

Cerebellum and Language: Regulation and Application

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Abstract

In recent years, the role of the cerebellum in language function has gained increasing recognition and emphasis. Based on its dense anatomical connections with cortical language areas, the cerebellum optimizes and predicts language, specifically participating in processes such as language generation, fluency, and control. Clinically, a deeper understanding of cerebellar language function provides crucial evidence for developing novel rehabilitation strategies for certain language disorders. This paper systematically integrates anatomical, mechanistic, and clinical evidence linking the cerebellum to language, emphasizing its indispensable role within the complete language network.

Keywords

Cerebellum, Language, Language Rehabilitation

1. Introduction

As a vital component of the human nervous system, the cerebellum has long been regarded as the primary regulator of motor and balance functions, primarily responsible for fine-tuning skeletal muscle movements, maintaining body posture, and facilitating motor learning. In recent years, with the advancement of neuroimaging techniques, research methodologies in neuroscience have become increasingly diverse. This evolution has shifted from isolated clinical case studies to the integration of neuroimaging modalities (such as functional Magnetic Resonance Imaging (fMRI), Positron Emission Tomography (PET), Diffusion Tensor Imaging (DTI), etc.) and Non-Invasive Brain Stimulation (NIBS) techniques and electrophysiological technologies for therapeutic and localization studies. Recently, scholars have attempted to establish Artificial Neural Networks (ANNs)

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consistent with actual brain physiology to investigate the processing mechanisms of various human brain functions [1]. Consequently, an increasing number of scholars recognize the cerebellum—particularly the right cerebellum—as a crucial regulatory region for non-motor functions such as cognition and language processing. Clinical observations indicate that cerebellar damage can induce “Cerebellar Cognitive Affective Syndrome (CCAS)”, manifesting as language dysfunction including syntactic deficits and impaired fluency. These symptoms, like the cognitive and psychiatric impairments associated with the syndrome, represent distinct manifestations of disrupted “optimization and coordination” functions following cerebellar injury [2]. This paper aims to integrate evidence from cerebellar anatomy, function, and corresponding clinical research to explore the regulatory mechanisms of the cerebellum in language processing and its clinical applications, while also reviewing current research controversies and future directions.

2. Relationship between Cerebellar Anatomy and Language Function

The cerebellum is divided into the paleocerebellum, archicerebellum, and neocerebellum based on the sequence of its development. The paleocerebellum corresponds to the flocculonodular lobe. The archicerebellum comprises the vermis, vermis pyramids, and vermis filaments within the anterior lobe. The neocerebellum occupies the remaining portion of the cerebellum, located in the lateral region, representing the most recently evolved segment. Research indicates that numerous functional regions within the neocerebellum, such as the right Lobule VI, VIII, and Crus I, play a significant role in regulating language functions. This also demonstrates the close connection between cerebellar anatomy and language function. Using fMRI, researchers observed activation patterns in the cerebellar functional regions of subjects. Compared to non-reading tasks, subjects exhibited significantly enhanced activation in the right Lobule VI, Lobule VIII, and right Lobule VIII during lexical reading tasks. These regions are hypothesized to represent cerebellar-specific lexical reading areas [3]. Furthermore, Ashida’s research revealed that during the maintenance phase of linguistic working memory, neural activity in the right cerebellar VI and bilateral Crus I linearly increased with rising memory load. Additionally, this region was also activated during verb generation tasks, with significant overlap between its activation patterns and those observed in linguistic working memory tasks [4]. Collectively, these findings indicate that the right cerebellar VI, VIII, and Crus I integrate language memory maintenance and generation processes, regulating multiple aspects of linguistic function. Zhang *et al.* reported that patients with Post-Stroke Aphasia (PSA) exhibit not only significantly reduced gray matter volume in the right cerebellar VI and Crus I but also weakened functional connectivity within the cerebellar circuits spanning the brain. Importantly, abnormalities in both regions showed significant correlations with the Western Aphasia Battery (WAB) scores, collectively revealing the cerebellum’s pivotal role in language deficits among PSA patients [5]. Similarly, Xu

observed increased variability in local functional activity within the cerebellar network (CBN) during the acute phase of PSA, suggesting its potential involvement in mediating spontaneous language recovery and further substantiating the cerebellum's critical function in language processing [6]. Furthermore, reciprocal fiber connections exist between the cerebellum and cerebral cortex, enabling collaborative regulation of motor, cognitive, and linguistic functions. Input pathways originate from neurons in language-related cortical regions (e.g., Broca's area, Wernicke's area), projecting downward to the pons where synapses form. Neurons in the pontine basal nuclei project Mossy Fibers (MF) axons to the contralateral cerebellar hemisphere. After processing and modulating the incoming signals in cerebellar Purkinje cells, granule cells, and others, the results are output to the dentate nucleus. The output pathway then projects fibers primarily from the dentate nucleus to the contralateral thalamus, ultimately projecting information to the cerebral cortex [7] [8]. Following Transcranial Magnetic Stimulation (TMS) of the cerebellum in subjects, Lukas Gassmann *et al.* observed increased Electroencephalographic (EEG) power in the left anterior lobe. They suggest that this EEG response, recorded under highly controlled experimental conditions, can be cautiously attributed to cerebellar TMS specifically activating the cerebellum-dentate nucleus-thalamus-cortex pathway. This provides evidence for assessing the functional integrity of the cerebellar dentate nucleus-thalamus-cortex pathway [9]. Further research indicates that cerebellar-cortical connections constitute a critical pathway for regulating language function: Abotalebi and Green proposed an adaptive control model for language control networks, outlining regions involved in language regulation and highlighting the substantial contribution of cerebellar-left prefrontal circuits to language control activities [10]. Similarly, Yuan *et al.* employed Multi-Voxel Pattern Analysis (MVPA) to investigate brain activation patterns during language control. Their findings revealed involvement of the left dorsolateral prefrontal cortex, left inferior frontal gyrus, left supplementary motor area, anterior cingulate cortex, bilateral precentral gyrus, and left cerebellum in language control tasks. Effective connectivity analysis further demonstrated that the frontal-cerebellar connection constitutes a critical component of the language control network [11]. In summary, the cerebellum regulates language functional activity through its intricate circuits with the cerebral cortex, operating via internal model mechanisms. This establishes the cerebellum's core role as a higher-order regulator within the language neural network.

3. Cerebellar Mechanisms for Language Function Regulation

Initially regarded solely as a coordinator of motor functions, the cerebellum is now recognized as a crucial "fine-tuning center" within the language network. It does not serve as a repository for linguistic content but rather, through its unique internal models and extensive cortical connectivity, efficiently optimizes and integrates linguistic information flows across three dimensions—generation, prediction, and control—ensuring the fluency and precision of language behavior.

3.1. Language Generation

Stoodley's meta-analysis revealed that language generation tasks involve activity regulation in the cerebellar hemisphere contralateral to the dominant hemisphere. Functional activation in the right posterior lateral cerebellum is also observable during language production [12]. Xi *et al.* analyzed fMRI activation patterns in Uyghur and Mandarin participants during verb generation tasks, revealing cerebellar activation in both language groups, suggesting cerebellar involvement in language production [13]. Yousofzadeh observed whole-brain connectivity and Magnetoencephalography (MEG) activity involving the right cerebellum during adolescent language generation tasks [14]. Geva *et al.* examined sentence processing and verbal fluency in four patients with focal strokes in different regions of the right posterior cerebellum. All patients exhibited varying degrees of language impairment, primarily manifested as deficits in language production, comprehension, and memory [15]. Oivi Parker Jones *et al.* analyzed activation patterns in distinct cerebellar regions during language tasks including generation, repetition, and auditory comprehension. Results indicated that bilateral activation in cerebellar lobule VIIb correlates with word generation and sequencing, right cerebellar lobule VIII with dominant motor execution of speech like verbal repetition and verb-noun generation, while activation within the right cerebellar crus II was linked to auditory comprehension [16].

3.2. Language Prediction

Lesage *et al.* found that impaired cerebellar function delays predictive processing in language tasks, indicating the cerebellum's predictive role extends beyond motor functions to play a significant role in language processing [17]. Argyropoulos and colleagues employed a language processing task where subjects associated verbs with specific nouns. They investigated the effects of TMS stimulation on the cerebellum during this semantic association task. Results showed that cerebellar TMS selectively enhanced performance on this lexical task, indicating the cerebellum's active role in language prediction [18]. Multiple studies by Lesage *et al.* revealed that during language prediction, fMRI showed increased activity in the right posterior external cerebellar region when anticipating upcoming linguistic content, correlated with the predictability of impending target words [19]. Bonhage and colleagues also used fMRI to demonstrate that during predictive saccadic reading tasks, predictions about words and word categories activate a neural network involving the premotor cortex, thalamus, caudate nucleus, hippocampus, and cerebellum [20]. Miall found that anodal transcranial direct current stimulation (tDCS) to the cerebellum reduced response latencies in language prediction tasks, further supporting cerebellar involvement in predictive language processing [21]. Additionally, Ohmae employed a cerebellar Artificial Neural Network (cANN) model to demonstrate that the cerebellar internal circuitry is crucial for language prediction and comprehension [1].

3.3. Language Control

Numerous scholars have demonstrated through non-invasive cerebellar stimulation studies that the cerebellum reflects error signals between predicted and actual outcomes during language processing via its internal modeling, thereby enhancing coordination in linguistic processes [22]. Rossi *et al.* investigated neural control mechanisms during code conversion in reading tasks involving noun phrase transformation. Results revealed significant cerebellar activation during noun phrase boundary conversion, suggesting cerebellar involvement in inhibitory language control processes [23]. Yuan employed fMRI combined with tDCS to investigate cerebellar performance in language functions, revealing distinct roles for the bilateral cerebellum in language generation. Specifically, the left cerebellum functions in cognitive control through connections with the cerebral cortex, while the right cerebellum demonstrated a significant enhancement in language control abilities in bilinguals following anodal tDCS stimulation [24].

Overall, the cerebellum integrates language generation, prediction, and control into a coordinated system through its intricate neural circuits: language generation constructs the fundamental linguistic framework, language prediction performs feedforward optimization of linguistic sequences based on this framework, while language control dynamically adjusts speech timing according to varying linguistic contexts. These three functions work in concert to ensure the seamless, precise, and contextually appropriate transformation from thought to speech.

4. Application of Non-Invasive Cerebellar Stimulation Techniques in Aphasia

Non-Invasive Brain Stimulation techniques refer to medical treatment technologies that regulate brain activity without surgery. They primarily achieve functional modulation by delivering non-invasive physical stimulation to specific brain regions using external specialized equipment. These techniques mainly include tDCS and repetitive transcranial magnetic stimulation (rTMS), which are currently widely applied in neuroscience research and rehabilitation fields. Given the cerebellum's indispensable role in language regulation, numerous scholars have explored applying cerebellar tDCS or cerebellar rTMS to aphasia rehabilitation, seeking novel, effective, and stable NIBS treatment protocols for aphasic patients. Research by Rajani Sebastian *et al.* demonstrated that repeated cerebellar tDCS combined with computerized aphasia therapy improves picture naming in chronic post-stroke aphasia [25]. Silke Coemans administered nine sessions of anodal cerebellar tDCS (ctDCS) combined with language therapy to a bilingual patient with chronic post-stroke aphasia caused by left frontal lobe ischemia. Results showed that compared to sham treatment, the subject demonstrated improved naming abilities in both first and second languages after ctTCD therapy [26]. Similarly, Coemans administered anodal cerebellar tDCS to seven patients with primary aphasia and post-stroke aphasia. The study found that patients' language functions recovered compared to baseline, and enhanced inhibitory control over lan-

guage was observed [27]. Turkeltaub used fMRI to observe functional connectivity in subjects and found that tDCS stimulation of the posterior lateral cerebellum on the right side enhanced functional connectivity between the right cerebellum and the cerebral cortex, thereby improving fluency during language generation [28]. Marangolo *et al.* administered tDCS to 12 aphasic patients during verb generation and verb naming tasks to investigate the combined effects of cerebellar tDCS and speech therapy on verb performance. Results showed no significant improvement in verb naming but marked enhancement in verb generation following tDCS treatment [29]. Additionally, Dale *et al.* demonstrated that cerebellar rTMS stimulation improved speech pauses and articulation difficulties in patients with progressive supranuclear palsy [30]. Collectively, these findings elevate the cerebellum's central role in language processing from theoretical understanding to clinical frontiers, providing novel targets for developing rehabilitation strategies for patients with language disorders. However, despite the promising prospects of Non-Invasive Cerebellar Stimulation techniques in language rehabilitation therapy, its clinical application still faces significant challenges, the most prominent of these is the high variability in patient response to treatment, highlighting the urgent need to develop personalized stimulation protocols based on individual etiology and neural circuit characteristics.

5. Summary and Outlook

In summary, the cerebellum's role in language function has evolved from a traditional motor coordination center to a critical node optimizing multidimensional regulatory processes involving language generation, prediction, and control. This theory not only deepens our understanding of language neural circuits but also offers new perspectives on elucidating the mechanisms underlying cerebellar involvement in language function regulation. Looking ahead, research priorities will focus on more precisely deciphering the dynamic information processing principles within the cerebellum, such as constructing computational models inspired by cerebellum-cortex circuits. These models will undergo closed-loop validation and optimization using multimodal neural data, thereby advancing the development of precise assessment and intervention strategies for cerebellar-cortical circuits, and establishing anatomical-functional correspondences between cerebellar structures and language functions using neuroimaging techniques. These efforts will provide new, more scientifically grounded evidence for personalized rehabilitation treatments for language disorders.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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