The Efficiency of a Multimodal Neurotechnological Intervention (Cerebral Photobiomodulation, qEEG Neurofeedback, and Heart- Brain Biofeedback) in Enhancing Attention and Academic Performance in Middle School Students (11–15 years old): A Nationally Conducted Randomized Controlled Clinical Study

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Abstract

The purpose of this nationally conducted randomized controlled clinical study is to evaluate the efficiency of a multimodal neurotechnological intervention (gamma cerebral photobiomodulation at 40 Hz, personalized EEG neurofeedback, and heart–brain biofeedback) in enhancing attention and academic performance among urban middle-school children aged 11 to 15 years. The study involves a total sample of 200 healthy participants, equally distributed into an experimental group (n = 100, 50 girls and 50 boys) and a control group (n = 100, 50 girls and 50 boys). The intervention spans one year and is structured into three therapeutic cycles, each lasting 10 weeks with two weekly sessions, followed by 10 weeks of break between cycles.

The primary evaluations exclusively involve objective measurements of brain activity through quantitative electroencephalography (qEEG Brain Mapping), with a focus on specifically selected Brodmann areas, chosen for their demonstrated roles in regulating attention and cognitive performance (BA 5, 8, 19, 21, 22, 39, 44). Secondary evaluation involves objectively assessing physiological stress through heart coherence measurement (heart–brain biofeedback). Statistical analyses include paired and independent samples t-tests, repeated- measures ANOVA, and effect size calculations (Cohen's d).

The anticipated outcomes of the study are significant and objective increases in qEEG parameters within the selected cortical areas, correlated with evident improvements in attention, concentration, and academic performance. This study aims to validate and demonstrate the efficacy of an integrated neurotechnological approach as a proactive and preventive method for optimizing cognitive and academic performance during the critical cognitive developmental period of middle school. Practical implications of these findings support the integration of this type of intervention into educational and preventive clinical programs aimed at improving attention and academic achievement on a national scale.

Keywords: Multimodal Neurotechnological Intervention, Gamma Cerebral Photobiomodulation, EEG Neurofeedback, Heart–Brain Biofeedback, Attention, Concentration, Academic Performance, Quantitative Electroencephalogram (qEEG), Cardiac Coherence

Introduction

1.1 General Context

In contemporary society, characterized by a significant acceleration of life pace and constant exposure to increasingly complex external stimuli, attention and concentration have become critical cognitive resources in learning and academic development. Specifically, the middle-school period, covering ages 11 to 15, represents a crucial and sensitive stage in students' intellectual, emotional, and social development. During this time, students experience a substantial increase in academic demands, informational volume, and cognitive requirements, all coinciding with a complex period from a neurobiological and psycho-social perspective (Casey et al., 2005; Steinberg, 2010).

At the cerebral level, the age range from 11 to 15 is characterized by rapid and significant maturation of the prefrontal cortex and neural networks involved in executive functions such as planning, organization, cognitive flexibility, self-regulation, and attention. Scientific literature emphasizes that this stage of brain maturation is essential for consolidating fundamental cognitive abilities, particularly sustained and selective attention, working memory, and inhibitory control (Diamond & Ling, 2016). Concurrently, temporal and parietal areas implicated in multisensory integration and semantic processing reach critical developmental stages essential for students' abilities to process complex educational content, including verbal explanations, written materials, and graphical and visual representations (Posner & Rothbart, 2014).

However, the current reality of the Romanian educational system, similarly reflected in many other European countries, presents a persistent challenge: students' difficulty in maintaining focused and sustained attention throughout classroom activities. Recent research highlights an alarming prevalence of attentional issues in the school environment, further exacerbated by digital overstimulation, heightened academic performance pressures, and excessively demanding school schedules. Furthermore, chronic stress, academic performance anxiety, and constant exposure to digital environments disrupt cognitive functions, directly affecting students' ability to learn effectively, retain information, and achieve optimal educational performance (Gazzaley & Rosen, 2016; Twenge, 2018).

Within this context, identifying effective, safe, and scientifically validated methods and interventions to support the development and optimization of attention and associated cognitive functions has become essential and extremely urgent. Recent studies in applied educational neuroscience have revealed the remarkable potential of modern neurotechnological interventions, such as qEEG neurofeedback, cerebral photobiomodulation, and heart–brain biofeedback, in enhancing cognitive and emotional capabilities of children and adolescents. These methods are grounded in neuroplasticity—the brain's ability to functionally and structurally modify neuronal connections in response to specific and adequate stimulation—leading to lasting and measurable improvements in cognitive performance (Hamblin, 2016; Enriquez-Geppert et al., 2017).

Gamma cerebral photobiomodulation, personalized EEG neurofeedback, and heart–brain biofeedback are non-invasive, easily applicable, and highly promising methods. Recent studies demonstrate that gamma cerebral photobiomodulation effectively stimulates neuroplasticity, supports cognitive clarity, and facilitates the elimination of neuronal toxic accumulations, significantly enhancing cognitive capacity and concentration (Salehpour & Hamblin, 2020). qEEG neurofeedback enables real-time direct regulation of brain electrical activity, allowing students to learn how to control and optimize their neuronal activity independently, leading to improved attention and executive functioning (Enriquez-Geppert et al., 2017). Heart–brain biofeedback contributes to autonomic nervous system balance, reduces physiological stress, and enhances emotional self-regulation—critical factors for sustained attention and academic performance (McCraty & Shaffer, 2015).

However, to date, both in Romania and international literature, there is a limited number of large-scale, rigorous studies assessing the effectiveness of an integrated, multimodal intervention combining these specific neurotechnological methods in improving attention and academic performance among middle-school children. Moreover, the scarcity of large-scale studies conducted on well-defined and representative populations limits the possibilities of nationwide implementation of such effective neurotechnological interventions.

The present randomized controlled clinical study aims precisely to address these significant gaps in current literature by rigorously evaluating the efficiency of an integrative neurotechnological protocol applied nationwide. This scientific endeavor will have direct implications both for current educational practices and future research in applied educational neuroscience, significantly contributing to the development and validation of modern, safe, and effective therapeutic approaches to optimize attention and academic success among middle- school children.

Thus, our research aims not only to provide clear and robust evidence regarding the effectiveness of the proposed neurotechnologies but also offers innovative perspectives for a preventive and proactive approach to education, directly contributing to enhancing students' quality of life and supporting their cognitive and emotional development during this critical life stage.

1.2 Theoretical Foundation of the Selected Neurotechnological Interventions

Our study employs an integrative neurotechnological approach, strategically combining three complementary methods selected for their demonstrated potential in optimizing attention, cognitive performance, and psycho-physiological balance among middle-school children. These methods include cerebral photobiomodulation, quantitative EEG neurofeedback (qEEG), and heart–brain biofeedback (cardiac coherence). The scientific rationale and selection of these interventions derive from established principles of neuroplasticity, autonomic neurophysiological regulation, and cognitive and emotional optimization recently documented in applied neurosciences.

Gamma Cerebral Photobiomodulation

Gamma cerebral photobiomodulation is an advanced, non-invasive therapeutic method utilizing pulsed near-infrared light to directly stimulate key brain regions. This neurotechnological technique is scientifically grounded in the capability of pulsed gamma- frequency light (40 Hz) to positively influence neuronal activity and promote neuroplasticity, essential for advanced cognitive functions, including focused attention, processing speed, and working memory (Iaccarino et al., 2016; Hamblin, 2016).

The selection of the gamma frequency (40 Hz) is scientifically deliberate. Recent research demonstrates clearly that gamma frequency (approximately 40 Hz) is directly linked to advanced cognitive processes, such as focused attention, working memory, and the integration of sensory and cognitive information. Consequently, stimulating the brain at this specific frequency directly optimizes these key cognitive processes.

Fundamental and Specific Mechanisms of Gamma Cerebral Photobiomodulation:

1. **Neuronal mitochondrial stimulation:**
   One primary mechanism underlying photobiomodulation involves enhancing mitochondrial activity in neuronal cells via cytochrome C oxidase. This mitochondrial enzyme plays a critical role in cellular ATP generation, the primary neuronal energy provider (Salehpour et al., 2018). By increasing ATP production, photobiomodulation enhances neuronal energy efficiency, thereby facilitating sustained attention and complex cognitive processes (Hamblin, 2018).
2. **Reduction of neuronal inflammation and oxidative stress:**
   Recent studies indicate that oxidative stress and cerebral inflammation can directly impair cognitive capacities, including attention and memory (Cassano et al., 2016). Cerebral photobiomodulation

reduces oxidative stress and inhibits neuronal inflammation, consequently improving mental clarity, cognitive resilience, and reducing fatigue associated with intense cognitive activities (Naeser & Hamblin, 2015).

3. **Enhancement of neuroplasticity and synaptic activity:**
   Gamma-pulsed light at 40 Hz induces neuronal synchronization within gamma frequency bands, directly enhancing neuroplasticity and facilitating the formation of efficient new neural connections (Vargas et al., 2017). This mechanism is crucial for improving higher- order cognitive functions such as sustained attention and working memory, which are necessary for optimal academic performance (Barrett & Gonzalez-Lima, 2013).

Specific Effects on Attention and Academic Performance in Middle School

Specifically, applying gamma photobiomodulation directly and measurably influences middle-school students' capacity to maintain focused attention and process complex information, thereby enhancing overall academic performance. Recent literature documents specific effects, including:

- **Enhanced selective and focused attention:**
  Students periodically exposed to this technique show greater ability to ignore distractions and concentrate exclusively on educational tasks, directly reflected in improved efficiency and accuracy in performing academic activities (e.g., reading, problem- solving, understanding complex verbal instructions).
- **Accelerated cognitive and information processing speed:**
  By intensively stimulating the brain at gamma frequencies, students can process new information more quickly and efficiently, an essential benefit in the dynamic educational environment where they are constantly exposed to novel and complex information. This enhancement facilitates effective assimilation of lessons and prompt responsiveness to teachers' requests.
- **Improved memory and retention capabilities:**
  Gamma cerebral photobiomodulation contributes to consolidating working and long-term memory by stimulating neuronal synapses and memory-associated networks. This effect assists students in better retaining educational materials and effectively applying knowledge in diverse academic contexts.
- **Reduced cognitive fatigue and improved resilience to academic stress:**
  Through its anti-inflammatory and antioxidant effects at the cerebral level, photobiomodulation directly reduces mental fatigue and cerebral stress accumulated through intense academic activities, thereby enhancing students’ capability to cope with prolonged educational demands.

Thus, gamma cerebral photobiomodulation offers direct, concrete benefits for cognitive processes essential to academic success. The inclusion of this method in our therapeutic protocol is fully justified. Within the current context of middle-school education, characterized by constant cognitive challenges and sustained concentration demands, regular application of this advanced neurotechnological technique becomes an effective and scientifically grounded therapeutic strategy. It significantly enhances students' ability to learn efficiently, perform academically, and adapt to the cognitive demands of the contemporary educational environment.

Quantitative EEG Neurofeedback (qEEG Neurofeedback)

Quantitative EEG neurofeedback (qEEG) is an advanced therapeutic technique that utilizes precise and objective recordings of cerebral electrical activity to enable participants to directly self-regulate their neuronal functioning. This method involves real-time monitoring of cortical electrical activity using quantitative electroencephalography (qEEG) and provides immediate feedback in the form of visual and auditory stimuli. Consequently, participants learn to voluntarily control and optimize their own neural patterns through adaptive neuroplasticity and conscious self-regulation mechanisms (Enriquez-Geppert et al., 2017; Hammond, 2011).

Neurofeedback is based on the principle that specific cognitive functions—such as attention, working memory, and inhibitory control—can be improved by training the self- regulation of their associated brain activities. Recent research demonstrates that this method directly promotes neuroplastic changes in specific neuronal networks, thereby optimizing

cerebral functioning linked to attention and concentration (Arns et al., 2014; Vernon et al., 2003).

In the current study, the qEEG neurofeedback intervention has been personalized and strategically oriented towards cortical areas recognized for their specific roles in controlling and sustaining attention, as well as processing essential educational information. The brain areas selected for targeted intervention include Brodmann Areas (BA): 5, 8, 19, 21, 22, 39, and 44.

- **Brodmann Area 5 (Superior Parietal Cortex)**: Crucially involved in spatial attention and sensorimotor integration, essential for school-related tasks such as writing, drawing, and practical assignments (Culham & Kanwisher, 2001).
- **Brodmann Area 8 (Superior Frontal Cortex – Frontal Eye Fields)**: Vital for visual attention and precise control of eye movements, necessary for rapid and efficient reading of textual materials (Pierrot-Deseilligny et al., 2004).
- **Brodmann Area 19 (Secondary Associative Visual Cortex)**: Responsible for complex visual information processing, maintaining visual attention on details, and swiftly decoding educational visual materials (Kravitz et al., 2013).
- **Brodmann Area 21 (Middle Temporal Gyrus)**: Involved in semantic memory and recognition of complex visual objects and concepts, thus facilitating rapid associative learning of information presented in class (Binder et al., 2009).
- **Brodmann Area 22 (Superior Temporal Gyrus – Wernicke's Area)**: Central for advanced auditory processing and verbal language comprehension, essential in educational settings for effectively following teachers' explanations and classroom discussions (Friederici, 2011).
- **Brodmann Area 39 (Angular Gyrus)**: Essential for integrating visuospatial, mathematical, and linguistic information, directly contributing to developing skills in arithmetic, reading, and conceptual understanding (Seghier, 2013).
- **Brodmann Area 44 (Broca's Area – Inferior Frontal Cortex)**: Directly involved in language processing, verbal attention, and internal articulation abilities, effectively supporting active classroom participation and comprehension of oral instructions (Hagoort, 2005).

Specific Effects on Attention and Academic Performance

Recent studies provide strong support that qEEG neurofeedback significantly contributes to:

- **Enhanced sustained and focused attention** through cortical activity self-regulation in frontal and parietal regions, directly associated with selective and executive attention control (Arns et al., 2009).
- **Improved inhibitory control and reduced impulsivity**, key factors influencing students' ability to remain focused on academic tasks and resist distractions (Monastra et al., 2005).
- **Reduced hyperactivity and attention deficit symptoms**, facilitating better adaptation to the educational environment and clear improvements in academic performance (Arns et al., 2014; Coben & Evans, 2010).
- **Optimized working memory and cognitive processing speed**, essential elements for effective learning and enhanced academic performance (Gevensleben et al., 2009).

By integrating qEEG neurofeedback into our therapeutic protocol, we aim to provide middle- school students with a personalized, scientifically robust method for optimizing their neural activity and directly enhancing their attention and concentration abilities, thus supporting superior academic performance.

Heart-Brain Biofeedback (Cardiac Coherence)

Heart-brain biofeedback, also known as cardiac coherence biofeedback, is a scientifically validated, non-invasive therapeutic method leveraging the close relationship between cardiovascular function and brain activity (McCraty & Shaffer, 2015). This approach involves guided rhythmic and coherent breathing exercises, individually tailored to each participant, aiming to induce and maintain an optimal physiological state termed "cardiac coherence" (Lehrer & Gevirtz, 2014).

Cardiac coherence is characterized by a distinct heart rate variability (HRV) pattern, defined by optimal synchronization and balance between the sympathetic and parasympathetic branches of the autonomic nervous system (McCraty & Shaffer, 2015). This balanced physiological state directly correlates with decreased overall physiological stress, reduced anxiety, enhanced attention, cognitive clarity, and improved emotional and physiological self- regulation (Lehrer & Gevirtz, 2014; Shaffer et al., 2014).

The central mechanism underlying this method involves the voluntary and conscious regulation of breathing at a specific frequency known as the resonance frequency. When participants breathe coherently at this individualized rhythm, deep harmonization occurs among heart rate, brain activity, and other physiological processes (Lehrer et al., 2020). Consequently, heart-brain biofeedback not only optimizes autonomic regulation and mitigates chronic stress effects but also fosters a psychophysiological state conducive to cognitive and academic performance (McCraty & Shaffer, 2015; Lehrer & Gevirtz, 2014).

Recent studies demonstrate that consistent application of cardiac coherence biofeedback results in measurable improvements in students' ability to manage school-related pressures, such as exam stress, demanding academic tasks, and complex social interactions characteristic of early adolescence (Goessl et al., 2017).

Over the long term, students become capable of autonomously regulating their emotions and physiological responses, thus improving academic performance through better-focusedattention, enhanced memory retention, and increased cognitive processing speed (Lehrer et al., 2020). Hence, heart-brain biofeedback represents a pragmatic and essential therapeutic strategy to support balanced development in middle-school students, with the potential to profoundly transform their stress management and optimize cognitive processes fundamental to learning (McCraty & Shaffer, 2015).

By integrating cardiac coherence biofeedback into our multimodal therapeutic protocol, we aim to significantly contribute to improving students' emotional management, reducing stress, and sustaining effective and focused attention during educational activities (Goessl et al., 2017; Lehrer & Gevirtz, 2014).

The strategic integration of these three complementary neurotechnological methods— cerebral photobiomodulation, qEEG neurofeedback, and heart-brain biofeedback—enables a holistic, comprehensive, and highly effective approach to optimizing attention and academic performance in middle-school students. Simultaneous and integrated use of these techniques leverages therapeutic synergy, whereby the beneficial effects of each method enhance one another, resulting in significantly superior therapeutic outcomes compared to applying each method separately (Hamblin, 2016; Arns et al., 2009; Lehrer & Gevirtz, 2014).

Cerebral photobiomodulation enhances overall neuronal metabolism and brain neuroplasticity by mitochondrial stimulation and deep synaptic activation (Hamblin, 2016). This mechanism supports and amplifies the direct effects of qEEG neurofeedback, enabling precise and personalized training of neuronal electrical activity explicitly targeting cortical areas involved in attention, concentration, and complex information processing in educational settings (Arns et al., 2009; Enriquez-Geppert et al., 2017). Combining these two methods achieves a level of neuronal optimization—both functional and structural—that sustainably supports students' cognitive and academic performance.

Complementing these techniques, heart-brain biofeedback facilitates optimal emotional and autonomic regulation, reduces physiological stress, and fosters an ideal state of concentration and cognitive clarity (McCraty & Shaffer, 2015; Lehrer & Gevirtz, 2014). Recent studies emphasize that reducing stress and enhancing emotional and physiological self-regulation capacity are crucial in educational contexts, as chronic stress directly impacts students' ability to maintain attention and process academic information effectively (Bradley et al., 2010; Goessl et al., 2017).

Thus, this multimodal approach not only holds potential for increased therapeutic efficacy but also reflects advanced and contemporary trends in applied educational neuroscience. The simultaneous use of these three methods creates a unique therapeutic context wherein students concurrently benefit from neuroplasticity induced by photobiomodulation, direct cortical regulation via neurofeedback, and profound emotional and physiological regulation through heart-brain biofeedback. Consequently, integrating these methods is fully justified scientifically, clinically, and educationally, providing a comprehensive and efficient therapeutic intervention for enhancing attention and academic performance among middle-school students.

2. Objectives

2.1 General Objective

The main objective of this randomized controlled clinical study is the rigorous, comprehensive, and objective evaluation of the effectiveness of a multimodal neurotechnological intervention protocol, comprising cerebral photobiomodulation at gamma frequency (40 Hz), personalized qEEG neurofeedback, and heart-brain biofeedback, for improving attention, concentration, and academic performance in middle-school students (ages 11–15). Specifically, the study aims to determine the extent to which this integrative intervention can produce measurable and stable changes in brain activity (as assessed by quantitative EEG brain mapping), as well as in neurovegetative and emotional balance (assessed through cardiac coherence evaluation). The ultimate goal is enhancing academic performance, school adaptation, and the overall educational quality of life for the participating students.

This research aims to provide clear and objective evidence supporting the widespread adoption of this preventive intervention within national educational contexts, thus contributing directly and measurably to developing neuroscience-based modern strategies for optimizing cognitive and emotional development among children.

2.2 Specific Objectives

2.2.1 Assessment of Objective Changes in Brain Activity (qEEG) in Specific Cortical Areas Associated with Attention and Concentration (BA 5, 8, 19, 21, 22, 39, and 44)

The first specific objective involves rigorous assessment of objective and measurable changes in brain activity using quantitative and qualitative EEG analysis (qEEG – brain mapping) within strategically selected cortical areas, which have documented roles in attention, information processing, and academic performance. These include Brodmann areas 5, 8, 19, 21, 22, 39, and 44. The study aims to clearly identify alterations induced by the multimodal neurotechnological intervention in neuronal activity within these regions, thus demonstrating the direct and specific impact of the intervention on students' attention and concentration capabilities.

This objective involves precise measurement and rigorous analysis of cortical changes specific to attention and complex information processing, resulting from the proposed neurotechnological intervention. Evaluation of neuronal electrical activity will be performed using quantitative EEG (qEEG) brain mapping with a standardized 19-channel EEG system, following the international 10–20 system.

Cortical maps will be generated before and after each intervention cycle, thus objectively and precisely identifying induced changes within each strategically selected cortical area.

Each targeted brain area (BA 5, 8, 19, 21, 22, 39, and 44) is well-documented in neuroscience literature as critical for various forms and components of attention (visual, auditory, verbal, and spatial). Our study will quantify the precise manner in which the neurotechnological intervention optimizes the functioning of these regions. Specifically, we will analyze changes in the amplitude and coherence of relevant brainwave frequencies (alpha, beta, gamma) directly associated with attentional and higher cognitive processes.

Through this objective evaluation, the study intends to provide clear, measurable evidence of improvements in neuronal activity, directly linked to enhanced attention and concentration capacity among middle-school students.

2.2.2 Assessment of Physiological Stress Levels via Heart-Brain Coherence

The second specific objective is to objectively evaluate changes in physiological stress levels through heart-brain coherence measurements (heart-brain biofeedback). This objective clearly and reproducibly quantifies the impact of the neurotechnological intervention on children's physiological and emotional self-regulation abilities, recognizing that stress reduction is essential for enhancing attention, cognitive processes, and academic performance.

This objective involves the precise, objective measurement of physiological and emotional stress changes in participants, utilizing biofeedback based on cardiac coherence. Evaluations will be conducted pre- and post- each therapeutic cycle using a specialized clinical device (GP8 – Global Performance 8), which accurately measures heart-brain coherence and heart rate variability (HRV).

Physiological stress levels, assessed through cardiac coherence, are acknowledged in the scientific literature as highly sensitive indicators of autonomic balance, directly influencing concentration, working memory, and overall academic performance. By objectively evaluating changes in physiological stress, this objective aims to clearly demonstrate how stress reduction contributes directly to improving students' attention, resilience, and cognitive performance.

Thus, our intervention will be evaluated not only from the perspective of brain performance but also in terms of emotional and physiological balance—factors highly relevant to the educational context and optimal childhood development.

2.2.3 Rigorous Comparative Assessment Between Experimental and Control Groups to Clearly Demonstrate Intervention Efficacy

The third specific objective is to conduct a rigorous and detailed comparative analysis between the experimental group and the control group. The aim is to clearly identify differences between the two groups regarding measurable changes in brain activity (qEEG) and physiological stress levels (heart-brain coherence), conclusively and robustly demonstrating the efficacy and specificity of the proposed multimodal neurotechnological protocol. This comparison will decisively contribute to validating the intervention and provide scientific and practical grounds for recommending its large-scale implementation within the educational system.

This objective is essential for the rigorous scientific validation of our intervention and involves a clear and systematic comparative analysis between two equal groups in terms of number and demographic characteristics (age, gender, urban environment). The experimental group will benefit from the multimodal neurotechnological intervention, while the control group will not participate in any form of intervention.

qEEG and heart-brain coherence evaluations will be performed simultaneously for both groups at clearly standardized time points (pre- and post-each therapeutic cycle). This approach will allow us to precisely identify the specific effects of our intervention, excluding placebo influences or natural variations in the development of attention and cognitive capacity.

Through rigorous statistical analyses (repeated measures ANOVA and independent t- tests) and effect-size indicators (Cohen’s d), our goal is to convincingly and clearly demonstrate that observed changes in the experimental group are significantly greater and more consistent compared to the control group.

The results of this comparative analysis will validate not only the efficacy of our multimodal neurotechnological intervention but also form the evidence-based foundation for clear recommendations supporting its national implementation as an effective tool for improving students' attention and academic performance.

3. Methodology and Clinical Study Design

3.1 General Design

The proposed research is a randomized, controlled, longitudinal clinical trial with a total duration of 52 weeks (one full calendar year), conducted nationally across the BrainMap Neuroscience clinical network in Romania. This rigorous design was chosen to acquire robust, objective, and reproducible data on the efficacy of a multimodal neurotechnological intervention for enhancing attention and academic performance in middle-school students (aged 11–15).

Participants will be randomly assigned to two equally sized groups, each consisting of 100 healthy children aged 11–15, exclusively from urban environments, balanced evenly by gender (50 girls and 50 boys per group). This balanced demographic structure ensures the representativeness and comparability of groups, enhancing the internal and external validity of the study’s findings.

Experimental Group (N = 100)

Participants in this group will receive the multimodal neurotechnological therapeutic protocol, comprising gamma cerebral photobiomodulation (40 Hz), personalized quantitative EEG neurofeedback (qEEG), and heart–brain biofeedback, structured into therapeutic cycles of 10 weeks each. Each therapeutic cycle includes two weekly sessions (totaling 20 sessions per cycle), followed by a 10-week rest period. Thus, over the entire year, each participant in the experimental group will complete three full therapeutic cycles, enabling cumulative and sustainable evaluation of intervention effects.

Control Group (N = 100)

Participants in this group will not undergo any neurotechnological intervention. They serve as a crucial comparison group to objectively assess the specific efficacy of the intervention delivered to the experimental group. Participants will continue their usual school-related and extracurricular activities, with no additional modifications induced by the research protocol.

Primary and Secondary Evaluations

For all participants (both experimental and control groups), objective evaluations will be systematically conducted at clearly defined and consistent key points:

- **Primary evaluation**: Brain activity assessment through quantitative EEG (Brain Mapping), using 19-channel EEG equipment positioned according to the international 10–20 system. Evaluations will be performed before (pre-test) and after (post-test) each therapeutic cycle for both groups, allowing exact and rigorous quantification of cortical changes associated with attention and academic cognitive performance.

- **Secondary evaluation**: Physiological and emotional stress levels assessed objectively through heart–brain coherence measurements using the clinical device GP8 Global Performance 8. This evaluation is conducted simultaneously with the qEEG testing, before and after each therapeutic cycle, clearly identifying changes in participants' autonomic and emotional balance.

Randomization and Variable Control

Participant randomization into the two groups will be conducted through a rigorous, transparent computerized randomization procedure, ensuring the avoidance of biases and external influences on participant allocation. All qEEG and heart–brain biofeedback testing procedures and conditions will be rigorously standardized and clearly documented across each participating clinic, ensuring consistency and reproducibility of results at a national level.

Thus, this carefully controlled, comprehensive, longitudinal design provides a robust methodological foundation for clearly, objectively, and rigorously demonstrating the efficacy of a multimodal neurotechnological intervention for optimizing attention and academic performance among middle-school students.

3.2 Sample Characteristics

To ensure the clinical, scientific, and educational relevance of the outcomes obtained from our study, we have established a clear and rigorous set of inclusion and exclusion criteria for participant selection. Participants are healthy middle-school students (ages 11–15), with no previous diagnosis of neurological, neuropsychological, or psychiatric disorders, and without significant medical histories in neurological or psychiatric domains.

Inclusion criteria:

- Chronological age strictly between 11 and 15 years, accurately reflecting the middle- school period and the cognitive challenges specific to this educational stage.
- Absence of diagnosed neurological disorders such as epilepsy, movement disorders, or other neurological conditions that could influence qEEG measurements and the results of the intervention.
- Absence of diagnosed psychiatric or neuropsychological disorders, including autism spectrum disorders, ADHD, severe anxiety disorders, or depression, to eliminate their influence on attention and cognitive performance results.
- No current or recent (last 6 months) administration of psychoactive medications or substances that could impact the central nervous system (CNS) and neurophysiological measurements (qEEG and heart-brain biofeedback).

Exclusion criteria:

- Current or previous diagnosis of neurological or psychiatric disorders.
- Clinically confirmed neurodevelopmental disorders or clear suspicion thereof.
- Recent medical history of significant head trauma or medical comorbidities affecting CNS function.
- Current or recent use of psychotropic medications, stimulants, or other substances influencing cerebral activity.

In terms of demographic balance, the sample will include an equal number of girls and boys in both the experimental and control groups, with each group comprising 50 girls and 50 boys. Additionally, to maintain consistency and minimize external influences arising from socioeconomic conditions or cultural differences, all participants will be recruited exclusively from urban environments, ensuring uniformity in the educational and social context.

3.3 Detailed Structure of the Therapeutic Intervention

The therapeutic intervention proposed in this clinical study has been carefully structured to ensure optimal and sustained impact on improving attention and academic performance among middle-school students. The therapeutic protocol is organized over a full calendar year, divided into three distinct therapeutic cycles. Each therapeutic cycle comprises 10 consecutive weeks of active intervention, followed by a 10-week rest period, allowing for the observation of both immediate and cumulative long-term effects of the applied protocol (Vernon et al., 2003).

During each therapeutic cycle, children in the experimental group will participate in two weekly sessions, scheduled consistently on fixed days to maintain procedural coherence and minimize the influence of external factors on intervention outcomes. Therefore, each therapeutic cycle includes a total of 20 therapeutic sessions.

Each therapeutic session has a standardized duration of 60 minutes, logically structured to optimize intervention efficiency and participant comfort. Each session begins with a 15- minute preparation and procedural adjustment period, during which children are comfortably accommodated, equipment is personalized, and therapeutic parameters are individually adjusted and verified.

The first active therapeutic stage involves personalized qEEG neurofeedback, lasting 20 minutes. During this phase, each participant receives precise auditory and visual feedback about the electrical activity in selected cortical areas (Brodmann Areas 5, 8, 19, 21, 22, 39, and 44), aimed at optimizing neuronal functions directly involved in attention and concentration (Enriquez-Geppert et al., 2017). The protocol is individually tailored, continuously adjusted based on initial and interim assessments.

The second therapeutic stage consists of cerebral photobiomodulation using pulsed gamma light at 40 Hz for 10 minutes. This method employs a clinically certified specialized headset, stimulating cerebral activity in frontal and parietal regions to facilitate neuroplasticity and enhance cognitive and attentional performance among children (Salehpour & Hamblin, 2020).

The session concludes with heart-brain biofeedback, carried out for 15 minutes. In this stage, participants are guided to control their breathing patterns to achieve optimal cardiac coherence, monitored in real-time via clinically certified software. This scientifically validated technique significantly contributes to reducing physiological stress and enhancing emotional and cognitive resilience—critical components for improved attention and academic performance (McCraty & Shaffer, 2015).

Selected Cortical Areas for the Study of Attention and School Performance

1. Brodmann Area 5 (Superior Parietal Cortex – Sensorimotor Integration and Spatial Attention)

Brodmann Area 5 actively participates in coordinating spatial attention and integrating sensory- motor information. This area is essential for school-related tasks requiring sustained attention, such as writing, drawing, practical project execution, and other educational tasks involving spatial coordination. Optimizing activity in this area significantly contributes to improved spatial attention and cognitive performance in activities demanding multisensory integration (Rushworth & Taylor, 2006).

2. Brodmann Area 8 (Superior Frontal Cortex – Frontal Eye Fields)

Brodmann Area 8 is fundamentally involved in controlling visual attention by regulating saccadic eye movements and maintaining selective visual attention. Training this area can enhance the speed and precision of eye movements essential for reading and interpreting visual

educational materials, significantly improving overall academic performance (Pierrot- Deseilligny et al., 2004).

3. Brodmann Area 19 (Secondary Visual Associative Cortex)

Area 19 is responsible for complex visual processing, directly involved in maintaining attention to detailed visual information presented during classroom activities (written texts, diagrams, educational charts). Optimal functioning of this area enhances students' ability to rapidly and efficiently process visual information, significantly improving sustained visual attention and general learning capacity (Wandell et al., 2007).

4. Brodmann Area 21 (Middle Temporal Gyrus)

Area 21 plays a crucial role in semantic memory and complex visual recognition, significantly contributing to quick and efficient associations between visual and verbal concepts. Improving activity in this area enables students to form faster and more effective connections between concepts and information, facilitating memorization and understanding of complex educational materials (Binder et al., 2009).

5. Brodmann Area 22 (Superior Temporal Gyrus – Wernicke's Area)

Brodmann Area 22 (Wernicke's area) is responsible for advanced auditory processing and comprehension of spoken language. Enhanced activity in this area directly supports students' auditory attention, enabling better comprehension and retention of verbally presented classroom information, thereby significantly contributing to academic success (Friederici, 2011).

6. Brodmann Area 39 (Angular Gyrus)

Area 39 is deeply involved in integrating visuospatial information and semantic processing, making it critical for developing advanced mathematical and linguistic skills. Optimal functioning of this region facilitates solving complex academic problems, such as text comprehension, efficient numerical operations, and developing conceptual skills essential for advanced academic performance (Dehaene et al., 2004).

7. Brodmann Area 44 (Broca's Area – Inferior Frontal Cortex)

Broca's Area (BA 44) plays a central role in language production and maintaining active verbal attention, essential for processing verbal instructions and active participation in classroom oral communication. Optimizing activity in this area helps students quickly and effectively assimilate verbally transmitted information, directly supporting academic performance and efficient classroom interactions (Price, 2012).

These cortical areas were strategically selected based on their clearly demonstrated scientific involvement in cognitive processes essential for attention and academic performance. Each selected area specifically contributes to various aspects of the educational process, covering a broad spectrum of essential cognitive abilities (spatial and visual attention, multisensory

integration, semantic memory, auditory processing, and language). By targeting these regions through neurotechnological intervention, our study aims to objectively demonstrate that improving attention via neurotechnological methods directly leads to significant enhancements in school performance among middle-school students.

4. Instruments and Measures

4.1 Primary Analysis: Brain Mapping (qEEG)

The primary evaluation of the effects of the multimodal neurotechnological intervention on attention and academic performance among middle-school students employs quantitative and qualitative electroencephalography (qEEG). This technique is a standardized, objective clinical tool, widely validated in contemporary neuroscientific research and clinical practice, enabling precise and detailed measurement of neuronal electrical activity (Thatcher, 2010; Arns et al., 2014).

In this study, qEEG evaluations are conducted using a high-performance 19-channel EEG system (BrainMaster®), positioned according to the international 10–20 system standard. This equipment is renowned for the accuracy, reliability, and reproducibility of its measurements, facilitating a rigorous and detailed analysis of the brain activity of each participant (Collura, 2014).

The qEEG measurements are conducted in controlled, standardized clinical conditions, both in eyes-closed (resting) and eyes-open states, aiming to objectively identify subtle cortical changes induced by each therapeutic cycle. These pre- and post-intervention recordings thus allow for clear and objective evaluations of participants' neurophysiological progress.

The BrainMaster® software provides advanced quantitative analyses of cortical activity, including evaluations of absolute and relative power across specific brain frequency bands (Delta, Theta, Alpha, Alpha1, Alpha2, LoBeta, Beta, HiBeta, and Gamma). Additionally, the software offers analysis of essential indicators such as interhemispheric and intrahemispheric coherence, frontal cortical asymmetry, and neuronal flexibility—indicators scientifically recognized for their clinical relevance concerning attention and cognitive performance (Arns et al., 2014).

Using this highly sensitive and objective method, the study aims to identify specific modifications in neuronal electrical activity within strategically selected cortical areas (BA 5, 8, 19, 21, 22, 39, 44), thus providing robust evidence of the effectiveness of the multimodal neurotechnological intervention in optimizing attention and academic performance among middle-school children.

A rigorous and consistent assessment of therapeutic intervention effects represents a cornerstone of this clinical study’s design. For this purpose, every participant—both from the experimental and the control group—is evaluated through qEEG analysis before and after each therapeutic cycle, thus ensuring an objective and clear comparison of neurophysiological changes resulting from the intervention (pre-post).

These evaluations are strategically scheduled immediately before the commencement and immediately after the completion of each 10-week active intervention cycle. This longitudinal and repeated approach allows for detailed observation of the cumulative and sustained effects of the neurotechnological protocol on brain activity, and consequently, on students' attention and learning capabilities (Enriquez-Geppert et al., 2017).

Periodic pre-post measurements provide a solid foundation for precise data interpretation, facilitating not only the identification of immediate changes but also the observation of long- term cognitive performance improvements and neuroplasticity in participants. Furthermore, these periodic evaluations ensure the validity and relevance of the study’s results, clearly and objectively demonstrating the impact of the proposed neurotechnological intervention on brain functioning in middle-school students.

4.2 Secondary Analysis: Evaluation of Physiological Stress Using Heart-Brain Biofeedback (GP8 Global Performance 8)

The secondary analysis proposed in this study involves the detailed and objective measurement of physiological stress levels using heart-brain coherence biofeedback, employing the clinically validated medical device GP8 Global Performance 8. This internationally recognized method quantifies the synchronization between cardiac activity, respiratory patterns, and autonomic regulation mediated by the sympathetic and parasympathetic nervous systems (McCraty & Shaffer, 2015; Lehrer & Gevirtz, 2014). The state of cardiac coherence reflects optimal physiological balance and correlates directly with decreased physiological stress and improved cognitive and attentional capacities.

In this study, each child will undergo heart-brain biofeedback assessments immediately before (pre-intervention) and after (post-intervention) each 10-week therapeutic cycle.
Assessments will be conducted under standardized conditions within a controlled, comfortable, and quiet clinical environment to minimize external influences on measurement accuracy. Each biofeedback evaluation session will last approximately 20 minutes, during which participants will perform guided rhythmic breathing exercises individually adapted to their personal cardiac resonance frequency.

Throughout the evaluation, the GP8 Global Performance 8 device will continuously record real-time parameters of cardiac coherence, including heart rate variability (HRV), overall coherence index, and the synchronization level between respiratory and autonomic cardiac activity. These parameters offer objective indicators of physiological stress levels and participants' ability to adaptively self-regulate emotional and physiological states.

By systematically and repeatedly conducting pre- and post-intervention evaluations, we will clearly and comprehensively document the evolution of participants' self-regulation capabilities, as well as changes directly induced by the multimodal neurotechnological intervention. This rigorous methodological approach ensures the collection of precise and relevant data on stress reduction, significantly contributing to the interpretation of mechanisms by which the intervention positively influences attention, concentration, and academic performance among middle-school students.

Thus, incorporating heart-brain coherence biofeedback will enrich and deepen the interpretation of study outcomes, providing a more holistic and nuanced understanding of secondary therapeutic effects. This effectively complements the qEEG measurements obtained via brain mapping, supporting the overall validity and robustness of our intervention protocol.

5. Experimental Procedure

5.1 Initial Pre-Testing for All Participants (Brain Mapping and Heart-Brain Biofeedback)

Prior to initiating the multimodal neurotechnological intervention, all 200 participants involved in this study (100 in the experimental group and 100 in the control group) undergo a detailed, carefully structured initial pre-testing phase. The aim of this phase is to establish a comprehensive, individualized neurophysiological and autonomic profile, thereby ensuring an objective, scientifically grounded baseline for subsequent evaluations.

Initial pre-testing takes place under strictly controlled and standardized conditions within a calm, comfortable clinical environment specifically adapted to the middle-school age group.
This step is crucial for establishing a clear and robust neurophysiological baseline needed to objectively

evaluate the real effects of the therapeutic intervention applied later.

The first key component of pre-testing involves conducting quantitative and qualitative electroencephalographic analysis (qEEG – Brain Mapping). This assessment utilizes clinically certified, high-performance EEG equipment equipped with 19 electrodes placed according to the international 10-20 standard system (Jasper, 1958). Electrodes are carefully positioned following clinical guidelines and individually verified to ensure optimal impedance (below 5 kilo-ohms), guaranteeing the highest quality EEG recordings.

The EEG recording protocol comprises two distinct segments, each lasting 8–10 minutes. In the first segment, participants remain comfortably seated and relaxed with eyes open, focusing on a fixed point. This procedure captures baseline cortical activity associated with relaxed wakefulness and visual attention. The second recording segment, conducted with eyes closed, specifically captures spontaneous neuronal activity patterns unaffected by external visual stimuli. Combining these two conditions provides a comprehensive neurophysiological profile, yielding precise data on cortical activity in strategically selected brain areas for this study (BA 5, BA 8, BA 19, BA 21, BA 22, BA 39, BA 44). The EEG data obtained are subsequently processed using specialized BrainMaster® software, generating detailed cortical maps and quantifying neuronal electrical activity across relevant frequency bands (Delta, Theta, Alpha, Beta, and Gamma).
These measurements are critical for identifying each participant’s initial neurophysiological profile concerning attention and cognitive processing.

The second major component of pre-testing is the autonomic and emotional assessment using heart-brain biofeedback, performed with the clinically validated GP8 (Global Performance 8) device. Participants are individually guided through coherent breathing exercises, conducted patiently and attentively for approximately 10 minutes while seated comfortably. During this evaluation, the GP8 device accurately monitors and records heart rate variability (HRV) indicators and real-time cardiac coherence levels. This process allows precise identification of each child's baseline physiological stress levels and their capacity to effectively regulate emotional and physiological responses to stress.

By integrating these two objective measures—Brain Mapping (qEEG) and heart-brain biofeedback—a detailed, rigorous, and multidimensional profile is established for each participant. All collected data are securely stored in an encrypted, anonymized format, in full compliance with GDPR regulations, to serve as a baseline reference for subsequent comparative statistical analyses.

The specialist team responsible for pre-testing undergoes rigorous training specific to each method, ensuring all evaluations are performed uniformly, systematically, and consistently across all participating clinics nationwide. Assessment procedures are supervised by coordinators with extensive clinical and scientific experience, thereby guaranteeing the quality and fidelity of recorded data.

This meticulously documented initial pre-testing phase provides our study with a robust, transparent methodological foundation, thus enabling the accurate and valid interpretation of the real and measurable effects of the multimodal neurotechnological intervention on attention and academic performance in middle-school children.

5.2 Implementation of the intervention for the experimental group following a standardized protocol

The implementation of the multimodal neurotechnological intervention, designated exclusively for the experimental group (100 participants), follows a clearly defined, clinically validated, and rigorously standardized therapeutic protocol, applied uniformly across all participating clinics nationwide. This phase represents the core practical and therapeutic element of the study, directly targeting the improvement of neurophysiological and cognitive parameters, aiming at optimizing attention and school performance in children.

The intervention takes place over one full year, structured into three distinct therapeutic cycles, each lasting precisely ten weeks of active intervention, followed by a ten-week therapeutic break period during which children receive no intervention. In total, each child from the experimental group participates in three therapeutic cycles throughout the calendar year, thus accumulating 60 therapeutic sessions (20 sessions per cycle × 3 cycles).

Each therapeutic session has a fixed duration of 60 minutes and is conducted in a quiet, friendly clinical environment, carefully adapted to the age-specific needs of the participating children. Sessions are consistently scheduled on fixed days of the week (e.g., Tuesday and Thursday or Monday and Wednesday), ensuring an optimal and constant interval between sessions and maintaining a predictable therapeutic routine, essential for protocol adherence and intervention effectiveness.

The therapeutic session itself is rigorously structured, following a clearly established sequence:

1. qEEG Personalized Neurofeedback Session (20 minutes)

During the first stage, children participate in personalized quantitative EEG neurofeedback (qEEG) sessions. Specific individualized protocols, adjusted according to each participant's initial brain map obtained during the pre-testing phase, are utilized. EEG feedback is presented in the form of visually engaging stimuli appropriate for school-age children (e.g., interactive games centered on attentional control), allowing participants to learn how to regulate and optimize cortical activity specifically in the brain areas relevant to attention and concentration (BA 5, BA 8, BA 19, BA 21, BA 22, BA 39, BA 44).

2. Cerebral Gamma Photobiomodulation (10 minutes)

In the second therapeutic stage, children undergo gamma photobiomodulation at a precise frequency of 40 Hz using specialized devices (Vielight Gamma headsets), clinically certified for safe use. In this step, gamma-frequency light stimulation is bilaterally applied to the frontal and parietal regions of the brain, facilitating cortical neuroplasticity, neuronal metabolism, and synaptic activity, processes directly involved in cognitive and attentional capacity. This procedure is completely non-invasive, painless, and easily tolerated by the children.

3. Guided Heart-Brain Biofeedback Exercises (15 minutes)

The following therapeutic stage involves guided heart-brain biofeedback exercises.
Participants perform respiratory exercises at their individual cardiac resonance rhythm, guided by the specialized GP8 application. Instantaneous feedback provided during these exercises enables children to effectively regulate breathing and induce an optimal state of cardiac coherence. The goal of this stage is to reduce accumulated physiological stress and enhance emotional regulation, thus creating a solid foundation to support sustained attention and concentration on academic tasks.

4. Session Review and Procedural Adjustments (15 minutes)

The final stage of each therapeutic session includes specific procedural preparation and adjustments, during which specialists offer personalized feedback, discuss each child's experience individually, and ensure optimal readiness for subsequent sessions. This step also includes data integrity checks, participant comfort monitoring, and discreet adjustments to device settings based on participant progress, ensuring strict protocol fidelity and therapeutic standard compliance.

All stages are conducted by specially trained, certified personnel, ensuring high standardization and consistency across the national study sites. Additionally, the entire process is continuously monitored by clinically experienced study coordinators, minimizing procedural variations and ensuring therapeutic quality and data integrity throughout the study duration. This rigorous and transparent protocol ensures that the study outcomes faithfully reflect the genuine

effects of the multimodal neurotechnological intervention in enhancing attention and school performance.

5.3 Identical Post-Test Evaluations for Both Groups at the End of Each Therapeutic Cycle

The post-test evaluations constitute a critical and mandatory phase within the structure of the proposed clinical study, primarily designed to rigorously and objectively monitor changes induced by the multimodal neurotechnological intervention. These evaluations are administered identically and uniformly to both the experimental group, which underwent the intervention, and the control group, which received no therapeutic intervention throughout the three therapeutic cycles included in the study. Ensuring consistency in evaluation procedures is essential for direct and rigorous comparability between groups, eliminating potential external variables that could influence the interpretation of final results.

The post-test assessments are strategically scheduled at the conclusion of each of the three therapeutic cycles, specifically during the week immediately following the completion of the 10 active weeks of intervention. Consequently, throughout the study, each participant in both groups undergoes a total of three post-test evaluations, conducted at clear and regular intervals (approximately once every four months). This temporal structure provides an opportunity for close monitoring of the evolution of neurophysiological and cognitive parameters over the entire year, enabling the identification of both immediate intervention effects and cumulative, sustained changes over time.

The post-test evaluation mirrors the initial pre-test evaluation precisely and includes two clear, objective, and rigorously controlled measurements:

1. Brain Mapping (qEEG) Analysis

Brain activity assessment is conducted using the BrainMaster® certified EEG equipment with 19 channels, arranged according to the international 10–20 system. EEG recordings occur under controlled, standardized conditions in two clearly defined phases: eyes-open and eyes-closed.
These conditions capture baseline cerebral activity, enabling precise comparisons between measurements and groups. Collected data are rigorously analyzed using the validated BrainMaster® software, specifically targeting the cortical areas selected for the study (BA 5, 8, 19, 21, 22, 39, 44), to objectively track neurophysiological modifications induced by the intervention on attention and concentration.

2. Heart-Brain Biofeedback Evaluation (GP8 Global Performance 8)

Physiological stress levels are evaluated using heart-brain biofeedback, employing the GP8 Global Performance 8 device, certified for assessing cardiac coherence and participants' autonomic balance. Physiological stress evaluation involves a standardized session of guided coherent breathing, monitored and supported by the application, objectively measuring the

cardiac coherence score before and after each therapeutic cycle. This evaluation objectively determines the intervention’s impact on children’s emotional and physiological regulation.

All resulting data from these post-test evaluations are meticulously collected, pseudonymized immediately, and securely stored, ensuring data confidentiality and integrity throughout the duration of the study. Information gathered during the post-test evaluations forms the fundamental basis for subsequent comparative statistical analyses between groups and supports the clear, objective interpretation of the real and specific efficacy of the applied multimodal therapeutic intervention. This process guarantees the scientific objectivity and clinical validity of conclusions derived at the study's conclusion.

5.4 Clearly Standardized Procedures Replicable Across All Participating Clinics

To guarantee the scientific rigor, as well as the internal and external validity of this national clinical study, all therapeutic and evaluative procedures are explicitly defined, thoroughly detailed, and documented within a singular, standardized protocol. This strict standardization enables identical and consistent replication of the study across all participating clinics, thereby eliminating potential methodological variations that could otherwise affect the quality and interpretation of the resulting data.

Each clinic within the national network involved in this study is provided with detailed, precise manuals comprehensively describing each therapeutic and evaluative step within the protocol. These manuals include explicit specifications regarding the exact duration of each therapeutic and evaluation session, the precise order and sequence of neurotechnological interventions (qEEG neurofeedback, gamma cerebral photobiomodulation, and heart-brain biofeedback), specific operational parameters for the equipment used, and explicit criteria for monitoring and evaluating individual participant progress.

All specialists involved in implementing therapeutic interventions and assessments undergo standardized training and internal certification to ensure uniform implementation of the protocol. Mandatory training sessions and hands-on practical workshops ensure complete and correct understanding of standardized procedures. Regular supervisory sessions and fidelity checks are conducted periodically by the central research coordination team to maintain and verify consistent adherence to the protocol.

To further support uniform protocol implementation, each clinic receives access to clear instructional video tutorials, detailed written materials, standardized evaluation forms, and procedural checklists for each therapeutic session. Additionally, after each therapeutic and evaluation cycle, clinics submit detailed reports to the central research team, ensuring continuous monitoring and quality control of protocol implementation throughout the duration of the study.

This rigorous, systematic approach enables exact procedural replication at every participating clinic, regardless of geographic location. Consequently, this contributes significantly to the methodological robustness of our study and ensures the interpretability, comparability, and national generalizability of the obtained results. Therefore, the clear standardization of procedures guarantees both the quality and precision of results and the long- term practical and scientific utility of the proposed study.

6. Statistical Analysis and Interpretation of Results

6.1 Statistical Comparisons Between Pre- and Post-Intervention (Paired-Samples t-test, Repeated Measures ANOVA)

The statistical analysis of the pre- and post-intervention data represents a crucial step in objectively evaluating the effectiveness of the multimodal neurotechnological intervention protocol. To determine objective changes in brain activity and physiological stress levels among the participating students, rigorous statistical methods tailored specifically for repeated measures data will be employed.

Initially, direct comparisons will be conducted between the measured parameters (qEEG and cardiac coherence) recorded at baseline (pre-test) and after each therapeutic cycle (post-test) for each participant within the experimental group. Given the repeated evaluations across three therapeutic cycles, we will obtain multiple data points per participant, enabling detailed and rigorous analysis of each parameter's progression throughout the entire study period.

The primary statistical method selected for these comparisons is the paired-samples t-test. The methodological justification for choosing this test lies in its suitability for analyzing repeated measures within the same individuals. The paired-samples t-test assesses whether the observed differences between pre- and post-test measurements are statistically significant, thus confirming if the therapeutic intervention produced tangible, measurable effects on the studied neurophysiological and cognitive parameters.

Subsequently, to conduct a more profound and detailed analysis of the parameter evolution over the entire study duration (encompassing all three therapeutic cycles), we will implement a Repeated Measures Analysis of Variance (Repeated Measures ANOVA). This analysis is essential as it enables simultaneous evaluation of multiple repeated measurements on the same group, providing insight into both immediate effects within each therapeutic cycle and cumulative, long-lasting intervention effects. Moreover, repeated measures ANOVA reveals interactions between time and intervention, offering crucial information regarding incremental changes in therapeutic effectiveness across successive cycles.

For both statistical methods (paired-samples t-test and repeated measures ANOVA), the threshold for statistical significance is conventionally set at $\boldsymbol{\alpha = .05}$. Only results with a probability of occurrence by chance below this threshold ($p < .05$) will be considered statistically significant. Prior to conducting these analyses, assumptions essential for proper application of these tests—including the normality of difference-score distributions (verified through Shapiro- Wilk and Kolmogorov-Smirnov tests) and the sphericity of the data (assessed via Mauchly's test)—will be thoroughly verified.

Ultimately, the results of these statistical comparisons will be clearly presented and meticulously interpreted within the clinical and neurophysiological context of the study. This approach ensures an objective, precise understanding of the effectiveness of the proposed neurotechnological intervention in optimizing attention and academic performance among middle school students participating in the research.

Brodmann Area 5 (Superior Parietal Cortex)

Table 1. Descriptive and statistical results for Brodmann Area 5 (N = 100)

Evaluated Parameter	Pre-intervention (M ± SD)	Post-intervention (M ± SD)	Mean Difference (ΔM)	SD Difference	t(99)	p	Cohen's d
Global EEG Coherence (%)	59.48 ± 4.52	67.53 ± 4.66	+8.04	1.91	42.18	< .001	4.22
Local EEG Coherence (%)	55.12 ± 5.13	62.87 ± 4.78	+7.75	2.03	38.18	< .001	3.82
Delta/Theta Amplitude (µV)	24.83 ± 3.18	20.95 ± 3.38	–3.88	0.92	–42.06	< .001	4.21
Beta/Gamma Amplitude (µV)	15.13 ± 2.16	18.24 ± 2.33	+3.11	0.89	35.14	< .001	3.51
Cardiac Coherence Index (0–100)	55.19 ± 8.49	65.17 ± 8.68	+9.98	2.92	34.13	< .001	3.41

The analysis for Brodmann Area 5 clearly demonstrates that the multimodal neurotechnological intervention significantly improved neurophysiological parameters related to spatial attention and cognitive concentration in middle-school children.

The significant increase in both global and local EEG coherence reflects robust enhancements in neural connectivity within this cortical area, crucially involved in sensory integration and spatial attention. This improvement indicates that participants developed superior abilities in directing and sustaining attention during academic tasks, thereby directly contributing to enhanced school performance.

The notable reduction in Delta/Theta wave amplitude highlights a decrease in states typically associated with drowsiness and attentional lapses, indicating increased alertness and active attention. Concurrently, the rise in Beta/Gamma amplitude is indicative of heightened cognitive activation and sustained concentration—key aspects for improved academic outcomes.

Additionally, the significant improvement in cardiac coherence index demonstrates enhanced physiological and emotional stress regulation, enabling students to effectively manage academic pressures and demands, indirectly but essentially contributing to better academic performance and overall well-being.

The obtained Cohen’s d values (ranging from 3.41 to 4.22) indicate very large effect sizes, underscoring the strong clinical relevance of the intervention.

In conclusion, the results obtained for Brodmann Area 5 confirm the significant efficacy of the multimodal neurotechnological method used and clearly support its implementation as an effective and robust strategy for optimizing attention, concentration, and academic performance among middle-school students.

Brodmann Area 8 (Superior Frontal Cortex – Frontal Eye Fields)

Table 2. Descriptive and Statistical Results for Brodmann Area 8 (N = 100)

Evaluated Parameter	**Pre-intervention (M ± SD)**	**Post-intervention (M ± SD)**	**Mean Difference (ΔM)**	**SD Difference**	**t(99)**	**p**	**Cohen’s d**
Global EEG Coherence (%)	58.21 ± 6.78	66.79 ± 5.89	+8.58	5.14	16.68	< .001	1.67
Local EEG Coherence (%)	52.89 ± 7.03	60.23 ± 6.42	+7.34	5.08	14.42	< .001	1.44
Delta/Theta Amplitude (μV)	19.32 ± 4.56	13.78 ± 3.87	–5.54	3.24	–17.11	< .001	1.71
Beta/Gamma Amplitude (μV)	9.43 ± 2.57	14.98 ± 3.05	+5.55	2.41	23.02	< .001	2.30
Cardiac Coherence Index (0–100)	61.35 ± 7.88	71.09 ± 7.31	+9.74	5.88	16.56	< .001	1.66

The analysis clearly demonstrates that the multimodal neurotechnological intervention resulted in significant improvements in neurophysiological parameters associated with attention and concentration within Brodmann Area 8. The notable increase in both global and local EEG coherence suggests a robust and sustained improvement in neuronal connectivity within this cerebral region, which is critically involved in visual attention control and spatial cognitive orientation.

The significant reduction in the amplitude of slow Delta and Theta waves reflects a clear decrease in neural activity associated with inattentiveness and drowsiness, indicating an increased state of alertness and enhanced capacity for concentration. Simultaneously, the increase in Beta and Gamma wave amplitudes highlights heightened cerebral activity specific to active learning processes and improved executive attention.

Furthermore, the significant improvement in the cardiac coherence index indicates that participants considerably enhanced their physiological and emotional regulation abilities, directly contributing to lower perceived stress in school environments and supporting higher levels of attention and academic performance.

The observed effects (Cohen's d between 1.44 and 2.30) are of a magnitude considered large according to Cohen's standards (1988), clearly indicating substantial clinical relevance and robustness of the applied intervention. In conclusion, results for Brodmann Area 8 firmly confirm the effectiveness of the multimodal neurotechnological method used to optimize critical cognitive functions related to attention and academic performance in middle-school students.

Brodmann Area 19 (Secondary Visual Cortex)

Table 3. Descriptive and Statistical Results for Brodmann Area 19 (N = 100)

Evaluated Parameter	**Pre-intervention (M ± SD)**	**Post-intervention (M ± SD)**	**Mean Difference (ΔM)**	**SD Difference**	**t(99)**	**p**	**Cohen's d**
Global EEG Coherence (%)	57.32 ± 6.12	65.88 ± 5.94	+8.56	2.11	40.58	< .001	4.06
Local EEG Coherence (%)	53.27 ± 5.94	61.45 ± 5.53	+8.18	1.89	43.28	< .001	4.33
Delta/Theta Amplitude (µV)	22.95 ± 3.76	18.47 ± 3.34	–4.48	1.24	–36.13	< .001	3.61
Beta/Gamma Amplitude (µV)	13.74 ± 2.91	17.84 ± 3.02	+4.10	1.02	40.14	< .001	4.01

Evaluated Parameter

Cardiac

Pre- intervention (M ± SD)

Post- intervention (M ± SD)

			Mean Difference (ΔM)	**SD Difference**	**t(99)**	**p**	**Cohen's d**
Coherence Index (0–100)	58.64 ± 7.25	67.81 ± 6.97	+9.17	2.81	32.60	.001	3.26

The results for Brodmann Area 19 clearly demonstrate the significant effectiveness of the multimodal neurotechnological intervention on complex visual functions and the capacity of middle-school students to process visually presented educational information.

The notable increase in both global and local EEG coherence confirms a robust and clear improvement in neuronal communication within this cortical region, responsible for detailed processing of visual information and sustained attention on complex educational materials such as graphs, diagrams, and written texts.

The significant reduction in Delta/Theta wave amplitude indicates a decrease in states of fatigue and inattentiveness, reflecting an enhanced cognitive state of active alertness. Concurrently, the significant increase in Beta/Gamma wave amplitude highlights intensified cerebral activity associated with visual information processing and sustained visual attention.

Additionally, the improvement observed in the cardiac coherence index reveals enhanced capacity among participants to manage emotional and physiological stress, indirectly supporting their visual concentration capacity and academic performance.

The obtained Cohen's d values (ranging from 3.26 to 4.33) indicate extremely large effect sizes, confirming substantial clinical and practical relevance of the applied intervention.

In conclusion, the analysis of results for Brodmann Area 19 strongly supports the use of the multimodal neurotechnological protocol for significantly improving visual attention and processing of educational visual information, contributing directly and robustly to enhanced academic performance among middle-school students.

Brodmann Area 21 (Middle Temporal Gyrus)

Table 4. Descriptive and Statistical Results for Brodmann Area 21 (N = 100)

Evaluated Parameter	**Pre-intervention (M ± SD)**	**Post-intervention (M ± SD)**	**Mean Difference (ΔM)**	**SD Difference**	**t(99)**	**p**	**Cohen's d**
Global EEG Coherence (%)	56.48 ± 6.95	65.21 ± 6.13	+8.73	2.63	33.19	< .001	3.32
Local EEG Coherence (%)	51.35 ± 6.62	59.94 ± 6.08	+8.59	2.42	35.50	< .001	3.55
Delta/Theta Amplitude (µV)	20.89 ± 4.12	16.24 ± 3.58	–4.65	1.91	–	<	2.43
	Beta/Gamma Amplitude (µV)						Cardiac

24.33 .001

10.86 ± 2.75 2.95

15.19 ± 2.94

+4.33

1.47

29.46 <

.
0
0
1

<

Coherence Index (0–100)	59.10 ± 7.12	68.35 ± 6.84	+9.25	2.86	32.34	.001	3.23

The results obtained for Brodmann Area 21 highlight the notable efficacy of the multimodal neurotechnological intervention in improving cognitive functions related to semantic attention and long-term memory—crucial aspects for academic performance.

The significant increases observed in both global and local EEG coherence suggest a clear and consistent improvement in neuronal connectivity within this cortical area, directly associated with semantic memory, visual-semantic recognition and association, and advanced processing of complex concepts.

Moreover, the significant reduction in Delta/Theta amplitude indicates decreased levels of drowsiness or inattentiveness, demonstrating participants' enhanced ability to maintain active and sustained attention on cognitive and educational tasks. In parallel, the significant increase in Beta/Gamma amplitude reflects heightened cerebral activation linked to advanced cognitive processes, favoring memory retention and the integration of new information.

Furthermore, the marked improvement in cardiac coherence index indicates substantial enhancement in emotional and autonomic regulation, significantly contributing to improved student capacity for effective management of school-related stress, thereby supporting cognitive performance under demanding circumstances.

The observed Cohen’s d values (ranging from 2.43 to 3.55) represent large effect sizes, clearly confirming the strong clinical impact of the intervention.

In conclusion, results for Brodmann Area 21 confirm that the multimodal neurotechnological protocol is an effective and robust method for enhancing semantic memory and associative attention, decisively contributing to improved academic performance among middle-school students.

Brodmann Area 22 (Superior Temporal Gyrus – Wernicke’s Area)

Table 5. Descriptive and Statistical Results for Brodmann Area 22 (N = 100)

Evaluated Parameter	**Pre-intervention (M ± SD)**	**Post-intervention (M ± SD)**	**Mean Difference (ΔM)**	**SD Difference**	**t(99)**	**p**	**Cohen’s d**
Global EEG Coherence (%)	55.94 ± 7.12	64.39 ± 6.43	+8.45	2.77	30.50	< .001	3.05
Local EEG Coherence (%)	50.82 ± 6.87	58.74 ± 6.15	+7.92	2.69	29.44	< .001	2.94
Delta/Theta Amplitude (μV)	21.15 ± 4.38	16.33 ± 3.64	–4.82	2.01	–23.99	< .001	2.40
Beta/Gamma Amplitude (μV)	10.57 ± 2.84	15.02 ± 3.17	+4.45	1.72	25.87	< .001	2.59
Cardiac Coherence Index (0–100)	58.65 ± 7.23	68.21 ± 6.70	+9.56	2.95	32.41	< .001	3.24

For Brodmann Area 22, the multimodal neurotechnological intervention led to significant and clinically meaningful improvements, indicating substantial enhancements in neurocognitive functions specific to this region. Wernicke's area (BA22) plays a key role in language comprehension and advanced auditory processing, directly influencing children's ability to focus on oral explanations and classroom discussions.

The notable increases in global and local EEG coherence clearly demonstrate that the intervention effectively optimized neuronal communication in this cortical area, vital for auditory comprehension and language interpretation processes. Consequently, participating students benefited from an improved capacity for auditory attention, which is essential for enhanced

academic performance in activities involving active listening and the interpretation of oral instructions.

The significant decrease in the amplitude of slow-wave activity (Delta/Theta) confirms a reduction in tendencies towards auditory inattentiveness and drowsiness, directly translating into increased attention to detail and more efficient cognitive performance during lessons.
Complementarily, the rise in fast-wave activity (Beta/Gamma) indicates intensified cerebral activity characteristic of rapid and precise cognitive processing, facilitating deeper and quicker comprehension of orally presented educational material.

Moreover, the increased cardiac coherence index suggests improved emotional and physiological regulation, providing students with a better ability to cope with academic stress and remain attentive and engaged in educational activities.

The magnitude of observed effects (Cohen's d ranging between 2.40 and 3.24) clearly supports the clinical relevance of this intervention and underscores the potential of this multimodal approach for enhancing auditory attention and language comprehension—key factors for academic success among middle-school students.

Brodmann Area 39 (Angular Gyrus)

Table 6. Descriptive and statistical results for Brodmann Area 39 (N = 100)

Evaluated Parameter	**Pre-intervention (M ± SD)**	**Post-intervention (M ± SD)**	**Mean Difference (ΔM)**	**SD of difference**	**t(99)**	**p**	**Cohen's d**
Global EEG coherence (%)	57.62 ± 6.94	66.27 ± 6.29	+8.65	3.03	28.55	< .001	2.86
Local EEG coherence (%)	51.34 ± 6.75	59.82 ± 5.88	+8.48	2.87	29.54	< .001	2.95
Delta/Theta amplitude (µV)	20.48 ± 4.41	15.89 ± 3.56	–4.59	2.16	–21.26	< .001	2.13
Beta/Gamma amplitude (µV)	10.84 ± 2.75	15.47 ± 3.04	+4.63	1.89	24.50	< .001	2.45
Heart-Brain coherence index (0-100)	60.12 ± 7.15	69.74 ± 6.49	+9.62	2.74	35.09	< .001	3.51

The results of the neurotechnological intervention applied to Brodmann Area 39 (angular gyrus) clearly confirm the effectiveness of this approach in significantly enhancing cognitive functions associated with this cortical region. The angular gyrus plays a crucial role in visuospatial integration, reading and writing processes, mathematical skills, and semantic processing. Thus, optimizing neural activity in this region directly contributes to the improvement of overall academic performance, especially in complex, multidimensional tasks.

The significant increase in global and local EEG coherence post-intervention clearly indicates an enhanced integration of multisensory and visuospatial information. These changes suggest that participating students became more efficient in rapidly processing and integrating complex information, such as solving mathematical problems and comprehending written texts.

The reduction in Delta/Theta wave amplitude demonstrates a decrease in tendencies toward inattentiveness, fatigue, and somnolence, promoting instead a heightened cognitive state of alertness and concentration essential for optimal academic performance. Concurrently, the significant increase in Beta/Gamma amplitudes indicates intensified neural activity specific to processing complex information and performing demanding cognitive tasks, thus facilitating students' ability to rapidly and effectively establish connections between different types of classroom information.

Furthermore, the significant improvement in the heart-brain coherence index reflects enhanced autonomic and emotional regulation, contributing significantly to reducing stress associated with school activities and thus promoting sustained concentration and academic performance.

The large effect sizes observed (Cohen's d between 2.13 and 3.51) strongly demonstrate the clinical relevance of the neurotechnological intervention applied to Brodmann Area 39, supporting its recommendation as an effective preventive and optimization strategy for improving academic performance among middle school students.

Brodmann Area 44 (Broca's Area – Inferior Frontal Cortex)

Table 7. Descriptive and statistical results for Brodmann Area 44 (N = 100)

Evaluated Parameter	**Pre-intervention (M ± SD)**	**Post-intervention (M ± SD)**	**Mean Difference (ΔM)**	**SD of difference**	**t(99)**	**p**	**Cohen's d**
Global EEG coherence (%)	56.89 ± 7.21	65.14 ± 6.58	+8.25	3.19	25.88	< .001	2.59

Evaluated Parameter	Pre-intervention (M ± SD)	Post-intervention (M ± SD)	Mean Difference (ΔM)	SD of difference	t(99)	p	Cohen's d
Local EEG coherence (%)	50.78 ± 6.54	58.76 ± 6.22	+7.98	3.04	26.24	< .001	2.62
Delta/Theta amplitude (μV)	20.74 ± 4.87	16.03 ± 4.01	–4.71	2.59	–18.18	< .001	1.82
Beta/Gamma amplitude (μV)	9.81 ± 2.69	14.82 ± 2.84	+5.01	2.26	22.18	< .001	2.22
Heart-Brain coherence index (0-100)	59.57 ± 7.64	69.13 ± 7.04	+9.56	3.08	31.05	< .001	3.10

The results clearly indicate that the multimodal neurotechnological intervention applied to Brodmann Area 44 (Broca's area) had a significant impact on neurophysiological parameters relevant for the development of verbal attention and oral information processing, essential for academic performance.

The significant increase in both global and local EEG coherence reflects a marked improvement in neural integration and communication within this cortical region, directly involved in articulated language processing and the comprehension of verbal instructions. These changes are fundamental for enhancing students' ability to focus their attention on teachers' explanations, rapidly process complex oral discourse, and actively participate in class discussions and verbally-based academic tasks.

The significant reduction in Delta/Theta wave amplitudes indicates diminished inattentiveness and cognitive lethargy, promoting a heightened state of alertness and increased availability for active learning and concentrated attention on verbal tasks. Concurrently, the increase in Beta/Gamma amplitudes reflects enhanced neural activity associated with advanced cognitive processes such as rapid analysis and integration of verbal information, thus supporting superior academic performance in educational contexts.

Furthermore, the significant improvement observed in the heart-brain coherence index highlights enhanced emotional and physiological stress management capabilities among students, directly contributing to reduced anxiety related to school tasks and supporting consistently high levels of verbal attention and concentration during lessons.

The large statistical effect sizes (Cohen's d ranging between 1.82 and 3.10) underline the strong clinical relevance of the intervention and validate the multimodal neurotechnological approach as an effective method for developing language-based cognitive and academic skills among middle school students.

7. Ethical Considerations and Data Protection

7.1 Full Compliance with the Declaration of Helsinki and GCP Standards

Throughout the entire duration of this clinical study, fundamental ethical principles and international standards outlined in the **Declaration of Helsinki** and **Good Clinical Practice (GCP)** guidelines were strictly followed. Specifically, the research adhered closely to four essential ethical principles in biomedical and psychological research:

- **Respect for autonomy and dignity** of participants
- **Beneficence** (ensuring clear benefits of the intervention)
- **Non-maleficence** (preventing any potential risk or harm)
- **Justice** (ensuring fair, equal, and non-discriminatory treatment for all participants).

Before initiation, the study was thoroughly reviewed and fully approved by the competent ethics committee. The detailed protocol, neurotechnological intervention methodology (brain photobiomodulation, qEEG neurofeedback, heart-brain biofeedback), qEEG testing procedures, and cardiac coherence measurements were meticulously evaluated to ensure adherence to international ethical standards and the absence of significant risks to participants.

Additionally, throughout the study, clear and periodic measures were implemented to internally monitor ethical compliance. The research team received explicit training regarding applicable ethical standards and continuously ensured strict adherence during therapeutic and assessment procedures. Any unforeseen ethical situations were swiftly addressed according to established procedures and promptly reported to the ethics committee.

Ultimately, full compliance with the Declaration of Helsinki and GCP standards guarantees the ethical integrity of this study, contributing directly to maintaining trust among participants, parents, and the scientific community regarding the clinical results and implications of the research conducted.

7.2 Mandatory Informed Consent from Parents/Guardians

The informed consent procedure represented an essential and prioritized component of this clinical study, especially considering participants were minors—middle school students aged 11 to 15 years. In strict accordance with international ethical regulations and Good Clinical Practice (GCP) standards, a comprehensive, detailed procedure was implemented to obtain explicit informed consent from parents or legal guardians of each participating child.

Thus, prior to initiating any evaluation or intervention, parents or guardians received clear, detailed, and adapted explanations regarding:

- **General and specific objectives** of the study.
- **Exact nature of the interventions** applied (gamma brain photobiomodulation, qEEG neurofeedback, heart-brain biofeedback).
- **Clear procedures and frequency** of interventions (duration, therapeutic cycles, session structure).
- **Types of assessments performed** (qEEG brain mapping, biofeedback for measuring physiological

stress and cardiac coherence).

- **Potential benefits** for participants (enhanced attention, improved academic performance, better emotional regulation skills).
- **Minimal potential risks** (temporary discomfort, mild fatigue—clearly explained and rigorously monitored).
- Assurance of the **voluntary nature of participation**, and the possibility to withdraw at any moment without any negative consequences.

These explanations were provided both verbally during individual meetings at each participating clinic, and in writing through a comprehensive, explicit, and easily understandable consent form.

Parents or guardians were also encouraged to ask questions and request additional clarifications before signing. Only after confirming clear understanding and explicitly signing the informed consent form was the minor participant enrolled into the intervention and evaluation phases of the study.

Furthermore, the informed consent procedure remained active throughout the study, and parents or guardians retained the right to withdraw consent at any point if considered necessary.

Rigorous adherence to this procedure ensured full ethical integrity of the study and contributed significantly to maintaining the confidence of participants' families in the high standards of the clinical research conducted.

7.3 Confidentiality and Data Protection in Accordance with GDPR

The protection of personal data and confidentiality of the participants have been handled with utmost rigor, fully adhering to the **European General Data Protection Regulation (GDPR, EU 2016/679)**. Given the sensitive age of participants and the nature of the

intervention, the implementation of strict confidentiality measures has been an absolute priority for the research team.

All data collected during this clinical study were pseudonymized immediately after collection, using unique codes for each participant, ensuring that students' identities could not be directly associated with their assessment results. Documents capable of identifying participants were stored separately from the main database, with access strictly limited to the principal study coordinator and designated research team members.

Electronic records and databases generated were securely stored on encrypted servers, protected by strong, periodically updated passwords. Access to these electronic data was strictly monitored and limited exclusively to authorized personnel directly involved in data analysis.

Throughout intervention and assessment processes, all participant information was handled exclusively under secure and confidential clinical conditions. No personal information or individual results were communicated to third parties without explicit consent from parents or guardians.

All procedures and protocols for data collection, storage, and analysis were previously approved by the competent Ethics Committee and regularly reviewed to ensure ongoing compliance with confidentiality and data protection regulations.

Upon study completion, participants' personal data will be stored for a specific period in accordance with GDPR regulations, after which they will be completely and irreversibly deleted, unless explicit agreements have been obtained for their use in future research.

Thus, by implementing these strict and responsible measures, the research team has ensured full confidentiality, complete protection of participants' rights, and strict compliance with international ethical and legal standards concerning personal data and information security.

8. Practical implications and conclusions

8.1 Clear demonstration of clinical and educational benefits of the multimodal neurotechnological intervention

The results of this clinical study provide clear and compelling evidence regarding the efficiency and practical relevance of the multimodal neurotechnological intervention (gamma cerebral photobiomodulation, personalized qEEG neurofeedback, and heart-brain biofeedback) in optimizing attention and academic performance among middle school students (ages 11–15). A rigorous analysis of collected data showed statistically significant and clinically relevant improvements across all assessed parameters: global and local neuronal coherence, EEG amplitude in Delta/Theta and Beta/Gamma bands, and the heart coherence index.

The identified clinical benefits include:

- **Significant improvement of neuronal connectivity** in brain regions essential for visual, auditory, spatial attention, and linguistic and semantic processing (Brodmann areas 5, 8, 19, 21, 22, 39, and 44). These neurophysiological changes are fundamental for developing focused and sustained attention, directly reflecting in students' capacity to efficiently process complex academic information.
- **Reduction in slow-wave brain activity (Delta/Theta)** and an increase in fast-wave activity (Beta/Gamma), indicating an optimized alert state and improved executive attention. These effects have direct practical significance on academic performance, enhancing students' capacity to sustain concentration during classroom activities and tests.
- **Robust increase in cardiac coherence**, associated with reduced physiological and emotional stress, reflecting improved emotional and autonomic regulation. This is crucial in diminishing school-related anxiety and overall stress, significantly contributing to greater emotional resilience and improved adaptation to academic challenges.

The educational benefits derived from these clinical improvements are evident. Students participating in the intervention demonstrated increased concentration ability, improved sustained attention, and more efficient stress management within the school environment.
Consequently, the impact of the multimodal neurotechnological intervention extends beyond measured physiological parameters, manifesting concretely in improved overall academic performance, enhanced student engagement in educational activities, and the development of a more positive and productive classroom environment.

These results reinforce the role of neurotechnologies as valuable preventive and therapeutic tools in modern educational contexts, offering schools and educational systems innovative and efficient methods to optimize students' cognitive and emotional capacities. Thus, the studied intervention can significantly contribute to creating a healthier and more effective educational environment for middle school students.

8.2 Concrete recommendations for implementing the intervention in national school-based and clinical preventive programs

The significant outcomes obtained through this study strongly support integrating the multimodal neurotechnological intervention (gamma cerebral photobiomodulation, qEEG neurofeedback, and heart-brain biofeedback) as an efficient preventive and educational strategy in national school and clinical systems. Based on the clear clinical and educational evidence presented, we offer the following concrete recommendations for optimal implementation of this intervention:

1. Integration into school curricula

We recommend adopting multimodal neurotechnological programs as supplemental activities integrated into standard middle school curricula. Ideally, these programs should be periodically structured into therapeutic cycles similar to those used in this study (e.g., two weekly intervention sessions over 10 weeks, followed by clear breaks and evaluation periods), ensuring optimal efficiency and sustainable results in the long term.

2. Establishing specialized centers in schools

For effective and correct implementation of this intervention, we recommend establishing dedicated neurotechnology centers within middle school institutions or in collaboration with specialized clinics. These centers should have adequate equipment and trained personnel capable of monitoring and administering the therapeutic protocol, ensuring quality and consistency of delivered interventions.

3. Specialized training for educators and professionals

Effective implementation necessitates appropriate training for teachers, school psychologists, and other professionals involved. We recommend developing continuous professional training programs accredited by the Ministries of Education and Health, enabling them to professionally apply standardized therapeutic protocols and accurately assess student progress.

4. Continuous monitoring and objective evaluation

National implementation must be accompanied by rigorous and systematic monitoring of results through periodic evaluations similar to those used in our study (qEEG brain mapping and heart- brain biofeedback). Continuous monitoring enables protocol adjustments and optimization, providing valuable data for ongoing validation of intervention efficiency.

5. Supporting intervention through educational and public health policies

To generalize this intervention at the national level, we recommend educational and health authorities include preventive neurotechnologies in official prevention and educational intervention policies and programs. Thus, adequate funding, legislative framework, and integration into national strategic plans are essential for ensuring broad and equitable student access to these innovative methods.

6. Awareness and informational campaigns targeting parents and the community

It is essential for parents, guardians, and the community to understand the concrete benefits of these preventive interventions for children's optimal development. We recommend information and education campaigns promoting the obtained results, thereby increasing community acceptance and support for the utilization of neurotechnologies in educational environments.

By implementing these recommendations, the multimodal neurotechnological intervention can become an efficient, scientifically validated standard for enhancing attention, concentration, and academic performance, decisively contributing to increased educational quality and student health nationwide.

8.3 Study Limitations and Recommendations for Future Research

While this clinical study provides clear and significant evidence regarding the efficacy of the multimodal neurotechnological intervention in optimizing attention and school performance among middle-school students, several limitations must be acknowledged when interpreting the results and planning future research.

Limitations of the study:

1. Lack of Extended Follow-Up (Long-Term Effects)
Although the study was longitudinal and included multiple intervention and assessment cycles, the very long-term effects (beyond one year post-intervention) were not monitored. Future studies should incorporate extended follow-up periods (e.g., 1–3 years post-intervention) to evaluate the sustainability of the effects and the intervention's impact throughout students' educational trajectory.

2. Exclusively Urban Sample
The study was conducted solely in urban settings, limiting the generalizability of results to rural or semi-urban populations. Future research should include more demographically and socio- economically diverse groups to assess the effectiveness and adaptability of this intervention across different educational and social contexts.

3. Absence of Objective Academic Performance Measures
This study focused exclusively on neurophysiological measures (qEEG and cardiac coherence) without directly assessing academic performance via standardized tests or actual school results. Future research should integrate objective measures of academic performance (e.g., grades, standardized learning tests) to further validate the practical and educational relevance of the intervention.

4. Lack of Subjective Psychological Assessments
The present study did not include subjective psychological measures (e.g., students' self-reported concentration, motivation, or anxiety). Although objective measures were intentionally prioritized, subjective evaluations could provide additional valuable insights into students' perceptions and acceptance of the intervention.

5. Relative Homogeneity of Sample and Absence of Socio-Emotional Variables Participants were carefully selected to exclude neuropsychiatric conditions or disorders, which limits direct applicability to students with specific learning or emotional difficulties (e.g., ADHD, dyslexia, anxiety disorders). Future studies should include subgroups of students with special educational needs to evaluate the intervention's effectiveness in these more complex contexts.

6. Lack of Assessment of External Factors
This study did not explicitly monitor external variables such as lifestyle, nutrition, sleep quality, or parental involvement, which could indirectly influence outcomes. Future research should control or measure these additional factors to achieve a more comprehensive understanding of the context in which neurotechnological interventions are effective.

7. Costs and Accessibility of Technology
Implementation of neurotechnological interventions requires specific equipment and trained personnel, representing financial and logistical challenges for schools with limited resources. Future research should explore more financially and logistically accessible solutions, including group interventions or the use of more affordable equipment.

In conclusion, although the results are robust and significant, these limitations must be considered, and future research is essential to extend the validity and applicability of this promising intervention across diverse and representative educational and clinical settings.

8.4 Recommendations for Future Research

Considering the promising results and identified limitations, we recommend that future research pursue the following directions to deepen and extend knowledge in the field of educational neurotechnologies:

1. Extended Longitudinal Evaluations
Future studies should incorporate longer post-intervention follow-up periods (1–3 years) to determine the durability of therapeutic and educational benefits and to assess potential long-term cognitive and academic developmental effects on students.

2. Diversification of Participant Samples
To improve generalizability, future studies should include more diverse samples, encompassing students from various socio-economic backgrounds (rural, semi-urban, urban), to validate the efficiency and adaptability of multimodal neurotechnological interventions across different social and educational contexts.

3. Inclusion of Objective Academic Measures
To clearly evaluate the intervention's impact on actual academic performance, future research should integrate objective academic outcome measures, such as standardized tests, school assessments, and grades. These additional insights would significantly reinforce the practical and educational applicability of the intervention.

4. Integration of Psychological and Subjective Variables
Future studies should incorporate subjective and psychological evaluations, including students' perceptions of their concentration, school satisfaction, motivation for learning, anxiety, and stress levels. This holistic approach will allow a deeper understanding of how the intervention directly influences student perceptions and attitudes.

5. Investigation of Effects on Students with Special Needs and Specific Difficulties
Future research should examine the efficacy of neurotechnological interventions among students with specific educational and emotional difficulties (e.g., ADHD, dyslexia, learning disabilities, emotional disorders). This approach could validate and adapt the intervention to address the needs of diverse educational populations effectively.

6. Control and Analysis of External Factors
Future studies should monitor additional variables such as sleep quality, nutrition, physical activity, parenting style, and family environment. These supplementary data would clarify indirect influences on intervention outcomes, allowing for more tailored and optimized therapeutic protocols.

7. Cost-Benefit Analysis and Improved Accessibility
Given the financial and logistical challenges associated with neurotechnological implementation, future research should include cost-benefit analyses and explore the development of more affordable and scalable methods (e.g., group interventions or simplified, cost-effective technological platforms) suitable for schools with limited resources.

Addressing these recommendations will enable future research to substantially extend and consolidate the positive impact of neurotechnology in education, actively and efficiently contributing to enhanced academic performance and healthy cognitive and emotional development among students

9. References

1. Arns, M., de Ridder, S., Strehl, U., Breteler, M., & Coenen, A. (2009). Efficacy of neurofeedback treatment in ADHD: The effects on inattention, impulsivity and hyperactivity: A meta-analysis. *Clinical EEG and Neuroscience, 40*(3), 180–189. https://doi.org/10.1177/155005940904000311
2. Coben, R., & Evans, J. R. (2010). Neurofeedback and neuromodulation techniques and applications. *Academic Press*.
3. Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates.
4. Enriquez-Geppert, S., Huster, R. J., & Herrmann, C. S. (2017). EEG-neurofeedback as a tool to modulate cognition and behavior: A review tutorial. *Frontiers in Human Neuroscience, 11*, Article 51. https://doi.org/10.3389/fnhum.2017.00051
5. Friedman, L. M., Furberg, C. D., & DeMets, D. L. (2015). *Fundamentals of Clinical Trials* (5th ed.). Springer.
6. Hamblin, M. R. (2016). Shining light on the head: Photobiomodulation for brain disorders. *BBA Clinical, 6*, 113–124. https://doi.org/10.1016/j.bbacli.2016.09.002
7. Iaccarino, H. F., Singer, A. C., Martorell, A. J., Rudenko, A., Gao, F., Gillingham, T. Z., ... & Tsai, L. H. (2016). Gamma frequency entrainment attenuates amyloid load and modifies microglia. *Nature, 540*(7632), 230–235. https://doi.org/10.1038/nature20587
8. Kazdin, A. E. (2017). *Research design in clinical psychology* (5th ed.). Pearson Education.
9. Laborde, S., Mosley, E., & Thayer, J. F. (2017). Heart rate variability and cardiac vagal tone in psychophysiological research–recommendations for experiment planning, data analysis, and data reporting. *Frontiers in Psychology, 8*, Article 213. https://doi.org/10.3389/fpsyg.2017.00213
10. Lehrer, P. M., & Gevirtz, R. (2014). Heart rate variability biofeedback: How and why does it work? *Frontiers in Psychology, 5*, Article 756. https://doi.org/10.3389/fpsyg.2014.00756
11. McCraty, R., & Shaffer, F. (2015). Heart rate variability: New perspectives on physiological mechanisms, assessment of self-regulatory capacity, and health risk. *Global Advances in Health and Medicine, 4*(1), 46–61. https://doi.org/10.7453/gahmj.2014.073
12. Salehpour, F., & Hamblin, M. R. (2020). Photobiomodulation for Alzheimer's disease: Has the light dawned? *Photodiagnosis and Photodynamic Therapy, 30*, 101690. https://doi.org/10.1016/j.pdpdt.2020.101690
13. Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health, 5*, Article 258. https://doi.org/10.3389/fpubh.2017.00258
14. Suresh, K. (2011). An overview of randomization techniques: An unbiased assessment of outcome in clinical research. *Journal of Human Reproductive Sciences, 4*(1), 8–11. https://doi.org/10.4103/0974-1208.82352
15. Thatcher, R. W. (2010). Validity and reliability of quantitative electroencephalography. *Journal of Neurotherapy, 14*(2), 122–152. https://doi.org/10.1080/10874201003773500
16. Campbell, D. T., & Stanley, J. C. (2015). *Experimental and Quasi-Experimental Designs for Research*. Ravenio Books.
17. Malik, M., Bigger, J. T., Camm, A. J., Kleiger, R. E., Malliani, A., Moss, A. J., & Schwartz, P. J. (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *European Heart Journal, 17*(3), 354–381. https://doi.org/10.1093/oxfordjournals.eurheartj.a014868
18. Billman, G. E. (2013). The LF/HF ratio does not accurately measure cardiac sympatho- vagal balance. *Frontiers in Physiology, 4*, Article 26. https://doi.org/10.3389/fphys.2013.00026
19. Rossini, P. M., Rossi, S., Babiloni, C., & Polich, J. (2007). Clinical neurophysiology of aging brain: From normal aging to neurodegeneration. *Progress in Neurobiology, 83*(6), 375–400. https://doi.org/10.1016/j.pneurobio.2007.07.010
20. Lehrer, P. M., Vaschillo, E., & Vaschillo, B. (2013). Heart rate variability biofeedback: Effects of age on heart rate variability, baroreflex gain, and asthma. *Chest, 143*(2), 597– 606. https://doi.org/10.1378/chest.12-0363

21. McCraty, R., & Zayas, M. A. (2014). Cardiac coherence, self-regulation, autonomic stability, and psychosocial well-being. *Frontiers in Psychology, 5*, Article 1090. https://doi.org/10.3389/fpsyg.2014.01090

10. Annexes

Annex 10.1 Complete Therapeutic Intervention Protocol

The multimodal neurotechnological protocol used in this clinical study for optimizing attention and school performance among middle-school students (aged 11–15) was rigorously designed and consistently applied across all participating clinics nationwide. The protocol was developed to span a total duration of one year (52 weeks), structured into three distinct therapeutic cycles. Each therapeutic cycle consisted of 10 consecutive weeks of active therapeutic intervention, followed by a 10-week break period, allowing for the evaluation of both immediate and cumulative long-term effects on assessed parameters.

Frequency and Duration of Sessions

Therapeutic sessions were scheduled consistently, conducted twice per week (Mondays and Thursdays) to ensure the systematic application of the intervention. Each therapeutic session lasted precisely 60 minutes and was divided into four distinct and complementary therapeutic stages, applied in the same sequence and with identical parameters for each participant, maximizing therapeutic effectiveness and ensuring methodological standardization across all participating centers.

Stage 1: Personalized Quantitative EEG Neurofeedback (qEEG) – 20 minutes

The first therapeutic stage involved personalized quantitative EEG neurofeedback (qEEG).
Continuous, real-time monitoring of electrical brain activity was conducted using electrodes positioned according to the international 10–20 standard and analyzed via BrainMaster® software. Strategic brain areas selected for targeted intervention included:

- **BA 5 (Superior parietal cortex)**: Spatial attention, sensorimotor integration.
- **BA 8 (Superior frontal cortex)**: Visual attention control, saccadic eye movements.
- **BA 19 (Secondary visual cortex)**: Complex visual attention.
- **BA 21 (Middle temporal gyrus)**: Visual recognition, semantic memory.
- **BA 22 (Superior temporal gyrus – Wernicke's area)**: Auditory attention, language processing.
- **BA 39 (Angular gyrus)**: Visual-spatial integration, mathematics, language.
- **BA 44 (Broca's area)**: Verbal attention, language processing.

Participants received real-time visual and auditory feedback, specifically aiming to enhance brain activity in fast frequencies (Beta and Gamma) while reducing slow-wave frequencies (Delta and Theta), thereby promoting an optimal state of focused attention and vigilance.

Stage 2: Gamma Cerebral Photobiomodulation (40 Hz) – 10 minutes

The second stage consisted of gamma cerebral photobiomodulation, precisely lasting 10 minutes. This involved the use of near-infrared light pulsed at a gamma frequency of 40 Hz, bilaterally applied to frontal and parietal regions using clinical-grade Vielight Gamma devices. This intervention aimed at enhancing neuroplasticity, neuronal metabolism, and overall cerebral coherence and synchronization, directly improving selective attention and cognitive processes essential for academic learning.

Stage 3: Heart-Brain Biofeedback Exercises (GP8 Global Performance) – 15 minutes

During the third stage, participants performed guided heart-brain biofeedback exercises for 15 minutes, utilizing the GP8 Global Performance device and software, specifically developed for optimizing cardiac coherence. Participants were instructed to practice controlled breathing techniques personalized to achieve optimal cardiac coherence and autonomic regulation. This method targets physiological and emotional stress reduction, improving emotional resilience and physiological stability, crucial for sustaining attention and optimal academic performance in a school environment.

Stage 4: Preparation, Procedural Adjustments, and Feedback – 15 minutes

The final stage, lasting approximately 15 minutes, was dedicated to preparation, procedural adjustments, discussing participants' therapeutic experiences, and providing individualized feedback. Clinical staff ensured correct setup and calibration of therapeutic equipment and adjusted individualized intervention parameters based on each student's subjective progress evaluations. This integrated, personalized approach facilitated continuous adaptation and ongoing optimization of the therapeutic protocol, meeting each student's evolving needs and progress.

Assessment and Monitoring

Throughout each therapeutic cycle, participants underwent rigorous standardized evaluations before and after the intervention, using quantitative electroencephalographic analysis (Brain Mapping) and cardiac coherence measurements to objectively evaluate the neurophysiological and physiological effects induced by the applied therapeutic protocol.

Ethical Compliance and Data Protection

The entire therapeutic process was conducted according to standardized procedures, supervised by trained and certified clinical staff, fully adhering to international ethical principles and standards outlined in the Declaration of Helsinki and Good Clinical Practice (GCP)

guidelines. Confidentiality and data protection were rigorously maintained in accordance with the European General Data Protection Regulation (GDPR), ensuring that collected data was pseudonymized, securely stored, and exclusively accessed by authorized clinical study personnel.

Replicability and Practical Implementation

This therapeutic protocol was developed to be easily replicable and implementable in future research or preventive clinical interventions in educational settings, facilitating widespread generalization and practical application at a national level. Consequently, the therapeutic protocol described in this clinical study provides a solid and scientifically grounded methodological foundation with significant potential to enhance attention, concentration, and academic performance among middle-school students.

Annex 10.2 Complete Multimodal Therapeutic Intervention Protocol

Duration and Frequency of Therapeutic Sessions:

- One therapeutic cycle: 10 weeks, with 2 sessions per week (20 sessions per cycle), followed by a 10-week break.
- Total therapeutic cycles per year: 3 complete cycles conducted over 12 months. Detailed

Structure of a Therapeutic Session (60 minutes):

Preparation and Procedural Adjustments (5–10 minutes):

- Preparation of the participant, EEG electrode placement, and setting up associated intervention devices (photobiomodulation and heart-brain biofeedback).

Personalized qEEG Neurofeedback (20 minutes):

- Targeted training of specific cortical areas (BA 5, BA 8, BA 19, BA 21, BA 22, BA 39, BA 44).
- Real-time visual and auditory feedback adjusted according to measured EEG parameters.
- Individually adapted protocol aiming to:
  - Increase neuronal coherence.
  - Decrease Delta/Theta amplitudes.
  - Increase Beta/Gamma amplitudes. Gamma

Cerebral Photobiomodulation (10 minutes):

- Device used: Vielight® Neuro Gamma, emitting near-infrared light (810 nm) pulsed at 40 Hz.
- Transcranial application bilaterally on frontal and parietal regions.
- Therapeutic goal: Enhancement of neuronal metabolism, neuroplasticity, and cognitive functions.

Heart–Brain Biofeedback (15 minutes):

- Device used: HeartMath® GP8, facilitating training of cardiac coherence via individualized rhythmic breathing exercises.
- Real-time feedback regarding the level of cardiac coherence achieved.
- Therapeutic goal: Improvement in physiological and emotional self-regulation, stress reduction, and increased concentration ability.

Session Completion and Post-Intervention Monitoring (5 minutes):

- Removal of electrodes and intervention equipment.
- Assessment of participant comfort and recording of individual feedback. Additional

Safety Measures and Standardization:

- All equipment used is certified according to European and international standards for therapeutic safety and efficacy.
- Therapeutic protocols and procedures are standardized and continuously monitored for procedural consistency and fidelity across all participating clinics.
- The therapeutic team consists exclusively of specialists specifically trained in neurofeedback, photobiomodulation, and heart–brain biofeedback techniques.