Analysis of Interdisciplinary Research Progress of the Basal Ganglia in Parkinson's Disease Based on Cognitive Mechanism of Neuronal Firing Patterns and Movement Disorders

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Abstract. Parkinson's disease (PD) is a neurodegenerative disorder characterized by the pathological core of degeneration of dopaminergic neurons in the substantia nigra. In recent years, numerous studies have revealed that the "firing rate hypothesis" alone cannot explain the diverse symptoms exhibited by PD. Instead, abnormalities in the pattern of neuronal firing and circuit oscillations are considered more critical pathogenic factors. The basal ganglia serve as an integrated center for both motor control and cognitive processing. The basal ganglia, including its burst firing at the cellular level, enhanced β oscillations at the population level, altered connectivity between frequency bands, and excessive synchronization in the cortex-basal ganglia network, can lead to multifaceted functional impairments. Interdisciplinary approaches have provided novel perspectives for elucidating PD mechanisms and developing individualized treatments, including the combination of electrophysiology and neuroimaging, computational modeling, closed-loop deep brain stimulation (DBS), and long-term monitoring using multi-modal techniques. In this paper, the author analyzes the connections between basal ganglia firing patterns, motor disorders, and cognitive mechanisms in PD. Furthermore, future translational directions are also discussed, thereby offering theoretical foundations and practical insights for the precise diagnosis and treatment of PD.

Keywords: Parkinson's Disease (PD); Basal Ganglia; Neuronal Firing Patterns; β Oscillations; Cognitive Impairment.

1. Introduction

The prevalence of Parkinson's disease (PD) continues to rise, yet effective treatment options remain limited. Understanding the cognitive mechanisms underlying abnormal neuronal firing and movement disorders is therefore crucial for advancing precise diagnosis and targeted interventions. The basal ganglia circuits—comprising the striatum, globus pallidus, subthalamic nucleus, and substantia nigra—form a complex network connected to the cerebral cortex and thalamus through the direct, indirect, and hyperdirect pathways. This system regulates not only motor initiation and execution but also higher-order functions such as reward learning, decision-making, and emotion processing [1].

While the traditional firing rate hypothesis attributes PD symptoms to altered average firing frequencies, recent evidence highlights the importance of abnormal firing patterns and pathological oscillations, which provide a more accurate reflection of basal ganglia dysfunction [2]. These oscillatory features serve as critical biomarkers for understanding disease mechanisms and developing real-time, personalized closed-loop deep brain stimulation (DBS). From the perspective of cognitive–motor integration, the widespread cognitive deficits observed in PD suggest that pathological changes extend beyond motor circuits. Excessive β oscillatory activity (13–30 Hz) disrupts normal information gating within the basal ganglia–thalamocortical loop, delaying movement initiation and impairing cognitive flexibility [2].

This study aims to analyze the interdisciplinary research progress on the basal ganglia in Parkinson's disease from an integrated cognitive-neurophysiological perspective. Methodologically, this study will employ a comprehensive literature review and conceptual synthesis. Ultimately, it aims to propose a cognitive oscillation framework that considers both motor and non-motor symptoms,

thereby providing theoretical and methodological guidance for future personalized closed-loop interventions.

2. Analysis of Abnormal Spectrum of Basal Ganglia Neuronal Firing Patterns

2.1 Cellular Level: Firing Rate, Bursting, and Phase Locking

Recordings from both PD patients and animal models have demonstrated significant abnormalities in firing patterns at the single-neuron level. First, the average firing frequency of neurons in the subthalamic nucleus (STN) and internal globus pallidus (GPi) is increased, showing sustained high-frequency firing, a phenomenon consistent with the traditional firing rate hypothesis. However, a more characteristic feature is the abnormal bursting firing pattern. Instead of normal single-spike firing, neurons often exhibit high-frequency clustered firing over short periods, which reduces the temporal precision of neural signals. Second, the variability of inter-spike intervals (ISIs) among neurons increases, manifested as unevenly distributed firing intervals and weakened sparse coding. Single-neuron firing shows strong phase locking with the β rhythm of local field potentials (LFPs). Neurons typically fire at a specific phase, which limits the time window for information transmission and reduces the amount of encoded information. Studies suggest that this abnormal phase coupling may constrain the dynamic integration of signals in the striatum and thalamus, thereby affecting movement initiation and cognitive updating [3,4]. Increased firing rate, bursting, and phase locking at the cellular level constitute the basic cellular phenotypes underlying neural circuit dysfunction in PD.

2.2 Population Level: Enhanced β Oscillations and Altered Cross-Frequency Coupling

At the population level, studies using LFPs and electroencephalography/magnetoencephalography (EEG/MEG) have identified the most prominent electrophysiological feature of PD, which is excessive activity in the β frequency band (13-30 Hz) [5]. Excessive β synchronization is not only evident at rest but also persists during movement preparation and execution due to insufficient inhibition. Normally, movement initiation is accompanied by a reduction in β power (event-related desynchronization, ERD). However, in PD patients, this process becomes delayed or attenuated, which is associated with bradykinesia. The amplitude of high-frequency γ oscillations (>60 Hz) is usually suppressed, thereby reducing the efficiency of local neural coding. Cross-frequency coupling studies have revealed enhanced β-phase γ-amplitude coupling (PAC) in the basal ganglia circuits of PD patients. Specifically, the phase of β rhythms determines the expression window of γ oscillations, limiting the flexibility of high-frequency oscillations. This excessive coupling locks the channels for task-related information, resulting in slowed sensorimotor transformation and cognitive updating. Therefore, enhanced β oscillations and abnormal PAC at the population level are not only characteristic manifestations of the disease but also key targets for regulatory interventions (e.g., closed-loop deep brain stimulation, DBS).

2.3 Network Level: Cortico-Basal Ganglia Circuit Synchronization

At the network level, PD patients exhibit excessive synchronization in the cortico-basal ganglia circuit. Circuits involving the motor cortex, STN, and GPi show high-amplitude coherence in the β band [6], indicating overly coupled signal transmission between relevant brain regions within the network, with a lack of flexible decoupling and reconfiguration. Functional magnetic resonance imaging (fMRI) and MEG studies have further found that long-range connections between the fronto-parietal cortex and the basal ganglia tend to become rigid in PD patients, with reduced small-world properties and diminished inter-regional communication. This excessive synchronization disrupts the normal "error amplification-inhibition" process, preventing the system from dynamically adjusting thresholds when encountering conflicts or uncertainties. Patients exhibit slowed movement initiation, hesitation, and reduced exploratory behavior. Additionally, symptoms such as resting tremor involve abnormal coupling of the cortico-cerebellar-basal ganglia circuit across different frequency bands

(θ/α), suggesting that abnormal network synchronization is frequency- and circuit-specific. Thus, excessive synchronization of the cortico-basal ganglia circuit network can be regarded as one of the core mechanisms underlying the multidimensional symptoms of PD.

3. Coupling Between Cognitive Mechanisms and Movement Disorders

3.1 Executive Function and Working Memory Gating

Impaired executive function is one of the most important non-motor symptoms of PD, with working memory gating being the most prominent deficit. In PD, pathologically enhanced β synchronization restricts the reduction of β activity (the "downswing" process), leading to reduced information updating efficiency. Behaviorally, this is manifested as slower responses in PD patients during tasks such as the n-back task, task-switching paradigms, and Stroop conflict tests, indicating a persistently elevated gating threshold [3]. Meanwhile, abnormal phase coupling between the STN and prefrontal cortex impairs executive inhibition and flexible switching abilities. Neuromodulation studies have shown that reducing STN β oscillations can improve cognitive flexibility, but excessive inhibition may lead to impulsion. These findings confirm that basal ganglia oscillations are the rhythmic basis for motor output as well as dynamic regulators of working memory and executive control. Abnormalities in these oscillations cause PD patients to move slowly and think slowly.

3.2 Slow Decision-Making and the Hyper-Inhibition Hypothesis

Slow decision-making is a cognitive impairment in PD, characterized by longer response time when making choices in conflicting or uncertain environments. The classic hyper-inhibition hypothesis posits that the STN is over-activated during conflict detection and maintains a persistently elevated threshold, preventing rapid motor or cognitive choices. When the STN receives conflict signals from the anterior cingulate cortex and prefrontal cortex, it immediately raises the decision-making threshold to ensure more cautious judgments, which serves a "braking" function. However, in PD, chronic enhancement of β oscillations keeps this threshold persistently elevated, resulting in generalized slowing. In addition to delaying movement initiation, it prolongs cognitive judgment [7]. Intraoperative recording evidence shows that stronger STN β activity correlates with longer response times and lower conflict-related error rates, indicating that patients adopt a "speed-for-accuracy" trade-off to maintain decision-making performance. Inhibiting STN β oscillations via DBS can shorten response times but may increase impulsive control disorders, reflecting a stability-flexibility dilemma in the circuit. Thus, the hyper-inhibition hypothesis explains the neurological mechanism of decision-making slowing in PD and highlights the need to balance safety and efficiency in individualized treatments.

4. Interdisciplinary Research Methods and Latest Research Progress

4.1 Integration of Electrophysiology and Multimodal Imaging

The application of electrophysiological and multimodal imaging techniques in PD research has provided a novel approach to exploring abnormal basal ganglia firing in depth. Intraoperative single-unit and LFP recordings enable direct observation of firing rates, bursting patterns, and β synchronization in nuclei such as the STN and internal GPi, laying the foundation for establishing correlations between "neural codes" and symptoms. High-field functional magnetic resonance imaging (fMRI) reveals the macroscopic network structure of the cortex-basal ganglia-thalamus circuit, while laminar fMRI can even decompose input-output patterns across different cortical layers. MEG and high-density EEG enable non-invasive long-range coherence monitoring, allowing systematic analysis of dynamic interactions across spatiotemporal scales [8]. In recent years, positron emission tomography (PET) imaging has been used to quantify the density of dopamine transporters and receptors, linking electrophysiological data with neurotransmitter status to construct a

comprehensive structural-functional-chemical relationship network map. This multimodal integration not solely confirms the causal relationship between β oscillations, cross-frequency coupling, and bradykinesia but clarifies the neural basis of cognitive impairment and functional disconnection in the frontal-basal ganglia circuit. Future research on the integration of electrophysiology and imaging may translate cross-scale observations into comprehensive neural network modeling for precise interventions.

4.2 Computational and Statistical Modeling

With the accumulation of large volumes of neural data, computational and statistical modeling has become an effective approach to understanding the circuit mechanisms of PD. State-space models can extract latent oscillatory states and their transition probabilities from complex cellular and LFP signals, revealing a correlation between the sequence of "high β → β downswing → γ burst" and movement initiation [9]. Reinforcement learning (RL) models are widely applied to patients' behavioral data to fit individual learning rates, exploration parameters, and credit assignment processes. By correlating these parameters with electrophysiological features, the impact of dopamine deficiency on value updating can be identified. Network control theory and causal inference tools have been applied to studies of the basal ganglia-cortex network to determine the role of key hub nodes (e.g., the STN) in maintaining circuit stability and the minimum intervention energy required. These models enable bidirectional mapping between neural activity and behavior, to infer clinical manifestations from firing activity and predict underlying circuit abnormalities from behavioral phenotypes. Using machine learning and individualized data modeling, dynamic and precise treatment strategies can be developed for patients, advancing the application of computational psychiatry in PD.

4.3 Evolution of Neuromodulation Technologies

DBS is a key therapeutic technology for PD, and its development reflects a trend from continuous stimulation to intelligent closed-loop stimulation [10]. Traditional high-frequency DBS improves symptoms such as bradykinesia and rigidity by continuously inhibiting pathological β synchronization in the STN or GPi but often causes side effects such as language impairment and impulsive control disorders. Recently, adaptive closed-loop DBS (aDBS) has emerged, which adjusts stimulation intensity based on real-time β power or cross-frequency coupling levels. Apart from reducing energy consumption, it also significantly minimizes adverse effects. Directional electrodes enable more precise stimulation of target nuclei while reducing impact on surrounding fibers. Phase-locked stimulation has become a new direction: applying pulses at a specific phase of β oscillations achieves better desynchronization effects. Non-invasive techniques such as transcranial alternating current stimulation (tACS) and transcranial magnetic stimulation (TMS) have also been applied to improve cognitive function. The combination of pharmacotherapy and neuromodulation (e.g., synchronized levodopa administration and DBS) has further expanded the scope of treatment. Overall, neuromodulation is shifting from single-frequency, single-target approaches to multi-frequency, cross-circuit, and personalized strategies. In the future, it may comprehensively improve both motor and cognitive symptoms.

5. Clinical Translation and Future Directions

5.1 Individualized and Phenotype-Driven Treatment

PD patients exhibit significant heterogeneity in symptom presentation and pathological mechanisms, making it difficult for a single treatment to address both motor and cognitive symptoms. The recently proposed concept of "phenotype-driven" treatment emphasizes individualized interventions based on patients' clinical manifestations and neurophysiological profiles. For example, patients with bradykinetic-rigid phenotypes characterized by prominent β oscillation abnormalities are more suitable for STN phase-specific closed-loop stimulation as the primary strategy. Patients

with tremor-dominant phenotypes may prioritize targets such as the ventral intermediate nucleus (VIM) of the thalamus or cerebellar-related circuits. For patients with cognitive slowing, it is recommended to require low-intensity or intermittent stimulation strategies while maintaining functional connectivity in the prefrontal-basal ganglia circuit. Pharmacotherapy is suggested to be combined with electrical stimulation (e.g., synchronized levodopa and DBS) to form a synergistic regimen. Additionally, stratifying patients through imaging (PET, fMRI) plus electrophysiology (LFP, PAC) with behavioral assessment enables precise matching of treatments. In the future, phenotype-driven individualized therapy will become a focus of clinical practice, improving efficacy while reducing side effects and providing patients with customized solutions tailored to their circuit conditions.

5.2 Task-State Closed-Loop Modulation and Neuro-Behavioral Co-Modulation

Traditional DBS primarily relies on resting-state biomarkers to set parameters, yet patients engage in various cognitive and motor tasks for most of their daily lives. The concept of task-state closed-loop modulation emerged in response, advocating for stimulation adjustments based on changes in brain electrical signals during specific activities. For instance, triggering stimulation when insufficient β power reduction is detected during movement preparation is able to promote movement initiation; leveraging θ oscillations during feedback learning can enhance strategy updating; and using γ bursts as markers of successful retrieval during language fluency tasks allows real-time parameter fine-tuning. The neuro-behavioral co-modulation model overcomes the limitation of traditional stimulation being disconnected from behavior by integrating neuro-physiological indicators with specific behavioral performance to form a dual-loop control system. Studies have shown that task-event-based stimulation outperforms resting-state parameters in improving both motor and cognitive function. In the coming future, task-state closed-loop training in natural environments (via mobile apps and VR platforms) and real-time, personalized modulation using multimodal data from implantable recorders and wearable devices will drive PD treatment toward intelligent rehabilitation.

6. Conclusion

This study provides a comprehensive synthesis of the cognitive–neurophysiological mechanisms underlying abnormal oscillatory activities in the basal ganglia circuits of Parkinson's disease. By integrating evidence from cellular to network levels, it emphasizes that excessive β synchronization and impaired cross-frequency coupling not only contribute to motor deficits but also underlie cognitive inflexibility and slowed decision-making. The proposed cognitive oscillation framework bridges motor and cognitive domains and offers theoretical implications for the design of personalized closed-loop neuromodulation strategies. Despite its comprehensive scope, this research remains limited in several aspects. First, the majority of reviewed evidence is derived from invasive recordings in advanced PD patients or animal models under anesthesia, which may not fully reflect naturalistic brain dynamics and cognitive–motor integration in daily behavior. Future research should focus on bridging microscopic neural dynamics with macroscopic behavioral and clinical outcomes through multi-scale modeling.

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