Howard Baker Talk Abstract Submission - Morgan Brown

Cognitive control is a multifaceted process that allows us to adaptively regulate behavior in response to internal goals or provided rules. This ability grants us the capacity to flexibly make contextually appropriate decisions based on environmental factors and objectives. Hierarchical cognitive control, a tiered form of this regulation, requires the integration of multiple levels of goals and subgoals that ultimately govern the responses we provide. Notably, this process engages the prefrontal cortex (PFC). Distinct functional and oscillatory dynamics have been identified in the PFC as this region is crucial for the management of complex tasks, a key aspect of hierarchical cognitive control. More specifically, distinguishable oscillatory patterns emerge within the PFC, particularly low-frequency oscillatory dynamics. As such, we see delta (2-3 Hz) oscillatory patterns associated with rule abstraction whereas theta (4-7 Hz) oscillations are linked to managing set size. Additionally, functional neuroimaging reveals the mid-dlPFC activates when rule abstraction increases as there is a greater demand for identifying and generalizing principles and patterns. This connection is often thought to be forged as the mid-dlPFC is essential for implementing complex strategies and representing abstract rules. On the other hand, the dorsal premotor area (PMd) generates a robust response when set-size increases, or when more rules have to be held. This region is often associated with basic rule execution and stimulus-response mappings, such as learned motor responses to specific cues. All in all, although EEG and fMRI findings suggest a role for these oscillations in specific regions of interest during a hierarchical control demand, causal evidence for their functional involvement remains scarce.

The present study implements a form of non-invasive brain stimulation coined as rhythmic transcranial magnetic stimulation (rTMS) to experimentally test the role of delta and theta oscillations in hierarchical cognitive control. Our central aim is that stimulation in specific frequency bands delivered to proposed regions of interest will enhance behavioral performance during cognitively demanding tasks. More specifically, we hypothesize delta frequency TMS to the mid-dlPFC will improve performance on tasks requiring an advanced level of abstractions, while theta-frequency TMS to the PMd will enhance performance on tasks involving larger set-sizes. Additionally, we integrated an arrhythmic stimulation pattern to serve as a frequency- and timing-specific control.

To test these hypotheses, we employ a within-subjects crossover design consisting of three sessions per participant. The first session serves as a baseline and involves a high-density EEG recording during the hierarchical cognitive control task which is intended to probe abstraction and set-size components of hierarchical cognitive control.In sessions two and three, participants perform the same task while receiving rhythmic TMS to either the mid-dlPFC or PMd. The order of stimulation sites is counterbalanced across participants. During stimulation sessions, TMS is applied at one of three frequencies: delta (2.2 Hz), theta (6.5 Hz), or arrhythmic. Each train consists of 5 pulses at 100% the participants motor threshold,where the last pulse is delivered in the first second after a stimulus presentation on each trial. The arrhythmic pattern maintains the same pulse count each train and duration is randomized to be either matched to either theta train duration or delta train duration with randomized inter-pulse intervals. Concurrent EEG is recorded throughout all sessions utilizing a 96-channel system.

The hierarchical cognitive control task comprises two main subtasks designed to independently manipulate abstraction and set-size. The response task is a low-abstraction condition requiring participants to execute stimulus-response mappings based on color cues. The dimension task is a high-abstraction condition that involves comparing visual objects based on shared dimensions such as texture or shape, requiring participants to apply abstract rules. Set-size is manipulated across both subtasks by varying the number of items held in memory (e.g., two versus four items). Each session includes 12 blocks of 48 trials, and stimulation conditions are fully crossed with task conditions such that each TMS type (delta, theta, arrhythmic) is paired equally with each cognitive control condition (low/high abstraction, low/high set-size).

Through this experimental design, we predict delta-frequency stimulation to the mid-dlPFC will enhance accuracy and/or reduce reaction time in high abstraction trials, consistent with its proposed role in abstract rule representation. In contrast, we expect theta-frequency stimulation to the PMd to improve performance in high set size trials, reflecting this region's involvement in stimulus-action mapping and working memory ability. Arrhythmic stimulation is intended to serve as a control purely to support the specificity of frequency-aligned stimulation. In addition to behavioral metrics, EEG data will be analyzed to assess changes in oscillatory power. We expect to observe increased delta power in the mid-dlPFC following delta TMS and increased theta power in the PMd following theta TMS, providing concrete neural evidence for successful oscillatory entrainment.

Behavioral data will be analyzed using repeated-measures ANOVAs and mixed-effects models with within-subject factors for stimulation type and cognitive task condition. EEG preprocessing will follow standard protocols using the EEGLAB and FieldTrip toolboxes. Raw data will be filtered, epoched to task events, re-referenced, and cleaned using independent component analysis. Spectral power and connectivity measures will be extracted to assess engagement of delta and theta oscillations in targeted regions.

Overall, this study harps on the functional contributions of low-frequency oscillations in cognitive control. By implementing frequency-specific TMS in conjunction with EEG, we aim to determine strong causal relationships and test whether delta and theta rhythms in regions of interest can modulate behavior. These findings propel our understanding of the neural basis of executive function and may contribute to neuromodulation-based interventions for disorders such as major depressive disorder which is marked by impaired cognitive flexibility and blunted executive functioning. This work informs not only theoretical models of cognition, but may guide the development of targeted therapeutic tools.