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Meta-AlignNN: A Meta-Learning Framework for Stable BCI Performance Across Subjects, Time, and Tasks

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Introduction: Practical application of brain-computer interfaces (BCIs) requires stable mapping between neuronal activity and behavior through various behavioral contexts and for different individuals. Because recorded neurons as well as neural activity from same neurons could change over time, BCIs require frequent recalibration to maintain robust performance. Early approaches to addressing BCI stability issues mainly focused on tackling the challenge of neural activity changes over time. However, future BCI applications involve diversified scenarios and subjects, requiring solutions that address neural variability across time, subjects, and tasks. This study proposes a meta-learning-based algorithm for achieving BCI stability, referred to as ”Meta-AlignNN.” It provides a unified solution for maintaining BCI stability.

Material, Methods and Results: Recent studies have explored stability and consistency of neural population dynamics across subjects, time, and tasks, highlighting how these properties support the generation and learning of complex behaviors [1, 2, 3], which forms the theoretical foundation for effectiveness of Meta-AlignNN. We aim to develop a meta-learner capable of aligning neural activity across subjects, time, and tasks, regardless of the changes or drifts in neural activity recorded from cortical electrodes. With minimal data, this meta-learner can align varying neural activity to the stable and consistent neural population latent dynamics across different subjects, time, and tasks, thereby maintaining high BCI performance. Meta-AlignNN consists of a meta-aligner and a decoder. Specifically, the decoder is first trained on several sessions to learn the relationship between latent states (extracted from neural activity) and movement intentions. Data from other recorded sessions (across different subjects, tasks, and time) are used to train the meta-aligner. During meta-training, the meta-aligner is trained using Model-Agnostic Meta-Learning strategy, with the decoder's parameters fixed. The trained meta-aligner can align varying neural activity into stable and consistent neural population latent dynamics across subjects, time, and tasks. The fixed decoder can then seamlessly predict behavior from these aligned dynamics. In practice, this approach achieved significant success in various cross-time, cross-task, and cross-subject experiments (offline decoding and real-time brain control) conducted over nearly two years involving three monkeys and four tasks (center-out reaching task, random-target reaching task, whack-a-mole, and *Black Myth: Wukong*). The real-time brain control accuracy across time, tasks, and subjects reached approximately 98.2%. Notably, in the real-time brain control scenario involving *Black Myth: Wukong*, the task was completed in near-theoretical minimum time.

Conclusion: In this study, we present a unified meta-learning framework, Meta-AlignNN, designed to address the limitations of earlier approaches and to ensure BCI stability and robustness across subjects, time, and tasks. Tested over two years on four tasks with three monkeys, the approach achieved high real-time brain control performance. By capitalizing on the consistency of neural population dynamics and requiring minimal data for recalibration, this framework provides a compelling solution for clinical and practical BCI applications. Future work will explore its adaptability to diverse tasks and populations.

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