

Trial-by-trial Computational Model of Category Learning Applied to fMRI Data

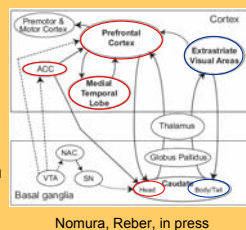
Nomura EM¹, Maddox WT⁴, Gitelman DR^{2,3}, Parrish TB³, Mesulam MM², Reber PJ¹

Northwestern University Departments of Psychology¹, Neurology², Radiology³ and University of Texas-Austin Department of Psychology⁴

INTRODUCTION

- **Category learning**
 - Different category structures depend on different learning strategies (Maddox et al., 2003)
 - **Rule-based (RB)** categorization
 - Conscious rule or reference stimulus, held in WM
 - New stimulus compared to the rule and categorized
 - **Information-integration (II)** categorization
 - implicit rule, unavailable to awareness
 - Stimulus evaluated within perceptual space and labeled based on similarity to prior examples
- **Evidence for multiple categorization systems**
 - behavioral dissociations
 - RB but not II learning disrupted with a WM load (Maddox, Ashby, et al, 2004)
 - II but not RB learning disrupted during delayed feedback conditions (Maddox, et al, 2003)
 - neuropsychology
 - PD patients impaired in II not RB category learning (Filoteo, et al., 2007)
 - neuroimaging
 - RB learning associated with greater activity in medial temporal lobe (MTL) and II learning with posterior body of the caudate (Nomura, Maddox et al., 2007)

- **A model of categorization systems in the brain**
 - adapted from the COVIS (Competition between Verbal and Implicit Systems) model (Ashby, 1998)
 - RB category learning system (red)
 - Prefrontal cortex (PFC) and anterior cingulate cortex (ACC) in cooperation with head of the caudate facilitate switching between rules
 - MTL/PFC connections store long-term rule



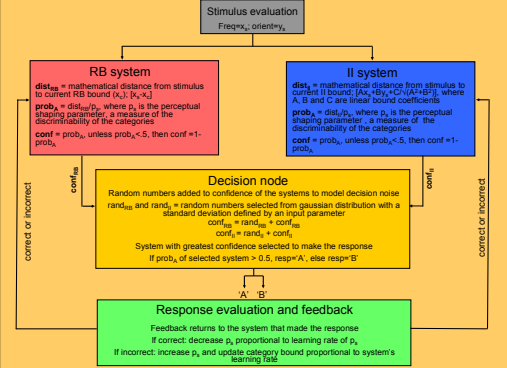
References
 Ashby FG (1992) Multidimensional Models of Perception and Cognition. Hillsdale, New Jersey: Lawrence Erlbaum Associates Publishers.
 Ashby, F.G., Alfonso-Reese, L.A., Turkken, A.U., & Waldron, E.M. (1998). A neuropsychological theory of multiple systems in category learning. *Psychological Review*, 105, 442-481.
 Filoteo, J.V., Maddox, W.T., & Song, D.D. (2007). Characterizing rule-based and information-integration deficits in patients with Parkinson's disease. *Neuropsychologia*, 45, 305-320.
 Maddox, W.T., Ashby, F.G., & Bohil, C.J. (2003). Delayed Feedback Effects on Rule-Based and Information-Integration Category Learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 29, 650-62.

MODELING METHODS AND SIMULATIONS

PINNACLE: A cognitive model of category learning

Parallel Interactive Neural Networks Aid Category Learning

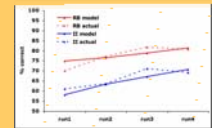
- 2 learning systems (RB and II) compete to acquire the categories on each trial
- decision node resolves competition by comparing confidence of each system
- system representations updated according to negative feedback



- 5 free parameters**
1. Learning rate of RB system
 2. Learning rate of II system
 3. Standard deviation of gaussian distribution of decision noise
 4. Starting perceptual shaping parameter
 5. Learning rate of perceptual shaping parameter

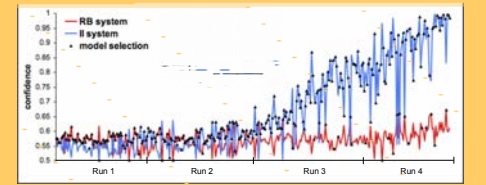
Simulation 1: Verified that model predictions fit group data across 80-trial blocks

- Minimized sum of squares difference (fit value) between model accuracy per block and actual subject group accuracy
- best fitting parameter set identified with downhill amoeba simplex search method
- PINNACLE response accuracy approximated actual RB and II group averages across 4 runs



Simulation 2: Trial-by-trial analysis of strategy use in individual subjects

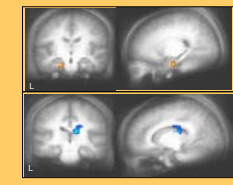
- found best fitting parameters for each subject that minimized the difference between the model prediction and the subject's responses
- used the maximum likelihood estimation (Ashby, 1992) for fit value assessment
- each subject's response profile was fit by the model to estimate strategy use on single trials
- representative II subject behavior fit by PINNACLE shows the relative confidence of the RB and II systems



RESULTS

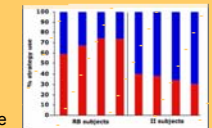
Successful category learning in MTL and caudate

- RB > II in left anterior MTL
- II > RB in right body of the caudate
- Replicates previous result (Nomura, Maddox et al, 2007) despite matching category discriminability in the current experiment



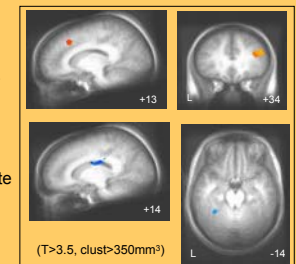
Strategy-mixing within groups

- PINNACLE-based model fits revealed RB and II experimental groups utilized a mixture of strategies within runs
- may help explain the lack of whole brain differential activity between groups



PINNACLE model applied to fMRI data

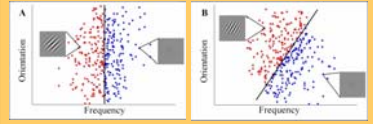
- fMRI activity associated with RB-fit trials contrasted with II-fit trials within-subject
 - RB>II (top): PFC and ACC
 - II>RB (bottom): caudate and extrastriate visual cortex



TASK AND IMAGING METHODS

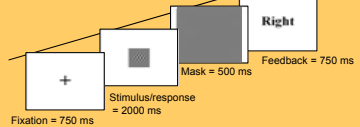
The RB and II stimuli

- Sine wave gratings that vary in frequency and orientation in accordance with either an RB (left) or II (right) category structure



The category learning task

- Learn the categories over 320 trials (split across 4 runs) using the feedback after each trial



Imaging & Data Analysis

- Whole-brain fMRI data were collected using the 3T GE scanner (35 3-mm slices, 330 reps, TR=2.0, TE=25 msec)
- 33 right-handed healthy volunteers were recruited from the NU community, but 2 were subsequently excluded due to movement artifact

- 80 fixation trials interpolated to facilitate deconvolution of responses to each trial
- *Successful Categorization* = differential activity for correct and incorrect trials
- Anatomical regions of interest (ROIs) of the MTL and caudate were drawn on individual participants and aligned with the ROI-AL method (Stark & Okada, 2003) to optimize sensitivity

CONCLUSIONS

- Converging evidence suggests RB and II category learning rely on distinct neural networks each capable of acquiring category representations
 - fMRI analysis of RB and II groups identified differential roles of the MTL and caudate
- PINNACLE successfully implemented a cognitive theory of competitive category learning systems that matched the observed human data
 - indicated strategy switching within and between subjects in both groups
- Modeling combined with fMRI revealed additional components of the RB and II networks not identified with traditional fMRI analyses
 - PFC and ACC were more active in RB-fit trials, perhaps facilitating the hypothesis-testing and executive control processes supporting RB learning mechanisms
 - Extrastriate visual cortex activity was greatest in II-fit trials, suggesting the important role of this area in acquiring a category representation via reciprocal loops through posterior caudate

Corresponding Author:
 Emi M. Nomura, Department of Psychology
 2029 Sheridan Road
 Evanston, IL 60208
 e-nomura@northwestern.edu
 http://reberlab.psych.northwestern.edu

Acknowledgements:
 This work was supported by National Institute of Mental Health grant R01-MH58748 (PJR) and the Mechanisms of Aging and Dementia Training Grant T32-AG20506 (EMN).

