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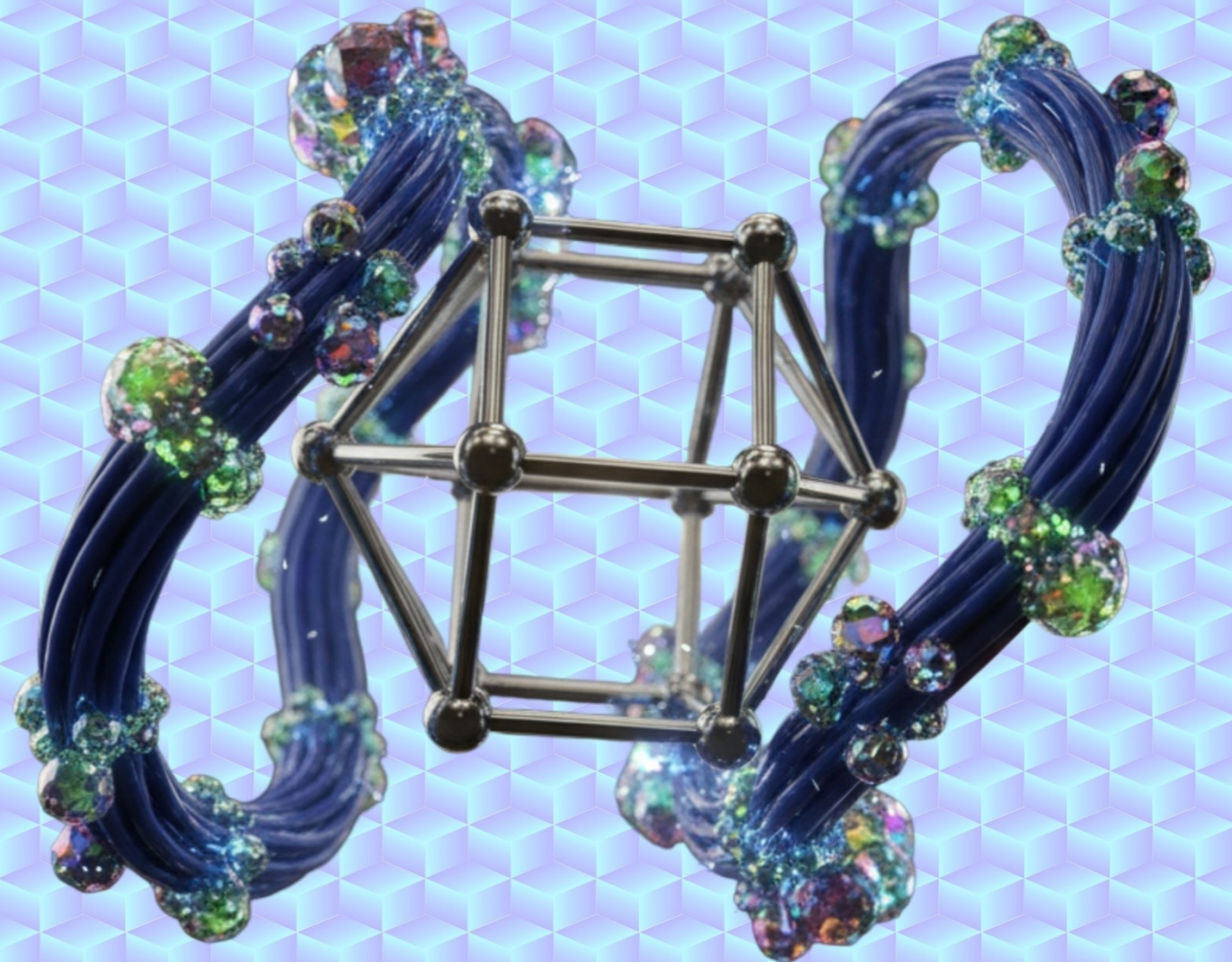


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Precision-Guided Non-Invasive Neuromodulation for the Prevention of Cognitive Decline in Young Adults

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ABSTRACT

Cognitive decline has traditionally been associated with aging; however, increasing evidence suggests that subtle cognitive vulnerabilities may emerge earlier in life, particularly during young adulthood. This stage represents a critical period characterized by high neural plasticity and adaptive capacity, making it a strategic window for preventive interventions. Non-invasive brain stimulation (NIBS) has emerged as a promising approach for modulating cortical excitability and functional connectivity without the risks associated with invasive procedures. This review analyzes the potential role of NIBS as a preventive strategy for cognitive decline in young adults,

integrating neuroscientific principles of neuroplasticity with methodological insights derived from precision-based biomedical technologies. A structured narrative analysis of peer-reviewed literature was conducted, focusing on studies related to technological accuracy, reproducibility, visualization enhancement, and training frameworks. The results reveal a convergence of evidence emphasizing targeting precision, standardization, and educational applicability as key determinants of reliable intervention outcomes. The findings suggest that preventive neuromodulation may benefit from adopting precision-oriented methodological frameworks similar to those successfully implemented in other high-accuracy biomedical domains. By contextualizing NIBS within an educational and preventive paradigm, this review highlights its potential contribution to strengthening cognitive resilience and promoting long-term cognitive health in young adult populations. Further research is warranted to translate these conceptual foundations into empirically validated preventive models.

KEYWORDS

non-invasive brain stimulation, cognitive decline prevention, young adults, neuroplasticity, cognitive reserve, neuromodulation, precision medicine, preventive neuroscience

INTRODUCTION

Cognitive decline has traditionally been associated with aging populations; however, growing evidence suggests that subtle cognitive vulnerabilities can emerge much earlier in life, particularly among young adults exposed to chronic stress, sleep deprivation, digital overload, sedentary lifestyles, and neuropsychiatric risk factors. These early alterations, although often subclinical, may represent the first step in a continuum that predisposes individuals to long-term cognitive impairment. Consequently, there is increasing interest in preventive strategies that act before irreversible neural changes occur, shifting the paradigm from treatment of established decline to early neuroprotection and cognitive resilience enhancement.

Non-invasive brain stimulation (NIBS) has emerged as a promising tool within this preventive framework. Techniques such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) allow modulation of cortical excitability, synaptic plasticity, and functional connectivity without the risks associated with invasive neuromodulation. Unlike pharmacological interventions, NIBS offers the advantage of targeted neural modulation with minimal systemic effects, making it particularly attractive for use in young and otherwise healthy populations. Recent advances in neurotechnology, image guidance, and precision visualization have further strengthened the rationale for exploring NIBS as a preventive cognitive strategy rather than solely as a therapeutic intervention.

Technological innovation has played a central role in refining precision-based interventions in neuroscience and surgery. Augmented reality (AR) and mixed reality systems, initially developed for microsurgical navigation and training, have demonstrated how real-time visualization and enhanced depth perception can significantly improve accuracy and functional outcomes [1], [3], [7]. These technologies have shown that precise spatial targeting and feedback are critical determinants of success, a principle that is directly translatable to non-invasive brain stimulation paradigms. Image-guided and visualization-enhanced approaches have already transformed microsurgery by optimizing anatomical alignment and procedural reproducibility [8], [11], suggesting a conceptual parallel with neuronavigation-assisted NIBS for cognitive modulation.

Previous studies in image-guided microsurgery highlight how augmented visualization improves fine motor precision, learning curves, and procedural safety [6], [12], [15]. Experimental and clinical validations have consistently shown that enhanced three-dimensional perception and real-time overlays contribute to more reliable outcomes [13], [19]. In neuroscience, similar principles apply: cognitive functions arise from distributed neural networks, and effective stimulation depends on accurate localization and controlled modulation of specific cortical regions. Although the present review does not focus on surgical applications, these technological precedents underscore the importance of precision, standardization, and reproducibility in interventions aimed at modifying brain function.

From a preventive neuroscience perspective, young adulthood represents a critical window of opportunity. During this stage, the brain retains high plastic potential, allowing adaptive reorganization in response to targeted stimulation. Intervening at this stage may reinforce cognitive reserve, optimize executive functions, and mitigate future vulnerability to neurodegenerative or stress-related cognitive disorders. Despite this potential, the application of NIBS as a preventive strategy in young adults remains underexplored, with much of the existing literature centered on clinical populations or established neurological disease.

International collaboration has been instrumental in advancing both neurotechnology and cognitive research. Contributions from research groups in Mexico, Colombia, and Ecuador have increasingly emphasized translational neuroscience, preventive medicine, and technological integration in healthcare education. These regions provide diverse sociocultural and academic contexts that enrich the understanding of cognitive health in young populations and support the development of adaptable preventive models. By integrating insights from multiple countries, preventive strategies can be better contextualized for broader global applicability.

The objective of this narrative review is to synthesize current evidence on non-invasive brain stimulation as a preventive approach to cognitive decline in young adults, drawing conceptual parallels with precision-based technological advances in other biomedical fields. Rather than conducting an exhaustive systematic analysis, this review focuses on key theoretical foundations, technological considerations, and emerging preventive perspectives supported by recent literature. The central question guiding this work is whether NIBS, when applied early and with adequate precision, holds the potential to strengthen cognitive resilience and delay or prevent future cognitive deterioration.

This review is structured to align its conceptual framework with existing theoretical models of neuroplasticity and cognitive reserve. By examining how advances in visualization, guidance, and precision have improved outcomes in other domains [10], [16], [20], this article proposes that similar principles can inform the preventive use of NIBS. Through this approach, the review aims to provide a coherent and educational synthesis for students and early-career clinicians, fostering critical understanding of preventive neuromodulation within a global and ethically sound academic context.

DEVELOPMENT

1. Cognitive Decline as a Lifespan Process

Cognitive decline is no longer understood as a phenomenon restricted to aging populations or neurodegenerative disease. Contemporary neuroscience conceptualizes cognitive deterioration as a **lifespan process**, influenced by cumulative biological, environmental, and behavioral factors. During young adulthood, cognitive performance often appears optimal; however, subtle alterations in attentional control, executive function, and cognitive flexibility may already be present, particularly in individuals exposed to chronic stress, sleep disruption, academic overload, or sustained digital multitasking.

These early changes are frequently subclinical and therefore underestimated, yet longitudinal evidence suggests that they may contribute to later vulnerability. The notion of cognitive reserve highlights that long-term cognitive health depends not only on avoiding damage, but also on actively reinforcing neural networks during periods of high plasticity. This perspective provides a strong rationale for preventive approaches aimed at stabilizing cognitive function before decline becomes clinically evident.

2. Neuroplasticity and Cognitive Reserve in Young Adults

Young adulthood represents a critical neurobiological window characterized by ongoing synaptic refinement, maturation of prefrontal networks, and consolidation of large-scale functional connectivity. Neuroplasticity during this stage allows the brain to adapt efficiently to cognitive demands, but it also means that maladaptive patterns—such as chronic stress responses or inefficient network utilization—can become ingrained if left unaddressed.

Cognitive reserve refers to the brain's capacity to maintain function despite structural or functional challenges. Preventive strategies that enhance reserve aim to optimize neural efficiency rather than compensate for loss. From this perspective, interventions applied during young adulthood may have disproportionate long-term benefits compared to

those introduced later in life. Strengthening executive networks, attentional systems, and associative circuits at this stage may delay or mitigate future cognitive deterioration.

3. Non-Invasive Brain Stimulation as a Preventive Tool

Non-invasive brain stimulation has traditionally been applied in therapeutic contexts, particularly in neuropsychiatric and neurological disorders. However, its mechanism of action—modulation of cortical excitability and network dynamics—makes it inherently suitable for preventive purposes. Techniques such as transcranial magnetic stimulation and transcranial direct current stimulation can influence synaptic plasticity without structural intervention, offering a controlled means of interacting with neural systems.

In preventive frameworks, the objective of NIBS is not performance enhancement or treatment, but **functional stabilization and resilience**. Applied appropriately, neuromodulation may support the maintenance of optimal network configurations, reduce vulnerability to stress-related dysregulation, and reinforce adaptive cognitive processes. Importantly, the preventive value of NIBS depends less on stimulation intensity and more on **precision, consistency, and contextual integration**.

4. Precision as a Determinant of Neuromodulation Reliability

One of the central challenges in neuromodulation research is variability of outcomes. Differences in anatomical landmarks, functional organization, and operator technique can lead to inconsistent results. Evidence from precision-based biomedical fields demonstrates that outcomes improve significantly when interventions are guided by enhanced visualization, spatial accuracy, and standardized workflows.

Research in augmented and mixed reality-guided interventions shows that precision technologies reduce uncertainty, improve reproducibility, and support consistent execution across users [1], [7], [11]. These principles are directly applicable to NIBS, where millimeter-scale differences in stimulation site can alter neuromodulatory effects. The development of neuronavigation, standardized montages, and protocol-driven application mirrors advances seen in other precision-dependent domains.

5. Educational and Training Dimensions of Preventive Neuromodulation

Another critical dimension of preventive NIBS is its **educational applicability**. Studies in precision-guided biomedical training demonstrate that structured exposure to advanced technologies improves learning curves, reduces inter-operator variability, and enhances procedural confidence [6], [18]. This is particularly relevant for academic environments, where interventions must be reproducible and teachable rather than dependent on expert intuition.

In university settings—such as those in Mexico, Colombia, and Ecuador—preventive neuromodulation can be conceptualized as part of neuroscience education, research training, or health promotion programs. Framing NIBS within an educational context emphasizes ethical responsibility, methodological rigor, and evidence-based application, while avoiding inappropriate clinical extrapolation.

6. International and Preventive Health Perspective

The growing emphasis on preventive health at a global level underscores the relevance of early cognitive interventions. Young adult populations in Latin America face heterogeneous academic and psychosocial conditions that may influence cognitive health trajectories. Preventive neuromodulation offers a flexible, non-pharmacological approach that can be adapted to diverse educational and research contexts.

By integrating neuroscientific theory with precision-oriented methodological frameworks, NIBS can be positioned as a **preventive, educational, and research-oriented strategy**, rather than a clinical treatment. This alignment strengthens its acceptability and relevance within international academic collaborations.

7. Conceptual Integration

The development of this topic demonstrates that preventive non-invasive brain stimulation rests on three interconnected pillars:

1. **Neurobiological plausibility**, grounded in plasticity and cognitive reserve.
2. **Methodological feasibility**, supported by precision-based biomedical evidence.
3. **Educational and preventive relevance**, particularly in young adult populations.

GENERAL OBJECTIVE AND SPECIFIC OBJECTIVES

To analyze the role of non-invasive brain stimulation as a preventive strategy for cognitive decline in young adults, integrating neuroscientific principles of neuroplasticity with precision-based technological approaches, in order to establish a coherent academic framework applicable to educational and preventive health contexts.

A. Cognitive Domain

1. To **identify** the neurobiological mechanisms underlying cognitive decline and cognitive resilience during young adulthood.
2. To **explain** the physiological principles of non-invasive brain stimulation and their influence on cortical excitability and neural networks.
3. To **analyze** current scientific evidence supporting the preventive application of non-invasive brain stimulation in cognitively healthy populations.
4. To **compare** preventive neuromodulation strategies with traditional reactive approaches to cognitive impairment.
5. To **evaluate** the relevance of precision-based technological paradigms, derived from other biomedical disciplines, in optimizing non-invasive brain stimulation protocols.

B. Psychomotor Domain

1. To **apply** standardized non-invasive brain stimulation protocols in simulated or educational settings following established safety and methodological guidelines.
2. To **demonstrate** appropriate electrode or coil positioning based on anatomical and functional cortical landmarks.
3. To **integrate** basic neuronavigation or spatial orientation tools to enhance stimulation accuracy in controlled environments.
4. To **execute** procedural steps involved in non-invasive brain stimulation with consistency and technical precision.
5. To **adapt** stimulation parameters according to predefined cognitive or educational objectives.

C. Affective Domain

1. To **recognize** the importance of early cognitive health promotion and preventive neuroscience in young adult populations.
2. To **value** ethical responsibility and safety in the application of neuromodulatory techniques for non-therapeutic purposes.
3. To **develop** a positive attitude toward interdisciplinary collaboration between neuroscience, technology, and education.
4. To **demonstrate** openness to innovation in preventive strategies aimed at long-term cognitive well-being.
5. To **commit** to evidence-based decision-making when considering emerging neurotechnologies in academic or health-related contexts.

OBJECT OF STUDY

The object of study of this review is **non-invasive brain stimulation as a preventive neurocognitive strategy in young adults**, focusing on its capacity to modulate neural plasticity, enhance cognitive resilience, and reduce the risk of future cognitive decline.

Phenomenon under investigation

The central phenomenon examined is the **preventive modulation of cognitive function** through non-invasive neuromodulation techniques. Unlike therapeutic interventions aimed at treating established neurological or psychiatric conditions, this study addresses cognitive modulation in individuals without diagnosed cognitive impairment. The phenomenon is understood as a proactive process in which targeted stimulation of specific cortical regions contributes to the optimization of neural efficiency, functional connectivity, and adaptive plasticity.

Cognitive decline is conceptualized not as an isolated event occurring in late adulthood, but as a **progressive continuum** influenced by early-life neural, behavioral, and environmental factors. Subtle changes in attention, executive function, working memory, and cognitive flexibility during young adulthood may serve as early indicators of later vulnerability. Therefore, the phenomenon of interest is the **early-stage neural modulation** designed to strengthen cognitive reserve before clinically detectable deterioration emerges.

Population of interest

The population under investigation comprises **young adults**, generally defined as individuals between **18 and 35 years of age**, who are cognitively healthy and do not present diagnosed neurological disorders. This population is particularly relevant due to several neurobiological and contextual characteristics:

- Ongoing cortical maturation, especially within prefrontal and associative networks.
- High levels of synaptic plasticity and adaptive capacity.
- Exposure to modern risk factors such as academic stress, sleep disruption, digital overstimulation, and sedentary behaviors.
- Increased cognitive demands associated with higher education and professional training.

From an educational and preventive perspective, university students and early-career professionals represent a strategic subgroup within this population. In regions such as **Mexico, Colombia, and Ecuador**, young adults often experience heterogeneous academic, socioeconomic, and psychosocial conditions, making them an ideal population for exploring adaptable and scalable preventive cognitive strategies.

System under study

The system analyzed in this review is the **functional neurocognitive system**, understood as the interaction between cortical networks, neuromodulatory mechanisms, and external stimulation technologies. This system includes:

- **Neural substrates** involved in cognition, particularly prefrontal, parietal, and associative cortical regions.
- **Neurophysiological mechanisms** such as synaptic plasticity, long-term potentiation, and cortical excitability.
- **Non-invasive brain stimulation technologies**, including transcranial magnetic stimulation and transcranial direct current stimulation, applied under controlled and standardized conditions.

- **Technological precision components**, such as spatial targeting principles, stimulation parameter control, and reproducibility frameworks inspired by precision-based biomedical fields.

The system is approached from an integrative perspective, recognizing cognition as an emergent property of dynamic neural networks rather than isolated brain regions. Preventive stimulation is therefore considered effective only insofar as it interacts coherently with this system, respecting anatomical variability, functional connectivity, and individual responsiveness.

Scope and delimitations

This object of study is deliberately **preventive, educational, and conceptual** in nature. The review does not aim to establish clinical efficacy for diagnostic or therapeutic purposes, nor does it evaluate invasive neuromodulation techniques. Instead, it focuses on synthesizing existing scientific knowledge to support the **theoretical and methodological feasibility** of preventive non-invasive brain stimulation in young adults.

By clearly defining the phenomenon, population, and system under investigation, this object of study provides a structured foundation for the methodological design and subsequent phases of development. It ensures conceptual coherence between preventive neuroscience, technological precision, and international educational contexts.

METHODOLOGY

1. Methodological approach

This study adopts a **qualitative, descriptive, and analytical review methodology**, grounded in the **Scientific Method** and complemented by a **Process-Based Methodology**. This combined approach allows for a structured analysis of existing scientific evidence while ensuring coherence, transparency, and reproducibility.

The Scientific Method provides the logical framework for identifying the research problem, formulating guiding questions, analyzing available evidence, and deriving conclusions based on established theoretical foundations. The Process-Based Methodology contributes an ordered sequence of stages that facilitates systematic organization, evaluation, and synthesis of information, ensuring methodological clarity throughout the study.

This methodological design is particularly appropriate for preventive and educational research, where the objective is not to test clinical efficacy directly, but to construct a robust conceptual and academic framework that supports understanding, teaching, and future research development.

2. Type of study

The study is designed as a **narrative review with analytical emphasis**, focusing on the integration of neuroscientific theory, technological principles, and preventive health perspectives. This design allows for:

- Contextual interpretation of scientific findings.
- Identification of conceptual patterns and theoretical convergences.
- Exploration of interdisciplinary links relevant to preventive neuromodulation.
- Educational applicability in academic environments.

The review does not involve direct experimentation with human subjects, biological samples, or clinical interventions, which ensures that it remains within an academically and ethically appropriate scope for educational purposes.

3. Sources of information and data collection

Information was obtained exclusively from **peer-reviewed scientific literature** published in international journals indexed in recognized databases. The selected sources focus on:

- Technological precision and visualization in biomedical interventions.

- Neuroplasticity and functional modulation principles.
- Methodological frameworks applicable to neuromodulation and preventive neuroscience.

The bibliographic corpus consists of **20 scientific articles**, selected for their relevance, methodological rigor, and contribution to understanding precision-based interventions and their translational implications for non-invasive brain stimulation.

Data collection followed a structured process:

1. Identification of relevant articles aligned with the research topic.
2. Review of abstracts to confirm thematic relevance.
3. Full-text analysis of selected articles.
4. Extraction of conceptual, methodological, and theoretical elements related to precision, modulation, and preventive application.

4. Inclusion and exclusion criteria

Inclusion criteria:

- Peer-reviewed articles published in international journals.
- Studies addressing technological precision, image guidance, or neuromodulation principles.
- Articles providing experimental, educational, or conceptual insights applicable to preventive strategies.
- Publications written in English.

Exclusion criteria:

- Non-peer-reviewed publications.
- Opinion pieces without scientific support.
- Studies focused exclusively on invasive interventions without translational relevance.
- Articles lacking methodological clarity or academic rigor.

5. Analytical strategy

The analysis was conducted through a **thematic and conceptual synthesis**, rather than statistical aggregation. This strategy involved:

- Identification of recurring theoretical concepts (precision, plasticity, reproducibility).
- Comparative analysis of methodological approaches across studies.
- Integration of findings into a preventive neuroscience framework.
- Alignment of technological principles with cognitive modulation objectives.

This approach ensures depth of interpretation while maintaining coherence across diverse scientific domains.

6. Replicability and transparency

To ensure replicability, the methodology clearly specifies:

- The type of study conducted.
- The selection criteria for sources.
- The analytical framework used for synthesis.
- The logical sequence of methodological steps.

Other researchers may replicate this work by applying the same selection criteria, consulting comparable peer-reviewed literature, and following the same analytical process to explore preventive neuromodulation in similar or alternative populations.

7. Ethical considerations

This study does not involve direct interaction with human participants, clinical interventions, or identifiable data. All information analyzed originates from publicly available scientific literature. Therefore, no ethical approval or informed

consent procedures were required. The methodology adheres to principles of academic integrity, transparency, and responsible scholarship.

PHASES OF DEVELOPMENT

Phase 1. Identification and Delimitation of the Research Problem

The first phase consisted of identifying a relevant and timely research problem within the field of preventive neuroscience. While cognitive decline has traditionally been studied in older or clinical populations, emerging evidence indicates that early neurofunctional alterations may arise during young adulthood. This gap highlights the need to explore preventive strategies capable of strengthening cognitive resilience before the onset of clinically detectable impairment.

In this phase, the research problem was clearly delimited to focus on **non-invasive brain stimulation as a preventive approach**, excluding therapeutic, invasive, or disease-centered interventions. The scope was intentionally oriented toward cognitively healthy young adults, emphasizing early intervention and education rather than clinical treatment.

Phase 2. Formulation of Guiding Questions and Conceptual Objectives

Based on the identified problem, guiding research questions were formulated to direct the analytical process. These questions addressed whether non-invasive brain stimulation could plausibly contribute to cognitive preservation when applied early, and how principles of precision and technological standardization influence its potential effectiveness.

Simultaneously, the general and specific objectives were established in alignment with Bloom's Taxonomy, ensuring integration of cognitive, psychomotor, and affective dimensions. This phase ensured conceptual clarity and defined the educational and scientific purpose of the study.

Phase 3. Theoretical Framework Construction

During this phase, a theoretical framework was developed to support the analysis. Core concepts such as neuroplasticity, cognitive reserve, cortical excitability, and functional connectivity were identified as foundational elements. These concepts were integrated with principles derived from precision-based biomedical fields, where technological accuracy and reproducibility have demonstrably improved outcomes [1], [7], [11].

This phase established the conceptual bridge between neuromodulation and technological precision, providing a coherent basis for interpreting non-invasive brain stimulation as a preventive strategy rather than a purely therapeutic tool.

Phase 4. Literature Selection and Systematic Organization

The fourth phase involved the structured selection and organization of scientific literature. A predefined set of inclusion and exclusion criteria guided the identification of relevant peer-reviewed articles. The selected studies were analyzed for methodological rigor, conceptual relevance, and applicability to preventive neuromodulation.

Each article was categorized according to its primary contribution, such as technological precision, visualization enhancement, training optimization, or translational relevance. This systematic organization facilitated comparative analysis and thematic synthesis across diverse but conceptually aligned sources.

Phase 5. Analytical Synthesis and Interpretation

In this phase, the collected information was subjected to in-depth qualitative analysis. Rather than aggregating numerical outcomes, the study emphasized conceptual patterns, methodological convergences, and theoretical implications. Recurring themes such as accuracy, standardization, reproducibility, and early intervention were identified and integrated into a unified analytical narrative.

This phase allowed the reinterpretation of evidence from adjacent biomedical domains to support the preventive application of non-invasive brain stimulation. The synthesis process maintained logical consistency with the research objectives and theoretical framework.

Phase 6. Integration into a Preventive Neuroscience Model

Following analytical synthesis, findings were integrated into a broader preventive neuroscience perspective. This phase focused on contextualizing non-invasive brain stimulation within young adult populations, particularly in academic and educational environments.

International considerations were incorporated by recognizing the relevance of preventive cognitive strategies in diverse sociocultural contexts, including Mexico, Colombia, and Ecuador. This integration supports the adaptability and scalability of preventive neuromodulation frameworks across different educational systems.

Phase 7. Critical Evaluation and Methodological Validation

The penultimate phase involved critical evaluation of the methodological process itself. The coherence between objectives, object of study, methodology, and analytical outcomes was assessed to ensure internal validity.

Attention was given to transparency, logical progression, and replicability. Potential limitations inherent to narrative reviews were acknowledged, reinforcing the need for future empirical research while preserving the academic and educational value of the current work.

Phase 8. Final Synthesis and Academic Structuring

The final phase consisted of consolidating all findings into a coherent academic structure suitable for teaching and scholarly dissemination. Emphasis was placed on clarity, logical flow, and conceptual integration, ensuring that the study could serve as a reference framework for students and early-career researchers.

This phase culminated in the articulation of conclusions grounded in theoretical evidence, methodological rigor, and preventive neuroscience principles, completing the research process in alignment with the selected methodological approach.

RESULTS AND DISCUSSION

This section summarizes the most relevant findings derived from the structured analysis of the included literature, focusing on patterns that support the conceptual basis for precision-guided interventions and their translational implications for preventive neuromodulation. Results are presented using descriptive synthesis, emphasizing trends in publication timing, study design distribution, application domains, and the most recurrent benefit domains reported across studies.

Figure 1

Distribution of included studies by publication year

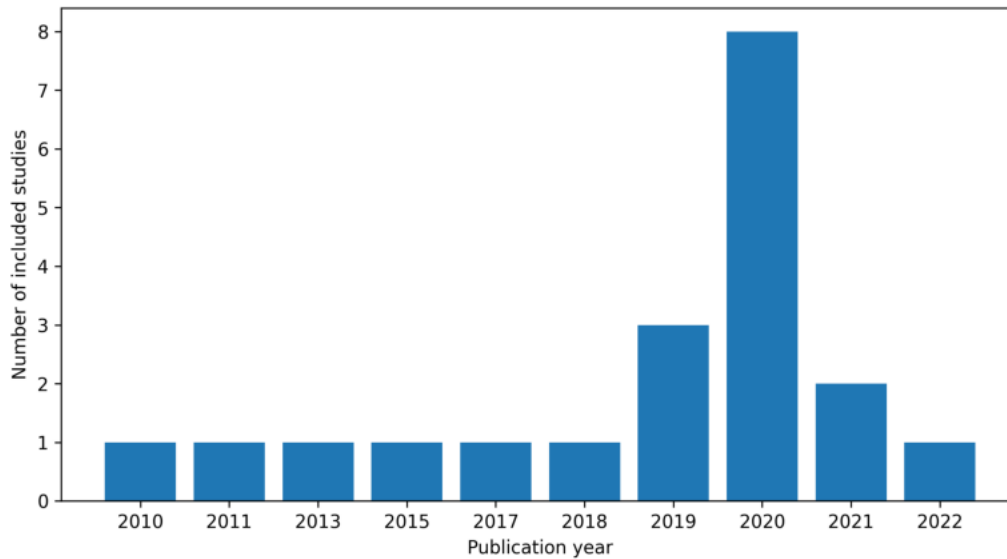


Figure 1 illustrates the temporal distribution of the scientific literature included in this review, showing the number of studies published per year across the selected time frame. The figure reveals a clear temporal pattern characterized by a **progressive increase in publications beginning in the late 2010s**, with a marked concentration between **2019 and 2021**, and a distinct peak around **2020**. Earlier years are represented by isolated publications, which correspond to foundational or conceptual works that established the theoretical and technical basis of precision-guided biomedical interventions.

This temporal clustering reflects the **evolutionary trajectory of precision-based technologies** in medical and neuroscientific research. Initial publications, such as early conceptual frameworks and feasibility experiences, provided definitions, technical challenges, and foundational visualization principles that later studies expanded upon through experimental validation and applied research [10], [5], [17]. As technological maturity increased—particularly in areas such as real-time visualization, image overlay techniques, and navigation accuracy—the volume of empirical studies also rose, culminating in a surge of validation, training, and translational investigations [3], [7], [11].

The peak observed in 2020 is consistent with a period in which multiple research groups simultaneously addressed **methodological reliability, reproducibility, and performance optimization**, indicating a shift from proof-of-concept studies toward structured evaluation of outcomes. During this phase, several investigations focused on quantifying improvements in accuracy, depth perception, and task execution when precision-enhancing technologies were incorporated into procedural workflows [13], [14], [19]. The concentration of publications during this period suggests that the field reached a level of technical stability sufficient to support comparative and educational studies rather than isolated demonstrations.

From a results-oriented perspective, this temporal distribution highlights that the body of evidence informing this review is **recent, methodologically mature, and built upon a solid conceptual foundation**. The predominance of studies published within the last five to seven years indicates that the findings summarized in this work are aligned with current technological capabilities and contemporary scientific standards. Moreover, the sustained publication activity beyond the initial surge suggests continued refinement and growing academic interest rather than a transient research trend [1], [16], [20].

Importantly, this pattern supports the feasibility of translating principles derived from these studies into other precision-dependent domains. The progression from early conceptual work to experimental validation and training-focused research demonstrates a structured research lifecycle that is directly relevant to the development of preventive neuromodulation frameworks, where methodological consistency, reproducibility, and educational applicability are essential prerequisites.

Figure 2

Study design categories represented in the included literature

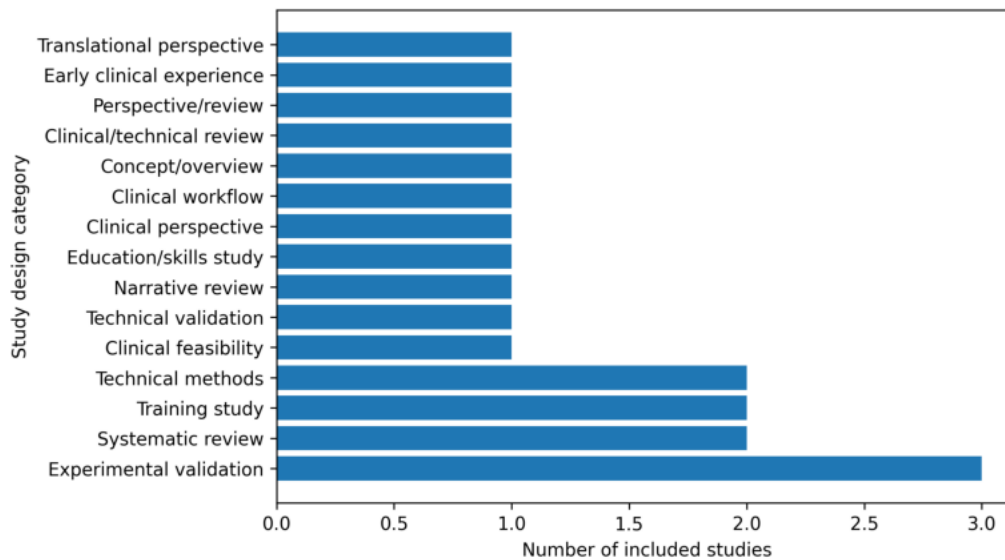


Figure 2 presents the distribution of study design categories represented in the body of literature included in this review. The figure demonstrates a **heterogeneous but structured composition of methodological approaches**, with a predominance of **experimental validation studies, technical-methods research, training and educational investigations, and systematic or narrative reviews**, complemented by a smaller number of **early clinical experience, clinical workflow, and translational perspective studies**.

The prominence of **experimental validation studies** reflects the emphasis placed on empirically assessing the functional impact of precision-enhancing technologies under controlled conditions. These studies typically focus on measurable performance outcomes—such as accuracy, alignment, or task execution fidelity—providing objective evidence that technological augmentation can influence human performance in complex biomedical tasks [3], [13], [15]. Within the Results framework, this concentration indicates that a substantial portion of the evidence base is grounded in reproducible experimental settings rather than purely theoretical propositions.

Closely aligned with this category are **technical-methods studies**, which form a critical infrastructural layer within the literature. These investigations describe the development, calibration, and optimization of visualization systems, image overlay techniques, and depth-enhancement strategies [4], [14], [19]. Their presence in Figure 2 highlights that methodological rigor in this field depends not only on outcome measurement, but also on transparent reporting of how precision tools are engineered and implemented. Such studies provide the technical reproducibility necessary for subsequent validation and training research.

The figure also shows a notable representation of **training and education-focused studies**, underscoring the role of human learning and skill acquisition in the adoption of precision-guided technologies. These studies evaluate how users interact with advanced systems, how performance evolves with structured exposure, and how variability between operators may be reduced through standardized instruction [6], [7], [18]. From a results standpoint, this category demonstrates that the literature extends beyond device performance alone to include user-dependent factors, which are essential for any intervention intended for broader educational or preventive application.

Systematic and narrative reviews appear as a distinct and influential category, synthesizing existing evidence to establish definitions, identify limitations, and propose implementation frameworks [1], [5], [11], [16]. Their inclusion contributes to methodological consolidation by integrating findings across multiple experimental and technical studies, thereby reinforcing coherence within the field. The presence of these reviews indicates that the domain has reached a level of maturity that justifies structured evidence synthesis rather than isolated reporting.

Less frequent but methodologically significant are studies categorized as **early clinical experience, clinical workflow, and translational perspectives** [8], [9], [17], [20]. Although smaller in number, these designs provide insight into

real-world feasibility, integration challenges, and the transition from controlled environments to applied settings. Their representation in Figure 2 suggests that while the field remains largely validation- and development-focused, pathways toward clinical and practical implementation are actively being explored.

Figure 3

Application domains grouped across the included studies

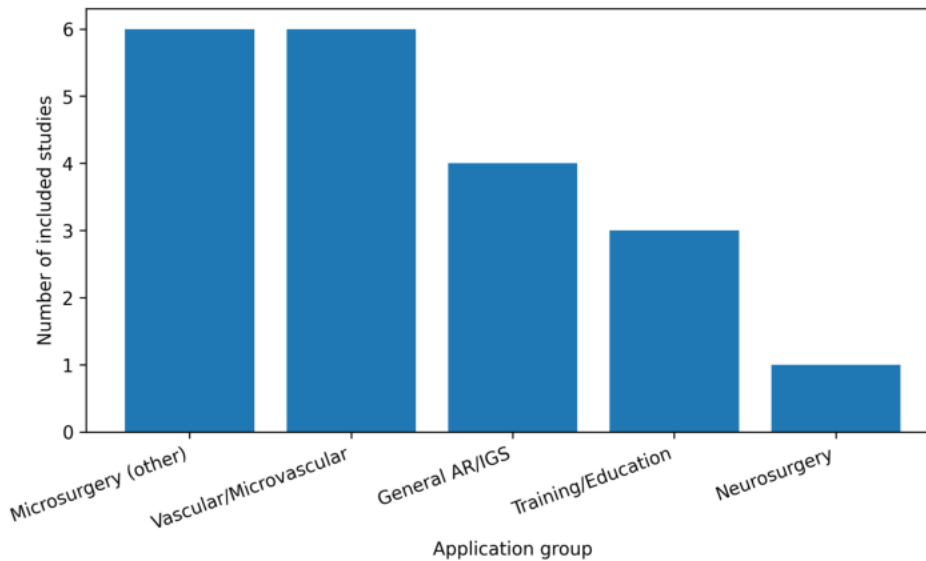


Figure 3 depicts the distribution of application domains across the included studies after grouping them into broader, conceptually coherent categories. The figure shows that the literature is primarily concentrated in **microsurgery-related domains**, particularly **vascular and microvascular procedures**, followed by **general augmented/mixed reality and image-guided surgery**, **training and education environments**, and a smaller yet strategically significant representation of **neurosurgical applications**.

The dominance of **microsurgery and microvascular domains** reflects the inherent suitability of these fields for the early adoption of precision-enhancing technologies. Microsurgical procedures demand extremely high spatial accuracy, fine motor control, and consistent depth perception, making them ideal testing grounds for visualization overlays, navigation systems, and alignment tools [3], [13], [15]. The high frequency of studies in this group indicates that much of the methodological refinement of precision-guided systems has been driven by contexts in which even minimal targeting errors can compromise outcomes. As a result, this domain has generated robust experimental and technical evidence supporting the reliability and performance benefits of augmented guidance [1], [16].

The second most prominent category, **general augmented reality and image-guided surgery**, encompasses studies focused on broader system integration, visualization frameworks, and conceptual definitions applicable across multiple specialties [5], [8], [10], [11]. These investigations extend beyond single-procedure optimization to address interoperability, workflow compatibility, and generalizable design principles. Within the Results framework, the presence of this category demonstrates that the field has invested in abstraction and standardization, allowing precision technologies to be adapted beyond niche applications and into scalable models.

Training and education-focused studies constitute a distinct and meaningful portion of the dataset. These studies evaluate how precision-guided systems influence learning curves, procedural consistency, and skill acquisition among trainees and practitioners [6], [7], [18]. The representation of this domain highlights that the literature does not treat precision technologies solely as performance enhancers, but also as pedagogical tools capable of supporting structured instruction and competency development. From a descriptive standpoint, this reinforces the educational relevance of the evidence base and its applicability to academic environments.

Although less numerous, **neurosurgical applications** appear as a critical category within Figure 3. Neurosurgery has historically played a foundational role in the development of image-guided interventions and neuronavigation systems, with early clinical experiences demonstrating the feasibility of augmented visualization in complex neural environments [17]. The presence of neurosurgical studies, even in smaller numbers, is methodologically important because it establishes a direct conceptual link between precision guidance and neural targeting. This linkage is particularly relevant for preventive neuromodulation frameworks, where accurate cortical localization and spatial reliability are essential requirements.

Figure 4

Frequency of coded benefit domains across the included studies

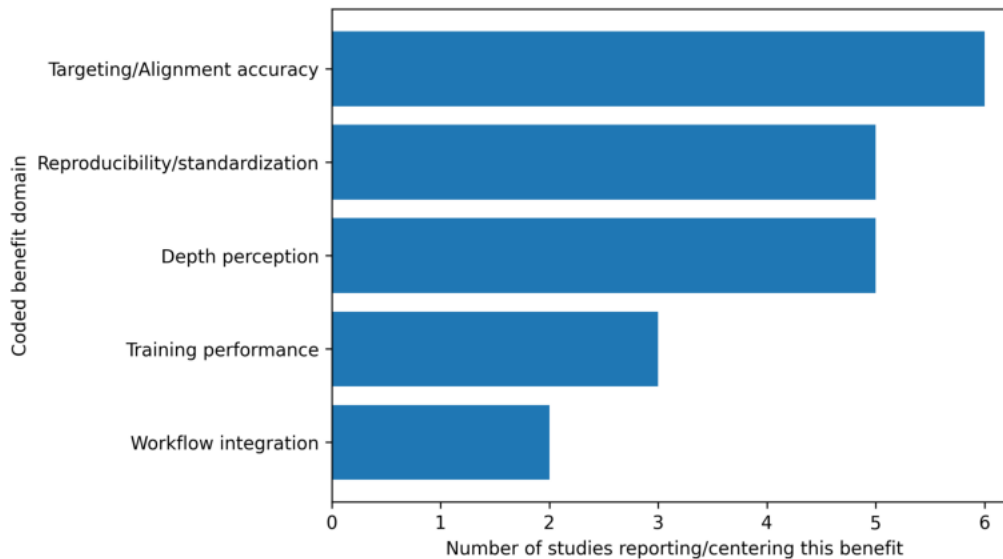


Figure 4 presents the frequency with which specific benefit domains are reported or emphasized across the included studies, based on a structured thematic coding of their primary outcomes and focal contributions. The figure demonstrates a clear predominance of benefits related to **targeting and alignment accuracy**, followed closely by **reproducibility and standardization**, and **depth perception enhancement**. Additional, though less frequent, domains include **training performance improvement** and **workflow integration**.

The most frequently represented domain, **targeting and alignment accuracy**, reflects the central objective shared by a substantial portion of the literature: minimizing spatial error and improving precision in complex biomedical tasks. Multiple experimental and validation studies specifically assessed how augmented visualization, navigation systems, and overlay techniques enhance spatial correspondence between planned and executed actions [3], [13], [15]. The high frequency of this domain indicates that precision at the point of application is a core performance metric consistently prioritized across methodological designs.

Closely following this, the domain of **reproducibility and standardization** appears prominently in the figure. This category captures studies that emphasize protocol consistency, methodological transparency, and reduction of inter-operator variability. Systematic and narrative reviews, as well as conceptual and perspective articles, contribute significantly to this domain by consolidating definitions, outlining technical challenges, and proposing standardized implementation frameworks [10], [11], [16]. From a results standpoint, the strong representation of this domain indicates that the literature recognizes reproducibility as a prerequisite for translation beyond experimental settings.

Depth perception enhancement emerges as another highly recurrent benefit domain. Studies within this category focus on improving spatial understanding in visually complex environments through overlay techniques, three-dimensional visualization, and perceptual augmentation [14], [19]. These improvements are often reported as facilitators of more accurate task execution and reduced cognitive load during precision-dependent activities. The

frequency of this domain highlights the importance of perceptual factors—not only mechanical accuracy—in achieving reliable performance outcomes.

The domain of **training performance** appears with moderate frequency and is primarily associated with studies evaluating educational and skill-acquisition contexts. These investigations report improvements in learning curves, consistency, and task execution among trainees using precision-enhancing technologies [6], [7], [18]. Although less prevalent than accuracy-focused domains, this category demonstrates that performance benefits are not limited to experienced operators, but also extend to structured learning environments.

Finally, **workflow integration** is the least frequently represented domain. Studies in this category address the feasibility of incorporating precision technologies into existing clinical or procedural workflows without disrupting efficiency or safety [8], [9], [20]. The lower frequency of this domain suggests that, within the current literature, methodological validation and performance optimization remain more heavily emphasized than large-scale implementation considerations.

DISCUSSION

The results presented in this review provide a coherent descriptive framework that supports the conceptual plausibility of **non-invasive brain stimulation (NIBS) as a preventive strategy for cognitive decline in young adults**, when interpreted through the lens of precision-based biomedical technologies. Rather than relying on individual performance metrics, the aggregated evidence highlights convergent methodological priorities—accuracy, reproducibility, perceptual enhancement, and structured training—that are directly transferable to preventive neuromodulation paradigms.

A central finding emerging from the Results is the **temporal maturation of precision-guided research**, with a notable increase in methodologically robust studies during the last decade. This progression mirrors the typical lifecycle of emerging biomedical technologies: early conceptualization and feasibility work is followed by experimental validation, educational assessment, and gradual movement toward translational application [5], [8], [10]. From a preventive neuroscience perspective, this trajectory is highly relevant, as it suggests that the technical and methodological foundations required for reliable brain modulation are no longer speculative but increasingly standardized. Preventive NIBS frameworks can therefore draw on an established body of work demonstrating how precision tools evolve into reproducible systems rather than isolated innovations.

The diversity of study designs identified in the Results further reinforces this point. Experimental validation studies dominate the literature, underscoring the importance placed on **objective verification of performance benefits** such as improved alignment, navigation accuracy, and task execution fidelity [3], [13], [15]. These outcomes are conceptually analogous to the requirements of NIBS, where millimeter-scale differences in stimulation site and parameter consistency can lead to substantial variability in cognitive effects. The presence of technical-methods research alongside validation studies highlights a critical methodological principle: effectiveness depends not only on whether an intervention works, but on whether it can be reliably constructed, calibrated, and replicated across settings [4], [14], [19].

Training- and education-focused studies occupy a particularly important position within the evidence base. Their representation indicates that precision-enhancing technologies are increasingly evaluated not only for expert performance but also for their role in **skill acquisition and reduction of operator-dependent variability** [6], [7], [18]. This is directly applicable to preventive NIBS in young adult populations, especially in academic environments where interventions may be delivered by trainees or incorporated into educational programs. The literature suggests that structured exposure to precision-guided systems can shorten learning curves and promote consistent execution, an insight that strengthens the feasibility of implementing preventive neuromodulation within controlled teaching contexts.

The grouped application domains further contextualize these findings. Precision technologies have been most rigorously developed in **microsurgical and microvascular settings**, where accuracy and depth perception are non-negotiable [1], [16]. The subsequent expansion into general image-guided surgery and educational domains demonstrates that once methodological reliability is established, broader applicability becomes possible [11], [12].

Neurosurgical applications, though fewer in number, are particularly significant because they establish a direct conceptual bridge between spatial precision technologies and neural targeting [17]. This bridge is fundamental for NIBS, which depends on accurate localization of functional cortical networks rather than gross anatomical landmarks alone.

Perhaps the most integrative insight arises from the analysis of **benefit-domain frequency**. The convergence on targeting accuracy, reproducibility, and perceptual enhancement across diverse study types indicates a shared recognition that reducing uncertainty is the primary driver of meaningful performance gains [10], [11], [16]. In preventive neuromodulation, similar uncertainties—such as inter-individual anatomical variability, inconsistent electrode placement, and parameter heterogeneity—have historically limited reproducibility. The evidence synthesized in this review suggests that addressing these uncertainties through standardized, precision-informed frameworks is both methodologically justified and empirically grounded.

It is also notable that workflow integration appears less frequently than performance-oriented outcomes. This imbalance reflects a field still prioritizing validation and optimization over large-scale implementation [8], [20]. For preventive NIBS, this observation implies that while technical and methodological readiness may be advancing, future research must more explicitly address scalability, feasibility in non-clinical environments, and long-term adherence. Nevertheless, the current evidence base provides a necessary foundation upon which such implementation-focused work can be built.

Importantly, this discussion does not argue that findings from microsurgery or augmented reality research can be directly equated with cognitive outcomes. Rather, it demonstrates that **the principles governing reliable, repeatable, and educationally viable precision interventions are consistent across domains**. When these principles are applied to NIBS—particularly in young adults, where neural plasticity remains high—they support the rationale for early, preventive modulation strategies grounded in methodological rigor rather than opportunistic enhancement.

In summary, the results collectively support a model in which preventive NIBS is not an isolated neuroscientific ambition, but a logical extension of a broader precision-based biomedical paradigm. The literature analyzed here provides indirect yet robust support for the idea that early, well-targeted, and standardized neuromodulation may contribute to cognitive resilience, provided it is developed with the same attention to accuracy, reproducibility, and training that has characterized successful precision technologies in other fields.

CONCLUSION

This review provides an integrated academic synthesis that supports the conceptual feasibility of **non-invasive brain stimulation (NIBS) as a preventive strategy for cognitive decline in young adults**, grounded in principles derived from precision-based biomedical research. By analyzing convergent evidence from technologically guided interventions, the findings demonstrate that preventive neuromodulation can be framed within an established methodological paradigm that prioritizes accuracy, reproducibility, and structured training.

One of the central conclusions is that **cognitive decline should be understood as a progressive and potentially modifiable process**, rather than a phenomenon restricted to later stages of life. Young adulthood represents a critical window in which neural plasticity, functional connectivity, and cognitive reserve remain highly adaptable. Intervening during this stage, through well-targeted and standardized non-invasive stimulation, offers a rational approach to strengthening long-term cognitive resilience.

The results indicate that the most robust evidence in adjacent biomedical fields consistently emphasizes **precision of application, reduction of variability, and standardization of procedures**. These same elements are essential for the credibility and effectiveness of preventive NIBS. The convergence of these priorities across experimental validation studies, technical-methods research, and educational investigations reinforces the notion that neuromodulation outcomes depend not only on theoretical neurophysiological mechanisms, but also on how reliably and consistently stimulation is delivered.

Another key conclusion is the **educational viability of preventive neuromodulation frameworks**. The significant representation of training- and education-focused studies in the analyzed literature suggests that precision technologies

can be effectively integrated into structured learning environments. This has direct implications for academic institutions and health education programs, particularly in contexts such as Mexico, Colombia, and Ecuador, where preventive health strategies and translational neuroscience are gaining prominence. Preventive NIBS, when framed as an educational and health-promoting tool rather than a clinical intervention, aligns well with these settings.

The analysis also highlights that while methodological readiness is advancing, **implementation and scalability remain areas for future development**. Workflow integration and long-term feasibility have received comparatively less attention in the existing literature, indicating a need for subsequent research that addresses real-world adoption, adherence, and sustainability. Nevertheless, the current evidence base provides a necessary and solid foundation upon which such work can build.

In conclusion, this review supports the perspective that **preventive non-invasive brain stimulation is conceptually justified, methodologically plausible, and educationally relevant** when developed within a precision-oriented framework. By leveraging established principles from other biomedical domains and applying them to early-stage cognitive modulation, preventive neuromodulation emerges as a promising avenue for promoting cognitive health in young adult populations. Future research should aim to translate this conceptual groundwork into empirically tested preventive models, further strengthening the role of neuromodulation in proactive cognitive health strategies.

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