnology, and education. Despite substantial advancements in understanding the mechanisms of the adult brain, the developing brain of a child presents unique challenges. Rapid developmental changes, significant variability across age groups, and the difficulty of real-time observation make the study of the child's brain particularly complex. This underscores the need for continued exploration of the neural basis of learning to better inform educational practices across all stages of life, from early childhood to older adulthood. Although neuroscience has elucidated many fundamental principles of brain function, translating these findings into practical educational methods remains difficult. The diverse learning systems of the brain, coupled with numerous environmental, biological, and social factors influencing learning, complicate the direct application of neuroscience to teaching. Furthermore, the limited use of brain imaging and other neuroscientific tools in educational research, particularly longitudinal studies, impedes a comprehensive understanding of how the brain develops during learning.Most existing studies focus on short-term testing in controlled environments rather than exploring dynamic, long-term brain changes during real-world educational activities. This gap highlights the need for methodologies akin to translational educational neuroscience, which draws inspiration from translational medicine. Translational educational neuroscience proposes a pathway for integrating neuroscientific insights into educational practice. This process begins with pilot studies that investigate the neural mechanisms of learning in controlled settings using small cohorts with appropriate control groups. Promising results can then be scaled to larger groups of students in real-world educational contexts. To ensure ethical integrity, such studies must adhere to stringent ethical standards akin to those in cognitive neuroscience and medicine, particularly when research involves children. Widespread adoption of translational approaches could revolutionize educational neuroscience by shifting it from a predominantly theoretical domain to one that generates practical applications. This would lay the groundwork for a new pedagogical science rooted in neuroscience, fostering the development of individualized learning trajectories and evidence-based teaching methodologies. For neuroscience to effectively integrate into education systems, particularly in Russia, several initiatives are necessary:

a. Enhancing Interdisciplinary Collaboration

- Establish platforms for dialogue between neuroscientists and educators to identify pressing challenges and collaboratively develop solutions.
- Foster partnerships between universities and neuroscience researchers through network-based master's programs, teacher training courses, and interdisciplinary research initiatives.

b. Expanding Neuroscience Education for Teachers

- Incorporate neuroscience-themed lectures and courses into teacher education and professional development programs.
- Equip teachers with scientific literacy to differentiate evidence-based practices from neuromyths, reducing the influence of unverified claims.

c. Supporting Interdisciplinary Research

- Increase financial support for interdisciplinary research involving neurobiology, pedagogy, and psychology. Collaborative efforts in these fields are essential for designing impactful, neuroscience-informed educational methodologies.

d. Promoting Longitudinal Research

- Prioritize longitudinal studies to assess the long-term effects of neuroscientific interventions and educational paradigms on students' cognitive and neural development.

By expanding the scope of interdisciplinary research, fostering collaboration, and implementing translational approaches, educational neuroscience can bridge the gap between fundamental discoveries and classroom applications. These efforts will not only advance our understanding of the neural basis of learning but also establish neuroscience as a vital foundation for the pedagogical science of the future.

Author Contributions

Conceptualization, M.K. (Mukhabbat Khakimova), I.K.; methodology, G.O.; formal analysis, G.M.; investigation, M.K. (Mekhribonu Kayumova); resources, S.A.; data curation, N.F.; writing—original draft preparation, R.P. and S.J.; supervision, S.M. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author, [Sh.J.].

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Conflicts of Interest

The authors declare that there is no conflict of interest.

References

[1] Goswami, U., 2016. Educational neuroscience: Neural structure-mapping and the promise of oscillations. Current Opinion in Behavioral Sciences. 10, 89–96. DOI: https://doi.org/10.1016/j.cobeha.2016.05.011

[2] Shaturaev, J., Muhabbat, H., Kurbonov, K., Kholmuratov, S., Nazirjon, R., Nilufar, F., Farxod, T., 2024. Crafting a Neutrosophic-Driven Tool to Probe Turnover Propensities in Manufacturing Entities. International Journal of Neutrosophic Science. 23(2), 221. DOI: https://doi.org/10.54216/IJNS.230218

[3] Krueger, F., Meyer-Lindenberg, A., 2019. Toward a model of interpersonal trust drawn from neuroscience, psychology, and economics. Trends in Neurosciences. 42(2), 92–101. DOI: https://doi.org/10.1016/j.tins.2018.10.004

[4] Chandler, J. A., Harrel, N., Potkonjak, T., 2019. Neurolaw today — A systematic review of the recent law and neuroscience literature. International Journal of Law and Psychiatry. 65. DOI: https://doi.org/10.1016/j.ijlp.2018.04.002

[5] De Brigard, F., Sinnott-Armstrong, W. (Eds.), 2022. Neuroscience and philosophy. MIT Press: Cambridge, Massachusetts, USA. DOI: https://doi.org/10.7551/mitpress/12611.001.0001

[6] Thomas, M. S. C., Ansari, D., Knowland, V. C. P., 2019. Annual research review: Educational neuroscience: Progress and prospects. Journal of Child Psychology and Psychiatry. 60(4), 477–492. DOI: https://doi.org/10.1111/jcpp.12973

[7] Han, H., Soylu, F., Anchan, D. M., 2019. Connecting levels of analysis in educational neuroscience: A review of multi-level structure of educational neuroscience with concrete examples. Trends in Neuroscience and Education. 17. DOI: http://dx.doi.org/10.1016/j.tine.2019.100113

[8] Bazhanov, V. A., Shkurko, Y. S., 2018. Modern neuroscience and education: New arguments in favor of old techniques]. Pedagogika. 8, 29–38.

[9] Kulikova, O. V., 2014. The neurodidactic approach as a factor of quality improvement: Teaching professional communication in foreign languages. Vestnik of Moscow State Linguistic University: Education and Teaching. 14, 107–114.

[10] Zeer, E. F., 2021. Neurodidactics — an innovative trend of personalised education. Vocational Education and Labour Market. 4, 30–38. DOI: https://doi.org/10.52944/P0RT.2021.47.4.002

[11] Thorndike, E. L., 1913. Educational psychology, Vol. 1: The original nature of man. Columbia University. DOI: https://doi.org/10.1037/13763-000

[12] Shaturaev, J., 2023. Modeling the Impact of Information on Audits on Taxpayer Risk Profiles and Evasions. ICFNDS '23: Proceedings of the 7th International Conference on Future Networks and Distributed Systems; 21-22 December 2023; Dubai, United Arab Emirates. 173–179. DOI: https://doi.org/10.1145/3644713.3644735

[13] Brockington, G., Balardin, J. B., Morais, G., Malheiros, A., Lent, R., Moura, L., Sato, J. R., 2018. From the laboratory to the classroom: The potential of functional near-infrared spectroscopy in educational neuroscience. Frontiers in Psychology. 9. DOI: https://doi.org/10.3389/fpsyg.2018.01840

[14] Davidesco, I., Matuk, C., Bevilacqua, D., Poeppel, D., Dikker, S., 2021. Neuroscience research in the classroom: Portable brain technologies in education research. Educational Researcher. 50(9), 649–656. DOI: https://doi.org/10.3102/0013189X211031563

[15] Tikidji-Hamburyan, R. A., Kropat, E., Weber, G. W., 2020. Preface: Operations research in neuroscience II. Annals of Operations Research. 289(1), 1–4. DOI: https://doi.org/10.1007/s10479-020-03574-z

[16] Williamson, B., 2019. Brain data: Scanning, scraping, and sculpting the plastic learning brain through neurotechnology. Postdigital Science and Education. 1(1), 65–86. DOI: https://doi.org/10.1007/s42438-018-0008-5

[17] Dimitropoulos, K., Mystakidis, S., Fragkaki, M., 2022. Bringing educational neuroscience to distance learning with design thinking: The design and development of a hybrid e-learning platform for skillful training. Proceedings of the 2022 7th South-East Europe Design Automation, Computer Engineering, Computer Networks and Social Media Conference; 23-25 September 2022; Ioannina, Greece. 1–6. DOI: https://doi.org/10.1109/SEEDA-CECNSM57760.2022.9932939

[18] Bruer, J. T., 1997. Education and the brain: A bridge too far. Educational Researcher. 26(8), 4–16. DOI: https://doi.org/10.3102/0013189X026008004

[19] Leisman, G., 2023. Neuroscience in education: A bridge too far or one that has yet to be built: Introduction to the "Brain Goes to School." Brain Sciences. 13. DOI: https://doi.org/10.3390/brainsci13010040

[20] Zull, J. E., 2020. The art of changing the brain: Enriching the practice of teaching by exploring the biology of learning. Stylus.

[21] Tardif, E., Doudin, P.-A., Meylan, N., 2015. Neuromyths among teachers and student teachers. Mind, Brain, and Education. 9(1), 50–59. DOI: https://doi.org/10.1111/mbe.12070

[22] Thomas, M. S. C., Ansari, D., Knowland, V. C. P., 2019. Annual research review: Educational neuroscience: Progress and prospects. Journal of Child

Psychology and Psychiatry. 60(4), 477–492. DOI: https://doi.org/10.1111/jcpp.12973

[23] Gazi, M. A. I., Nahiduzzaman, M., Shaturaev, J., Dhar, B. K., Halim, M. A., 2022. Dynamic Nexus between macroeconomic factors and CO2 emissions: Evidence from oil-producing countries. Frontiers in Environmental Science. 10, 1–19. DOI: https://doi.org/10.3389/fenvs.2022.1005814

[24] Vygotsky, L. S., 1934. Thinking and speech. Государственное социально-экономическое издательство.

[25] Stepanov, V. G., 2020. Neuropedagogy. Brain and effective development of children and adults: Age, learning, creativity, career guidance. Академический проект.

[26] Mareschal, D., Johnson, M., Sirios, S., et al., 2007. Neuroconstructivism: How the brain constructs cognition. Oxford University Press: Oxford, UK.

[27] Sala, G., Fernand, G., 2017. Does far transfer exist? Negative evidence from chess, music, and working memory training. Current Directions in Psychological Science. 26(6), 515–520. DOI: https://doi.org/10.1177/0963721417712760

[28] Park, H. J., Friston, K., 2013. Structural and functional brain networks: From connections to cognition. Science. 342(6158). DOI: https://doi.org/10.1126/science.1238411

[29] Petersen, S. E., Posner, M. I., 2012. The attention system of the human brain: 20 years after. Annual Review of Neuroscience. 35, 73–89. DOI: https://doi.org/10.1146/annurev-neuro-062111-150525

[30] Howard-Jones, P., 2014. Neuroscience and education: Myths and messages. Nature Reviews Neuroscience. 15(2), 817–824. DOI: https://doi.org/10.1038/nrn3817

[31] Ruiz-Ariza, A., Grao-Cruces, A., Marques de Loureiro, N. E., Martínez-López, E. J., 2017. Influence of physical fitness on cognitive and academic performance in adolescents: A systematic review from 2005–2015. International Review of Sport and Exercise Psychology. 10(1), 108–133. DOI: https://doi.org/10.1080/1750984X.2016.1184699

[32] Hughes, S. M., Dunn, W., Roy, P., 2014. The challenges of applying laboratory-based neuroscience research to classroom settings. Journal of Educational Neuroscience. 2(3), 221-238.

[33] Saffran, J. R., Aslin, R. N., Newport, E. L., 1996. Statistical Learning by 8-Month-Old Infants. Science, 274(5294), 1926–1928. DOI: https://doi.org/10.1126/science.274.5294.1926

[34] Lebedev, M. A., Nicolelis, M. A. L., 2006. Brain–machine interfaces: Past, present, and future. Trends in Neurosciences. 29(9), 405-414. DOI: https://doi.org/10.1016/j.tins.2006.07.004

[35] Thomas, M. S. C., Ansari, D., Knowland, V. C. P., 2019. Annual research review: Educational neuroscience: Progress and prospects. Journal of Child Psychology and Psychiatry. 60(4), 477–492. DOI: https://doi.org/10.1111/jcpp.12973

[36] Hramov, A. E., Maksimenko, V. A., Pisarchik, A. N., 2021. Physical principles of brain-computer interfaces and their applications for rehabilitation, robotics, and control of human brain states. Physics Reports. 918, 1–133. DOI: https://doi.org/10.1016/j.physrep.2021.03.002

[37] Gazi, M. A. I., Islam, M. A., Shaturaev, J., Dhar, B. K., 2022. Effects of Job Satisfaction on Job Performance of Sugar Industrial Workers: Empirical Evidence from Bangladesh. Sustainability (Switzerland). DOI: https://doi.org/10.3390/su142114156

[38] Drugova, E. A., Zhuravleva, I. I., Zakharova, U. S., et al., 2022. Artificial intelligence for learning analytics and instructional design steps: An overview of solutions. Вопросы образования / Educational Studies Moscow. (4), 107–153. DOI: https://doi.org/10.17323/1814-9545-2022-4-107-153

[39] Kurkin, S. A., Grubov, V. V., Maksimenko, V. A., et al., 2020. System for monitoring and adjusting the learning process of primary schoolchildren based on EEG data analysis. Information and Control Systems. 5, 50–61. DOI: https://doi.org/10.31799/1684-8853-2020-5-50-61

[40] Hattie, J., 2021. Visible learning for teachers. Maximizing impact on learning. Национальное образование.

[41] Daley, N., Rawson, A. K., 2019. Elaborations in expository text impose a substantial time cost but do not enhance learning. Educational Psychology Review. 31(2), 197–222. DOI: https://doi.org/10.1007/s10648-018-9451-9

[42] Budson, A. E., Richman, K. A., Kensinger, E. A., 2022. Consciousness as a memory system. Cognitive and Behavioral Neurology. 35(4), 263–297. DOI: https://doi.org/10.1097/WNN.0000000000000319

[43] Oberman, L. M., Ramachandran, V. S., 2007. The simulating social mind: The role of the mirror neuron system and simulation in the social and communicative deficits of autism spectrum disorders. Psychological Bulletin. 133(2), 310–327. DOI: https://doi.org/10.1037/0033-2909.133.2.310

[44] Diosdedet, C., Labordo, J., 2024. Assessing the Influence of Differentiated Instruction on Enhancing Reading Comprehension Skills among Learners: A Quasi-Experimental Study. New English Teach. 18(2), 13–28. http://www.assumptionjournal.au.edu/index.php/newEnglishTeacher/article/view/7951