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Original Paper

Promising Neuroscience Methods in Exploring the Spatiotemporal Mechanisms underlying Speech Motor Control

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Abstract

Speech motor control is a complex neuromotor behavior that requires the combined efforts of feedforward control and feedback control subsystems. With the advent of neuroscience, multiple lines of research have explored the spatiotemporal mechanisms underlying this process. The purpose of this review was to point out several promising neuroscience methods and their unique values in enriching the speech motor control literature. We discussed the clinical value of noninvasive brain stimulation methods, and the theoretical value of invasive brain recording methods, as well as the predictive value of brain connectivity techniques. Based on prior findings, we propose a roadmap for future research, identifying structure-function coupling that supports speech motor control.

Keywords

speech motor control, brain stimulation, brain recording, brain connectivity, structure-function coupling

1. Introduction

Speech motor control is one of the most complex motor behaviors humans have ever mastered. It is dynamically involved in motor planning/programming, execution, and both internal/external monitoring of sensory feedback. Speech motor control has been neurocomputationally modeled with the basic feedforward and feedback control architectures (Guenther, 2016), and empirically investigated with the feedback perturbation paradigms that involve real-time perturbations of speakers' auditory feedback (Houde & Jordan, 1998). Most research has traditionally relied on behavioral measurement using feedback perturbation paradigms (Bauer et al., 2006; Houde & Jordan, 1998; Villacorta et al., 2007). However, motor adjustments merely index the endpoint of successive mental processes that precede initiation of corrective motor commands, making it difficult to examine how the brain processes feedback perturbations leading to final motor corrections.

2. Clinical Value of Noninvasive Brain Stimulation

Continuous Theta Burst Stimulation (cTBS) is a specific transcranial magnetic stimulation tool that induces strong and long-lasting inhibitory effects on cortical excitability (Dai et al., 2022a, 2022b). The use of cTBS in recent years has resulted in improved speech motor control performance in normal (Dai et al., 2022a; Li et al., 2023a, 2023b; Liu et al., 2020) and disordered speech (Dai et al., 2022b; Lin et al., 2022; Zhu et al., 2023). For examples, Lin et al. (2022) demonstrated the efficacy of cTBS applied over the right cerebellum in reducing speech motor disorders in patients with Spinocerebellar Ataxia (SCA). The results indicated that, compared to a sham condition, active cTBS over the right cerebellum elicited significantly smaller vocal compensation and increased P1 and P2 amplitudes but reduced N1 amplitudes in response to pitch perturbations. Given that patients with SCA present abnormally larger vocal compensation and/or reduced P2 amplitudes relative to healthy individuals, Lin et al. (2022) provided the neurobehavioral evidence for a causal link between reduced speech motor abnormalities and inhibited right cerebellar activity in patients with SCA. The role of right cerebellum has also been confirmed in patients with Parkinson's Disease (PD; Zhu et al., 2023). In addition to right cerebellum, more studies have acknowledged the modulating role of cTBS over the dorsolateral prefrontal cortex (Liu et al., 2020), bilateral supramarginal gyrus (Li et al., 2023b), left supplementary motor area (Dai et al., 2022a) and inferior frontal gyrus (IFG; Li et al., 2023a) in healthy individuals, as well as the clinical role of cTBS over the left supplementary motor area in patients with PD (Dai et al., 2022b). Altogether, these studies highlight cTBS as a promising noninvasive strategy for treating patients with speech motor disorders.

3. Theoretical Value of Invasive Brain Recording

Stereoelectroencephalography (SEEG) is an alternative tool to intracranial monitoring, in which depth electrodes are placed through percutaneous twist drill holes and are secured to the skull to define coordinates in the brain sterotactically (Youngerman et al., 2019). SEEG has been used to test a hypothesis whether the cascaded processing from the word-lemma level to the motor program level follows a direct or indirect route (Li, 2022). The results indicated that onset latencies of high-gamma responses were the earliest in visual word processing regions (inferior occipital gyrus and posterior fusiform gyrus), followed by motor processing regions (BA44), and finally auditory processing regions (superior temporal gyrus and Heschl's gyrus), supporting a direct retrieval from the word-lemma to its motor program. Because of the high temporal/spatial resolutions, SEEG is a promising tool opening an avenue for examining the spatiotemporal mechanisms underlying speech motor control. However, due to the detrimental effects on the human brain, only few studies have examined speech motor control under restricted circumstances in patients receiving neurosurgery using invasive brain recording methods such as SEEG (Li, 2022) and electrocorticography (ECoG; Forseth et al., 2020).

4. Predictive Value of Brain Connectivity Techniques

Brain connectivity describes the networks of functional and anatomical connections across the brain. Recently, interest has been growing in performing connectivity analyses to map out the communication networks needed for the brain to function. First, phase coherence, defined as estimates of the consistency of relative phase between signals within a set frequency band (Bowyer, 2016), is a promising connectivity technique for uncovering functional integration across the speech motor network. Sengupta and Nasir (2015) found that participants' adaptation to sustained formant perturbations was accompanied by significant changes in theta-gamma phase coherence. Specifically, the phase coherence progressively declined over fronto-temporal electrodes but increased over central electrodes, suggesting a remapping of coherence over an interacting speech motor network. Sengupta et al. (2016) also found that people who stutter showed abnormally higher alpha-beta and alpha-gamma coherence than non-stuttering controls. Second, functional connectivity, defined as statistical interdependence among spatially distant neurophysiological regions (Friston, 2011), is another promising connectivity technique for elucidating the coordinated activities within speech motor network. Evidence suggests that functional connectivity between certain brain regions can be significant neural markers predicting speech motor control performance at the individual (Botha et al., 2018; Ohashi & Ostry, 2021) and group (Manes et al., 2018; Ohashi & Ostry, 2021) levels. For example, adults' adaptation to formant perturbations was positively correlated with functional connectivity between the right IFG and associative sensory regions (Ohashi & Ostry, 2021). Altogether, these brain connectivity data can lay the groundwork for developing customized diagnostic tools and personalized treatment approaches for tackling speech motor disorders.

5. Future Research

The vibrancy of neuroscience methods in linking behavior to its brain bases or vice versa, and its relevance to grand challenges in the treatment of speech motor disorders motivate continued research in the field of speech motor control. Finally, a roadmap is presented for future neuroscience research, that is to identify structure-function coupling that supports speech motor control. Speech motor control has a biological basis in the structure and function of the human brain (Guenther, 2016), however, current research has examined its structural (Chen et al., 2021; Mollaei & Chinoor, 2024) and functional networks (Botha et al., 2018; Ohashi & Ostry, 2021) independently. A combined Functional Magnetic Resonance Imaging (fMRI) and Diffusion Tensor Imaging (DTI) study found that functional (hemodynamic fMRI signal) and structural (fractional anisotropy value) markers related to the left IFG were positively correlated with phonetic discrimination task improvement, which converges on the role of left IFG in speech motor control (Alotaibi et al., 2023). Despite this indirect evidence, the structure-function coupling associated with speech motor control remains unknown. Thus, future investigations are warranted to identify the region-specific structure-function coupling that supports speech motor control.

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References

Alotaibi, S., Alsaleh, A., Wuerger, S., & Meyer, G. (2023). Rapid neural changes during novel speech-sound learning: An fMRI and DTI study. *Brain and Language*, *245*, 105324. https://doi.org/10.1016/j.bandl.2023.105324

Bauer, J. J., Mittal, J., Larson, C. R., & Hain, T. C. (2006). Vocal responses to unanticipated perturbations in voice loudness feedback: An automatic mechanism for stabilizing voice amplitude. *The Journal of the Acoustical Society of America*, *119*(4), 2363-2371. https://doi.org/10.1121/1.2173513

Botha, H., Utianski, R. L., Whitwell, J. L., Duffy, J. R., Clark, H. M., Strand, E. A., ... & Jones, D. T. (2018). Disrupted functional connectivity in primary progressive apraxia of speech. *NeuroImage: Clinical*, *18,* 617-629. https://doi.org/10.1016/j.nicl.2018.02.036

Bowyer, S. M. (2016). Coherence a measure of the brain networks: Past and present. *Neuropsychiatric Electrophysiology*, *2*, 1-12. https://doi.org/10.1186/s40810-015-0015-7

Cai, X., Yin, Y., & Zhang, Q. (2023). Behavioral and ERP evidence of differences in pitch feedback control in late bilinguals' L1 and L2 speech production. *Bilingualism: Language and cognition*, *26*(4), 776-794. https://doi.org/10.1017/S1366728923000019

Chen, N., Zhao, C., Wang, M., Jones, J. A., Liu, P., Chen, X., ... Liu, H. (2021). Linking cortical morphology to interindividual variability in auditory feedback control of vocal production. *Cerebral Cortex*, *31*(6), 2932-2943. https://doi.org/10.1093/cercor/bhaa401

Dai, G., Chen, M., Chen, X., Guo, Z., Li, T., Jones, J. A., ... Liu, D. (2022). A causal link between left supplementary motor area and auditory-motor control of vocal production: Evidence by continuous theta burst stimulation. *NeuroImage*, *264*, 119767. https://doi.org/10.1016/j.neuroimage.2022.119767

Dai, G., Wang, M., Li, Y., Guo, Z., Jones, J. A., Li, T., ... Liu, H. (2022). Continuous theta burst stimulation over left supplementary motor area facilitates auditory-vocal integration in individuals with Parkinson's disease. *Frontiers in Aging Neuroscience*, *14,* 948696. https://doi.org/10.3389/fnagi.2022.948696

Forseth, K. J., Hickok, G., Rollo, P. S., & Tandon, N. (2020). Language prediction mechanisms in human auditory cortex. *Nature Communications*, *11*(1), 5240. https://doi.org/10.1038/s41467-020-19010-6

Friston, K. J. (2011). Functional and effective connectivity: A review. *Brain connectivity*, *1*(1), 13-36. https://doi.org/10.1089/brain.2011.0008

Guenther, F. H. (2016). *Neural Control of Speech*. MIT Press.

Houde, J. F., & Jordan, M. I. (1998). Sensorimotor adaptation in speech production. *Science*, *279*(5354), 1213-1216. https://doi.org/10.1126/science.279.5354.1213

Lin, Q., Chang, Y., Liu, P., Jones, J. A., Chen, X., Peng, D., ... Liu, H. (2022). Cerebellar continuous theta burst stimulation facilitates auditory-vocal integration in spinocerebellar ataxia. *Cerebral Cortex*, *32*(3), 455-466. https://doi.org/10.1093/cercor/bhab222

Li, S. (2022). *Investigation of phonological-lexical representation transformation in speech production and perception* [Doctoral thesis]. [Shanghai (IL)]: East China Normal University.

Li, T., Chang, Y., Zhao, S., Jones, J. A., Chen, X., Gan, C., ... Liu, H. (2023). The left inferior frontal gyrus is causally linked to vocal feedback control: Evidence from high-definition transcranial alternating current stimulation. *Cerebral Cortex*, *33*(9), 5625-5635. https://doi.org/10.1093/cercor/bhac447

Li, T., Zhu, X., Wu, X., Gong, Y., Jones, J. A., Liu, P., ... Liu, H. (2023). Continuous theta burst stimulation over left and right supramarginal gyri demonstrates their involvement in auditory feedback control of vocal production. *Cerebral Cortex*, *33*(1), 11-22. https://doi.org/10.1093/cercor/bhac049

Liu, D., Dai, G., Liu, C., Guo, Z., Xu, Z., Jones, J. A., ... Liu, H. (2020). Top-down inhibitory mechanisms underlying auditory-motor integration for voice control: Evidence by TMS. *Cerebral Cortex*, *30*(8), 4515-4527. https://doi.org/10.1093/cercor/bhaa054

Manes, J. L., Tjaden, K., Parrish, T., Simuni, T., Roberts, A., Greenlee, J. D., ... Kurani, A. S. (2018). Altered resting-state functional connectivity of the putamen and internal globus pallidus is related to speech impairment in Parkinson's disease. *Brain and Behavior*, *8*(9), e01073. https://doi.org/10.1002/brb3.1073

Mollaei, F., & Chinoor, M. A. B. (2024). Microstructural white matter changes underlying speech deficits in Parkinson's disease. *Brain and Language*, *249*, 105378. https://doi.org/10.1016/j.bandl.2024.105378

Ohashi, H., & Ostry, D. J. (2021). Neural development of speech sensorimotor learning. *Journal of Neuroscience*, *41*(18), 4023-4035. https://doi.org/10.1523/jneurosci.2884-20.2021

Scheerer, N. E., Behich, J., Liu, H., & Jones, J. A. (2013). ERP correlates of the magnitude of pitch errors detected in the human voice. *Neuroscience*, *240*, 176-185. https://doi.org/10.1016/j.neuroscience.2013.02.054

Sengupta, R., & Nasir, S. M. (2015). Redistribution of neural phase coherence reflects establishment of feedforward map in speech motor adaptation. *Journal of Neurophysiology*, *113*(7), 2471-2479. https://doi.org/10.1152/jn.00731.2014

Sengupta, R., Shah, S., Gore, K., Loucks, T., & Nasir, S. M. (2016). Anomaly in neural phase coherence accompanies reduced sensorimotor integration in adults who stutter. *Neuropsychologia*, *93*, 242-250. https://doi.org/10.1016/j.neuropsychologia.2016.11.004

Tourville, J. A., Reilly, K. J., & Guenther, F. H. (2008). Neural mechanisms underlying auditory feedback control of speech. *NeuroImage*, *39*(3), 1429-1443. https://doi.org/10.1016/j.neuroimage.2007.09.054

Villacorta, V. M., Perkell, J. S., & Guenther, F. H. (2007). Sensorimotor adaptation to feedback perturbations of vowel acoustics and its relation to perception. *The Journal of the Acoustical Society of America*, *122*(4), 2306-2319. https://doi.org/10.1121/1.2773966

Youngerman, B. E., Khan, F. A., & McKhann, G. M. (2019). Stereoelectroencephalography in epilepsy, cognitive neurophysiology, and psychiatric disease: Safety, efficacy, and place in therapy. *Neuropsychiatric Disease and Treatment*, *15*, 1701-1716. https://doi.org/10.2147/NDT.S177804

Zhu, X., Dai, G., Wang, M., Tan, M., Li, Y., Xu, Z., ... Liu, H. (2023). Continuous theta burst stimulation over right cerebellum for speech impairment in Parkinson’s disease: Study protocol for a randomized, sham-controlled, clinical trial. *Frontiers in Aging Neuroscience*, *15*, 1215330. https://doi.org/10.3389/fnagi.2023.1215330