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Beyond Phase Estimation: A Multidimensional Gating Framework for Robust Real-Time Closed-Loop Neural Stimulation

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Abstract

Neural oscillatory phase is widely used as a control variable in real-time closed-loop stimulation, yet its validity under strict causal constraints and noisy conditions has rarely been systematically examined. We introduce a Multidimensional Gating Framework (MGF), a plug-in and estimator-agnostic module that determines whether phase information should be admitted into control by evaluating instantaneous amplitude, narrowband signal-to-noise ratio (SNR), and spectral peak ratio (PR) within a strictly causal window. Using causal streaming replay on a public resting-state EEG dataset, we benchmarked Hilbert based phase estimation and endpoint-corrected Hilbert estimation with and without MGF. Among feasible subjects, MGF significantly reduced phase dispersion for both estimators, while robustly suppressing catastrophic phase errors. In contrast, ungated approaches exhibited systematic failures under the same conditions.

Keywords: closed-loop stimulation; EEG; real-time phase estimation; phase locking