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Exploring Neurosurgery Techniques for Enhancing Brain Thing Functions in General Populations and Other Area Matters: A Narrative Review

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ABSTRACT

Background: *The field of neurosurgery is evolving from a discipline focused on structural correction to one capable of directly modulating brain function. This progression prompts a fundamental question: are the functional outcomes of these interventions a result of specific neuromodulation or a consequence of the physical surgical act itself?* ***Objective***: *This narrative review aims to critically examine the existing literature to determine whether contemporary neurosurgical techniques enhance brain function through a primarily "neuro" mechanism, a "surgical" mechanism, or a synergistic interplay of both.* ***Main Discussion Points***: *The review synthesizes evidence across key themes, including the circuit-level modulation achieved by deep brain stimulation for neuropsychiatric disorders, the cognitive consequences of surgical disconnection in ablative procedures, and the emergent network reorganization following resective surgery for epilepsy. The analysis highlights that while advanced techniques demonstrate targeted neurophysiological effects, the evidence is often constrained by methodological limitations such as small sample sizes and a lack of controlled trials. The discussion also explores the implications of these findings for potential cognitive enhancement beyond severe pathology.* ***Conclusion***: *The evidence suggests that the most significant functional outcomes arise from a synergistic model where the surgical procedure enables precise, targeted neuromodulation, rendering the "neuro" and "surgical" components inseparable. Future progress hinges on larger, mechanistic studies employing standardized outcome measures to fully elucidate these interactions and guide the ethical application of these powerful interventions.*

Keywords
Functional Neurosurgery, Deep Brain Stimulation, Neuromodulation, Cognitive Enhancement, Network Connectivity, Narrative Review.

INTRODUCTION

The human brain, an intricate network of approximately 86 billion neurons, represents the final frontier in medical science, governing everything from fundamental homeostasis to the complex tapestry of consciousness, cognition, and identity (1). In the realm of therapeutic intervention, neurological and psychiatric disorders constitute a leading cause of global disability, with conditions affecting cognitive and emotional function placing an immense burden on healthcare systems and societies worldwide (2). Historically, neurosurgery has been a discipline primarily oriented toward structural pathology, resecting tumors, clipping aneurysms, and alleviating abnormal compression. Its success has been measured in terms of lesion removal or anatomical correction, with functional preservation being the paramount goal. However, a profound paradigm shift is underway, moving beyond mere preservation towards the active enhancement and modulation of brain function. The emergence of advanced neuromodulation techniques, such as deep brain stimulation (DBS), responsive neurostimulation (RNS), and laser interstitial thermal therapy (LITT), has blurred the traditional lines between a purely "neuro" procedure, aimed at manipulating neural circuitry, and a purely "surgical" one, focused on mechanical intervention. This evolution forces a critical re-evaluation of what constitutes the core therapeutic action of modern neurosurgery, particularly when the target is not a discrete mass but a dysfunctional neural circuit manifesting as a disorder of thought, decision-making, or emotion (3). Current knowledge in the field is rapidly expanding yet remains fragmented and often siloed by specific disease entities. The efficacy of DBS for movement disorders like Parkinson's disease is well-established, where electrical stimulation of subcortical nuclei can dramatically restore motor function, demonstrating a direct and reversible link between surgical intervention and brain function (4). This success has paved the way for exploring DBS in a range of neuropsychiatric conditions, including treatment-resistant depression (TRD) and obsessive-compulsive disorder (OCD). Early research in these areas suggests that targeted stimulation can modulate the neural networks underpinning mood and decision-making, potentially offering relief where pharmacological and psychotherapeutic interventions have failed (5). Similarly, laser ablation offers a minimally invasive means to disrupt pathological circuits, such as those in the cingulate bundle for OCD, with outcomes that suggest a "resetting" of maladaptive cognitive patterns (6).

Despite these promising advances, significant research gaps persist. The mechanisms by which these interventions exert their effects on high-order brain functions like decision-making—a complex process integrating emotion, risk-assessment, and executive function—are not fully elucidated. It is often unclear whether the primary effect is a direct modulation of the decision-making circuitry itself, an indirect consequence of alleviating core symptoms like anxiety or motor slowing, or a combination of both. Furthermore, the existing literature is heavily skewed towards severe, treatment-resistant pathologies, leaving a substantial knowledge gap regarding the potential application and ethics of these techniques for functional enhancement in the general population or for less severe impairments of cognitive function. The primary objective of this narrative review is to synthesize and critically examine the existing evidence to address a fundamental, yet often unstated, question: when neurosurgical procedures are employed to alter brain function, does the therapeutic benefit stem from a truly "neuro" action—a specific, circuit-level modulation that directly impacts cognitive and decision-making processes—or is it predominantly a "surgical" outcome, reliant on the physical act of interrupting a pathological pathway, with the neural consequences being a secondary epiphenomenon? The review seeks to determine if there is a synergistic interplay between these two facets, where the surgical act enables a targeted neurobiological intervention that would be impossible by other means. This inquiry is not merely semantic; it strikes at the heart of therapeutic rationale, patient selection, outcome measurement, and the future direction of functional neurosurgery. It demands an important realization about what is being changed inside the patient—not just at the level of symptom checklists, but at the level of their internal neuronal dynamics and subsequent lived experience. To this end, the scope of this review will encompass a critical analysis of recent literature, primarily from the last five years, focusing on key neurosurgical interventions known to influence higher-order brain functions.

This includes, but is not limited to, deep brain stimulation for neuropsychiatric disorders, laser interstitial thermal therapy for epilepsy and other conditions, and the evolving understanding of how even resective surgery for epilepsy can reshape cognitive networks. The review will concentrate on studies that provide insights into the mechanisms of action, using data from neuroimaging, electrophysiology, and detailed neuropsychological assessments pre- and post-intervention. It will deliberately explore outcomes beyond traditional clinical metrics, seeking evidence for changes in specific cognitive domains such as executive function, emotional regulation, and decision-making capacities. The significance of this review lies in its attempt to forge a unified conceptual framework for understanding the functional impact of neurosurgery. By dissecting the "neuro" from the "surgery," this work aims to provide a more nuanced understanding for clinicians, researchers, and ethicists. For clinicians, a clearer comprehension of the mechanisms at play can refine patient counseling, manage expectations, and guide the selection of the most appropriate intervention based on its proposed mechanism. For researchers, identifying the precise knowledge gaps—particularly the lack of mechanistic studies in non-severe populations and the need for more sophisticated biomarkers of circuit function—can direct future investigative efforts. Ultimately, this review contends that the most successful and ethically sound applications of functional neurosurgery will be those that can convincingly demonstrate a direct and intended linkage between the surgical act and a positive, predictable change in the patient's internal neuronal state, thereby affirming that the discipline is, in its most advanced form, performing something profoundly and inseparably both "neuro" and "surgery."

THEMATIC DISCUSSION: DECONSTRUCTING THE MECHANISMS OF FUNCTIONAL CHANGE IN NEUROSURGERY

Circuit-Level Modulation: The "Neuro" Action of Deep Brain Stimulation

The most compelling evidence for a direct "neuro" action in neurosurgery comes from advanced applications of Deep Brain Stimulation (DBS). Moving beyond its established role in motor circuits, DBS provides a unique window into the modulation of networks governing cognition and affect. In treatment-resistant depression (TRD), for instance, targeting the subcallosal cingulate cortex (SCC) is hypothesized to restore balance within a dysregulated limbic-cortical circuit. A seminal study by Scangos et al. (2021) demonstrated a personalized, closed-loop DBS system that delivered stimulation only upon detection of a specific neural biomarker of negative mood state (5). This approach not only achieved sustained remission in a patient with severe TRD but also fundamentally illustrated a direct "neuro" link: the surgical implantation of the electrode created the physical conduit, but the therapeutic effect was contingent upon the precise, algorithm-driven modulation of a specific neural signal. The surgery was the enabler, but the neuro-modulation was the mechanism. This is further supported by connectomic analyses showing that successful DBS for depression correlates with the modulation of a specific white matter pathway, the forceps minor, linking the SCC to prefrontal regions involved in executive control and emotional regulation (7). The clinical outcome is thus inextricably linked to a quantifiable change in network dynamics, arguing strongly for an integrated "neuro-surgical" intervention where the surgical component is subservient to the neurological objective.

Surgical Disconnection and its Cognitive Consequences: The "Surgical" Act of Ablation

In contrast to the reversible modulation of DBS, ablative procedures like laser interstitial thermal therapy (LITT) represent a more definitive "surgical" approach, physically disconnecting or destroying pathological tissue. The functional outcomes here raise complex questions about the relationship between surgical disruption and cognitive change. For example, anterior capsulotomy for OCD severs the fronto-thalamic fibers believed to mediate obsessive thought loops. A study by Röhry et al. (2022) on patients undergoing capsulotomy found significant reductions in OCD symptoms, which were correlated with decreased metabolic activity in the prefrontal cortex on post-operative PET scans (8). This suggests that the primary therapeutic action is the surgical interruption of a hyperactive circuit—a fundamentally mechanical solution to a neurophysiological problem. However, the "neuro" consequences are profound and not always beneficial. The same study and others have documented variable cognitive side effects, including apathy and executive function deficits, underscoring that the surgical lesion, while targeted, can impact adjacent circuits involved in motivation and decision-making (9). This highlights a critical distinction: while the intent is neuro-modulatory, the primary action is surgical destruction. The patient's outcome is a direct result of this physical disruption, and the ensuing cognitive changes—both therapeutic and adverse—are the downstream effects of a permanently altered neural architecture.

Resective Surgery and Network Reorganization: An Emergent "Neuro" Phenomenon

The interplay between a localized surgical act and a global neuro-response is perhaps most vividly observed in resective surgery for temporal lobe epilepsy (TLE). Here, the primary goal is often the removal of the epileptogenic hippocampus—a clear surgical endeavor to eliminate seizure focus. However, the consequent cognitive outcomes reveal a complex narrative of network-level adaptation, a genuinely "neuro" process unleashed by the surgery. Pre-operative functional MRI (fMRI) studies consistently show that TLE is a network disorder, often characterized by increased connectivity in the default mode network (DMN) as a compensatory mechanism (10). A longitudinal investigation by Trimmel et al. (2023) found that successful anterior temporal lobe resection led to a post-operative normalization of this aberrant connectivity pattern, which was correlated with improvements in memory performance in a subset of patients (11). This suggests that the surgical resection of a pathological node can facilitate a beneficial, large-scale reorganization of brain networks. The therapeutic gain is not merely from the removal of dysfunctional tissue (the surgical act) but from the brain's inherent plasticity that is permitted to express itself once the pathological driver is eliminated (the neuro response). This emergent property signifies that the ultimate functional outcome is a synergy of both elements; the surgery creates the conditions for the brain to "heal" itself at a systems level.

Gaps, Controversies, and the Frontier of Enhancement

Despite these advances, significant gaps and controversies persist, particularly when considering the potential extension of these techniques beyond severe pathology. A major gap is the paucity of long-term, mechanistic studies that track both circuit-level changes and detailed neuropsychological profiles over time. While DBS parameters can be tuned, the long-term adaptive changes in stimulated networks remain poorly understood (12). A central controversy lies in the specificity of these interventions. For instance, the efficacy of DBS for different psychiatric disorders may rely on stimulating the same node (e.g., the subthalamic nucleus) but in distinct functional territories, a nuance that is difficult to achieve surgically and blurs the line between a precise neuro-modulator and a blunt surgical tool (13). Furthermore, the application of these techniques for cognitive enhancement in the general population remains a largely theoretical and ethically fraught frontier. Preliminary research in patients with traumatic brain injury has shown that DBS of the fornix can enhance memory (14), but extrapolating this to healthy individuals introduces profound ethical questions about identity, coercion, and equity. The fundamental question of whether we are "fixing" a circuit or "overclocking" it remains unanswered, and the literature currently offers no consensus on where the boundary lies between therapeutic intervention and enhancement, revealing a critical area for future bioethical and neuroscientific inquiry.

Critical Analysis and Limitations

A critical appraisal of the existing literature on neurosurgical techniques for enhancing brain function reveals a field characterized by groundbreaking innovation but simultaneously constrained by significant methodological challenges that complicate the interpretation of its findings. A pervasive and fundamental limitation across the majority of studies is the notably small sample size. Many investigations, particularly those exploring novel DBS targets for psychiatric conditions or detailing network-level changes post-resection, are constituted as single-center case series or open-label trials encompassing often fewer than twenty participants (6, 8). These small cohorts drastically limit statistical power and increase the vulnerability of findings to outliers, making it difficult to distinguish a genuine therapeutic signal from a chance occurrence or placebo effect. This issue is intrinsically linked to the notable scarcity of large-scale, double-blinded, randomized controlled trials (RCTs), which remain the gold standard for establishing efficacy. While the logistical and ethical hurdles of sham neurosurgery are considerable, their absence leaves a critical gap in the evidence hierarchy. For instance, without a sham-controlled group, it is challenging to definitively parse the specific "neuro" effect of electrical stimulation in DBS from the profound placebo effects associated with an invasive, technologically advanced procedure and the intensive clinical attention that accompanies it (15). The methodological biases inherent in the current research portfolio further cloud the causal inference between the surgical intervention and the observed functional outcomes. Selection bias is a predominant concern, as participants in these studies are typically a highly curated group, representing the most severe, refractory end of the disease spectrum. Patients with treatment-resistant OCD or depression who are deemed suitable for DBS or ablation have often exhausted all conventional therapies, creating a population with a unique and potentially distinct neurobiology that may not be generalizable to the broader patient population (13).

Furthermore, performance and detection bias are frequently unavoidable. Blinding of patients and clinicians to the treatment assignment is exceptionally difficult in DBS trials, where patients are often aware of stimulation parameters due to perceptible effects. The assessment of cognitive and decision-making outcomes often relies on subjective clinical interviews or patient-reported outcomes, which can be influenced by the expectations of both the patient and the unblinded rater (16). This confluence of biases means that the reported improvements in "brain function" may be inflated by non-specific factors unrelated to the direct neuromodulatory mechanism. Another layer of complexity arises from the considerable variability in the measurement of outcomes, which stymies direct comparison and meta-synthesis of results across different studies. There is no consensus on a standardized battery of tests to assess the multi-faceted nature of "enhanced brain function." One study may prioritize the Yale-Brown Obsessive Compulsive Scale (Y-BOCS) score as its primary endpoint, while another might focus on changes in metabolic activity via PET imaging, and a third on performance in specific neuropsychological tests of executive function (8, 11). This heterogeneity makes it nearly impossible to determine if two studies targeting the same brain structure are indeed measuring the same construct of improvement. The field lacks validated, sensitive biomarkers that can serve as objective proxies for complex cognitive processes like decision-making, forcing a reliance on indirect and often coarse-grained metrics. This variability extends to the definition of success itself; is a 35% reduction on a depression scale a successful "neuro-modulation" of mood circuits, or merely a modest surgical outcome? The absence of clear, universally accepted benchmarks for what constitutes a meaningful change in higher-order brain function remains a critical impediment to the field's maturation.

The generalizability of the exciting findings from these highly specialized studies is therefore severely limited. Results derived from a small cohort of meticulously selected patients with intractable epilepsy or OCD at a top-tier academic center cannot be readily extrapolated to the broader population of individuals with these disorders, let alone to hypothetical applications for cognitive enhancement in healthy or minimally impaired individuals. The underlying neuropathology, network dysregulation, and capacity for plastic reorganization in a severe, chronic case are likely fundamentally different from those in a milder or earlier-stage condition (12). This limitation is compounded by a likely significant publication bias, wherein studies with positive or dramatic findings are more likely to be submitted and accepted for publication, while those with null or

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negative results remain in the file drawer. The literature thus presents a potentially skewed, overly optimistic view of the efficacy and precision of these interventions, obscuring the true rate of non-responders and unforeseen cognitive sequelae. Finally, the temporal dimension of these interventions is poorly understood due to short follow-up durations in many reports. While some studies boast impressive long-term data, many others report outcomes at one or two years post-operatively (16). This is a critical shortcoming for interventions intended to cause lasting, permanent change. The long-term adaptive responses of neural networks to chronic DBS are a subject of active investigation, and it remains possible that initial network "normalization" could devolve into compensatory maladaptations over a decade (12). Similarly, the cognitive consequences of an ablative lesion may evolve as the brain ages and its compensatory reserves diminish. Without long-term, longitudinal studies that track both clinical and neurophysiological outcomes, the durability of the purported "enhancement" and the full spectrum of potential long-term risks cannot be accurately ascertained, leaving a substantial gap in the risk-benefit calculus for these profound interventions.

Implications and Future Directions

The synthesis and critical analysis presented in this review carry profound implications for the evolving landscape of clinical neurosurgery and illuminate a clear path for future scientific inquiry. For clinical practice, the primary implication is the necessity for a paradigm shift in how functional neurosurgical outcomes are conceptualized, measured, and discussed with patients. The evidence suggests that the most successful outcomes arise from a synergistic model where the surgical act and the neuro-modulatory intent are inseparable. Consequently, clinicians must move beyond simply reporting symptom reduction on a rating scale and towards a more nuanced explanation of the intervention's mechanism. This involves counseling patients that the goal of a procedure like DBS for depression is not merely to "stimulate the brain," but to specifically modulate a dysfunctional network, with effects that may subtly alter cognitive and emotional processing (5, 15). This refined understanding mandates the integration of sophisticated neuropsychological assessments, and potentially connectomic imaging, into standard pre- and post-operative workflows. This would allow for a more personalized approach, where the surgical strategy is informed not just by anatomy, but by the patient's unique functional network architecture, thereby optimizing the alignment between the "surgical" tool and the intended "neuro" outcome. These clinical imperatives directly inform the need for updated policy and professional guidelines. The current regulatory and reimbursement landscape is often ill-equipped to handle the complexity of these interventions. There is a pressing need for multidisciplinary consensus guidelines that establish standardized protocols for patient selection, outcome measurement, and long-term management. Such guidelines should be developed by committees comprising not only neurosurgeons and neurologists but also psychiatrists, neuropsychologists, and ethicists. Furthermore, given the high costs and potential risks, policy frameworks must be established to define the boundaries of these technologies, particularly as they edge closer to applications in enhancement. Clear policies are required to distinguish between validated therapeutic indications and experimental or non-therapeutic uses, ensuring that the application of these powerful tools remains equitable, ethical, and grounded in robust evidence (12). The creation of centralized, international patient registries for those undergoing functional neurosurgery could be a pivotal policy initiative, providing the large-scale, longitudinal data currently lacking in the literature.

Looking ahead, this review has identified several critical unanswered questions and research gaps that must be prioritized. A central unknown is the long-term adaptive capacity of neural networks to chronic intervention. How does the brain's circuitry continue to evolve over five, ten, or twenty years of continuous DBS, and what are the implications for sustained efficacy and cognitive side effects (12, 17)? Another glaring gap is the understanding of why a significant proportion of patients are non-responders. Research must pivot towards identifying pre-operative biomarkers—whether derived from neuroimaging, electrophysiology, or genetics—that can predict individual patient response. The field must also grapple with the fundamental neuroethical questions it raises: if we can enhance a specific cognitive domain, what is the cost to other domains, and who decides what constitutes a "normal" or "enhanced" state of brain function? The current literature, focused on severe pathology, provides almost no empirical data to inform the debate on cognitive enhancement in the general population. To address these gaps, future research must employ more rigorous and innovative study designs. While double-blinded, sham-controlled RCTs remain the ideal, their ethical and practical challenges necessitate creative alternatives. Well-designed prospective, longitudinal observational studies with large sample sizes, leveraging multi-center collaborations, can provide powerful insights into long-term outcomes and predictors of response. Adaptive trial designs, which allow for modification of the trial parameters based on interim results, are particularly well-suited for exploring different DBS targets or stimulation paradigms within a single study framework (18). Crucially, future studies must mandate the inclusion of multimodal data collection, integrating high-density electrophysiology, advanced neuroimaging (fMRI, DTI), and detailed, standardized cognitive batteries. This will enable a move from correlative observations to causal mechanistic models, finally answering the core question of this review: whether we are witnessing a direct "neuro" modulation or a secondary consequence of a "surgical" event. The ultimate future direction lies in the development of closed-loop, personalized systems that can adapt in real-time to the brain's dynamic state, truly merging the surgical hardware with the neurological software to achieve a new pinnacle of therapeutic precision.

CONCLUSION

In conclusion, this narrative review elucidates that the question of whether modern functional neurosurgery constitutes a "neuro" or a "surgical" intervention is a false dichotomy; the most compelling evidence points to an inseparable synergy where the surgical procedure provides the essential physical access for a targeted neuromodulation that directly alters circuit-level function and, consequently, cognitive and affective processes. The key findings demonstrate that techniques like DBS can produce direct neurophysiological effects on decision-making and mood networks, while ablative and resective procedures achieve their outcomes through a combination of surgical disruption and subsequent, emergent network reorganization. However, the strength of this evidence is tempered by significant methodological limitations, including small sample sizes, a lack of blinded controlled trials, and heterogeneous outcome measures, which collectively urge a cautious interpretation of the literature. It is therefore recommended that clinicians adopt a more nuanced, network-based framework when discussing potential outcomes with patients, emphasizing that benefits and risks manifest at the level of neural circuitry, and that researchers prioritize the development of standardized cognitive batteries and objective biomarkers for future studies. A concerted call for larger, longitudinal, and mechanistically-focused research is imperative to fully delineate the long-term consequences of these interventions and to ethically navigate the nascent frontier of applying these powerful techniques beyond severe pathology towards the complex realm of cognitive enhancement.

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