EEG Evidence of Sequential Dynamics During Hierarchical Cognitive Control

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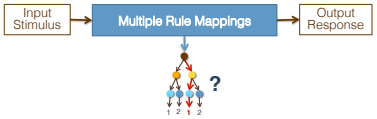
Introduction

- Many of the rules that we use to guide our everyday actions have an underlying hierarchical structure
- When applying these rules, multiple latent decisions intervene between stimulus and response
- Functional MRI has provided evidence of hierarchical organization for rule processing in the prefrontal cortex, much less is known about the temporal dynamics underlying the processing of these complex rules

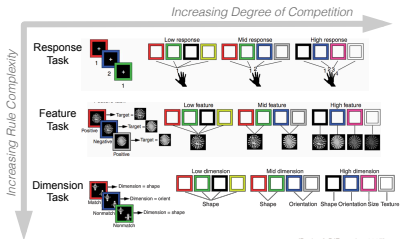


Does processing of hierarchical rules unfold in a sequential manner, with decisions at each level of a rule represented serially by discrete decision states? Or do they occur in parallel, such that all levels complete at the same time?

Methods

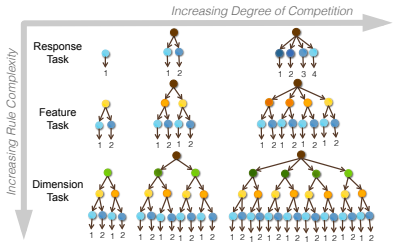
- 64 Channel EEG System
- N = 33
- Blocked experimental design

Hierarchical Task



(Badre & D'Esposito, 2007)

Two Axes for Manipulating Rule Difficulty



References

Badre, D. & D'Esposito, M. (2007). FMRI evidence for a hierarchical organization of the prefrontal cortex. J. Cogn. Neurosci., 19(12), 2082-2087.
Borst, J.P. & Anderson, J.R. (2013). Discovering processing stages by combining EEG with hidden Markov models. In Proceedings of the 35th Annual Conference of the Cognitive Science Society. Austin, TX: Cognitive Science Society.

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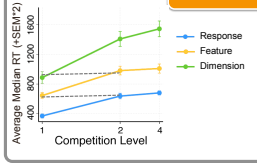
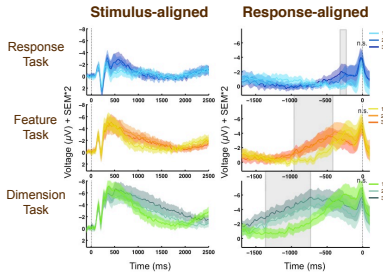
Behavioral Results



- Parametric effects of policy level on response times
- No significant differences in accuracy across tasks

Event-Related Potentials

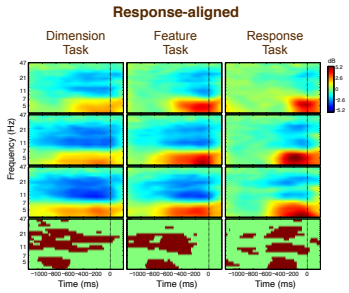
- Exemplar Fz channel obtained by SVD of neighboring channels
- Elongation of ERP with increasing control demands
  (gray box indicate significant interaction effects at p < 0.01, bonferroni-corrected)
- No significant difference at the time of response suggests top level rules completed first



- Effects are consistent even at the level of examining the global field potential

Time Frequency Analysis

- Differences in theta power near stimulus onset show an effect of increasing the level of competition among cues
- No significant differences in theta power close to response, when one would be processing the lower order rules
- But could be an effect of longer response times…



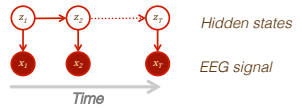
(Significant at p < 0.01, bonferroni-corrected)

Overall Summary

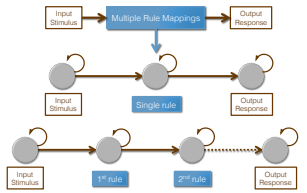
- Event-related potential and time-frequency analysis suggest sequential processing dynamics
- However, ERP and time-frequency effects could simply reflect longer response times
- Hidden Markov modeling revealed that longer response times with increasing policy order is not associated with adding additional discrete processing states
  - Increased rule complexity is related to systematically more intertrial variability in brain states
  - But each trial was explained by two states regardless of the # of levels in the rule

Hidden Markov Modeling

Objective:
Use hidden Markov modeling to uncover latent states from observed EEG data
(Borst & Anderson, 2013)

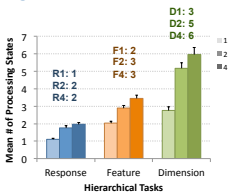


Prediction:
Given indications of sequential processing from ERP and time-frequency results, the number of discrete EEG states detected with hidden Markov modeling should show an association with rule complexity, but not competition.

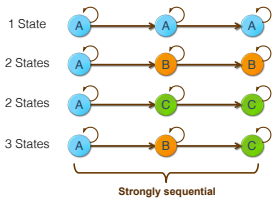


How does model complexity (# of states) scale with rule complexity of the hierarchical task design?

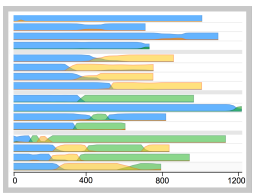
- Model selection performed by selecting the model with the greatest evidence
  - Determined using Bayesian information criterion, as it penalizes both model complexity and sequence length
- Satisfactory model fit empirically confirmed by comparing real versus simulated EEG data (by sampling from the learn distributions)



Does fitting greater HMM states with increasing rule complexity reflect more intervening states per trial or intertrial variability?

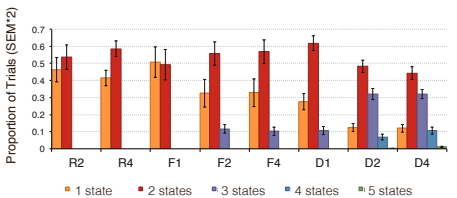


Schematic of possible sequence types with three estimated states



Example posterior state sequences predicted from trials in the Feature task (level 2) from a single subject

How many discrete states can be detected from individual trials?



- Most trials can be explained with only two states