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Neuropedagogical Technologies for Training Future Primary School Teachers

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Abstract: *In light of the growing importance of neuroscience experiments and the integration of their methodical findings into adult education, this article proposes neuropedagogical technologies designed for training future primary school teachers. It also introduces a model of such training, which has undergone quasi-experimental verification within a short didactic timeframe in Ukraine's educational context. The authors critically examined key and supporting neuroscientific theories relevant to neuropedagogy in teacher training, using methods such as pedagogical selection, modelling and quasi-experimental implementation of neuropedagogical technologies. Their findings show that, within just two months, third-year students demonstrated improvements in academic neuromarkers, including engagement, self-management, reflection and effective independent attention-shifting. This allowed experts to subtly adjust personalised learning paths based on clear and consistent neurofeedback, revealing varying levels of process effectiveness. The international relevance of the article stems from the declining interest in neuropedagogy in the Western world, contrasted by the growing enthusiasm in Eastern European countries, which are embracing neuroscientific innovations with fresh perspectives.*

Keywords: *personalised learning paths; a dynamic trajectory; neurofeedback; neuroeducational model; switching; emotional intelligence; self-management; quasi-experimental verification.*

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1. Introduction

Since the 1990s, with the rise of neuroscience in Western Europe, conversations emerged about the potential of applying neuropedagogy to education and improving essential life skills in adults (Lohmeier, 1998; Siebert, 2003). It became clear that implementing neuropedagogical approaches for both adults and students is vital, as it allows for more personalised learning by considering one's neurophysiological traits, leading to increased overall effectiveness. Continuous advances in brain research have provided new insights for optimising cognitive processes, reducing stress and anxiety during learning, and enhancing the skills of adult professionals. Moreover, neuropedagogy has proven to be particularly effective in developing metacognitive abilities such as self-regulation and critical thinking, which are especially important for more mature learners pursuing independent education.

Additionally, the media and economic organisations supported integrating neuroscience into multi-level education and lifelong learning. In the early 2000s, the Organisation for Economic Cooperation and Development (OECD) launched an initiative to reorient education towards brain-centric science based on evidence from proven experiments on effectiveness (Becker, 2006).

2. Research Relevance

Primary school teachers undergo specialised training that is particularly dynamic, as they are tasked with applying neuropedagogical knowledge extensively to promote children's emotional and cognitive development during crucial early sensitive periods. With advancements in neuroscience, future teachers can learn through personalised, dynamic learning paths with neurofeedback, aligning closely with the competencies they will need in primary education. Despite a substantial number of general studies, research and developments in neuropedagogy within higher education, specifically focused on training primary school teachers, are notably scarce in dissertation collections, major scientific databases, and other academic resources. This gap is especially relevant in Eastern Europe, where educational standards are rapidly converging with global norms, embracing innovations, neuro-technological advances, and experimental teacher training projects for those working with young learners.

The "zone of imminent reform" has been pinpointed in areas affecting emotional intelligence, which has become a primary focus for transformation in young learners and adults and a central priority in neuropedagogy.

Recently, Ukrainian higher education pedagogy, represented by the authors, has shown significant interest in two key areas: first, exploring international approaches to training primary school teachers and preschool teachers; second, conducting active research and applying neuropedagogical technologies in fields within higher education where implementation seems more accessible, such as creative pedagogy and physical and military education. At the same time, novice neuropedagogues remain cautious about expanding into other training areas, recognising that neuropedagogical preparation for working with young school-age children demands particular attention and ethical sensitivity.

Therefore, this article has a multi-faceted aim. First, the authors seek to review core and partial neuropedagogical and neuropsychological research to assess its value for adult education. Building on this, they intend to identify relevant studies and design methodical frameworks and specific technologies (drawing from their own practical experience) for the pilot training of future primary school teachers. They plan to test these approaches within a quasi-experimental framework, focusing not on academic achievement but on tracking neuromarkers within experimental groups, such as learning self-management, reflection, responsiveness, and effective multitasking across various sources of educational information.

3. Research Methods

Research methods include a critical literature review, adaptation of existing neuropedagogical techniques for this article's focus, approaches to selection, and neuropedagogical modelling of the educational process and its specific technologies. Statistical and descriptive generalisation methods were used in the final stages of the article. The quasi-experimental study involved 128 third-year bachelor's degree students majoring in primary education at Pavlo Tychyna Uman State Pedagogical University (Ukraine), with 63 students in the control group and 65 in the experimental group.

This research is grounded in the neuropsychological principles established by Ukrainian psychologists and educators, which have been tested within the post-Soviet context for a long time. Although neuropedagogy has recently increased in popularity in Ukrainian educational science, influenced by current Western neuroscientific trends, one still benefits from a robust Ukrainian tradition. This tradition, known during Soviet times as pedagogical psychology, psychology of upbringing, developmental psychology, and psychophysiology, remains relevant. Even international scholars acknowledge Luria (1970) and Vygotsky (2013) as pioneers of neuropedagogy. Luria's theory (1970) of systemic localisation of higher mental functions explains how different brain regions contribute to specific cognitive tasks. Besides, he developed diagnostic and rehabilitation methods for individuals with brain injuries (Luria, 1970). His work on the neurological basis of learning for children with special needs laid the groundwork for neuropedagogical educational adaptations for students with various cognitive profiles. Meanwhile, Vygotsky (2013) demonstrated that higher mental functions in children develop through social interactions and cultural tools, foundational elements in neurophysiology. His most well-known concepts include the zone of proximal development (ZPD), which defines a child's potential abilities, and inner speech, a psychoneurological function essential for complex educational and cognitive processes (Vygotsky, 2013).

To conclude the introduction, it would be valuable to establish a clear and practical connection between these theories and validated neuropedagogical methods. Furthermore, it is crucial to demonstrate how ZPD supports the design of personalised learning pathways within the context of the problem in question. This can be achieved by embracing scientific-methodological continuity, progression, and dynamics to draw a robust neuropedagogical correlation.

Neuropedagogy, rooted in understanding how the learner's brain functions during education, aligns seamlessly with the study of ZPD and inner speech, which reflect the latest advancements in neuroscience.

Specifically, this alignment can be observed in 1) *brain plasticity*, where ZPD demonstrates the brain's adaptive capacity in response to social interactions; 2) *prefrontal cortex activation*, responsible for planning, self-regulation, and abstract thinking as core processes integral to the development of inner speech; 3) the significance of social context, which, in dynamic learning environments, not only stimulates the formation of neural connections through interaction but also fosters a "mutual enrichment network". In this network, individuals are both consumers and creators of knowledge, reinforcing neural pathways through collaborative learning. This concept is encapsulated in the modern term "neurosociety".

Thus, the enduring contributions of scholars such as Vygotsky (2013) find direct and practical applications in neuropedagogical frameworks, providing a strong foundation for current approaches.

4. Research Ethics

It is important to note that the group of students from Pavlo Tychyna Uman State Pedagogical University (Ukraine), who participated in testing the pilot neuropedagogical teaching technology for future primary school teachers, provided voluntary consent both individually and collectively (during a discussion with their academic group) and expressed strong interest in the project. The university's ethics committee approved the implementation of the authors' technology, while the methodology department authorised its use for two calendar months as part of the experimental teaching framework.

5. Neuropedagogical Advances in Adult Education and Teacher Training: Trends, Challenges, and Insights

Before proceeding with a quasi-experimental evaluation of the authors' pilot model, it is important to first trace the development of neuropedagogy, emphasising its educational dimensions rather than its strictly neurophysiological aspects. This will enable a constructive and critical assessment of earlier and more recent advancements in this area.

In terms of key interdisciplinary research that has significantly influenced today's neuropedagogy, the contributions of Goswami (2006), a prominent developmental cognitive neuroscientist at the University of Cambridge, are noteworthy. Her work focuses on the cognitive development of children with moderate intellectual limitations and the use of neuropsychological markers to measure progress in learning, particularly in foundational skills such as reading and speaking (Goswami, 2006). After all, neuropedagogy's most evident impact is seen in working with children who have special educational needs. In contrast, neuropsychology remains more relevant for studying cognitive-emotional disorders than for normative functioning.

Relevant to this research are the works of Sarah-Jayne Blakemore, a psychologist and cognitive neuroscientist, and her colleague Uta Frith, both of whom investigate the influence of neurophysiological processes on learning and early human development (Blakemore & Frith, 2005). Notably, as individuals grow older, they become less responsive to neurodiagnostic educational technologies, which heightens the importance of this article.

Among the prominent figures in neuropedagogy, Geake (2009) stands out for his work on integrating neuroscientific knowledge into educational programs and projects. His ideas are adaptive, focusing on enhancing traditional teaching methods through neuropedagogical refinements at various educational levels.

In terms of adult neuroeducation, the ongoing projects at the University of Buenos Aires, led by Kurt Fischer, professor of medicine, psychology, and pedagogy, are worth mentioning. Together with Antonio Battro and Pierre Léna, Fischer co-edited "The Educated Brain", a collection of works by leading researchers in neuroeducation. This compilation examines the historical, epistemological, and practical aspects of integrating neuroscience into education, emphasising the holistic integration of medical, psychological, and humanitarian dimensions of learning (Battro, Fischer, & Léna, 2008).

Also notable are the contributions of Dehaene (2009; 2011), a French cognitive neurobiologist and writer. Dehaene (2009; 2011) has made significant advancements in the methodology of teaching mathematics by exploring the neural basis of learning, memory, and the brain's processing of mathematical and abstract information. His work offers valuable insights into the cognitive and methodological aspects of education beyond the humanities.

Thus, research in the field of adult neuropedagogy generally focuses on two key areas:

- *Neurotechnologies in education*. The increasing use of interactive technologies and online resources that engage brain regions not typically activated in traditional teaching is becoming more prevalent in teacher training. This includes multisensory platforms for online learning and simulations, which allow teachers to improve their skills in a virtual setting.
- *Cognitive learning styles and individual differences*. Studies show that considering the cognitive styles of students and adults, whether visual, auditory, or kinaesthetic, along with their sensitivities and preferences, can greatly improve the effectiveness of learning.

It is now crucial to critically examine studies specifically related to the professional training of future primary school teachers. In the German-speaking neuropedagogical discourse post-2010, distinct didactic goals have been identified under the acronym ESKIL (Emotional, sozial & kognitiv intelligente Lehre), meaning "Emotionally, Socially and Cognitively Intelligent Teaching". The primary objective of this neuropedagogical approach is to enhance the professionalism of teachers by expanding their expertise through the integration of brain-based teaching methods. Researchers have also worked to create structured learning environments with effective frameworks and guidelines that ensure a well-managed and efficient learning process. A central goal is to promote student autonomy by encouraging learners to take responsibility for their education, fostering independence and self-directed learning (referred to as academic neuro-subjectivity). Throughout the learning process, emphasis should be placed not only on the outcomes but also on improving the process itself. Additionally, much attention is given to developing teachers' emotional and social skills, crucial for creating a positive learning environment and engaging effectively with future students (micro-neurosocial orientation) (Frankl, 2012).

At the same time, research conducted by Ukrainian universities on the potential use of neuropedagogical technologies has revealed promising results. Firstly, the physical and technological resources (such as multimedia visualisation and simulation capabilities) are well-equipped to support the creation of a conducive learning environment. Secondly, the academic community demonstrates a high level of sensitivity and readiness for neuro-subjective interaction. Higher education institutions can establish collaborative spaces where teachers and neurologists work together to develop new methods and approaches. Additionally, they can offer professional development programs for teachers in neuropedagogy.

Vozniuk (2019a) provides a comprehensive overview of the neuropedagogical potential in adult education, emphasising that Ukrainian universities use neuropedagogy to develop more effective teaching methods, enhance cognitive processes in students, and optimise the learning experience. Key areas of its current use include:

- *Understanding cognitive and mental processes*. Teachers investigate how students process information, store memories, focus attention, and find motivation. This allows one to develop teaching strategies that enhance material acquisition and promote critical thinking and reflection.
- *Implementing innovative technologies*. Tools such as Virtual Reality (VR) and Augmented Reality (AR) create immersive, interactive learning environments that engage multiple senses and activate various brain regions, making learning more dynamic.
- *Enhancing brain functionality*. Specialised games, tasks, and exercises are used to improve attention, memory, creativity, and analytical thinking in students.
- *Personalised learning*. A tailored approach to students based on their unique characteristics and neuro-profiles allows for customised teaching methods, better addressing individual educational needs.

Kobylianska and Kyssa (2024) analyse the prospects and challenges of neuropedagogy in today's higher education institutions. They are among the first to emphasise the integration of advanced technologies, blended learning, and self-learning stimulation technologies with positive reinforcement, as well as the wider use of augmented and virtual realities. However, this advancement faces obstacles due to the mechanical application of neuroscientific knowledge in educational contexts, ethical and medical risks related to pedagogical neuro-interventions, and the inadequate development and experimental validation of effective methods and teaching strategies. Similar findings can be derived from a detailed study of the international neuropedagogical discourse, which reveals that education experts and teachers have effectively mastered theoretical neuro-knowledge and can diagnose brain responses and educational outcomes without relying on medical equipment (using adapted cognitive-psychological methods). Nevertheless, there remains a significant gap in the methodology for effectively training specialists in higher education institutions through neuropedagogical processes, with only several isolated pilot projects, most of which are short-term (Riccardi, 2023).

After analysing this critical review, one can make a noteworthy observation: the popularity of neuropedagogy in the Western world is slowly diminishing. However, in the post-Soviet states of Eastern Europe, it is experiencing a revival. Recent neurophysiological research has opened new opportunities and provided fresh data to support this growth.

A concise yet comprehensive discussion is essential here. In the early 2000s, the concept of "brain-based learning" gained widespread traction in Western education, driven by early breakthroughs in neuroscience and its popularisation through bestsellers by Jensen (2005) and Medina (2009). However, this enthusiasm was soon tempered by a wave of "neuromyth" critiques.

In contrast, by the 2020s, many Eastern European and post-Soviet countries have shown a growing demand for educational modernisation. In this context, neuropedagogy a) is recognised as a forward-thinking approach, b) offers practical and innovative tools to enhance learning outcomes, and c) draws on Western expertise and the latest advancements in neuroscience.

Moreover, neuropedagogy integrates seamlessly with established methodical traditions, facilitating the incorporation of cutting-edge neurophysiological findings into familiar teaching practices. To enrich this discussion, it would be beneficial to include a review of the most notable and frequently cited studies in the field.

The effectiveness of neuropedagogical methods and technologies in training primary school teachers by stimulating their subjectivity as an innate foundational structure has been experimentally confirmed. Competencies such as pedagogical leadership, creativity, and self-regulation, as critical elements in the upcoming quasi-experiment (see the next section), were shown to be particularly responsive to this stimulation. Furthermore, neuro-oriented approaches to shaping the "communicative profile" of future teachers through one-to-one interaction were validated in this field.

Eastern European universities play a crucial role in advancing "the second wave" of neuropedagogy by conducting research that explores how various factors influence learning and brain development. These studies form the basis for developing new teaching methods and programs that integrate neuropedagogical principles and use the latest technologies. Key innovations include personalised and active learning approaches, collaborative spaces where teachers and neurologists can work together, as well as professional development programs for teachers.

Despite these advances, a significant challenge remains: most neuropedagogical research is focused on children, whether typical or with special needs, with little overlap in adult education. Meanwhile, Ukraine's higher education system, currently undergoing significant reforms, urgently needs to incorporate brain technologies and neuro-cognitive patterns tailored to adult learners, defined by conscious decision-making, strong self-regulation, self-organisation, and overall subjectivity.

6. Quasi-Experimental Evaluation of the Author's Neuropedagogical Methods for Training Future Primary School Teachers

This research would seem speculative or, at best, a critical review without introducing a pilot neuropedagogical model for training future primary school teachers. During the pre-experimental modelling phase, emphasis was placed on four key principles: 1) integrating the latest neuropedagogical advancements and technologies in adult education; 2) aligning expected learning outcomes with the standards for primary teacher training; 3) ensuring a correlation between the educational process and expected learning outcomes, alongside their direct involvement in neuropedagogical activities in primary school; 4) using all available information and technology resources to support multi-channel knowledge perception and the use of neurofeedback.

Given that 85% of bachelor's degree students majoring in primary education are over 18 years old, one approaches their training from an "adult education" perspective. Furthermore, the proposed methodology was implemented among third-year students, where all participants were 18 years or older.

The pilot neuropedagogical methodology was designed on the idea of *personalised learning pathways*, using dynamic neuropsychological profiles of students to develop tailored learning plans and flexible use of neurotechnologies that address each student's unique strengths and weaknesses. These traits are identified through neurofeedback, which then informs continuous adjustments to primary teacher training. The authors' approach draws from the recent work of specialists in neuropedagogy (Nouri, Tokuhama-Espinosa, & Borja, 2022) who promote an integrative-technological, interdisciplinary approach in neuropedagogical practices.

Students were free to select their preferred didactic channels, express their responses, and decide when and how to shift their focus if they experienced a subjective decrease in attention, concentration, or interest. The authors adapted the controlled neurofeedback method from neuropsychology and neurology, which involves learning guided by devices or psychodiagnostic tools, influencing brain neurons in response to multimedia stimuli. An adaptation of a similar approach in neuropedagogy, known as "visible learning", emphasises the importance of feedback, self-regulation (reflection), and active student participation in shaping their learning process (Hattie & Yates, 2013). Their approach integrates a wide range of multimedia resources, including YouTube clips and methods for tracking biorhythmic patterns such as slow-fast thinking, focus-defocus, and the ebb and flow of self-control.

The operational framework for recording and controlling neurofeedback drew on Hattie and Yates' method (2013). The authors of this article refined, enhanced, and simplified the method to ensure its applicability in regular classroom settings. The approach included methods detailed in Table 1. For experts using hardware tools for neurofeedback monitoring, Apple Watch fitness trackers were employed. These devices were well-received by students due to their intuitive interface, seamless integration with iPhones, and compatibility with popular and medical applications. Non-hardware methods involved expert observation with written documentation.

The key academic neuro-markers targeted included interest, attention (sustainability, distraction, and switching), self-management (self-regulation), reflection, concentration, inter-channel switching, and neurophysiological indicators.

The focus of the subsequent neuro-pedagogical modelling and quasi-experimental pilot training for future primary school teachers was on developing neuro-cognitive learning scenarios. These scenarios were semantically oriented and based on the methods proposed by Iatrellis, Kameas, & Fitsilis (2018). In a neuro-oriented educational process, as noted by Iatrellis, Kameas, & Fitsilis (2018), personalisation requires constant reconfiguration of learning schemes, as each student's academic status, curriculum, and circumstances within the educational institution are constantly changing. This enabled the authors to effectively structure a model (see Fig. 1) featuring open and interconnected environmental, technological, and neurosocial (communicative-feedback) external layers, along with a personal-subjective internal layer. This approach is consistent with the more traditional concept of "blended learning" in higher education, where semantic stimuli that directly activate specific brain functions are integrated at all stages and levels of interaction. In this context, signs, symbols, signals, and responses are closely related concepts that form the foundational structure of the neurosocial educational microenvironment.

Figure 1, labelled with Roman numerals (I – IV), illustrates four open layers of the neuropedagogical process, within which interactions occur.

In this context, 1 – an open, emotionally and semantically sensitive self-regulating individual; 2 – a continuously evolving personalized learning pathway (the arrow indicates intent); 3 – semantic multimodal signals (knowledge portions) that populate the layers, allowing the individual to switch between them and generate feedback, referred to as neurofeedback (the varying sizes of symbols labelled as 3 represent the differing intensity and importance of individual signals).

The dashed connections symbolically represent the interrupted connections and responses related to shifts in self-directed learning behaviour.

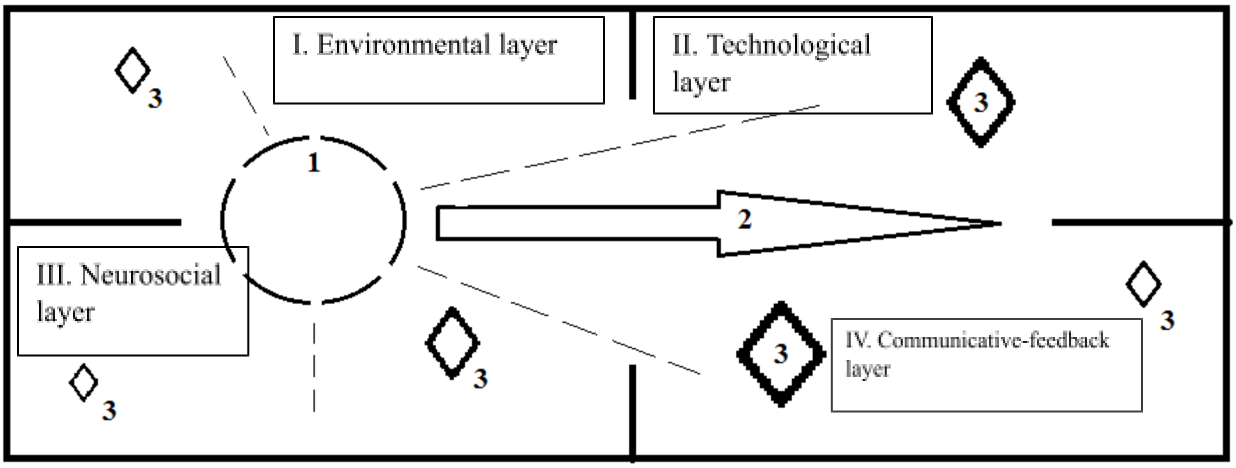

Figure 1. Neuropedagogical parameters of experimental training for future primary school teachers (Source: the authors' own conception)

The neuro-learning process adhered to a repetitive micro-scenario, namely, a cognitive-emotional contact (interaction, "semantic dose" of information) – neurofeedback – positive or negative reinforcement. In instances of negative reinforcement, students would independently switch to a different channel of information or interaction method, either on their own or following expert recommendations.

Key personal resources employed in this process included behaviour (interaction) and perception (information acquisition). The primary didactic resources consisted of multi-channel formats (multimedia representations of information), while the main neuropedagogical resources involved reinforcement and switching, which enhanced neuroplasticity and fostered positive motivation. Process management was performed through a) self-management and b) external adjustments (secondary function) by a group of experts, including the article's authors.

Consequently, the educational contours of this pilot project were open and interwoven, centred around a dynamically behavioural individual who self-monitors their neuro-sensitivity. The experts, who observe the students and the neuropedagogical context through markers of reactivity, activity, and proactivity (neurofeedback), do not influence the situation as they remain external to the process.

Given that the primary focus of the article is on the neuropedagogical technologies used to train future primary school teachers, it will delve deeper into the borrowed and original technologies implemented. Participants in the quasi-experimental study could choose from these technologies, switching between them as needed within the didactic framework. The pilot technology structure included, as mentioned earlier, flexible contours across environmental, neurosocial, communicative-feedback, and technological dimensions, which will be presented in a table format (see Table 1).

Table 1. The technological framework of the pilot neuropedagogical training for future primary school teachers (Source: the authors' own conception)

General technology	Implementation
Multimedia multi-channel technologies	**The ability to choose information sources:** analogue, video, audio, tactile materials (signals, information, sources). **The ability to switch between information channels.**
Virtual reality (VR)	**Virtual environments:** classroom simulations that enable future teachers to practice their teaching skills within a virtual space. **Simulated learning scenarios:** options to select different interaction scenarios with pupils, helping future teachers develop effective responses to various pedagogical challenges.
Augmented reality (AR)	**Interactive learning materials:** using AR to develop interactive textbooks and educational resources that improve information acquisition. **Enhanced interaction: t**he ability to explore abstract concepts through visualisations provided by AR applications.
Neurofeedback	**Self-monitoring** of mental processes, including attention, concentration, and interest, along with their fluctuations and duration, leading to modifications in academic behaviour. **Monitoring brain activity and reactivity:** Experts employ specialised techniques to observe cognitive processes and emotional-volitional states during learning, facilitating adjustments to the personalised learning pathway through tailored suggestions and recommendations**.**
Gamification and emotional reward	**Educational games.** Using educational games to boost motivation and actively involve students in the learning process by offering straightforward rewards for achievements. **Achievement system.** Introducing a system of points, praise, extra breaks during lessons, and other incentives for academic accomplishments to foster engagement and interest in the subject.
Adaptive learning platforms	**Personalised learning programs.** Using platforms that adjust to each student's unique needs, delivering materials and tasks customised to their knowledge levels and learning speeds. **Learning data analysis.** Gathering and analysing student progress data to provide insightful feedback and enhance instructional methods.

During the intervals between classes, individual neuro-coaches from the expert group were assigned to students to aid in developing personalised growth plans and adapting teaching methods to meet their specific needs and abilities. Mentorship groups were also established among the students, facilitated by experts, where they could share experiences and receive guidance from more experienced educators through collaborative discussions and analysis of pedagogical scenarios.

This approach led to the establishment of relatively well-defined (dynamic) neuropsychological profiles for the students and personalised learning pathways. This information was used to further refine individual learning plans, considering each student's strengths and weaknesses.

The descriptive results of the experimental project are presented in Table 2.

Table 2. Operationalising and interpreting neurofeedback (Source: the authors' own conception)

Methods for monitoring/controlling neurofeedback	**Identified academic neuromarkers**	**Changes after two months**
NON-INSTRUMENTAL (Psychodiagnostic)		
Tracking kinetic and facial changes (head rotation, changes in facial expressions)	Attention focusing/defocusing; maintenance, distraction, channel switching	Reduction in involuntary distractions and defocusing
Eye movement speed (slowing down / speeding up)		Slower, more conscious channel switching
INSTRUMENTAL		
Heart rate variability	Moderate or high variability	Increased variability, enhanced interest, and self-regulation
Breathing rate	Accelerated or normal	Slowed down – improved concentration and attention
Breathing depth	Even, moderate depth	Deepened – improved reflection and self-control

After the short-term implementation of the project (2 months), which focused on neuropedagogical pilot training for future primary school teachers, the authors observed moderate positive changes. Based on these findings, they concluded that longitudinal studies are necessary to explore the project's impact.

Following the implementation of the project in the core courses for third-year students, the authors observed that a significant majority (79%) frequently switched between channels. They partially attribute this behaviour to students' habits and reliance on social media and other virtual stimuli that provide short-term dopamine. While this frequent switching helped students maintain interest in the overarching topic, it led to a fragmented understanding of the material, which they absorbed in semantic doses. One might expect that this self-directed approach to neuropedagogy, when applied consistently alongside traditional methods, will still produce a notable academic impact as it engages the entire cognitive spectrum, allowing the didactic material to be processed in various signal forms.

The authors observed slight positive neurodynamic (neuroplastic) changes in the experimental groups, which were not the primary focus of observation. These include increased motivation, heightened interest, a sense of agency, and greater academic-behavioural flexibility. It follows that these technologies have the potential to significantly improve the training process for future primary school teachers in the long term, equipping them with both theoretical knowledge and practical skills essential for effective teaching.

Although the authors did not directly measure changes in academic performance, the results of the quasi-experimental study revealed a notable increase in self-control, motivation, purposeful switching between channels of knowledge delivery, emotional engagement, and overall involvement in the learning process. In contrast, the control group of 63 students who did not participate in the pilot project exhibited no changes in these metrics, or any fluctuations remained within the normal range of biorhythms.

7. Conclusions

The first overarching methodological conclusion regarding neuropedagogy for future primary school teachers is shaped by the anticipated competencies and neurophysiological characteristics of their future pupils. While high school teachers can concentrate on fostering social skills in pupils through more complex contexts, such as group projects and discussions, where emotional development may not be the primary focus, primary school pupils are still at the early stages of cognitive and emotional-volitional growth. This necessitates that teachers possess a profound understanding of the core principles of early brain development and the ability to tailor educational materials accordingly, which in turn influences the neuropedagogical approaches to teacher training.

A detailed analysis of neuropedagogical and related neuro-oriented research reveals that their foundational orientations tend to be overly broad. Nonetheless, in practice, these have translated into partial methodological guides for conducting interviews, analysing and assessing reflection, as well as discussions in collaborative settings, thereby aiding in the systematic accumulation of experience for neuropedagogical modelling. One can conclude that the prospects for neuroeducation and the demands for teacher training are advancing faster than the availability of effective practices. While the search for systematic frameworks for adult neuropedagogy continues, it is evident that, first, the meta-theoretical and epistemological foundations of neuropedagogy, neurophysiology, and anthropology are primed for educational modelling, and second, there has been a shift in the paradigm of university education itself. According to Huber (2015), neuroscientific research over the past decades has created a new image of humanity, accompanied by discoveries about the inherent neuro-attributions of natural learning and upbringing processes.

The results of the neuropedagogical modelling, followed by a quasi-experimental validation of a short academic pilot project, revealed the following conclusions:

1. For the neuropedagogical training of future primary school teachers, it is beneficial to adopt an integrative technological interdisciplinary approach (Nouri, Tokuhama-Espinosa, & Borja, 2022). This approach uses neuropsychological profiles of students to develop personalised learning plans, considering each student's unique characteristics, which are essential for effective learning. Moreover, the "visible learning" concept (Hattie & Yates, 2013), which focuses on feedback and self-regulation among students, has proven to be practically applicable. The neuro-cognitive scenario theories of Iatrellis, Kameas, and Fitsilis (2018) also facilitate personalised learning, necessitating students' dynamic neuroplasticity and their ongoing adaptation to changing circumstances, individual needs, and varying biorhythmic backgrounds.

2. The proposed methodology for personalised learning pathways, which includes frequent and purposeful switching between channels, has demonstrated positive effects on motivation, reflection, self-management, and students' awareness of specific emotions and interests in a "here and now" context. This bodes well for future, more systematic developments.

3. The proposed general methodology needs to be refined with specific scenarios for each application in academic practice, as the outline model offered only a broad understanding during testing.

Besides, the authors further established that the neuropedagogy for training primary school teachers is directly relevant to and aligns with the specific needs of younger pupils, considering their cognitive and emotional development stages. In contrast, neuropedagogy for other profiles is tailored to the more advanced cognitive abilities, academic demands, and less flexible neuroplasticity of older pupils.

This article, detailing the process and outcomes of the quasi-experimental validation of the authors' neuropedagogical technology for training primary school teachers, has confirmed the high neuro-stimulating validity of the technologised micro-social environment within higher education institutions. Additionally, it has partially enriched the meta-theory and overall direction of new post-nonclassical pedagogy and pedagogical futurology, which have been previously discussed (Vozniuk, 2019b) and are now taking on increasingly defined and tangible shapes.

8. Research Limitations

This article does not examine the academic (learning outcomes) and statistical changes resulting from the implementation of the authors' neuropedagogical technology. Thus, the authors anticipate that this issue will be explored in subsequent publications.

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To enhance sensitivity to the semantic structures of educational material, the authors implemented the following physical technologies as additional stimulating mechanisms:

- **Neurointeractive classrooms and laboratories**. These environments featured dynamic lighting that was adjusted based on students' brain activity, fostering optimal conditions for concentration and learning. Additionally, a variable sound environment was created, which adapted to students' emotional states, assisting them in either relaxing or focusing.
- **Biofeedback trainers for stress management**. It was decided to introduce neuro-meditative techniques and practices designed to equip future teachers with strategies for managing stress and boosting their emotional resilience through meditation and breathing exercises. Interactive games were also integrated to facilitate emotional management within a framework of rest and rewards.
- **Neuro-immersive learning journeys**. This approach involved creating or using pre-designed virtual trips that allowed students to explore various educational institutions worldwide, observe diverse teaching methods, and engage with teachers from different cultures. It also encompassed "cultural immersions" aimed at helping future primary school teachers gain insights into the varied contexts they may encounter in their careers.
- **Neuro-pedagogical simulators of conflict and problem situations**. These included both required and optional conflict role-plays, as well as simulation platforms that enabled students to practice handling conflict management scenarios that could arise in the classroom, receiving real-time feedback in the process.
- **Self-analysis of behaviour**. Algorithms were employed to facilitate self-analysis of students' behaviour during simulations, providing them with recommendations for enhancing their communication skills and conflict-resolution strategies.

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