

BIOGRAPHICAL SKETCH

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NAME: **Benjamin Hayden**

eRA COMMONS USER NAME (credential, e.g., agency login): **hayden@neuro**

POSITION TITLE: **Associate Professor**

EDUCATION/TRAINING *(Begin with baccalaureate or other initial professional education, such as nursing, include postdoctoral training and residency training if applicable. Add/delete rows as necessary.)*

INSTITUTION AND LOCATION	DEGREE (if applicable)	Completion Date MM/YYYY	FIELD OF STUDY
Rice University, Houston, TX	B.A.	05/2000	Chemistry
University of California, Berkeley, Berkeley, CA	Ph.D.	06/2005	Molecular and Cell Biology
University of California, Berkeley, Berkeley, CA	Post-doc	10/2005	Psychology
Duke University	Post-doc	06/2011	Neurobiology

A. Personal Statement

I am interested in understanding the neural mechanisms by which our brains make and control our choices. I have a particular interest in understanding self-control, learning, and decision-making. My research is closely inspired by foraging theory and by behavioral ecology more generally. As such a major focus of the lab's methods development comes in making our task environments ever more naturalistic. The lab uses single unit recordings in rhesus macaques performing computerized and freely moving tasks and records in reward regions. We are especially interested in the cingulate cortex (dorsal anterior and posterior, dACC and PCC), orbitofrontal cortex (OFC), ventromedial prefrontal cortex (vmPFC), and the striatum. I recently moved my lab from the University of Rochester to the Center for Magnetic Resonance Research at the University of Minnesota. There, my lab and I have begun working to understand expand our understanding of these regions and processes by incorporating measures of hemodynamic response.

B. Positions and Honors**Positions**

2000 Webpage Designer, full-time, Dac-Net, Rice University
 2005 Postdoctoral Researcher, Gallant Lab, Helen Wills Neuroscience Institute, UC Berkeley
 2005- 2011 Postdoctoral Researcher, Platt Lab, Dept. Neurobiology, Duke University
 2011-2016 Assistant Professor, Dept. of Brain and Cognitive Sciences, University of Rochester
 2016-2017 Associate Professor, Dept. of Brain and Cognitive Sciences, University of Rochester
 2017-present Associate Professor, Dept. of Neuroscience, University of Minnesota

Honors

1999 Summer Medical And Research Training program, Baylor College of Medicine
 1999-2000 Rice Undergraduate Scholars Program fellow
 2005 Valedictorian, Class of 2005, Dept. Molecular and Cell Biology, UC Berkeley
 2009 Best post-doc talk, Department of Neurobiology Retreat
 2009 Outstanding Young Investigator Award, Society for Neuroeconomics

2010	Best poster, post-doc category, Motivated Neural Networks conference
2010	Spotlight poster, COSYNE meeting
2011	Travel Award, American College of Neuropsychopharmacology Annual Meeting
2012	Sloan Foundation Fellowship
2012	Poster selected for Data Blitz, Annual ACNP meeting
2013	NARSAD Young Investigator Award
2013	Elected as Associate Member, American College Neuropsychopharmacology
2014	Klingenstein-Simons Foundation Fellowship
2014	Templeton Fellowship
2015	Best paper, Psychonomic Society

C. Contributions to Science

C.1. Neural mechanisms of economic choice

We are keenly interested in developing a basic understanding of the neural mechanisms that support economic choice. Our work supports the idea that value comparison depends on a mutual inhibition operation that occurs simultaneously in multiple reward regions, including the vmPFC (Strait et al., 2014), the ventral striatum (Strait et al., 2015) and dACC (Azab and Hayden, 2017). More broadly, our work argues against standard modular and localized functional models, but instead supports distributed and hierarchical ones (Hunt and Hayden, 2017). One exciting new direction lies in linking neural representations of offers with those of past outcomes, to begin to understand how learning drives choice processes (Wang and Hayden, 2017).

- Strait, C. E., Sleezer, B. J., and **Hayden, B. Y.** (2015) Signatures of value comparison in ventral striatum neurons. *PLoS Biology* (2015). doi:10.1371/journal.pbio.1002173
- Strait, C. E., Blanchard, T. C., and **Hayden, B. Y.** (2014) Reward value comparison via mutual inhibition in ventromedial prefrontal cortex. *Neuron*. 82(1), 1-10. PMID 24881835
- Azab, H. and **Hayden, B. Y.** (2017). Correlates of decision dynamics in the dorsal anterior cingulate cortex. *PLoS Biology*. In press.
- Hunt, L. and **Hayden, B. Y.** (2017) A distributed, hierarchical, and recurrent framework for reward-based choice. *Nature Reviews Neuroscience*. 18 172-182.
- Wang, Z. M. and **Hayden, B. Y.** (2017). Reactivation of associative structure specific neural responses to outcomes during prospective evaluation. *Nature Communications*. 8 article 15821

C.2. Neural basis of foraging decisions

Animals, including humans, are evolved to make decisions in the context of foraging. We believe in making use of the body of insights about the psychological basis of foraging, aggregated in the form of foraging theory, to drive our neuroscientific questions. This involves a theoretical reorientation – towards accept-reject decisions, towards consideration of long-term strategic considerations. It also involves using classic foraging problems as direct inspiration for tasks – we have used both the patch-leaving problem and the diet selection (Hayden et al., 2011; Blanchard and Hayden, 2015; Blanchard et al., 2015a). It also involves consideration of the need to trade off immediate reward for the delayed benefits derived from information – a major driver in curiosity (Blanchard et al., 2015b.) This work has led us to propose major changes in the way we think about economic choice (Hayden, 2018).

- Hayden, B. Y.**, Pearson, J. M., and Platt, M. L. (2011) Neuronal basis of sequential foraging in a patchy environment. *Nature Neuroscience* (2011). Vol 14 (7) 933-941. PMID 21642973.
- Blanchard, T. C. and **Hayden, B. Y.** (2014). Neurons in dorsal anterior cingulate cortex signal post-decisional variables in a foraging task. *Journal of Neuroscience* (2014). 34(2) 646-655. PMID 24403162.
- Blanchard, T. C. and **Hayden, B. Y.** (2015). Monkeys are more patient in a foraging task than in a standard intertemporal choice task. *PLoS One*. 10(2) e0117057.

- Blanchard, T. C., **Hayden***, **B. Y.**, and Bromberg-Martin*, E. S. (*=co-senior authors). (2015). Orbitofrontal cortex uses distinct codes for different choice attributes in decisions motivated by curiosity. *Neuron* 85, 602-614.
- Hayden, B. Y.** (2018). Economic choice: the foraging perspective. *Current Opinion in Behavioral Science* (2018) 24 1-6.

C.3. Function of the dorsal anterior cingulate cortex

The dorsal anterior cingulate cortex (dACC) is a major hub of cortex whose role is clearly linked to cognition, emotion, reward, learning, and several other functions. My work has explored its specific role in two aspects of economic choice: (1) comparing values to implement decisions (Azab and Hayden, 2018; Blanchard and Hayden, 2014), and (2) monitoring the consequences of actions and linking them to adjustments or changes in behavior (Hayden et al., 2009; Hayden et al., 2011). Together this work emphasizes the broad economic functions of dACC and links it with other major theories of its function (Heilbronner and Hayden, 2016). A major focus of our recent work has been to determine the unique role of dACC by comparing its economic and executive functions to those of other brain regions, especially the subgenual anterior cingulate cortex (Azab and Hayden, 2018; Strait et al., 2016). This work emphasizes the continuity of function across cingulate regions and other adjacent regions.

- Heilbronner, S. R. and **Hayden, B. Y.** (2016) Dorsal anterior cingulate cortex: a bottom-up view. *Annual Review of Neuroscience*. 39 p 149-170
- Azab, H. and **Hayden, B. Y.** (2018). Correlates of economic choice processes in dorsal and subgenual anterior cingulate cortices. *European Journal of Neuroscience*. In press.
- Blanchard, T. C. and **Hayden, B. Y.** (2014) Neurons in dorsal anterior cingulate cortex signal post-decisional variables in a foraging task. *Journal of Neuroscience*. 34(2) 646-655. PMID 24403162.
- Hayden, B. Y.**, Heilbronner, S. R., Pearson, J. M., and Platt, M.L. (2011) Surprise signals in anterior cingulate cortex: neuronal encoding of unsigned reward prediction errors driving adjustments in behavior. *Journal of Neuroscience*. Vol 31(11) 4178-87. PMCID: 3070460.
- Hayden, B. Y.**, Pearson, J. M., and Platt, M. L. Fictive reward signals in anterior cingulate cortex. (2009) *Science* vol. 324 (5929) p. 948-950. PMCID: 3096846.
- Strait, C. E., Sleezer, B. J., Blanchard, T. C., Azab, H., Castagno, M. D., and **Hayden, B. Y.** (2016) Neuronal selectivity for spatial position of offers and choices in five reward areas. *Journal of Neurophysiology* 115(3) p 1098-1111. DOI:10.1152/jn.00325.2015.

C.4. Neural basis of executive control

Decision-makers do not only make decisions; we also regulate those decisions based on contextual factors like rule (stimulus-response mappings) and changing task demands. A full understanding of decision-making requires an understanding of contextual modulation of decision-making. Our lab is particularly interested in the role of ostensible reward regions in executive control. A major discovery of the lab is that core reward regions (OFC and VS) play critical roles in executive control, even outside the domain of classic economic tasks (Sleezer and Hayden, 2016; Sleezer et al., 2016; Sleezer et al., 2017)). The presence of control signals outside the canonical control network suggests that control may be more distributed than is often believed. This fact in turn has led us to consider new types of models of control, ones based on distributed control systems such as bee swarms and animal flocks (Eisenreich et al., 2016).

- Sleezer, B. J. and **Hayden, B. Y.** (2016) Differential contributions of ventral and dorsal striatum to early and late phases of cognitive set reconfiguration. *Journal of Cognitive Neuroscience* 28(12) p 1849-1864.
- Sleezer, B. J., Castagno, M. D., and **Hayden, B. Y.** (2016). Rule encoding in orbitofrontal cortex and striatum guides action selection. *Journal of Neuroscience* 36(44) p 11223-11237.
- Sleezer, B. J., Loconte, G., Castagno, M.D., and **Hayden, B.Y.** (2017). Neuronal responses support a role for orbitofrontal cortex in cognitive set reconfiguration. *European Journal of Neuroscience*. 45(7) 940-951.
- Eisenreich, B., Akaishi, R., and **Hayden, B. Y.** (2016). Control without controllers: towards a distributed neuroscience of executive control. *Journal of Cognitive Neuroscience*. 29(10) 1684-1698.

C.5. Neural basis of self-control

Self-control refers to the deliberate withholding of action in the face of the temptation to do otherwise. Dysregulation of self-control is associated with the progression into addiction, as well as with diseases like depression and obsessive-compulsive disorder. Our lab has been interested in delineating the neural processes associated with successful and failed self-control. Our work suggests that maintenance of reward representations is key to persistence – a key element of self-control (Blanchard et al., 2015). Other work investigates the validity of the intertemporal choice task, a classic measure of self-control in animals (Blanchard et al., 2013, Blanchard and Hayden, 2015). We conclude that the task provides a poor measure of self-control, and propose that other tasks, especially foraging-inspired ones, are superior (Hayden, 2015).

Blanchard, T. C., Strait, C. E., and **Hayden, B. Y.** (2015) Ramping ensemble activity in dorsal anterior cingulate cortex neurons during persistent commitment to a decision. *Journal of Neurophysiology* 114(4) p 2439-2449

Blanchard, T. C., Pearson, J. M., and **Hayden, B. Y.** (2013). Postreward delays and systematic biases in measures of animal temporal discounting. *Proceedings of the National Academy of Sciences*. Vol. 110(38) 15491-15496. PMID 24003113.

Blanchard, T. C. and **Hayden, B. Y.** (2015). Monkeys are more patient in a foraging task than in a standard intertemporal choice task. *PLoS One*. 10(2) e0117057.

Hayden, B. Y. Time discounting and time preferences in animals: a critical review. (2015). *Psychonomic Bulletin and Review*. Vol 23(1) 39-53.

D. Additional Information: Research Support and/or Scholastic Performance

Applying a neuroeconomics paradigm for the assessment of central fatiguability in an aging population.

Role: Co-I (PI: Feng Vankee Lin). NIH R21 AG053193 (2016-2016) [BYH: 0.45 months]

Neural basis of reward-based choice. Role: PI. NIH R01 DA037229 (2015-2020)

Neuronal basis of persistence. Role: PI. NIH R01 DA038615 (2015-2020)

Repeated cocaine exposure and striatal contributions to cognitive control. Role: PI. R01 DA038106 (2014-2019)

Flexible control of reward-based decisions. Role: PI. NSF CAREER award BCS 1253576 (2013-2018)

Do reward-based choices depend on neuronal simulation of possible rewards? Role: PI. Klingenstein-Simons Fellowship