


REVIEW

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γ neuromodulations: unraveling biomarkers for neurological and psychiatric disorders

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Abstract

γ neuromodulation has emerged as a promising strategy for addressing neurological and psychiatric disorders, particularly in regulating executive and cognitive functions. This review explores the latest neuromodulation techniques, focusing on the critical role of γ oscillations in various brain disorders. Direct γ neuromodulation induces γ -frequency oscillations to synchronize disrupted brain networks, while indirect methods influence γ oscillations by modulating cortical excitability. We investigate how monitoring dynamic features of γ oscillations allows for detailed evaluations of neuromodulation effectiveness. By targeting γ oscillatory patterns and restoring healthy cross-frequency coupling, interventions may alleviate cognitive and behavioral symptoms linked to disrupted communication. This review examines clinical applications of γ neuromodulations, including enhancing cognitive function through 40 Hz multisensory stimulation in Alzheimer's disease, improving motor function in Parkinson's disease, controlling seizures in epilepsy, and modulating emotional dysfunctions in depression. Additionally, these neuromodulation strategies aim to regulate excitatory-inhibitory imbalances and restore γ synchrony across neurological and psychiatric disorders. The review highlights the potential of γ oscillations as biomarkers to boost restorative results in clinical applications of neuromodulation. Future studies might focus on integrating multimodal personalized protocols, artificial intelligence (AI) driven frameworks for neural decoding, and global multicenter collaborations to standardize and scale precision treatments across diverse disorders.

Keywords γ oscillations, Neuromodulation, Cross frequency coupling, Deep brain stimulation (DBS), Transcranial magnetic stimulation (TMS), Neurological disorders, Psychiatric disorders

Background

Neuromodulation has emerged as an essential therapeutic strategy in the treatment of neurological and psychiatric disorders [1–3]. This non-pharmacological treatment

strategy is specialized in clinical conditions where traditional pharmacological or behavior modifications have adverse reactions and limited effectiveness, such as in Alzheimer's disease (AD), Parkinson's disease (PD), epilepsy, and depression [4–6]. By targeting brain regions and neural circuits, neuromodulation provides the perspective to directly influence abnormal brain states, thereby improving cognitive, emotional, and motor phenotypes in damaged individuals [7–9]. Since the effectiveness of these interventions might rely on their capability to modulate the brain's neuronal oscillations across different neuronal oscillations, comprehending the

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relationship between neuromodulation and oscillatory activity is critical for enhancing treatment outcomes.

γ oscillations are progressively identified as vital in recognizing the neural basis underlying psychological and cognitive processes such as perception, attention, memory, and motor functions. These oscillations have the potential as neurobiological markers for early detection, identification, and intervention of various brain disorders, offering the understanding of the dysregulated neural dynamics underlying various clinical symptoms [10–13]. Alterations in γ oscillations are identified to be relevant to adaptations in cognitive processes, emotional regulation, and neural plasticity [14–18]. Imbalances between excitatory and inhibitory processes, as mirrored in raised γ oscillations in the visual cortex including GABAergic interneurons, underscore the relevance of γ rhythms in maintaining neuronal homeostasis [19, 20]. Besides, γ oscillations are modulated by metabotropic glutamate receptors (mGluRs), which also contribute to cognitive functions such as perception and attention [21–24]. As BF GABAergic projection neurons, particularly those containing parvalbumin (PV), play a critical role in triggering cortical γ oscillations. Optogenetic stimulation of BF PV neurons in mice preferentially increases cortical γ band oscillations (GBO) by entraining cortical oscillators at a resonant frequency of approximately 40 Hz, while inhibition of these neurons reduces GBO power [25]. This mechanism is independent of cholinergic neurons and likely involves synchronization of cortical PV interneurons. These findings highlight BF PV neurons as a potential therapeutic target for disorders involving abnormal γ oscillations, such as schizophrenia [25]. Overall, γ oscillations have rich biological implications in coordinating complex brain functions, positioning them as promising targets for neuromodulation [26–29].

Notably, γ oscillations have been linked to a series of neurological disorders, such as neurodegenerative disorders like AD and PD [30]. From the micro-perspective, decreased γ oscillations affecting microglial features have been found to precede plaque development in AD [31]. γ oscillations, generated by striatal cholinergic interneurons, play a crucial role in influencing movement actions within cortical-striatal circuits [32]. γ oscillations of inhibitory nerve cells after stroke have been observed to undermine vascular and lead to behavioral disorder [33]. Besides, γ oscillations have been linked to sensory perception, working memory, and motor control functions in patients with PD, and enhancing the γ oscillations could increase the plasticity of the primary motor cortex in PD [34, 35]. Overall, the relationship between disrupted γ activity and abnormal brain functions of neurological disorders has been identified by neural evidence from macro- and micro-perspectives, emphasizing

the further need for precise treatment with γ oscillatory neuromodulation.

Besides, disturbances in γ oscillations have been highly related to a wide variety of psychiatric symptoms, with the restoration of these oscillations emerging as a prospective healing approach [36]. Modified γ activity has been related to psychotic symptoms in drug-naive patients revealing relationships between γ oscillatory patterns and the remaining symptoms [37–40]. Decreased γ oscillations of the limbic cortex have been observed in mice presenting anxiety and anhedonia-like habits [36, 41], implying the relevance of oscillatory disruptions in schizophrenia. Furthermore, γ oscillations could help discriminate different disease states in mental disorders, such as anxiety, depression, or suicide risk [42–44]. Emerging studies indicate that modulating γ activity might alleviate many psychiatric symptoms in both animal models and humans [45–47]. Notably, previous studies highlight the role of basal forebrain (BF) γ oscillations in modulating the default mode network (DMN), a brain network linked to internally focused cognition and dysregulated in brain functional disorders. BF γ oscillations are elevated during quiet wakefulness and suppressed during externally directed tasks, mirroring DMN activity patterns [48, 49]. In rodents, BF γ coherence with the anterior cingulate cortex (ACC), a key DMN hub, suggests functional influence [48]. A study confirmed that BF drives DMN changes during rest-task transitions, while the mediodorsal thalamus engages during internally focused cognition [49]. These findings underscore BF γ modulation as a therapeutic target for DMN-related disorders like epilepsy and depression, offering mechanistic insights into psychiatric symptoms.

Despite the growing understanding of γ oscillations in neurological and psychiatric disorders, there is a significant gap in research specifically addressing the role of γ neuromodulations as a treatment strategy. The present review aims to bridge the gap by systematically examining how γ oscillations affect neurological and psychiatric conditions and the potential benefits of γ neuromodulations for patients. By thoroughly assessing the existing literature on γ neuromodulations from clinical perspectives, and identifying their physiological mechanisms and intervention outcomes, this review seeks to enhance our understanding of γ neuromodulations as promising therapeutic strategies, ultimately improving the efficacy of treatments for neurological and psychiatric diseases.

Exploring brain dynamics for γ oscillations of the neuromodulations

To build an elaborate neuromodulation system of neuronal oscillations, the essential procedures include acquiring, preprocessing, and analyzing the oscillatory

activity data (Table 1). In the data acquisition process, various tools are utilized to optimize the collection of neuronal oscillations, including advanced electroencephalogram (EEG) systems equipped with dense electrode arrays and sophisticated Magnetoencephalography (MEG) sensors, which rely on superconducting quantum interference device (SQUID) technology [50–52] (Fig. 1a). After data collection, preprocessing at the channel level is essential to clean the raw data and reduce artifacts like eye blinks muscle activity, and environmental noise [53, 54] (Fig. 1b). This preprocessing pipeline involves techniques such as band-pass filtering, independent component analysis (ICA), and automatic artifact rejection to ensure high-quality data [55, 56] (Fig. 1c, d). Source reconstruction further refines this by constructing head models (based on the individual magnetic resonance imaging data) and source models (to localize active brain regions), enabling the identification of brain areas that display altered oscillatory patterns [57–59] (Fig. 1e). After the source localization, oscillatory activity can be mapped from the sensor space to the brain's voxel or regional level (Fig. 1f). However, it is important to note that source localization relies on inference under multiple assumptions, and the results may not always fully or accurately reflect actual brain activities.

Neuronal oscillations in specific frequency bands, such as θ , α , β , and γ , dynamically change in response to cognitive tasks or external stimuli (Fig. 1g), offering detailed insights into localized brain activity. Common methods for analyzing these oscillations, including event-related potential (ERP) and time–frequency analyses, are particularly useful for examining brain power within specific temporal periods and frequency bands, typically focused on one specific brain region or sensor [60, 61]. ERP analysis measures brain responses that are time-locked

to sensory or cognitive events, revealing how oscillatory power in a single region changes in response to stimuli (Fig. 1h). Similarly, time–frequency analysis quantifies how power in specific frequency bands evolves within a given brain region or sensor [62–65] (Fig. 1i). Techniques like wavelet transform and short-time Fourier transforms are used to decompose the signal into its time–frequency components, allowing the tracking of oscillatory power fluctuations [66–68].

To explore relationships between different brain regions, frequency-specific functional connectivity methods, such as coherence and phase-locking value (PLV) [69–71], are commonly applied to assess synchronization at specific frequencies [72–74] (Fig. 1j). These methods offer insights into network-level communication by measuring how different regions of the brain interact and coordinate their oscillatory activity, which is crucial for understanding the brain's functional architecture and how different areas collaborate during cognitive tasks [75–77]. Beyond connectivity, dynamic approaches such as the Hidden Markov Model (HMM) provide a further understanding of brain networks by modeling brain states as discrete, temporally evolving entities (Fig. 1k) [78–80]. These models enable the identification of transient brain states and their transitions over time, capturing the dynamic nature of brain activity [81–83] (Fig. 1l). Key descriptors from HMM analysis, such as fractional occupancy (the time the brain spends in each state) and state transition matrices (mapping probabilities of transitions between states), provide valuable information about the stability, flexibility, and adaptability of neural networks [84, 85] (Fig. 1m). To accurately extract γ activity from the human brain, utilizing dynamic algorithms to capture comprehensive features is a promising approach. Monitoring changes in dynamic features enables the

Table 1 Overview of procedures for analyzing γ oscillations

Procedures	Description	Key techniques	Application
Data acquisition	Collection of neuronal oscillation data	Neuroimaging tools, such as Electroencephalogram (EEG), Magnetoencephalography (MEG)	Optimizes data collection
Preprocessing	Cleaning raw data and reducing artifacts	Band-pass filtering, independent component analysis (ICA), artifact rejection	Ensures high-quality data
Source reconstruction	Localizing active brain regions based on MRI data	Beamforming, head model, source model	Identifies oscillatory patterns in brain region levels
Frequency-band analysis	Examining oscillations in specific frequency bands	Event-related potential (ERP), time–frequency analysis	Analyzes frequency-specific brain activities
Functional connectivity analysis	Assessing synchronization between brain regions	Coherence, phase-locked value (PLV)	Reveals network-level communication
Dynamic modelling	Understanding the brain dynamics	Hidden Markov Model (HMM), sliding window	Captures transient brain states

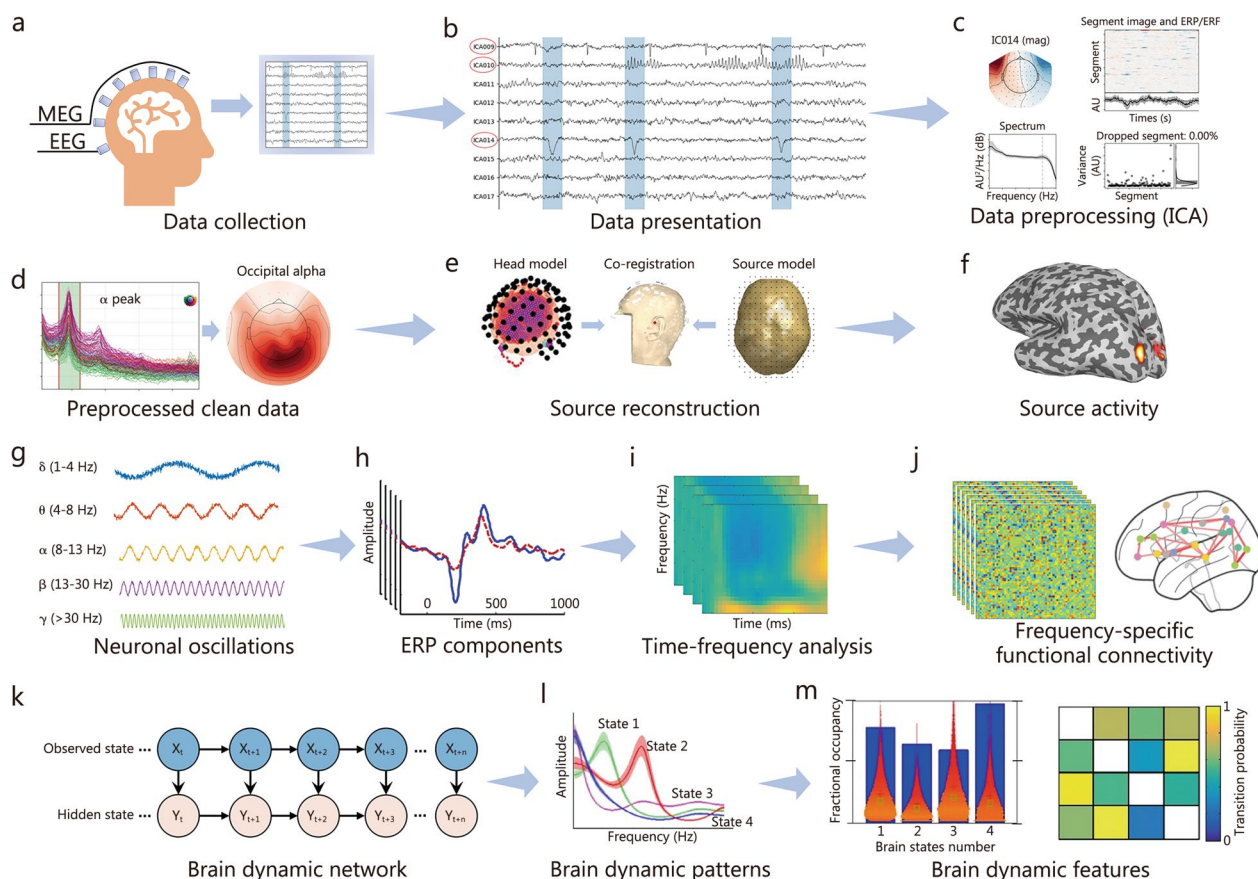


Fig. 1 Strategies for collecting and analyzing neuronal oscillations. **a** Data collection procedure using EEG/MEG. **b** Data presentation and reduce artifacts. **c** ICA for extracting clean data. **d** Preprocessed clean data in sensors (visual α oscillations). **e** Source reconstructions. **f** Source power (visual α oscillations). **g** The presentation for neuronal oscillations. **h** ERP analysis. **i** Time–frequency analysis. **j** Frequency-specific functional connectivity, including connectivity matrices and brain connectivity maps. **k** Brain dynamic models (Hidden Markov Model). **l** Brain dynamic patterns describing the power spectra of different brain states. **m** Brain dynamic features including fractional occupancy and transition probability of each brain state. EEG electroencephalogram, MEG magnetoencephalography, ICA independent component analysis, ERP event-related potential

detailed evaluation of the performance of the neuromodulation system, which can be conducted in both real-time (online) and retrospective (offline) systems.

Combining this dynamic framework with time–frequency power analysis and functional connectivity methods could create a state-of-the-art approach to studying γ oscillations in the neuromodulations [86–88]. This integrated perspective enhances our understanding of stable and transient neuronal activity patterns, revealing how neuromodulation interventions influence cognitive ability and its underlying functional architecture.

Key neuromodulation strategies in modulating γ oscillations

Neuromodulation technologies regulating neuronal oscillations have obtained significant attention in the clinical neuroscience field [89]. Non-pharmacological treatments such as repetitive transcranial magnetic stimulation (rTMS), transcranial alternating current

stimulation (tACS), transcranial direct current stimulation (tDCS), neurofeedback, and deep brain stimulation (DBS) present promising strategies for modulating neuronal oscillations and improving cognitive and emotional functions across various disorders [90–97].

Each of these techniques influences brain activity in unique ways, assisting in the restoration of brain executive or cognitive functions that are often disrupted in both neurological and psychiatric disorders. As illustrated in Table 2, TMS could enhance high-frequency oscillations (γ , β) and simultaneously reduce low-frequency (α , θ , δ) rhythms [98–102] (Fig. 2a). This modulation might adjust the neural communication within frontal-limbic circuits, improving mood stabilization and impulse control [103–105]. Therefore, rTMS has the potential to reduce psychotic symptoms in individuals with treatment-resistant conditions [106].

Through direct entrainment, tACS can synchronize neuronal oscillations with the applied alternating

Table 2 Overview of neuromodulation technologies in neurological and psychiatric disorders

Neuromodulation technology	Mechanism of action	Applications	Key features	Limitations
Transcranial magnetic stimulation (TMS)	Non-invasive magnetic pulses to modulate cortical excitability	Depression, obsessive-compulsive disorder, stroke recovery	Precise cortical stimulation, non-invasive	Limited depth penetration, variable individual response
Deep brain stimulation (DBS)	Electrical stimulation via implanted electrodes	Parkinson's disease, epilepsy, depression	Highly targeted, adjustable stimulation intensity	Invasive, risk of infection, surgical complications
Transcranial direct current stimulation (tDCS)	Low electrical current is applied to the scalp	Depression, anxiety, stroke rehabilitation	Non-invasive, relatively low cost	Limited spatial resolution, inconsistent outcomes
Transcranial alternating current stimulation (tACS)	An alternating current is applied to the scalp to modulate oscillations	Schizophrenia, depression, cognitive enhancement	Targets specific frequency bands (e.g., γ , θ)	Inconsistent effects, poorly understood long-term effects
Neurofeedback (NFB)	Real-time feedback based on brain activity to encourage self-regulation	Attention deficit hyperactivity disorder, anxiety, depression	Allows self-regulation of brain functions through training	Non-invasive, training-based therapy

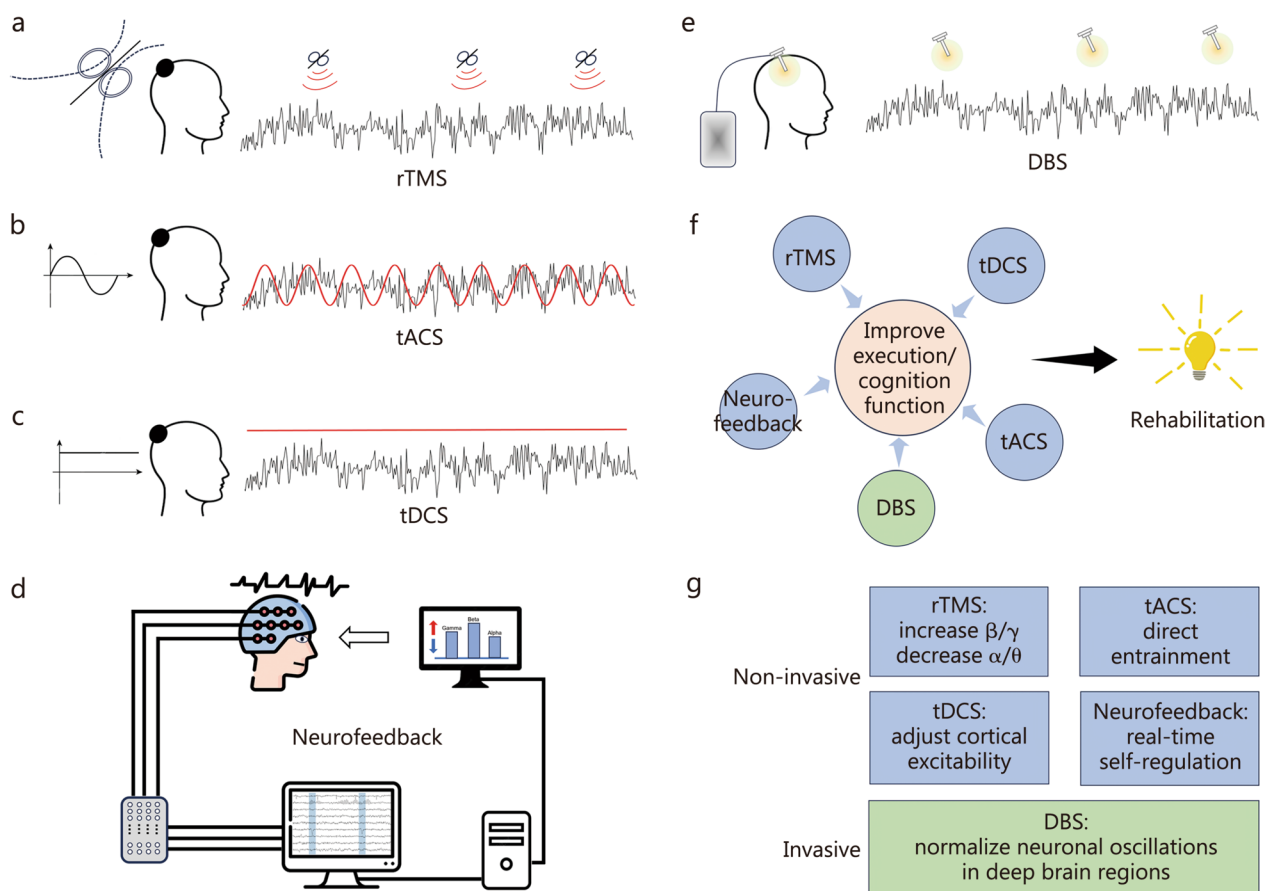


Fig. 2 Schematic representation of neuromodulation technologies. Schematic representation of non-invasive neuromodulations rTMS (a), tACS (b), tDCS (c), Neurofeedback (d), and invasive neuromodulation DBS (e). f Neuromodulation treatments enhance cognitive and executive functions, which in turn leads to the rehabilitation of clinical symptoms. g Key features for non-invasive and invasive neuromodulation. rTMS repetitive transcranial magnetic stimulation, tACS transcranial alternating current stimulation, tDCS transcranial direct current stimulation, DBS deep brain stimulation

current, offering a targeted way to influence specific frequency bands [107–109] (Fig. 2b). This technique can also modulate γ oscillations [110–112]. By restoring the γ rhythmic activity of disrupted brain networks, tACS may improve the processing of emotional stimuli and alleviate feelings of guilt that contribute to suicide risk [95, 113, 114]. Conversely, tDCS adjusts cortical excitability by delivering low-level electrical currents to the brain, either enhancing or inhibiting activity in targeted regions [115, 116] (Fig. 2c). This modulation can correct abnormal oscillatory patterns and improve emotional regulation. By increasing excitability in areas such as the prefrontal cortex, tDCS may promote better cognitive control and emotional resilience [117–119].

Neurofeedback offers real-time self-regulation neuromodulation mechanisms, allowing individuals with various mental disorders to monitor and adjust their oscillatory activity to achieve the desired brain states [120–122] (Fig. 2d). By training individuals to modulate

γ oscillatory rhythms, this approach has shown the potential to enhance emotional stability, reduce stress responses, and improve cognitive flexibility [123–125]. For example, EEG-based neurofeedback can alleviate a series of symptoms including emotional dysregulation, cognitive deflections, attention difficulties, and motor control disturbance [126–129]. Previous evidence underscores its psychological relevance: approximately 75% of participants can learn γ modulation, with success rates influenced by baseline traits like fluid intelligence [130]. In preclinical AD and older adults, γ -band neurofeedback achieved 71% accuracy in enhancing neural synchronization, though cognitive gains were limited by high baseline performance [131]. Another meta-analytic evidence further supports the clinical relevance of γ neurofeedback, showing a medium effect size (Cohen’s $d = -0.39$) for reduced frontal γ power in schizophrenia patients during working memory tasks [132]. Despite these benefits, neurofeedback faces limitations. Success rates vary

significantly due to neurophysiological heterogeneity, sample size constraints, and baseline cognitive performance [133]. Predicting outcomes remains challenging, compounded by the time-intensive and costly nature of training protocols [134]. Nevertheless, this patient-centered approach empowers individuals to actively engage in their treatment, fostering healthier brain activity patterns and offering a promising adjunct to conventional therapies.

DBS, as a more invasive technique, directly stimulates deep brain regions, such as the subgenual cingulate or ventral striatum [135–138] (Fig. 2e). By normalizing neuronal oscillations in deep brain areas, DBS might silence local neural activity to alleviate pathological symptoms, as exemplified in patients with PD [139, 140]. For patients with movement disorders and treatment-resistant psychiatric conditions, DBS offers a powerful means of modulating brain functional networks and alleviating motor symptoms (like tremors, rigidity, and shaking) and psychiatric symptoms (depression, anxiety, and mania).

Among the various neuromodulation techniques, both rTMS and tACS can modulate γ oscillations, though their mechanisms and specificity differ. rTMS enhances γ activity as part of broader network changes involving β and θ rhythms, reflecting its systemic neuromodulatory effects [141, 142]. In contrast, tACS directly entrains γ oscillations through phase-locked sinusoidal currents, achieving sharper spectral precision by synchronizing endogenous neural oscillations to the applied frequency [113, 143]. While rTMS induces broader neurophysiological changes, tACS enables more targeted synchronization, highlighting the distinct therapeutic applications of these modalities [144]. Notably, DBS can affect γ oscillatory activity but is more invasive and typically reserved for severe movement disorders and psychiatric conditions. Neurofeedback offers a novel approach for individuals to learn self-regulation of γ activity, yet it requires active participation and may not provide the same level of direct modulation as tACS. Therefore, tACS stands out as the most effective option for directly regulating γ oscillations on most occasions. Together, these non-pharmacological interventions show considerable promise in enhancing cognitive and emotional functions by directly addressing oscillatory imbalances in the brain, providing essential therapeutic options for both neurological and psychiatric disorders (Fig. 2f, g).

Treatment via γ neuromodulation

Restoration of cross-frequency coupling (CFC) using γ neuromodulation

CFC refers to the interaction between neuronal oscillations of different frequency bands, wherein the phase, amplitude, or power of one oscillatory rhythm influences

the dynamics of the other [145, 146]. The most widely studied form of CFC is phase-amplitude coupling (Fig. 3a), where the phase of a lower-frequency oscillation modulates the amplitude of a higher-frequency oscillation [147, 148]. θ – γ phase amplitude coupling (PAC) and θ – γ PAC have been extensively examined as critical mechanisms for organizing neural activity across various brain regions [149, 150].

γ neuromodulation can alter the neuromodulatory system by modifying the interactions between different brain oscillations. This impacts neurotransmitter release, synaptic plasticity, and brain network synchronization (Fig. 3b), which are all essential for the regulation of cognition and behavior in neurological and psychiatric disorders. Specifically, major neuromodulatory systems, including the noradrenergic, dopaminergic, and cholinergic systems, exert significant influence on CFC patterns. The noradrenergic system, originating from the locus coeruleus, enhances γ power and modulates CFC during arousal and attentional processes [151, 152] (Fig. 3c). The dopaminergic system, particularly in the ventral tegmental area, plays a critical role in working memory, influencing β – γ coupling in these cognitive functions [153–155] (Fig. 3d). The cholinergic system, via the basal forebrain, modulates θ – γ coupling, essential for memory encoding and retrieval [156–158] (Fig. 3e). Altering CFC through neuromodulatory interventions like TMS and DBS has shown promise in correcting abnormal neural communication [159–162].

CFC has gained considerable attention for its role in understanding the neural mechanisms underlying neurological and psychiatric disorders. In the context of neurological disorders, CFC alterations have been identified in diseases such as PD and AD, where they are associated with motor and cognitive deficits [163–167]. Specifically, disrupted θ – γ PAC is observed in AD [168], while changes in β – γ CFC are linked to motor dysfunction in PD [169]. Besides, CFC has been linked to key neural processes like corticostriatal function and higher-order cognitive activities, both of which are implicated in psychiatric disorders [170, 171]. Such findings point to the broader applicability of CFC as a biomarker across a wide range of psychiatric conditions, with implications for both diagnosis and treatment. Since the application of CFC in neuromodulation holds significant therapeutic potential (Fig. 3f), by targeting specific oscillatory patterns and restoring healthy CFC, these interventions may help alleviate cognitive and behavioral symptoms associated with disrupted cross-frequency communication (Fig. 3g). Specifically, patients may exhibit an over-activated CFC pattern before γ neuromodulation, followed by a rapid transition to an inhibited-activated CFC pattern during stimulation. After the stimulation, the

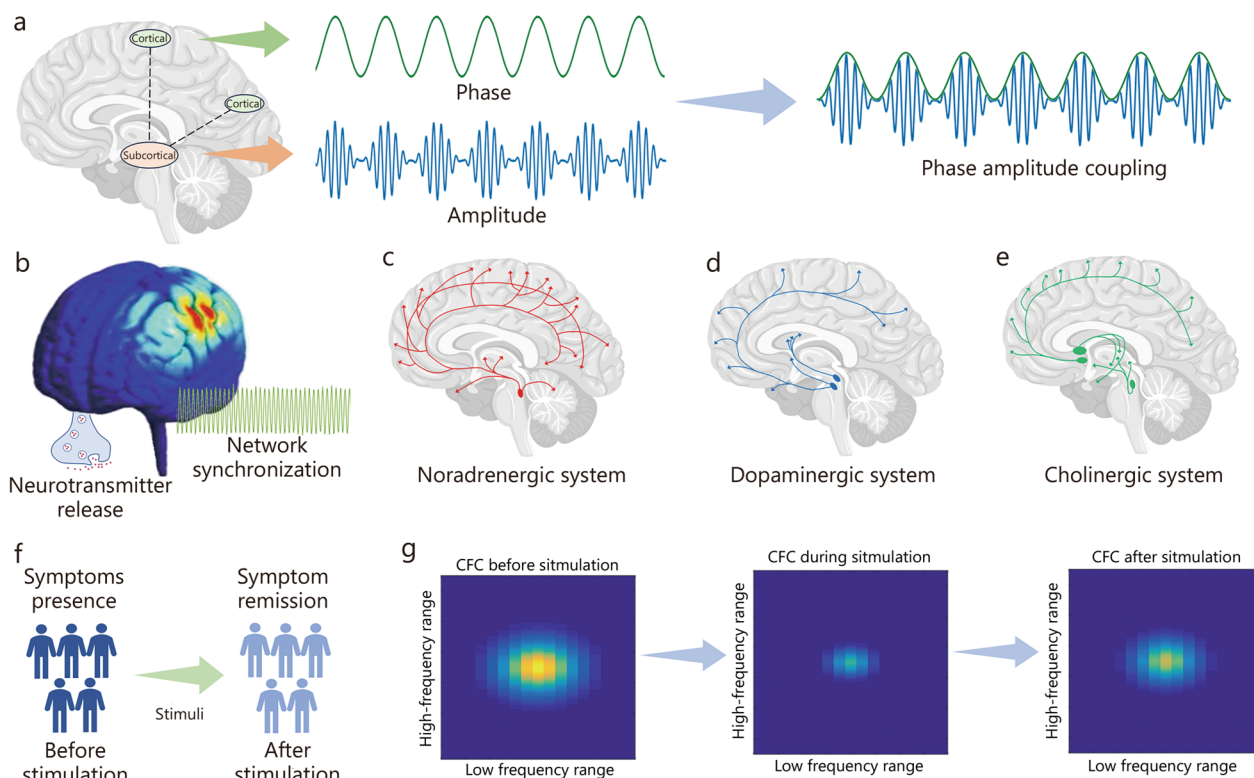


Fig. 3 CFC mechanisms and neuromodulation. **a** Phase-amplitude coupling, where the phase of a lower-frequency oscillation modulates the amplitude of a higher-frequency oscillation. **b** Neuromodulation alters neurotransmitter release and brain network synchronization. The noradrenergic system (**c**), the dopaminergic system (**d**), and the cholinergic system (**e**) modulate cross-frequency coupling. **f, g** Simulation of phase-amplitude coupling illustrating changes before, during, and after neuromodulation. The neuromodulation intervention effectively restores cross-frequency coupling patterns. CFC cross-frequency coupling

previously over-activated patterns may partially return but remain significantly weakened compared to their initial state, correlating with a reduction in the symptoms of the disorder.

As the understanding of CFC deepens, its role as a diagnostic and therapeutic tool in clinical practice is likely to expand, offering new avenues for personalized and targeted treatments. The integration of CFC-based neuromodulation with emerging evidence on its causal role in cognition, language, and decision-making will pave the way for innovative therapeutic strategies in psychiatric disorders.

Brain disorders

Multisensory 40 Hz γ neuromodulation associated cognitive function in AD

γ neuromodulation has emerged as a promising therapeutic approach for cognitive decline in AD. In animal experiments, optogenetic neuromodulation targeting γ oscillations has been explored as a strategy to delay or mitigate cognitive decline in AD patients [172]. Specifically, multisensory γ stimulation at 40 Hz has shown

significant potential in reducing AD pathology by decreasing amyloid- β accumulation. This is achieved through suppression of its production, enhanced microglial clearance, promotion of cerebrospinal fluid movement via aquaporin-4 polarization, and increased arterial pulsation and lymphatic vessel expansion, all contributing to amyloid- β clearance [31, 173, 174] (Fig. 4a). These findings highlight the therapeutic potential of 40 Hz γ stimulation as a non-invasive intervention for AD.

From the clinical perspective, early research using DBS applied to the fornix demonstrated cognitive and behavioral improvements in AD patients by activating key regions like the hippocampus and medial prefrontal areas [175]. Non-invasive methods, such as γ rhythmic sensory stimulation (RSS) and tACS, have also shown promising outcomes. Specifically, γ RSS improved memory and reduced brain volume loss in early AD patients [176], while tACS targeting frontal areas enhanced cognitive functions like working memory and cognitive control [95, 177]. tACS has gained popularity due to its cost-effectiveness and portability, though TMS also demonstrated positive effects on γ activity and cognition [178,

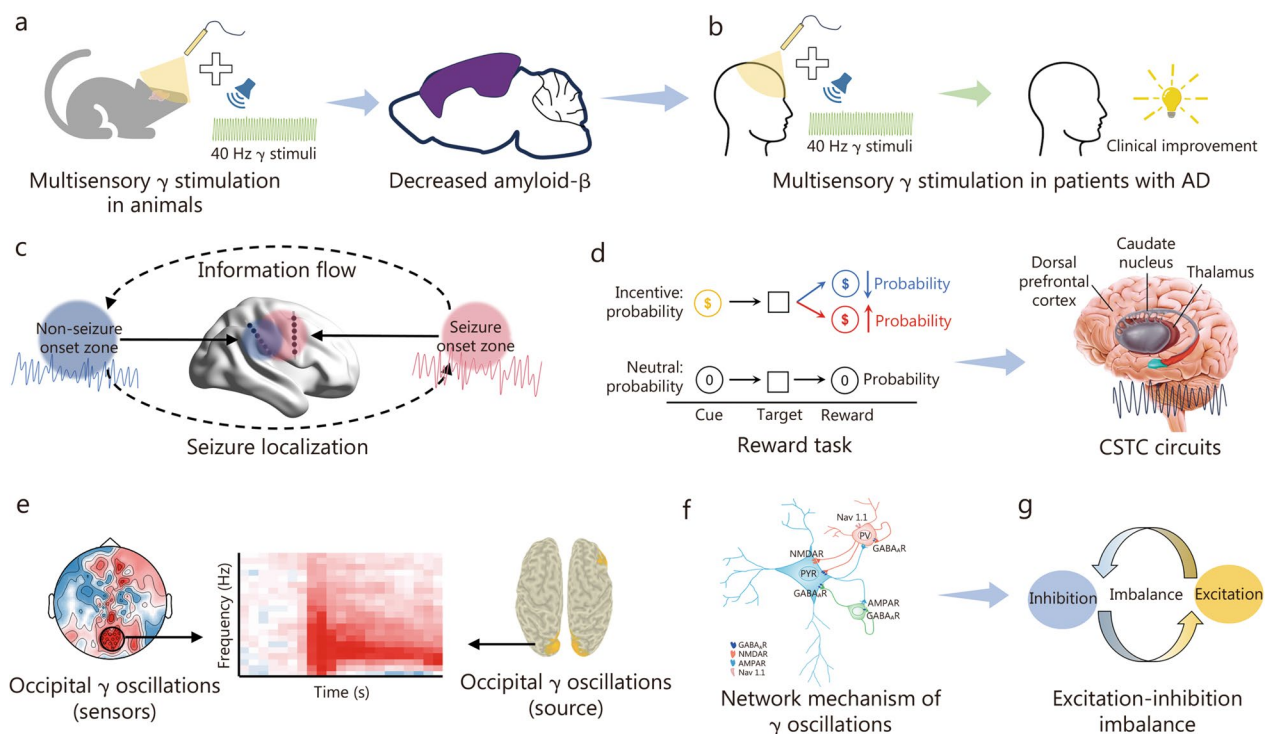


Fig. 4 Diverse impacts of γ modulations in neurological and psychiatric disorders. **a** The 40 Hz multisensory stimulation contributing to the clearance of amyloid- β in Alzheimer's disease mouse models. **b** The 40 Hz multisensory stimulation showed improvements in diverse clinical symptoms in patients with Alzheimer's disease. **c** Localization of seizure onset zones and prediction of seizure outcomes in epilepsy with γ oscillations. **d** The cortico-striatal-thalamic-cortical (CSTC) circuit shows the role of γ oscillations in obsessive-compulsive disorder during reward-based tasks. **e** Increased γ oscillations of occipital regions in patients with depression and schizophrenia. **f** The biological network mechanisms underlying γ oscillations. **g** Depiction of excitatory-inhibitory imbalance. AD Alzheimer's disease, CSTC cortico-striatal-thalamic-cortical, PYR pyramidal neurons, PV parvalbumin, GABA γ -aminobutyric acid

179]. New approaches like multisensory stimulation with neurofeedback, which enhance γ activity through light, auditory stimulations, and operant conditioning, have been linked to improvements in working memory and cognitive functions in AD and mild cognitive impairment patients [180–182] (Fig. 4b). γ -band synchronization can also be self-modulated through EEG-neurofeedback, showing potential in the elderly population [131]. Preliminary trials indicate that γ -neurofeedback significantly boosts frontal γ responses, reinforcing its promise as a therapeutic tool for AD-related cognitive decline [183].

γ oscillations neuromodulation improving motor function in PD

γ neuromodulation has shown potential as a therapeutic approach for improving motor functions in PD with control-theoretical principles to modulate hippocampal γ oscillations through posterior cingulate cortex stimulation [184]. The effect of stimulation intensity on γ band entrainment was explored, comparing the entrained signal during rest and repetitive movement [185]. Sub-harmonic entrainment of cortical γ oscillations to DBS in PD

patients has been recorded via EEG, with γ entrainment proposed as a new biomarker for motor improvement in PD [185, 186].

Additionally, phase-dependent neuromodulation has been investigated, with β -phase and γ amplitude implicated in PD pathology [187]. Fast θ – γ oscillation entrainment in PD patients has shown benefits, especially in the absence of dyskinesia [186]. While DBS is a widely used therapy, its lack of adaptability to changing clinical and neural conditions has been noted [188]. γ power suppression has been linked to tremor reduction in patients undergoing DBS, and cortical γ oscillations have been associated with levodopa-induced dyskinesia in PD [189, 190]. Collectively, these findings advocate for the continued exploration and refinement of γ neuromodulation techniques to enhance motor function and improve the quality of life for individuals with PD.

γ neuromodulations in seizure control for epilepsy

In epilepsy, key oscillatory patterns include the spike-wave complex (SWC) and high-frequency oscillations (HFOs) [191]. The previous one is an EEG marker of

paroxysmal depolarization shifts, particularly in the absence of seizures, disrupting cognitive functions. The HFOs, classified as ripples (80 – 250 Hz) and fast ripples (250 – 600 Hz), serve as biomarkers for the epileptogenic zone and often occur during slow-wave sleep [192]. The presence of these specific γ components can predict favorable surgical outcomes, emphasizing their importance in identifying cortical areas for effective seizure control [192]. Consequently, γ neuromodulation might be considered a promising therapeutic strategy for epilepsy, facilitating targeted interventions and restoring balance in seizure management. Specifically, it aids in localizing seizure onset zones (SOZ) and predicting seizure outcomes using directional CFC data collected by brief resting-state stereo-electroencephalography (SEEG) data, achieving 88% SOZ localization accuracy and 92% prediction accuracy by analyzing directional information flow between SOZ and non-SOZ in the γ frequency band, offering a faster pathway to effective seizure control [193] (Fig. 4c).

Additionally, dynamic mode decomposition has been used to identify epileptic networks in focal epilepsy patients, highlighting its potential for neuromodulation therapies [194]. Closed-loop brain stimulation studies emphasize γ frequency modulation in non-lesional refractory motor epilepsy, further exploring the neurophysiological effects [195]. γ Knife Surgery has demonstrated non-destructive neuromodulatory effects, backed by both clinical and experimental data, and has been highlighted as a potential treatment option [196, 197]. Other neuromodulation techniques, like DBS and vagus nerve stimulation (VNS), have also shown promise in epilepsy treatment, with VNS desynchronizing epileptiform activity in the γ band and thalamic DBS modulating γ and high- γ oscillations in the hippocampus [198, 199].

Besides, thalamic neuromodulation, particularly DBS targeting the anterior nucleus of the thalamus (ANT), represents an innovative and FDA-approved treatment approach for drug-resistant epilepsy [200]. Bilateral ANT stimulation has been shown to reduce seizures by 40.5% at 3 months and by 75.0% at 5 years, with efficacy best documented for focal onset seizures in the temporal or frontal lobes [201]. Other thalamic sub-nuclei, such as the centromedian nucleus and pulvinar, have also been explored for their potential in treating generalized or multifocal seizures and posterior limbic seizures, respectively [201]. While thalamic DBS is associated with side effects such as paresthesias, mood changes, and memory disturbances, it offers a valuable option for patients with refractory epilepsy who are not candidates for resective surgery [201].

While some studies suggest that low-frequency rTMS and tDCS can impact epileptiform activity, their

effectiveness in reducing clinical seizures remains uncertain [202–204]. The variability in results from randomized controlled trials highlights the importance of careful interpretation, as the effects of active rTMS have varied from no benefit to significant improvement [205]. In contrast, invasive techniques such as VNS and DBS show a more definitive pathway for seizure control, with evidence indicating that these methods effectively intervene in comparable γ -related neural pathways. These findings collectively underscore the therapeutic potential of neuromodulation for γ activity in epilepsy management.

Psychiatric disorders

γ neuromodulations within CSTC in obsessive compulsive disorder (OCD)

Neuromodulation has emerged as a helpful approach for alleviating symptoms of OCD, particularly through high-frequency modulation, including β – γ modulation, which has been shown to produce significant and lasting improvements in obsessive–compulsive behaviors [206]. This effect may be linked to maladaptive habit learning, which is a key feature of OCD pathology [207–209]. This finding indicates that by disrupting these entrenched patterns, γ neuromodulation can facilitate a more adaptive response to triggers, thereby reducing the frequency and intensity of compulsive behaviors. Invasive techniques like theros capsulotomy and γ knife capsulotomy have also been explored, yielding varying outcomes in the OCD treatment [210]. Responsive DBS targeting ventral striatal activity has demonstrated efficacy in reducing OCD symptoms, as have other neuromodulatory approaches, such as γ knife ventral capsulotomy [211–213]. Non-invasive methods, such as TMS, remain experimental but are being investigated as potential treatments for OCD [214].

The cortico-striato-thalamo-cortical (CSTC) circuitry, which is involved in the regulation of habits and goal-directed behavior, plays a central role in OCD, with dysfunction in this loop contributing to the disorder's repetitive behaviors [215–217]. Modulating this circuit, particularly through pathways involving γ -aminobutyric acid (GABA) between the dorsal medial pallidum and thalamus, has shown promise in improving symptoms [218]. The involvement of reward-related circuits in the CSTC loop suggests that altering the activity in these regions could help in managing the compulsive and repetitive behaviors of OCD (Fig. 4d). Considering the convincing connection between the CSTC circuitry, obsessive–compulsive behavior, and GABA, non-invasive neuromodulation that targets γ oscillations within the CSTC represents a promising therapeutic approach for future OCD treatments.

Auditory-driven γ oscillations neuromodulation in schizophrenia

Schizophrenia is a psychiatric disorder marked by significant deficits in working memory and disrupted γ neuromodulation [132]. A novel therapeutic approach to address these deficits is γ Entrainment Using Sensory Stimulation (GENUS), designed to restore impaired neural activity through sensory-driven entrainment. This strategy aims to enhance γ oscillations, thereby addressing cognitive deficits and providing deeper insights into the pathophysiology of schizophrenia [219]. Consistent deficits in γ -range auditory steady-state responses (ASSRs) have also been observed in schizophrenia, signaling underlying preclinical neural impairments [220, 221]. Furthermore, alterations in schizophrenia-related genes have been associated with abnormal γ frequency responses to auditory stimulation [222]. Altered expression of genes involved in GABAergic transmission has been found in schizophrenia, affecting GABA neuromodulation [223]. These findings underscore the intricate interplay between genetic factors and γ oscillatory activity in schizophrenia, highlighting the importance of developing targeted interventions to address γ dysregulation.

TACS has emerged as an effective intervention, given that schizophrenia patients exhibit reduced task-related γ oscillations and diminished synchronization [224]. γ neuromodulation has also been explored through neurofeedback training, showing potential in enhancing working memory in individuals with schizophrenia [225]. Together, these findings emphasize the critical role of γ dysfunction in schizophrenia's cognitive impairments, suggesting that sensory-driven especially auditory-driven γ modulation using TACS could represent a potential target for the precise therapeutic interventions of schizophrenia.

Multimodal γ neuromodulation in depression

γ neuromodulation has emerged as a promising therapeutic approach for depression, showing potential to alleviate both depressive symptoms and cognitive impairments. Enhancing or silencing cortical γ oscillations through olfactory bulb-driven closed-loop neuromodulation has been found to modulate depressive symptoms effectively [226]. γ oscillations, primarily governed by GABA, also play a significant role in the longitudinal changes within depressive circuitry in response to neuromodulation therapies [227]. Additionally, γ neuromodulation has been associated with sustained improvements in working memory and depression symptoms, particularly in patients with stronger expertise-dependent cognitive structures [228]. γ activity, including resting-state EEG γ power and $\theta - \gamma$ coupling, has shown a strong

correlation with depression and may be modifiable through interventions such as rTMS [142]. VNS, which is FDA-approved for epilepsy and depression, has also emerged as a promising neuromodulation therapy [229]. Similarly, a recent study has revealed that high-frequency DBS of the habenula has shown potential clinical efficacy in alleviating symptoms of treatment-resistant depression [230].

Recent studies highlight the potential of γ -band modulation in improving treatment outcomes. Dysregulated γ -band functional connectivity induced by the emotional stimuli, particularly within the fronto-parietal control network, may help explain the mechanisms behind neuromodulation therapies. Abnormal γ dynamics, such as those seen in low- γ brain states, have been linked to varying responses to depression treatments [26, 231]. Notably, non-phase-locked γ oscillations (50–70 Hz) of the occipital cortices, which are induced by emotional stimuli, have emerged as potential biomarkers for predicting treatment efficacy in patients with mood disorders [232] (Fig. 4e). Besides, as DMN dysregulation is linked to depressive pathology, emerging evidence indicates that the BF modulates maladaptive self-referential processing through γ -mediated state transitions between rest and task engagement [49]. Targeting BF nuclei (e.g., cholinergic circuits) to normalize γ synchrony could restore emotional balance, consistent with findings that γ dysregulation contributes to disordered cognition across psychiatric disorders, including schizophrenia [25]. These mechanisms offer therapeutic pathways for neuromodulation in psychiatric conditions [48, 233]. These findings underscore the therapeutic promise of γ neuromodulation and its potential for enhancing future treatment strategies in depression and related disorders, with ongoing research needed to fully harness its benefits in clinical practice.

Neuromodulation of γ oscillations regulating the excitatory-inhibitory imbalance

γ oscillations play a critical role in cognitive and emotional processes, making them valuable biomarkers in both neurological and psychiatric diseases. These oscillations are closely linked to the excitatory-inhibitory (E/I) balance, which is crucial for proper information processing and neural plasticity [234]. γ oscillations are generated through mechanisms like pyramidal-interneuron network γ (PING) and interneuron network γ (ING), where excitatory pyramidal cells and inhibitory interneurons, such as parvalbumin-expressing (PV^+), somatostatin-expressing (SST^+), and vasoactive intestinal peptide (VIP) interneurons, interact to produce γ -frequency oscillations [235–239] (Fig. 4f). Disruptions in these networks, such as excessive excitation or impaired

inhibition, lead to aberrant γ oscillations, which can reflect maladaptive neural dynamics in neurological and psychiatric diseases [240, 241].

The mechanisms underlying γ modulation involve the interaction of GABAergic (inhibitory) and glutamatergic (excitatory) neurotransmission. GABAergic neurotransmission is particularly important for maintaining γ rhythms, as GABAA receptor activity regulates inhibitory postsynaptic currents (IPSCs) [234, 239, 242, 243]. Conversely, glutamatergic transmission is essential for fast synaptic activity and contributes to γ band generation [244]. Disruptions in either GABAergic or glutamatergic systems can cause uncommon γ oscillations, which are commonly observed in neurological and psychological diseases. For instance, decreases in γ -band ASSRs in schizophrenia are connected to deficits in GABAergic transmission, highlighting the significance of γ modulation for cognitive and psychological processing in these clients [245].

γ oscillations reflect the brain's capability to maintain an optimum E/I equilibrium, which is vital for both neurological and psychiatric health. Outside stimulations, intrinsic factors like GABA resting degrees, and the structural buildings of the cortex influence this equilibrium [246, 247]. In condition states, the imbalance of excitation and inhibition causes modified γ patterns, adding to cognitive deficiencies and psychological dysregulation [248]. Neuromodulation therapies aimed at restoring γ oscillations offer a promising avenue for treating neurological and psychiatric disorders by addressing these underlying imbalances [249–251]. These therapies, including DBS, TMS, and sensory-based interventions, show the potential to improve clinical symptoms and enhance cognitive functions in neurological and psychiatric diseases. By targeting the disruptions in γ activity, neuromodulation may lead to more effective treatments for a range of physical and psychological health.

Restoration of γ synchrony via neuromodulation

γ oscillations play a significant role in various neurological disorders, as they are crucial for maintaining neuronal synchrony, which is essential for normal cognitive and motor functions. Neuronal synchrony refers to the coordinated timing of neural firing across different brain regions, enabling effective communication and integration of information essential for complex cognitive tasks and motor control. When synchrony is disrupted, it can lead to impaired functioning and contribute to the pathophysiology of various neurological disorders.

In AD, γ oscillations have been linked to amyloid- β clearance and neuroinflammation [252]. Animal studies have shown that 40 Hz γ entrainment using sensory stimulation, such as light flicker or sound, can reduce amyloid

plaques and tau pathology in mouse models of AD, suggesting that γ modulation might slow the progression of neurodegeneration by promoting neuronal synchrony and clearing toxic protein accumulation [31, 173, 174]. By enhancing neuronal synchrony, these interventions may improve the brain's ability to communicate effectively and manage metabolic waste, which is critical for preserving cognitive functions.

Similarly, in PD, altered γ synchronization is associated with motor symptoms [253]. DBS, particularly in the subthalamic nucleus (STN), helps modulate γ activity, restoring more physiological oscillatory patterns and improving motor function by reducing pathological synchrony within basal ganglia-cortical circuits [254, 255]. In epilepsy, γ oscillations are disrupted by an E/I imbalance, contributing to the hyperexcitable neural activity that leads to seizures [256, 257]. Neuromodulation techniques, such as TMS and DBS, aim to restore γ oscillations by rebalancing excitatory and inhibitory transmission [191]. These interventions stabilize neuronal networks by modulating γ rhythms, effectively re-establishing synchrony among neural circuits and reducing both the frequency and intensity of symptoms. By restoring neuronal synchrony, these therapies help prevent seizure initiation and promote overall neural stability, underscoring the critical role of γ oscillations in maintaining healthy brain function.

In psychiatric disorders like depression and schizophrenia, abnormal γ oscillations are associated with E/I imbalance, which affects emotional regulation and cognitive functions [258–263] (Fig. 4g). Disrupted γ power has been observed in patients with depression or schizophrenia, serving as a potential marker of synaptic homeostasis dysregulation [27, 221, 264–266]. Neuromodulation therapies, such as tACS and DBS, target γ oscillations to restore this balance and alleviate symptoms. By modulating γ activity, these interventions may improve outcomes by enhancing emotional processing and reducing depressive symptoms. The common mechanisms underlying these approaches include the restoration of synaptic plasticity and the facilitation of better neural communication, which together highlight the therapeutic potential of γ neuromodulation across both neurological and psychiatric disorders. This suggests that further exploration of γ oscillation modulation could be key to developing effective treatments for a range of conditions marked by neural dysregulation.

Limitations

Regardless of the encouraging possibility of γ neuromodulation in neurological and psychological diseases, several limitations remain (Fig. 5a–c). Firstly, individualized differences in response to γ oscillation

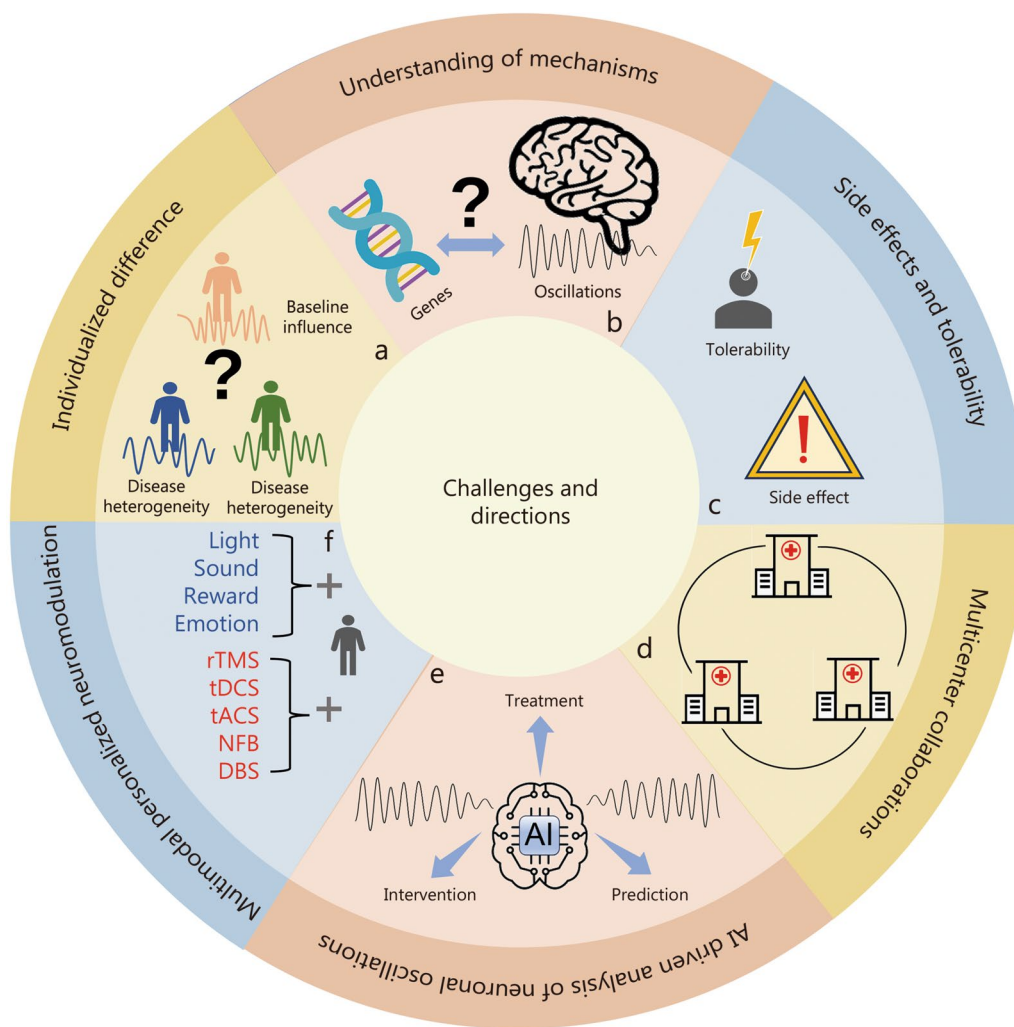


Fig. 5 Limitations and future directions in utilizing γ neuromodulations. **a** Individualized differences for γ neuromodulations. **b** Understanding of the neurobiological mechanisms. **c** Side effects and tolerability. Future directions: **d** Multicenter collaborations to enhance treatment efficiency. **e** AI-driven analysis for customized interventions. **f** multimodal individualized methods. rTMS repetitive transcranial magnetic stimulation, tDCS transcranial direct current stimulation, tACS transcranial alternating current stimulation, NFB Neurofeedback, DBS Deep brain stimulation, AI Artificial intelligence

modulation provide a substantial challenge. The efficacy of therapy can differ substantially across individuals because of variables such as genetic proneness, baseline neural activity, and the intricacy of neurocircuitry involved in each disorder. Tailoring treatments to individual profiles remains difficult, limiting the current capacity for precision therapy. Secondly, there is a limited understanding of the underlying biological mechanisms by which γ oscillations affect cognitive and emotional regulation. While γ oscillations are known to be involved in excitatory-inhibitory balance, synaptic plasticity, and network communication, the specific pathways and interactions that modulate these processes during neuromodulation are not fully

understood. This hampers the ability to optimize therapeutic protocols. Technologies such as spatiotemporal multi-omics could help explore the molecular mechanisms underlying these oscillatory disruptions, shedding light on gene expression, epigenetic regulation, and metabolic pathways [267–269]. Lastly, side effects and tolerability pose concerns. γ neuromodulation, whether through rTMS, DBS, or other tools, can cause unintended side effects such as headaches, mood shifts, or cognitive disturbances, with individual tolerability varying widely. Ensuring both safety and efficacy across diverse patient populations remains a critical area for improvement. Addressing these limitations will be key to advancing the clinical utility of γ neuromodulation.

Future directions

Several promising avenues emerge for subsequent exploration (Fig. 5d–f). Firstly, multimodal personalized neuromodulations are critical. Integrating data from multiple neuroimaging techniques and combining different neuromodulation methods (e.g., rTMS, DBS, tACS) during the multisensory environment (light, sound, emotion, and reward stimuli) could allow for more individualized treatment plans, tailored to the unique neurobiological profiles of patients. This could improve precision and effectiveness by targeting specific neural circuits with optimized parameters [270, 271]. Secondly, artificial intelligence (AI) driven analysis of neuronal oscillations shows significant promise, with established machine learning frameworks identifying neural oscillatory biomarkers for disorders such as post-traumatic stress disorder (PTSD), ASD, and depression [272, 273]. Besides, Artificial neural networks (ANNs) further highlight low- γ oscillations as optimal for decoding behavioral states [274]. The latest advancements utilize large language models (LLMs) to expand the scope of neuronal oscillatory activities. Specifically, large language model meta AI-2 (LLaMa-2) enables semantic reconstruction of visual stimuli from γ -modulated EEG [275], while Generative pre-trained transformer-4 (GPT-4) detects schizophrenia via interpretable EEG analysis, revealing γ -related neural signatures [276]. By integrating neural oscillation data with clinical and cognitive metrics, AI holds the potential to enhance the efficiency of treatment predictions and optimize intervention strategies. Lastly, fostering multicenter collaborations will be essential for advancing the field. Large-scale, cross-institutional studies can provide robust data on the variability of neuromodulation responses across diverse populations. This would help with the growth of standardized procedures and boost the generalizability of findings. Joint networks might also increase the discovery of biomarkers for treatment reactions, consequently refining γ modulation approaches and increasing their restorative reach throughout various neurological and psychiatric conditions.

Conclusions

In summary, this review highlights the vital role of γ neuromodulation in sharpening executive functions and cognitive processes throughout a range of neurological and psychiatric disorders. By describing the elaborate systems of γ oscillations and their possibility as biomarkers for therapeutic efficacy, we highlight the significance of these characteristics for reliable medical applications. The combination of cutting-edge neuroimaging techniques with targeted neuromodulation strategies offers promising

avenues for future research, specifically in refining treatment protocols to enhance patient outcomes. Further investigation into the biological mechanisms driving individual variability in responses to γ modulation will be essential for advancing precision medicine in neuromodulation therapies.

Abbreviations

ACC	Anterior cingulate cortex
AD	Alzheimer's disease
AI	Artificial intelligence
ANNs	Artificial neural networks
ANT	Anterior nucleus of the thalamus
ASSRs	Auditory steady-state responses
BF	Basal forebrain
CFC	Cross-frequency coupling
CSTC	Cortico-striato-thalamo-cortical
DBS	Deep brain stimulation
DMN	Default mode network
E/I	Excitatory-inhibitory
EEG	Electroencephalogram
ERP	Event-related potential
FGF	Fibroblast growth factors
GABA	γ -aminobutyric acid
GBO	γ band oscillations
GENUS	γ entrainment using sensory stimulation
GPT-4	Generative pre-trained transformer-4
HFO	High-frequency oscillations
HMM	Hidden markov model
ICA	Independent component analysis
ING	Interneuron network γ
IPSCs	Inhibitory postsynaptic currents
LLaMa-2	Large language model meta AI-2
LLMs	Large language models
MEG	Magnetoencephalography
mGluRs	Metabotropic glutamate receptors
NFB	Neurofeedback
OCD	Obsessive compulsive disorder
PAC	Phase amplitude coupling
PD	Parkinson's disease
PING	Pyramidal-interneuron network γ
PLV	Phase-locking value
PTSD	Post-traumatic stress disorder
PV+	Parvalbumin-expressing
RSS	Rhythmic sensory stimulation
rTMS	Repetitive transcranial magnetic stimulation
SEEG	Stereo-electroencephalography
SOZ	Seizure onset zones
SQUID	Superconducting quantum interference device
SST+	Somatostatin-expressing
STN	Subthalamic nucleus
SWC	Spike-wave complex
tACS	Transcranial alternating current stimulation
TMS	Transcranial magnetic stimulation
VIP	Vasoactive intestinal peptide
VNS	Vagus nerve stimulation

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Authors' contributions

ZPD, QW, PW, YNZ, CLF, MYD, HLZ, HW, HT, SQZ, XKL, JSJ, LXC and ZGW drafted the manuscript. ZPD, QW, PW, YNZ, CLF, MYD, HLZ, HW, HT, SQZ, and LXC

performed the substantive revision. ZPD, QW, PW, YNZ, CLF, MYD, HLZ, HW, HT, SQZ, and LXC investigated and surveyed the literature. ZPD, QW, PW, YNZ, CLF, MYD, XKL, JSJ, LXC, ZGW contributed to the concept of the study. LXC and ZGW provided funding support. ZPD, XKL, JSJ, LXC, and ZGW designed the work. All authors have read and approved the final manuscript.

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Declarations

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Competing interests

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References

- Temel Y, Heschem SA, Jahanshahi A, Janssen ML, Tan SK, van Overbeeke JJ, et al. Neuromodulation in psychiatric disorders. *Int Rev Neurobiol*. 2012;107:283–314.
- Johnson MD, Lim HH, Netoff TI, Connolly AT, Johnson N, Roy A, et al. Neuromodulation for brain disorders: challenges and opportunities. *IEEE Trans Biomed Eng*. 2013;60(3):610–24.
- Edwards CA, Kouzani A, Lee KH, Ross EK. Neurostimulation devices for the treatment of neurologic disorders. *Mayo Clin Proc*. 2017;92(9):1427–44.
- Fecteau S. Influencing human behavior with noninvasive brain stimulation: direct human brain manipulation revisited. *Neuroscientist*. 2023;29(3):317–31.
- Conroy SK, Holtzheimer PE. Neuromodulation strategies for the treatment of depression. *Am J Psychiatry*. 2021;178(12):1082–8.
- Mosilhy EA, Alshial EE, Eltaras MM, Rahman MMA, Helmy HI, Elazoul AH, et al. Non-invasive transcranial brain modulation for neurological disorders treatment: a narrative review. *Life Sci*. 2022;307:120869.
- Brunoni AR, Teng CT, Correa C, Imamura M, Brasil-Neto JP, Boechat R, et al. Neuromodulation approaches for the treatment of major depression: challenges and recommendations from a working group meeting. *Arg Neuropsychiatr*. 2010;68(3):433–51.
- Soleimani G, Nitsche MA, Bergmann TO, Towhidkhal F, Violante IR, Lorenz R, et al. Closing the loop between brain and electrical stimulation: towards precision neuromodulation treatments. *Transl Psychiatry*. 2023;13(1):279.
- Ferrarelli F, Phillips ML. Examining and modulating neural circuits in psychiatric disorders with transcranial magnetic stimulation and electroencephalography: present practices and future developments. *Am J Psychiatry*. 2021;178(5):400–13.
- Li Y, Cao D, Wei L, Tang Y, Wang J. Abnormal functional connectivity of EEG gamma band in patients with depression during emotional face processing. *Clin Neurophysiol*. 2015;126(11):2078–89.
- Swann NC, de Hemptinne C, Miodinovic S, Qasim S, Wang SS, Ziman N, et al. Gamma oscillations in the hyperkinetic state detected with chronic human brain recordings in Parkinson's disease. *J Neurosci*. 2016;36(24):6445–58.
- Traikapi A, Konstantinou N. Gamma oscillations in Alzheimer's disease and their potential therapeutic role. *Front Syst Neurosci*. 2021;15:782399.
- Dai Z, Pei C, Zhang S, Tian S, Chen Z, Zhou H, et al. Attenuated alpha-gamma coupling in emotional dual pathways with right-Amygdala predicting ineffective antidepressant response. *CNS Neurosci Ther*. 2022;28(3):401–10.
- Iosifescu DV, Greenwald S, Devlin P, Mischoulon D, Denninger JW, Alpert JE, et al. Frontal EEG predictors of treatment outcome in major depressive disorder. *Eur Neuropsychopharmacol*. 2009;19(11):772–7.
- McLoughlin G, Gyurkovics M, Palmer J, Makeig S. Midfrontal theta activity in psychiatric illness: an index of cognitive vulnerabilities across disorders. *Biol Psychiatry*. 2022;91(2):173–82.
- Wilkening J, Wittler F, Goya-Maldonado R. Suicidality and relief of depressive symptoms with intermittent theta burst stimulation in a sham-controlled randomized clinical trial. *Acta Psychiatr Scand*. 2022;146(6):540–56.
- Zhao Y, He Z, Luo W, Yu Y, Chen J, Cai X, et al. Effect of intermittent theta burst stimulation on suicidal ideation and depressive symptoms in adolescent depression with suicide attempt: a randomized sham-controlled study. *J Affect Disord*. 2023;325:618–26.
- Lee SM, Jang KI, Chae JH. Electroencephalographic correlates of suicidal ideation in the theta band. *Clin EEG Neurosci*. 2017;48(5):316–21.
- Atallah BV, Scanziani M. Instantaneous modulation of gamma oscillation frequency by balancing excitation with inhibition. *Neuron*. 2009;62(4):566–77.
- Touboul J, Destexhe A. Can power-law scaling and neuronal avalanches arise from stochastic dynamics?. *PLoS One*. 2010;5(2):e8982.
- Gladding CM, Fitzjohn SM, Molnár E. Metabotropic glutamate receptor-mediated long-term depression: molecular mechanisms. *Pharmacol Rev*. 2009;61(4):395–412.
- Uhlhaas PJ, Singer W. Abnormal neural oscillations and synchrony in schizophrenia. *Nat Rev Neurosci*. 2010;11(2):100–13.
- Wang H, Peng RY. Basic roles of key molecules connected with NMDAR signaling pathway on regulating learning and memory and synaptic plasticity. *Mil Med Res*. 2016;3:1–7.
- Lei HY, Pi GL, He T, Xiong R, Lv JR, Liu JL, et al. Targeting vulnerable microcircuits in the ventral hippocampus of male transgenic mice to rescue Alzheimer-like social memory loss. *Mil Med Res*. 2024;11(1):16.
- Kim T, Thankachan S, McKenna JT, McNally JM, Yang C, Choi JH, et al. Cortically projecting basal forebrain parvalbumin neurons regulate cortical gamma band oscillations. *Proc Natl Acad Sci U S A*. 2015;112(11):3535–40.
- Dai Z, Shao J, Zhou H, Chen Z, Zhang S, Wang H, et al. Disrupted fronto-parietal network and default-mode network gamma interactions distinguishing suicidal ideation and suicide attempt in depression. *Prog Neuropsychopharmacol Biol Psychiatry*. 2022;113:110475.
- Arikan MK, Gunver MG, Tarhan N, Metin B. High-Gamma: a biological marker for suicide attempt in patients with depression. *J Affect Disord*. 2019;254:1–6.

28. Gilbert JR, Ballard ED, Galiano CS, Nugent AC, Zarate CA Jr. Magnetoencephalographic correlates of suicidal ideation in major depression. *Biol Psychiatry Cogn Neurosci Neuroimaging*. 2020;5(3):354–63.
29. Fitzgerald PJ, Watson BO. Gamma oscillations as a biomarker for major depression: an emerging topic. *Transl Psychiatry*. 2018;8(1):177.
30. Nicolás MJ, López-Azcárate J, Valencia M, Alegre M, Pérez-Alcázar M, Iriarte J, et al. Ketamine-induced oscillations in the motor circuit of the rat basal ganglia. *PLoS One*. 2011;6(7):e21814.
31. Iaccarino HF, Singer AC, Martorell AJ, Rudenko A, Gao F, Gillingham TZ, et al. Gamma frequency entrainment attenuates amyloid load and modifies microglia. *Nature*. 2016;540(7632):230–5.
32. Kondabolu K, Roberts EA, Bucklin M, McCarthy MM, Kopell N, Han X. Striatal cholinergic interneurons generate beta and gamma oscillations in the corticostriatal circuit and produce motor deficits. *Proc Natl Acad Sci U S A*. 2016;113(22):E3159–68.
33. Balbi M, Xiao D, Vega MJ, Hu H, Vanni MP, Bernier LP, et al. Gamma frequency activation of inhibitory neurons in the acute phase after stroke attenuates vascular and behavioral dysfunction. *Cell Rep*. 2021;34(5):108696.
34. Garcia-Rill E, Virmani T, Hyde J, D'Onofrio S, Mahaffey S. Arousal and the control of perception and movement. *Curr Trends Neurol*. 2016;10:53.
35. Guerra A, Asci F, D'Onofrio V, Sveva V, Bologna M, Fabbrini G, et al. Enhancing gamma oscillations restores primary motor cortex plasticity in Parkinson's disease. *J Neurosci*. 2020;40(24):4788–96.
36. Li Q, Takeuchi Y, Wang J, Gellért L, Barcsai L, Pedraza LK, et al. Reinstating olfactory bulb-derived limbic gamma oscillations alleviates depression-like behavioral deficits in rodents. *Neuron*. 2023;111(13):2065–75.e5.
37. Liu X, Liu S, Li M, Su F, Chen S, Ke Y, et al. Altered gamma oscillations and beta-gamma coupling in drug-naive first-episode major depressive disorder: association with sleep and cognitive disturbance. *J Affect Disord*. 2022;316:99–108.
38. Liu X, Zhang H, Cui Y, Zhao T, Wang B, Xie X, et al. EEG-based major depressive disorder recognition by neural oscillation and asymmetry. *Front Neurosci*. 2024;18:1362111.
39. Voetterl HTS, Sack AT, Olbrich S, Stuiver S, Rouwhorst R, Prentice A, et al. Alpha peak frequency-based Brainmarker-I as a method to stratify to pharmacotherapy and brain stimulation treatments in depression. *Nat Ment Health*. 2023;1(12):1023–32.
40. Tong X, Xie H, Fonzo GA, Zhao K, Satterthwaite TD, Carlisle NB, et al. Symptom dimensions of resting-state electroencephalographic functional connectivity in autism. *Nat Ment Health*. 2024;2(3):287–98.
41. Hirano Y, Oribe N, Kanba S, Onitsuka T, Nestor PG, Spencer KM. Spontaneous gamma activity in schizophrenia. *JAMA Psychiat*. 2015;72(8):813–21.
42. Zhang J, Emami Z, Safar K, McCunn P, Richardson JD, Rhind SG, et al. Teasing apart trauma: neural oscillations differentiate individual cases of mild traumatic brain injury from post-traumatic stress disorder even when symptoms overlap. *Transl Psychiatry*. 2021;11(1):345.
43. Mathalon DH, Sohal VS. Neural oscillations and synchrony in brain dysfunction and neuropsychiatric disorders: it's about time. *JAMA Psychiat*. 2015;72(8):840–4.
44. Hirano Y, Uhlhaas PJ. Current findings and perspectives on aberrant neural oscillations in schizophrenia. *Psychiatry Clin Neurosci*. 2021;75(12):358–68.
45. Kayarian FB, Jannati A, Rotenberg A, Santarnecchi E. Targeting gamma-related pathophysiology in autism spectrum disorder using transcranial electrical stimulation: opportunities and challenges. *Autism Res*. 2020;13(7):1051–71.
46. Yuen J, Rusheen AE, Price JB, Barath AS, Shin H, Kouzani AZ, et al. Biomarkers for deep brain stimulation in animal models of depression. *Neuromodulation*. 2022;25(2):161–70.
47. Guan A, Wang S, Huang A, Qiu C, Li Y, Li X, et al. The role of gamma oscillations in central nervous system diseases: mechanism and treatment. *Front Cell Neurosci*. 2022;16:962957.
48. Nair J, Klaassen AL, Arato J, Vysotski AL, Harvey M, Rainer G. Basal forebrain contributes to default mode network regulation. *Proc Natl Acad Sci U S A*. 2018;115(6):1352–7.
49. Harrison BJ, Davey CG, Savage HS, Jamieson AJ, Leonards CA, Moffat BA, et al. Dynamic subcortical modulators of human default mode network function. *Cereb Cortex*. 2022;32(19):4345–55.
50. da Silva FL. EEG and MEG: relevance to neuroscience. *Neuron*. 2013;80(5):1112–28.
51. Puce A, Hämäläinen MS. A review of issues related to data acquisition and analysis in EEG/MEG studies. *Brain Sci*. 2017;7(6):58.
52. Marhl U, Jodko-Władzińska A, Brühl R, Sander T, Jazbinšek V. Transforming and comparing data between standard SQUID and OPM-MEG systems. *PLoS One*. 2022;17(1):e0262669.
53. Robbins KA, Touryan J, Mullen T, Kothe C, Bigdely-Shamlo N. How sensitive are EEG results to preprocessing methods: a benchmarking study. *IEEE Trans Neural Syst Rehabil Eng*. 2020;28(5):1081–90.
54. Zhang H, Zhou QQ, Chen H, Hu XQ, Li WG, Bai Y, et al. The applied principles of EEG analysis methods in neuroscience and clinical neurology. *Mil Med Res*. 2023;10(1):67.
55. Debener S, Thorne J, Schneider TR, Viola FC. 3.1 using ICA for the analysis of multi-channel EEG data. In: Ullsperger Markus, Debener Stefan, editors. *Simultaneous EEG and fMRI: recording, analysis, and application*. Oxford University Press; New York; 2010. p. 121–34. <https://doi.org/10.1093/acprof:oso/9780195372731.003.0008>.
56. Mammone N, La Foresta F, Morabito FC. Automatic artifact rejection from multichannel scalp EEG by wavelet ICA. *IEEE Sens J*. 2012;12(3):533–42.
57. Litvak V, Friston K. Electromagnetic source reconstruction for group studies. *Neuroimage*. 2008;42(4):1490–8.
58. Mattout J, Henson RN, Friston KJ. Canonical source reconstruction for MEG. *Comput Intell Neurosci*. 2007;2007:67613.
59. Dalal SS, Zumer JM, Guggisberg AG, Trampus M, Wong DD, Sekihara K, et al. MEG/EEG source reconstruction, statistical evaluation, and visualization with NUTMEG. *Comput Intell Neurosci*. 2011;2011:758973.
60. Herrmann CS, Rach S, Vosskuhl J, Strüber D. Time-frequency analysis of event-related potentials: a brief tutorial. *Brain Topogr*. 2014;27:438–50.
61. Dien J. Applying principal components analysis to event-related potentials: a tutorial. *Dev Neuropsychol*. 2012;37(6):497–517.
62. Pachori RB. *Time-frequency analysis techniques and their applications*. Boca Raton: CRC Press; 2023.
63. Morales S, Bowers ME. Time-frequency analysis methods and their application in developmental EEG data. *Dev Cogn Neurosci*. 2022;54:101067.
64. Roach BJ, Mathalon DH. Event-related EEG time-frequency analysis: an overview of measures and an analysis of early gamma band phase locking in schizophrenia. *Schizophr Bull*. 2008;34(5):907–26.
65. Ho MH, Ombao H, Edgar JC, Canive JM, Miller GA. Time-frequency discriminant analysis of MEG signals. *Neuroimage*. 2008;40(1):174–86.
66. Wirsing K. Time frequency analysis of wavelet and Fourier transform. In: Mohammdy S, editor. *Wavelet theory*. IntechOpen; 2021. <https://doi.org/10.5772/intechopen.94521>.
67. Baba T. Time-frequency analysis using short time Fourier transform. *Open Acoust J*. 2012;5(1):32–8.
68. Stanković L, Alieva T, Bastiaans MJ. Time-frequency signal analysis based on the windowed fractional Fourier transform. *Signal Process*. 2003;83(11):2459–68.
69. Brkić D, Sommariva S, Schuler AL, Pascarella A, Belardinelli P, Isabella SL, et al. The impact of ROI extraction method for MEG connectivity estimation: practical recommendations for the study of resting state data. *Neuroimage*. 2023;284:120424.
70. Sareen E, Zahar S, Van De Ville D, Gupta A, Griffa A, Amico E. Exploring MEG brain fingerprints: evaluation, pitfalls, and interpretations. *Neuroimage*. 2021;240:118331.
71. Rizkallah J, Amoud H, Fracchini M, Wendling F, Hassan M. Exploring the correlation between M/EEG source-space and fMRI networks at rest. *Brain Topogr*. 2020;33(2):151–60.
72. Srinivasan R, Winter WR, Ding J, Nunez PL. EEG and MEG coherence: measures of functional connectivity at distinct spatial scales of neocortical dynamics. *J Neurosci Methods*. 2007;166(1):41–52.
73. Winter WR, Nunez PL, Ding J, Srinivasan R. Comparison of the effect of volume conduction on EEG coherence with the effect of field spread on MEG coherence. *Stat Med*. 2007;26(21):3946–57.
74. Chholak P, Kurkin SA, Hramov AE, Pisarchik AN. Event-related coherence in visual cortex and brain noise: an MEG study. *Appl Sci*. 2021;11(1):375.
75. Zhang Q, Hu Y, Potter T, Li R, Quach M, Zhang Y. Establishing functional brain networks using a nonlinear partial directed coherence method to predict epileptic seizures. *J Neurosci Methods*. 2020;329:108447.

76. Wang ZM, Zhou R, He Y, Guo XM. Functional integration and separation of brain network based on phase locking value during emotion processing. *IEEE Trans Cogn Dev Syst.* 2020;15(2):444–53.
77. Liu D, Cao T, Wang Q, Zhang M, Jiang X, Sun J. Construction and analysis of functional brain network based on emotional electroencephalogram. *Med Biol Eng Comput.* 2023;61(2):357–85.
78. Hao Z, Zhai X, Cheng D, Pan Y, Dou W. EEG microstate-specific functional connectivity and stroke-related alterations in brain dynamics. *Front Neurosci.* 2022;16:848737.
79. Vidaurre D, Quinn AJ, Baker AP, Dupret D, Tejero-Cantero A, Woolrich MW. Spectrally resolved fast transient brain states in electrophysiological data. *Neuroimage.* 2016;126:81–95.
80. Hamilton A, Northoff G. Abnormal ERPs and brain dynamics mediate basic self disturbance in schizophrenia: a review of EEG and MEG studies. *Front Psychiatry.* 2021;12:642469.
81. Koenig T, Studer D, Hubl D, Melie L, Strik W. Brain connectivity at different time-scales measured with EEG. *Philos Trans R Soc B.* 2005;360(1457):1015–24.
82. Michel CM, Koenig T. EEG microstates as a tool for studying the temporal dynamics of whole-brain neuronal networks: a review. *Neuroimage.* 2018;180(Pt B):577–93.
83. Bai Y, He J, Xia X, Wang Y, Yang Y, Di H, et al. Spontaneous transient brain states in EEG source space in disorders of consciousness. *Neuroimage.* 2021;240:118407.
84. Baker AP, Brookes MJ, Rezek IA, Smith SM, Behrens T, Probert Smith PJ, et al. Fast transient networks in spontaneous human brain activity. *Elife.* 2014;3:e01867.
85. Fu Z, Iraj A, Turner JA, Sui J, Miller R, Pearlson GD, et al. Dynamic state with covarying brain activity-connectivity: On the pathophysiology of schizophrenia. *Neuroimage.* 2021;224:117385.
86. Liu C, Han T, Xu Z, Liu J, Zhang M, Du J, et al. Modulating gamma oscillations promotes brain connectivity to improve cognitive impairment. *Cereb Cortex.* 2022;32(12):2644–56.
87. Mostame P, Sadaghiani S. Oscillation-based connectivity architecture is dominated by an intrinsic spatial organization, not cognitive state or frequency. *J Neurosci.* 2021;41(1):179–92.
88. Hramov AE, Frolov NS, Maksimenko VA, Kurkin SA, Kazantsev VB, Pisarchik AN. Functional networks of the brain: from connectivity restoration to dynamic integration. *Phys Usp.* 2021;64(6):584.
89. Vicente R, Rizzuto M, Sarica C, Yamamoto K, Sadr M, Khajuria T, et al. Enhanced interplay of neuronal coherence and coupling in the dying human brain. *Front Aging Neurosci.* 2022;14:813531.
90. Alexander ML, Alagapan S, Lugo CE, Mellin JM, Lustenberger C, Rubinow DR, et al. Double-blind, randomized pilot clinical trial targeting alpha oscillations with transcranial alternating current stimulation (tACS) for the treatment of major depressive disorder (MDD). *Transl Psychiatry.* 2019;9(1):106.
91. Krause MR, Vieira PG, Thivierge JP, Pack CC. Brain stimulation competes with ongoing oscillations for control of spike timing in the primate brain. *PLoS Biol.* 2022;20(5):e3001650.
92. Martin DM, McClintock SM, Forster JJ, Lo TY, Loo CK. Cognitive enhancing effects of rTMS administered to the prefrontal cortex in patients with depression: a systematic review and meta-analysis of individual task effects. *Depress Anxiety.* 2017;34(11):1029–39.
93. Chou YH, That VT, Sundman M. A systematic review and meta-analysis of rTMS effects on cognitive enhancement in mild cognitive impairment and Alzheimer's disease. *Neurobiol Aging.* 2020;86:1–10.
94. Haller N, Senner F, Brunoni AR, Padberg F, Palm U. Gamma transcranial alternating current stimulation improves mood and cognition in patients with major depression. *J Psychiatr Res.* 2020;130:31–4.
95. Kim J, Kim H, Jeong H, Roh D, Kim DH. tACS as a promising therapeutic option for improving cognitive function in mild cognitive impairment: a direct comparison between tACS and tDCS. *J Psychiatr Res.* 2021;141:248–56.
96. Palm U, Hasan A, Strube W, Padberg F. tDCS for the treatment of depression: a comprehensive review. *Eur Arch Psychiatry Clin Neurosci.* 2016;266:681–94.
97. Zhao K, Fonzo GA, Xie H, Oathes DJ, Keller CJ, Carlisle NB, et al. Discriminative functional connectivity signature of cocaine use disorder links to rTMS treatment response. *Nat Ment Health.* 2024;2(4):388–400.
98. Arns M, Drinkenburg WH, Fitzgerald PB, Kenemans JL. Neurophysiological predictors of non-response to rTMS in depression. *Brain Stimul.* 2012;5(4):569–76.
99. Corlier J, Carpenter LL, Wilson AC, Tirrell E, Gobin AP, Kavanaugh B, et al. The relationship between individual alpha peak frequency and clinical outcome with repetitive transcranial magnetic stimulation (rTMS) treatment of major depressive disorder (MDD). *Brain Stimul.* 2019;12(6):1572–8.
100. Valiulis V, Gerulskis G, Dapšys K, Vistartaite G, Siurkute A, Maciulis V. Electrophysiological differences between high and low frequency rTMS protocols in depression treatment. *Acta Neurobiol Exp.* 2012;72(3):283–95.
101. Kavanaugh BC, Fukuda AM, Gemelli ZT, Thorpe R, Tirrell E, Vigne M, et al. Pre-treatment frontal beta events are associated with executive dysfunction improvement after repetitive transcranial magnetic stimulation for depression: a preliminary report. *J Psychiatr Res.* 2023;168:71–81.
102. Zrenner B, Zrenner C, Gordon PC, Belardinelli P, McDermott EJ, Soekadar SR, et al. Brain oscillation-synchronized stimulation of the left dorsolateral prefrontal cortex in depression using real-time EEG-triggered TMS. *Brain Stimul.* 2020;13(1):197–205.
103. Li CT, Juan CH, Lin HC, Cheng CM, Wu HT, Yang BH, et al. Cortical excitatory and inhibitory correlates of the fronto-limbic circuit in major depression and differential effects of left frontal brain stimulation in a randomized sham-controlled trial. *J Affect Disord.* 2022;311:364–70.
104. Lai CH. Fronto-limbic neuroimaging biomarkers for diagnosis and prediction of treatment responses in major depressive disorder. *Prog Neuropsychopharmacol Biol Psychiatry.* 2021;107:110234.
105. Tang Y, Jiao X, Wang J, Zhu T, Zhou J, Qian Z, et al. Dynamic functional connectivity within the fronto-limbic network induced by intermittent theta-burst stimulation: a pilot study. *Front Neurosci.* 2019;13:944.
106. Bozzay ML, Primack J, Barredo J, Philip NS. Transcranial magnetic stimulation to reduce suicidality—a review and naturalistic outcomes. *J Psychiatr Res.* 2020;125:106–12.
107. Paulus W. Transcranial electrical stimulation (tES-tDCS; tRNS, tACS) methods. *Neuropsychol Rehabil.* 2011;21(5):602–17.
108. Helfrich RF, Schneider TR, Rach S, Trautmann-Lengsfeld SA, Engel AK, Herrmann CS. Entrainment of brain oscillations by transcranial alternating current stimulation. *Curr Biol.* 2014;24(3):333–9.
109. Herrmann CS, Strüber D. What can transcranial alternating current stimulation tell us about brain oscillations?. *Curr Behav Neurosci Rep.* 2017;4(2):128–37.
110. Pahor A, Jaušovec N. The effects of theta and gamma tACS on working memory and electrophysiology. *Front Hum Neurosci.* 2018;11:651.
111. Aktürk T, de Graaf TA, Güntekin B, Hanoğlu L, Sack AT. Enhancing memory capacity by experimentally slowing theta frequency oscillations using combined EEG-tACS. *Sci Rep.* 2022;12(1):14199.
112. Guerra A, Asci F, Zampogna A, D'Onofrio V, Petrucci S, Ginevrino M, et al. Gamma-transcranial alternating current stimulation and theta-burst stimulation: inter-subject variability and the role of BDNF. *Clin Neurophysiol.* 2020;131(11):2691–9.
113. Nissim N, Pham D, Poddar T, Blutt E, Hamilton R. The impact of gamma transcranial alternating current stimulation (tACS) on cognitive and memory processes in patients with mild cognitive impairment or Alzheimer's disease: a literature review. *Brain Stimul.* 2023;16(3):748–55.
114. Herrmann CS, Rach S, Neuling T, Strüber D. Transcranial alternating current stimulation: a review of the underlying mechanisms and modulation of cognitive processes. *Front Hum Neurosci.* 2013;7:279.
115. Wong PL, Yang YR, Tang SC, Huang SF, Wang RY. Comparing different montages of transcranial direct current stimulation on dual-task walking and cortical activity in chronic stroke: double-blinded randomized controlled trial. *BMC Neurol.* 2022;22(1):119.
116. Molae-Ardekani B, Márquez-Ruiz J, Merlet I, Leal-Campanario R, Guart A, Sánchez-Campusano R, et al. Effects of transcranial Direct Current Stimulation (tDCS) on cortical activity: a computational modeling study. *Brain Stimul.* 2013;6(1):25–39.
117. Dedoncker J, Brunoni AR, Baeken C, Vanderhasselt MA. A systematic review and meta-analysis of the effects of transcranial direct current stimulation (tDCS) over the dorsolateral prefrontal cortex in healthy and neuropsychiatric samples: influence of stimulation parameters. *Brain Stimul.* 2016;9(4):501–17.

118. Chan MMY, Yau SSY, Han YMY. The neurobiology of prefrontal transcranial direct current stimulation (tDCS) in promoting brain plasticity: a systematic review and meta-analyses of human and rodent studies. *Neurosci Biobehav Rev.* 2021;125:392–416.
119. Nejati V, Majidnezhad M, Nitsche M. The role of the dorsolateral and ventromedial prefrontal cortex in emotion regulation in females with major depressive disorder (MDD): a tDCS study. *J Psychiatr Res.* 2022;148:149–58.
120. Mirifar A, Keil A, Ehrlenspiel F. Neurofeedback and neural self-regulation: a new perspective based on allostasis. *Rev Neurosci.* 2022;33(6):607–29.
121. Pinheiro J, de Almeida RS, Marques A. Emotional self-regulation, virtual reality and neurofeedback. *Comput Hum Behav Rep.* 2021;4:100101.
122. Arpaia P, Coyle D, D'Errico G, De Benedetto E, Paolis LTD, du Bois N, Grassini S, Mastrati G, Moccaldi N, Vallefucio E. Virtual reality enhances EEG-based neurofeedback for emotional self-regulation. In: Paolis Lucio Tommaso De, Arpaia Pasquale, Sacco Marco, editors. *Extended reality: first international conference, XR Salento 2022, Lecce, Italy, July 6–8, 2022, proceedings, Part II.* Cham: Springer Nature Switzerland; 2022. p. 420–31. https://doi.org/10.1007/978-3-031-15553-6_29.
123. Ros TJ, Baars BJ, Lanius RA, Vuilleumier P. Tuning pathological brain oscillations with neurofeedback: a systems neuroscience framework. *Front Hum Neurosci.* 2014;8:1008.
124. Riaño Garzón ME, Díaz Camargo EA, Torrado Rodríguez JL, Uribe Alvarado JJ, Contreras Velásquez JC, Fierro Zárate CA, et al. Neurofeedback effects on cognitive performance in children with attention deficit. *Archivos Venezolanos de Farmacología Y Terapéutica.* 2018;37(3):205–11.
125. Da Silva JC, De Souza ML. Neurofeedback training for cognitive performance improvement in healthy subjects: a systematic review. *Psychol Neurosci.* 2021;14(3):262.
126. Steingrímsson S, Bilonic G, Ekelund AC, Larson T, Stadig I, Svensson M, et al. Electroencephalography-based neurofeedback as treatment for post-traumatic stress disorder: a systematic review and meta-analysis. *Eur Psychiatry.* 2020;63(1):e7.
127. Aupperle R, Kuplicki R, Tsuchiyagaito A, Akeman E, Sturycz-Taylor C, DeVille D, et al. Ventromedial prefrontal cortex activation and neurofeedback modulation during episodic future thinking for individuals with suicidal thoughts and behaviors. *Behav Res Ther.* 2024;176:104522.
128. Choi YJ, Choi EJ, Ko E. Neurofeedback effect on symptoms of post-traumatic stress disorder: a systematic review and meta-analysis. *Appl Psychophysiol Biofeedback.* 2023;48(3):259–74.
129. Trambaiolli LR, Kohl SH, Linden DEJ, Mehler DM. Neurofeedback training in major depressive disorder: a systematic review of clinical efficacy, study quality and reporting practices. *Neurosci Biobehav Rev.* 2021;125:33–56.
130. Khodakarami Z, Firoozabadi M. Psychological, neurophysiological, and mental factors associated with gamma-enhancing neurofeedback success. *Basic Clin Neurosci.* 2020;11(5):701–14.
131. Andrade K, Houmani N, Guieysse T, Razafimahatratra S, Klarsfeld A, Dreyfus G, et al. Self-modulation of gamma-band synchronization through EEG-neurofeedback training in the elderly. *J Integr Neurosci.* 2024;23(3):67.
132. Shu IW, Granholm EL, Singh F. Targeting frontal gamma activity with neurofeedback to improve working memory in schizophrenia. *Curr Top Behav Neurosci.* 2023;63:153–72.
133. Sho'ouri N. Predicting the success rate of healthy participants in beta neurofeedback: determining the factors affecting the success rate of individuals. *Biomed Signal Process Contrl.* 2021;69:102753.
134. Magdy Rady R, Elsalamawy D, Rizk MRM, Abdel Alim O, Diaa MN. Enhancing affordable EEG to act as a quantitative EEG for inattention treatment using MATLAB. *Neural Comput Appl.* 2025;37:5849–71.
135. Kisely S, Li A, Warren N, Siskind D. A systematic review and meta-analysis of deep brain stimulation for depression. *Depress Anxiety.* 2018;35(5):468–80.
136. Figeo M, Riva-Posse P, Choi KS, Bederson L, Mayberg HS, Kopell BH. Deep brain stimulation for depression. *Neurotherapeutics.* 2022;19(4):1229–45.
137. Sheth SA, Mayberg HS. Deep brain stimulation for obsessive-compulsive disorder and depression. *Annu Rev Neurosci.* 2023;46:341–58.
138. Sheth SA, Bijanki KR, Metzger B, Allawala A, Pirtle V, Adkinson JA, et al. Deep brain stimulation for depression informed by intracranial recordings. *Biol Psychiatry.* 2022;92(3):246–51.
139. Lozano AM, Dostrovsky J, Chen R, Ashby P. Deep brain stimulation for Parkinson's disease: disrupting the disruption. *Lancet Neurol.* 2002;1(4):225–31.
140. Eusebio A, Cagnan H, Brown P. Does suppression of oscillatory synchronisation mediate some of the therapeutic effects of DBS in patients with Parkinson's disease? *Front Integr Neurosci.* 2012;6:47.
141. Zhang X, Zhao X, Shao Z, Wen X, Lu L, Li M, et al. The potential of electroencephalography coherence to predict the outcome of repetitive transcranial magnetic stimulation in insomnia disorder. *J Psychiatr Res.* 2023;160:56–63.
142. Noda Y, Zomorodi R, Saeki T, Rajji TK, Blumberger DM, Daskalakis ZJ, et al. Resting-state EEG gamma power and theta-gamma coupling enhancement following high-frequency left dorsolateral prefrontal rTMS in patients with depression. *Clin Neurophysiol.* 2017;128(3):424–32.
143. Lee ARYB, Yau CE, Mai AS, Tan WA, Ong BSY, Yam NE, et al. Transcranial alternating current stimulation and its effects on cognition and the treatment of psychiatric disorders: a systematic review and meta-analysis. *Ther Adv Chronic Dis.* 2022;13:20406223221140390.
144. Koch G, Altomare D, Benussi A, Bréchet L, Casula EP, Dodich A, et al. The emerging field of non-invasive brain stimulation in Alzheimer's disease. *Brain.* 2024;147(12):4003–16.
145. Hyafil A, Giraud AL, Fontolan L, Gutkin B. Neural cross-frequency coupling: connecting architectures, mechanisms, and functions. *Trends Neurosci.* 2015;38(11):725–40.
146. Yeh CH, Zhang C, Shi W, Lo MT, Tinkhauser G, Oswal A. Cross-frequency coupling and intelligent neuromodulation. *Cyborg Bionic Syst.* 2023;4:0034.
147. Onslow ACE, Bogacz R, Jones MW. Quantifying phase-amplitude coupling in neuronal network oscillations. *Prog Biophys Mol Biol.* 2011;105(1–2):49–57.
148. Tort ABL, Komorowski R, Eichenbaum H, Kopell N. Measuring phase-amplitude coupling between neuronal oscillations of different frequencies. *J Neurophysiol.* 2010;104(2):1195–210.
149. Attaheri A, Choisealalpa AN, Di Liberto GM, Rocha S, Brusini P, Mead N, et al. Delta-and theta-band cortical tracking and phase-amplitude coupling to sung speech by infants. *Neuroimage.* 2022;247:118698.
150. Sotero RC. Topology, cross-frequency, and same-frequency band interactions shape the generation of phase-amplitude coupling in a neural mass model of a cortical column. *PLoS Comput Biol.* 2016;12(11):e1005180.
151. Granados MdMY. Mechanisms underlying memory enhancement in humans. Madrid, Spain: Universidad Politécnica de Madrid; 2017.
152. Weiss E, Kann M, Wang Q. Neuromodulation of neural oscillations in health and disease. *Biology.* 2023;12(3):371.
153. Marco-Pallarés J, Münte TF, Rodríguez-Fornells A. The role of high-frequency oscillatory activity in reward processing and learning. *Neurosci Biobehav Rev.* 2015;49:1–7.
154. Ruggiero RN, Rossignoli MT, Marques DB, de Sousa BM, Romcy-Pereira RN, Lopes-Aguiar C, et al. Neuromodulation of hippocampal-prefrontal cortical synaptic plasticity and functional connectivity: implications for neuropsychiatric disorders. *Front Cell Neurosci.* 2021;15:732360.
155. Chartove J. Delta/theta-rhythmically interleaved gamma and beta oscillations in striatum: modeling and data analysis. Boston, MA, USA: Boston University; 2020.
156. Gedankien T, Tan RJ, Qasim SE, Moore H, McDonagh D, Jacobs J, et al. Acetylcholine modulates the temporal dynamics of human theta oscillations during memory. *Nat Commun.* 2023;14(1):5283.
157. Decker AL, Duncan K. Acetylcholine and the complex interdependence of memory and attention. *Curr Opin Behav Sci.* 2020;32:21–8.
158. Howe WM, Gritton HJ, Lusk NA, Roberts EA, Hetrick VL, Berke JD, et al. Acetylcholine release in prefrontal cortex promotes gamma oscillations and theta-gamma coupling during cue detection. *J Neurosci.* 2017;37(12):3215–30.
159. Yakubov B, Das S, Zomorodi R, Blumberger DM, Enticott PG, Kirkovski M, et al. Cross-frequency coupling in psychiatric disorders: a systematic review. *Neurosci Biobehav Rev.* 2022;138:104690.

160. Johnson KA, Okun MS, Scangos KW, Mayberg HS, de Hemptinne C. Deep brain stimulation for refractory major depressive disorder: a comprehensive review. *Mol Psychiatry*. 2024;29(4):1075–87.
161. Cappon DB, Pascual-Leone A. Toward precision noninvasive brain stimulation. *Am J Psychiatry*. 2024;181(9):795–805.
162. Njenga C, Ramanuj PP, de Magalhães FJC, Pincus HA. New and emerging treatments for major depressive disorder. *BMJ*. 2024;386:e073823.
163. Cai L, Wei X, Wang J, Yu H, Deng B, Wang R. Reconstruction of functional brain network in Alzheimer's disease via cross-frequency phase synchronization. *Neurocomputing*. 2018;314:490–500.
164. Wang X, Cui X, Ding C, Li D, Cheng C, Wang B, et al. Deficit of cross-frequency integration in mild cognitive impairment and Alzheimer's disease: a multilayer network approach. *J Magn Reson Imaging*. 2021;53(5):1387–98.
165. Musaeus CS, Nielsen MS, Musaeus JS, Høgh P. Electroencephalographic cross-frequency coupling as a sign of disease progression in patients with mild cognitive impairment: a pilot study. *Front Neurosci*. 2020;14:790.
166. Muthuraman M, Bange M, Koirala N, Ciolac D, Pinteá B, Glaser M, et al. Cross-frequency coupling between gamma oscillations and deep brain stimulation frequency in Parkinson's disease. *Brain*. 2020;143(11):3393–407.
167. Gong R, Mühlberg C, Wegscheider M, Fricke C, Rumpf JJ, Knösche TR, et al. Cross-frequency phase-amplitude coupling in repetitive movements in patients with Parkinson's disease. *J Neurophysiol*. 2022;127(6):1606–21.
168. Chen X, Li Y, Li R, Yuan X, Liu M, Zhang W, et al. Multiple cross-frequency coupling analysis of resting-state EEG in patients with mild cognitive impairment and Alzheimer's disease. *Front Aging Neurosci*. 2023;15:1142085.
169. Hodnik T, Roytman S, Bohner NI, Marusic U. Beta-gamma phase-amplitude coupling as a non-invasive biomarker for Parkinson's disease: insights from electroencephalography studies. *Life*. 2024;14(3):391.
170. Dai Z, Zhou H, Zhang W, Tang H, Wang T, Chen Z, et al. Alpha-beta decoupling relevant to inhibition deficits leads to suicide attempt in major depressive disorder. *J Affect Disord*. 2022;314:168–75.
171. Chattun MR, Zhang S, Chen Y, Wang Q, Amdanee N, Tian S, et al. Caudothalamic dysfunction in drug-free suicidally depressed patients: an MEG study. *Eur Arch Psychiatry Clin Neurosci*. 2020;270(2):217–27.
172. Ko H, Yoon SP. Optogenetic neuromodulation with gamma oscillation as a new strategy for Alzheimer's disease: a narrative review. *J Yeungnam Med Sci*. 2022;39(4):269–77.
173. Murdock MH, Yang CY, Sun N, Pao PC, Blanco-Duque C, Kahn MC, et al. Multisensory gamma stimulation promotes glymphatic clearance of amyloid. *Nature*. 2024;627(8002):149–56.
174. Martorell AJ, Paulson AL, Suk HJ, Abdurrob F, Drummond GT, Guan W, et al. Multi-sensory gamma stimulation ameliorates Alzheimer's-associated pathology and improves cognition. *Cell*. 2019;177(2):256–71.
175. Laxton AW, Tang-Wai DF, McAndrews MP, Zumsteg D, Wennberg R, Keren R, et al. A phase I trial of deep brain stimulation of memory circuits in Alzheimer's disease. *Ann Neurol*. 2010;68(4):521–34.
176. Chan D, Suk HJ, Jackson BL, Milman NP, Stark D, Klerman EB, et al. Gamma frequency sensory stimulation in probable mild Alzheimer's dementia patients: results of a preliminary clinical trial. *PLoS One*. 2022;17(12):e0278412.
177. Sprugnoli G, Munsch F, Cappon D, Paciorek R, Macone J, Connor A, et al. Impact of multisession 40 Hz tACS on hippocampal perfusion in patients with Alzheimer's disease. *Alzheimers Res Ther*. 2021;13(1):203.
178. Traikapi A, Kalli I, Kyriakou A, Stylianou E, Symeou RT, Kardama A, et al. Episodic memory effects of gamma frequency precuneus transcranial magnetic stimulation in Alzheimer's disease: a randomized multiple baseline study. *J Neuropsychol*. 2023;17(2):279–301.
179. Hoy KE, Emonson MRL, Bailey NW, Rogers C, Coyle H, Stockman F, et al. Gamma connectivity predicts response to intermittent theta burst stimulation in Alzheimer's disease: a randomized controlled trial. *Neurobiol Aging*. 2023;132:13–23.
180. Jones KT, Gallen CL, Ostrand AE, Rojas JC, Wais P, Rini J, et al. Gamma neuromodulation improves episodic memory and its associated network in amnesic mild cognitive impairment: a pilot study. *Neurobiol Aging*. 2023;129:72–88.
181. Singh F, Shu IW, Granholm E, Pineda JA. Revisiting the potential of EEG neurofeedback for patients with schizophrenia. *Schizophr Bull*. 2020;46(4):741–2.
182. Keizer AW, Verment RS, Hommel B. Enhancing cognitive control through neurofeedback: a role of gamma-band activity in managing episodic retrieval. *Neuroimage*. 2010;49(4):3404–13.
183. Lin Y, Shu IW, Singh F. Frontal gamma as a marker of effective training during neurofeedback to improve memory in patients with mild cognitive impairment. In: 2023 11th International IEEE/EMBS Conference on Neural Engineering (NER). Baltimore, MD, USA. IEEE. 2023:1–4.
184. Davila CE, Wang DX, Ritzer M, Moran R, Lega BC. A control-theoretical system for modulating hippocampal gamma oscillations using stimulation of the posterior cingulate cortex. *IEEE Trans Neural Syst Rehabil Eng*. 2022;30:2242–53.
185. Mathiopoulou V, Habets JGV, Feldmann LK, Busch JL, Roediger J, Behnke JK, et al. DBS-induced gamma entrainment as a new biomarker for motor improvement with neuromodulation. *medRxiv*. 2024; <https://doi.org/10.1101/2024.04.25.24306357>.
186. Sermon JJ, Olaru M, Anso J, Cernera S, Little S, Shcherbakova M, et al. Sub-harmonic entrainment of cortical gamma oscillations to deep brain stimulation in Parkinson's disease: model based predictions and validation in three human subjects. *Brain Stimul*. 2023;16(5):1412–24.
187. Hwang BY, Salimpour Y, Tsehay YK, Anderson WS, Mills KA. Perspective: phase amplitude coupling-based dependent neuromodulation in Parkinson's disease. *Front Neurosci*. 2020;14:558967.
188. Oehrn CR, Cernera S, Hammer LH, Shcherbakova M, Yao J, Hahn A, et al. Personalized chronic adaptive deep brain stimulation outperforms conventional stimulation in Parkinson's disease. *medRxiv*. 2023;2023.08.03.23293450. <https://doi.org/10.1101/2023.08.03.23293450>.
189. Beudel M, Little S, Pogossyan A, Ashkan K, Foltynie T, Limousin P, et al. Tremor reduction by deep brain stimulation is associated with gamma power suppression in Parkinson's disease. *Neuromodulation*. 2015;18(5):349–54.
190. Güttler C, Altschüler J, Tanev K, Böckmann S, Haumesser JK, Nikulin VV, et al. Levodopa-induced dyskinesia are mediated by cortical gamma oscillations in experimental Parkinsonism. *Mov Disord*. 2021;36(4):927–37.
191. Giovanni A, Capone F, di Biase L, Ferreri F, Florio L, Guerra A, et al. Oscillatory activities in neurological disorders of elderly: biomarkers to target for neuromodulation. *Front Aging Neurosci*. 2017;9:189.
192. Jiruska P, Alvarado-Rojas C, Schevon CA, Staba R, Stacey W, Wendling F, et al. Update on the mechanisms and roles of high-frequency oscillations in seizures and epileptic disorders. *Epilepsia*. 2017;58(8):1330–9.
193. Jiang H, Kokkinos V, Ye S, Urban A, Bagić A, Richardson M, et al. Interictal SEEG resting-state connectivity localizes the seizure onset zone and predicts seizure outcome. *Adv Sci*. 2022;9(18):e2200887.
194. Ramos AN, Krishnan B, Alexopoulos AV, Bingaman W, Najm I, Balacio JC, et al. Epileptic network identification: insights from dynamic mode decomposition of sEEG data. *J Neural Eng*. 2024;21(4):046061.
195. Zrenner C, Ziemann U. Closed-loop brain stimulation. *Biol Psychiatry*. 2024;95(6):545–52.
196. Régis J, Bartolomei F, Hayashi M, Chauvel P. Gamma knife surgery, a neuromodulation therapy in epilepsy surgery! *Acta Neurochir Suppl*. 2002;84:37–47.
197. Yang R, Xiong B, Wang M, Yang W, Gao Y, Yangyang X, Deng H, Pan W, Wang W. Gamma knife surgery and deep brain stimulation of the centromedian nucleus for chronic pain: a systematic review. *Asian J Surg*. 2023;46(9):3437–46. <https://doi.org/10.1016/j.asjsur.2023.06.026>.
198. Gouveia FV, Warsi NM, Suresh H, Matin R, Ibrahim GM. Neurostimulation treatments for epilepsy: Deep brain stimulation, responsive neurostimulation and vagus nerve stimulation. *Neurotherapeutics*. 2024;21(3):e00308.
199. Silva AB, Khambhati AN, Speidel BA, Chang EF, Rao VR. Effects of anterior thalamic nuclei stimulation on hippocampal activity: chronic recording in a patient with drug-resistant focal epilepsy. *Epilepsy Behav Rep*. 2021;16:100467.
200. Samanta D, Aungaroon G, Albert GW, Karakas C, Joshi CN, Singh RK, et al. Advancing thalamic neuromodulation in epilepsy: bridging adult data to pediatric care. *Epilepsy Res*. 2024;205:107407.
201. Fisher RS. Deep brain stimulation of thalamus for epilepsy. *Neurobiol Dis*. 2023;179:106045.

202. Wang Z, Zhang X, Meiduo G, Song M, Wang S. Time-effectiveness of low-frequency rTMS for epilepsy and improvement in cognitive function in patients: a systematic review and meta-analysis. *Epilepsy Res.* 2024;199:107277.
203. Tseriotis VS, Kimiskidis VK, Chlorogiannis DD, Arnaoutoglou M, Kouvelas D, Konstantis G, et al. Repetitive transcranial magnetic stimulation in murine models of epilepsy: a systematic review of methodological aspects and outcomes. *Epilepsy Res.* 2024;208:107468.
204. Sudbrack-Oliveira P, Barbosa MZ, Thome-Souza S, Razza LB, Gallucci-Neto J, da Costa L, Valiengo L, Brunoni AR. Transcranial direct current stimulation (tDCS) in the management of epilepsy: a systematic review. *Seizure.* 2021;86:85–95. <https://doi.org/10.1016/j.seizure.2021.01.020>.
205. Pereira LS, Müller VT, da Mota GM, Rothenberg A, Fregni F. Safety of repetitive transcranial magnetic stimulation in patients with epilepsy: a systematic review. *Epilepsy Behav.* 2016;57(Pt A):167–76.
206. Grover S, Nguyen JA, Viswanathan V, Reinhart RM. High-frequency neuromodulation improves obsessive-compulsive behavior. *Nat Med.* 2021;27(2):232–8.
207. Lee I, Kim KM, Lim MH. Theta and gamma activity differences in obsessive-compulsive disorder and panic disorder: insights from resting-state EEG with eLORETA. *Brain Sci.* 2023;13(10):1440.
208. Ankan MK, Günver MG, İlhan R. Gamma oscillations predict paroxetine response of patients with obsessive compulsive disorder. *J Obsessive Compuls Relat Disord.* 2021;28:100620.
209. Gillan CM. Recent developments in the habit hypothesis of OCD and compulsive disorders. *Curr Top Behav Neurosci.* 2021;49:147–67.
210. Kammen A, Cavaleri J, Lam J, Frank AC, Mason X, Choi W, et al. Neuro-modulation of OCD: a review of invasive and non-invasive methods. *Front Neurol.* 2022;13:909264.
211. Nho Y-H, Rolle CE, Topalovic U, Shivacharan RS, Cunningham TN, Hiller S, et al. Responsive deep brain stimulation guided by ventral striatal electrophysiology of obsession durably ameliorates compulsion. *Neuron.* 2024;112(1):73–83.
212. Wu H, Hariz M, Visser-Vandewalle V, Zrinzo L, Coenen VA, Sheth SA, et al. Deep brain stimulation for refractory obsessive-compulsive disorder (OCD): Emerging or established therapy?. *Mol Psychiatry.* 2021;26(1):60–5.
213. Karas PJ, Lee S, Jimenez-Shahed J, Goodman WK, Viswanathan A, Sheth SA. Deep brain stimulation for obsessive compulsive disorder: evolution of surgical stimulation target parallels changing model of dysfunctional brain circuits. *Front Neurosci.* 2019;12:998.
214. Cocchi L, Zalesky A, Nott Z, Whybird G, Fitzgerald PB, Breakspear M. Transcranial magnetic stimulation in obsessive-compulsive disorder: a focus on network mechanisms and state dependence. *Neuroimage Clin.* 2018;19:661–74.
215. Calzà J, Gürsel DA, Schmitz-Koep B, Bremer B, Reinholz L, Berberich G, et al. Altered cortico-striatal functional connectivity during resting state in obsessive-compulsive disorder. *Front Psychiatry.* 2019;10:319.
216. Fajnerova I, Gregus D, Francova A, Noskova E, Koprivova J, Stopkova P, et al. Functional connectivity changes in obsessive-compulsive disorder correspond to interference control and obsessions severity. *Front Neurol.* 2020;11:568.
217. Ansari Asl M, Asgari P, Bakhti SZ. Treatment approaches based on neuroscientific data in patients with obsessive-compulsive disorder. *Int Clin Neurosci J.* 2021;8(3):107–17.
218. Lapidus KAB, Stern ER, Berlin HA, Goodman WK. Neuromodulation for obsessive-compulsive disorder. *Neurotherapeutics.* 2014;11(3):485–95.
219. Black T, Jenkins BW, Laprairie RB, Howland JG. Therapeutic potential of gamma entrainment using sensory stimulation for cognitive symptoms associated with schizophrenia. *Neurosci Biobehav Rev.* 2024;161:105681.
220. Griskova-Bulanova I, Sveistyte K, Bjekic J. Neuromodulation of gamma-range auditory steady-state responses: a scoping review of brain stimulation studies. *Front Syst Neurosci.* 2020;14:41.
221. Thuné H, Recasens M, Uhlhaas PJ. The 40-Hz auditory steady-state response in patients with schizophrenia: a meta-analysis. *JAMA Psychiat.* 2016;73(11):1145–53.
222. Metzner C, Mäki-Marttunen T, Karni G, McMahon-Cole H, Steuber V. The effect of alterations of schizophrenia-associated genes on gamma band oscillations. *Schizophrenia.* 2022;8(1):46.
223. Bullock WM, Cardon K, Bustillo J, Roberts RC, Perrone-Bizzozero NI. Altered expression of genes involved in GABAergic transmission and neuromodulation of granule cell activity in the cerebellum of schizophrenia patients. *Am J Psychiatry.* 2008;165(12):1594–603.
224. Pathak H, Sreeraj VS, Venkatasubramanian G. Transcranial alternating current stimulation (tACS) and its role in schizophrenia: a scoping review. *Clin Psychopharmacol Neurosci.* 2023;21(4):634–9.
225. Shu IW, Lin Y, Granholm EL, Singh F. A focused review of gamma neuromodulation as a therapeutic target in Alzheimer's spectrum disorders. *J Psychiatr Brain Sci.* 2024;9(1):e240001.
226. Kay LM. COVID-19 and olfactory dysfunction: A looming wave of dementia?. *J Neurophysiol.* 2022;128(2):436–44.
227. Pathak Y, Salami O, Baillet S, Li Z, Butzon CR. Longitudinal changes in depressive circuitry in response to neuromodulation therapy. *Front Neural Circuits.* 2016;10:50.
228. Grover S, Wen W, Viswanathan V, Gill CT, Reinhart RM. Long-lasting, dissociable improvements in working memory and long-term memory in older adults with repetitive neuromodulation. *Nat Neurosci.* 2022;25(9):1237–46.
229. Austelle CW, Cox SS, Wills KE, Badran BW. Vagus nerve stimulation (VNS): recent advances and future directions. *Clin Auton Res.* 2024;34(6):529–47.
230. Wang Z, Jiang C, Guan L, Zhao L, Fan T, Wang J, et al. Deep brain stimulation of habenula reduces depressive symptoms and modulates brain activities in treatment-resistant depression. *Nat Ment Health.* 2024;2:1045–52.
231. Dai Z, Zhang S, Wang H, Chen Z, Zhang W, Hu X, et al. Hampered gamma oscillations induced by sad emotion underlying suicide attempt in major depressive disorder. *Psychiatry Clin Neurosci.* 2023;77(1):20–9.
232. Klimesch W. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Res Brain Res Rev.* 1999;29(2–3):169–95.
233. Broyd SJ, Demanuele C, Debener S, Helps SK, James CJ, Sonuga-Barke EJ. Default-mode brain dysfunction in mental disorders: a systematic review. *Neurosci Biobehav Rev.* 2009;33(3):279–96.
234. Buzsáki G, Wang XJ. Mechanisms of gamma oscillations. *Annu Rev Neurosci.* 2012;35:203–25.
235. Pancotti L, Topolnik L. Cholinergic modulation of dendritic signaling in hippocampal GABAergic inhibitory interneurons. *Neuroscience.* 2022;489:44–56.
236. Reyes AD, Shin H, Adesnik H. Functional roles of cortical inhibitory interneurons. In: Martin Usrey W, Murray Sherman S, editors. *The cerebral cortex and thalamus.* Oxford University Press; 2023. p. 72–80. <https://doi.org/10.1093/med/9780197676158.003.0008>.
237. Posłuszny A. Updating the picture of layer 2/3 VIP-expressing interneuron function in the mouse cerebral cortex. *Acta Neurobiol Exp.* 2019;79(4):328–37.
238. Dipoppa M, Ranson A, Krumin M, Pachitariu M, Carandini M, Harris KD. Vision and locomotion shape the interactions between neuron types in mouse visual cortex. *Neuron.* 2018;98(3):602–15.e8.
239. Antonoudiou P, Tan YL, Kontou G, Upton AL, Mann EO. Parvalbumin and somatostatin interneurons contribute to the generation of hippocampal gamma oscillations. *J Neurosci.* 2020;40(40):7668–87.
240. Sohal VS, Rubenstein JL. Excitation-inhibition balance as a framework for investigating mechanisms in neuropsychiatric disorders. *Mol Psychiatry.* 2019;24(9):1248–57.
241. Maestú F, de Haan W, Busche MA, DeFelipe J. Neuronal excitation/inhibition imbalance: core element of a translational perspective on Alzheimer pathophysiology. *Ageing Res Rev.* 2021;69:101372.
242. Takada N, Pi HJ, Sousa VH, Waters J, Fishell G, Kepecs A, et al. A developmental cell-type switch in cortical interneurons leads to a selective defect in cortical oscillations. *Nat Commun.* 2014;5:5333.
243. Pelkey KA, Chittajallu R, Craig MT, Tricoire L, Wester JC, McBain CJ. Hippocampal GABAergic inhibitory interneurons. *Physiol Rev.* 2017;97(4):1619–747.
244. Fell J, Axmacher N. The role of phase synchronization in memory processes. *Nat Rev Neurosci.* 2011;12(2):105–18.
245. Bartos M, Vida I, Jonas P. Synaptic mechanisms of synchronized gamma oscillations in inhibitory interneuron networks. *Nat Rev Neurosci.* 2007;8(1):45–56.

246. Ray S, Maunsell JHR. Do gamma oscillations play a role in cerebral cortex? *Trends Cogn Sci*. 2015;19(2):78–85.
247. Duncan NW, Wiebking C, Northoff G. Associations of regional GABA and glutamate with intrinsic and extrinsic neural activity in humans—a review of multimodal imaging studies. *Neurosci Biobehav Rev*. 2014;47:36–52.
248. Bi D, Wen L, Wu Z, Shen Y. GABAergic dysfunction in excitatory and inhibitory (E/I) imbalance drives the pathogenesis of Alzheimer's disease. *Alzheimers Dement*. 2020;16(9):1312–29.
249. Tiesinga P, Sejnowski TJ. Cortical enlightenment: are attentional gamma oscillations driven by ING or PING? *Neuron*. 2009;63(6):727–32.
250. Milicevic KD, Barbeau BL, Lovic DD, Patel AA, Ivanova VO, Antic SD. Physiological features of parvalbumin-expressing GABAergic interneurons contributing to high-frequency oscillations in the cerebral cortex. *Curr Res Neurobiol*. 2024;6:100121. <https://doi.org/10.1016/j.crneur.2023.100121>.
251. Kang YJ, Clement EM, Sumsy SL, Xiang Y, Park IH, Santaniello S, et al. The critical role of persistent sodium current in hippocampal gamma oscillations. *Neuropharmacology*. 2020;162:107787.
252. Peña-Ortega F. Brain arrhythmias induced by amyloid beta and inflammation: involvement in Alzheimer's disease and other inflammation-related pathologies. *Curr Alzheimer Res*. 2019;16(12):1108–31.
253. Ulloa JL. The control of movements via motor gamma oscillations. *Front Hum Neurosci*. 2022;15:787157.
254. Petersson P, Kühn AA, Neumann W-J, Fuentes R. Basal ganglia oscillations as biomarkers for targeting circuit dysfunction in Parkinson's disease. *Prog Brain Res*. 2020;252:525–57.
255. Stefani A, Trendafilov V, Liguori C, Fedele E, Galati S. Subthalamic nucleus deep brain stimulation on motor-symptoms of Parkinson's disease: focus on neurochemistry. *Prog Neurobiol*. 2017;151:157–74.
256. Marafiga JR, Pasquetti MV, Calcagnotto ME. GABAergic interneurons in epilepsy: More than a simple change in inhibition. *Epilepsy Behav*. 2021;121(Pt B):106935.
257. Van Van Hugte EJH, Schubert D, Nadif KN. Excitatory/inhibitory balance in epilepsies and neurodevelopmental disorders: depolarizing γ -aminobutyric acid as a common mechanism. *Epilepsia*. 2023;64(8):1975–90.
258. Marchisella F, Creutzberg KC, Begni V, Sanson A, Wearick-Silva LE, Tractenberg SG, et al. Exposure to prenatal stress is associated with an excitatory/inhibitory imbalance in rat prefrontal cortex and amygdala and an increased risk for emotional dysregulation. *Front Cell Dev Biol*. 2021;9:653384.
259. Li N, Wang L, Li L, Yang MZ, Wang QX, Bai XW, et al. The correlation between gut microbiome and atrial fibrillation: pathophysiology and therapeutic perspectives. *Mil Med Res*. 2023;10(1):51.
260. Page CE, Coutellier L. Prefrontal excitatory/inhibitory balance in stress and emotional disorders: evidence for over-inhibition. *Neurosci Biobehav Rev*. 2019;105:39–51.
261. Wang HL, Sun YX, Liu X, Wang H, Ma YN, Su YA, et al. Adolescent stress increases depression-like behaviors and alters the excitatory-inhibitory balance in aged mice. *Chin Med J*. 2019;132(14):1689–99.
262. Han K, Lee M, Lim HK, Jang MW, Kwon J, Lee CJ, et al. Excitation-inhibition imbalance leads to alteration of neuronal coherence and neurovascular coupling under acute stress. *J Neurosci*. 2020;40(47):9148–62.
263. Shen LP, Zhang WC, Deng JR, Qi ZH, Lin ZW, Wang ZD. Advances in the mechanism of small nucleolar RNA and its role in DNA damage response. *Mil Med Res*. 2024;11(1):53.
264. Gilbert JR, Gerner JL, Burton CR, Nugent AC, Zarate CA Jr, Ballard ED. Magnetoencephalography biomarkers of suicide attempt history and antidepressant response to ketamine in treatment-resistant major depression. *J Affect Disord*. 2022;312:188–97.
265. Gilbert JR, Ballard ED, Galiano CS, Nugent AC, Zarate CA Jr. Magnetoencephalographic correlates of suicidal ideation in major depression. *Biological Psychiatry: Cogn Neurosci Neuroimaging*. 2020;5(3):354–63.
266. Grent-'t-Jong T, Gajwani R, Gross J, Gumley AI, Krishnadas R, Lawrie SM, et al. Association of magnetoencephalographically measured high-frequency oscillations in visual cortex with circuit dysfunctions in local and large-scale networks during emerging psychosis. *JAMA Psychiat*. 2020;77(8):852–62.
267. Wang WJ, Chu LX, He LY, Zhang MJ, Dang KT, Gao C, et al. Spatial transcriptomics: recent developments and insights in respiratory research. *Mil Med Res*. 2023;10(1):38.
268. Chu L, Li N, Deng J, Wu Y, Yang H, Wang W, et al. LC-APC1⁺-MS/MS method for the analysis of ten hormones and two endocannabinoids in plasma and hair from the mice with different gut microbiota. *J Pharm Biomed Anal*. 2020;185:113223.
269. Chu LX, Wang WJ, Gu XP, Wu P, Gao C, Zhang Q, et al. Spatiotemporal multi-omics: exploring molecular landscapes in aging and regenerative medicine. *Mil Med Res*. 2024;11(1):31.
270. Zhang W, Sweeney JA, Bishop JR, Gong Q, Lui S. Biological subtyping of psychiatric syndromes as a pathway for advances in drug discovery and personalized medicine. *Nat Ment Health*. 2023;1(2):88–99.
271. Guo LK, Su Y, Zhang YYN, Yu H, Lu Z, Li WQ, et al. Prediction of treatment response to antipsychotic drugs for precision medicine approach to schizophrenia: randomized trials and multiomics analysis. *Mil Med Res*. 2023;10(1):24.
272. Noda Y, Sakae K, Wada M, Takano M, Nakajima S. Development of artificial intelligence for determining major depressive disorder based on resting-state EEG and single-pulse transcranial magnetic stimulation-evoked EEG indices. *J Pers Med*. 2024;14(1):101.
273. Zhang Y, Naparstek S, Gordon J, Watts M, Shpigel E, El-Said D, et al. Machine learning-based identification of a psychotherapy-predictive electroencephalographic signature in PTSD. *Nat Ment Health*. 2023;1:284–94.
274. Chen Q, Flad E, Gatewood RN, Samih MS, Krieger T, Gai Y. Gamma oscillation optimally predicts finger movements. *Brain Res*. 2025;1848:149335.
275. Liu A, Jing H, Liu Y, Ma Y, Zheng N. Hidden states in LLMs improve EEG representation learning and visual decoding. *ECAI*. 2024;392:2130–7.
276. Guerra M, Milanese R, Deodato M, Ciobanu MG, Fasano F. Exploring the diagnostic potential of LLMs in schizophrenia detection through EEG analysis. In: 2024 IEEE International Conference on Bioinformatics and Biomedicine (BIBM) Lisbon, Portugal, 2024, p. 6812–9. <https://doi.org/10.1109/BIBM62325.2024.10821830>.
277. Oostenveld R, Fries P, Maris E, Schoffelen JM. FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Comput Intell Neurosci*. 2011;2011:156869.
278. Gramfort A, Luessi M, Larson E, Engemann DA, Strohmeier D, Brodbeck C, et al. MEG and EEG data analysis with MNE-Python. *Front Neurosci*. 2013;7:267.