Angela Yu – Research Overview

My research program aims to elucidate the neural basis of cognitive processes using a combination of **theoretical** and **experimental** methods. My group studies the broad topic of **cognition under uncertainty**, encompassing problems in *perception, attention, learning, prediction, decision-making, cognitive control, active sensing, affective cognition, and social cognition*. The theoretical tools we utilize include Bayesian probability theory, decision theory, stochastic control theory, information theory, and game theory. The experimental methods we employ include psychophysics, eye-tracking, and functional brain imaging. We also collaborate with various experimental groups, utilizing electrophysiology, neuroimaging, pharmacology, and psychiatry, to investigate the neural basis of healthy and abnormal cognitive processing. In the following, I first describe several major strands of ongoing research in my group, and then follow up with an overview of anticipated future directions.

Active Cognition

A major line of research in my lab deals with active cognition, or how the brain actively engages with a noisy, imperfectly known environment to achieve specific behavioral goals. We have used Bayesian probability theory and stochastic control theory to understand how the brain negotiate the tension between exploration and exploitation (Zhang & Yu, 2013) and between speed and accuracy (Yu, 2007; Frazier & Yu, 2008), as well as the dynamic allocation of covert (Yu, Dayan, & Cohen, 2009) and over attention (Yu & Huang, 2014; Ahmad, Huang, & Yu, 2014) according to environmental statistics and behavioral goals. This body of work contributes to a formal framework for investigating active cognition, an important area that has been relatively neglected in cognitive neuroscience due to its computational complexity.

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Rational Irrationality

A related line of research in my lab has been to understand how apparently irrational or heuristic behavior in humans in various behavioral contexts may actually reflect rational or adaptive decision strategies under conditions of uncertainty. Utilizing Bayesian ideal-observer models, we have shown rational inference and decision-making naturally give rise to apparently sub-optimal behavior in a variety of classical psychology paradigms, including the widely observed tendency of humans to show apparently superstitious sequential effects in experiments with randomized stimulus presentation (Yu & Cohen, 2009; Ma & Yu, 2015), to allocate choice preferences using a matching rather than maximizing (optimal) strategy (Yu & Huang, 2014), to exhibit grouping effects in visual crowding (Zhang, Song, & Yu, 2015), and to alter relative preferences for consumer products in the presence/absence of other options (Shenoy & Yu, 2013). The last of these phenomena contributed to Kahneman and Tversky's Prospect Theory, which explains human decision-making behavior largely in terms of heuristics and biases; our work showed that there is no need to invoke an ad hoc heuristic explanation, since such contextual effects are natural consequences of using the available options as a means to gain information about the broader market.

Yu, A J & Cohen, J D (2009). Sequential effects: Superstition or rational behavior? Advances in Neural Information Processing Systems 21: 1873-1880.

Shenoy, P & **Yu, A J** (2013). A rational account of contextual effects in preference choice: What makes for a bargain? Proceedings of the Thirty-Fifth Annual Conference of the Cognitive Science Society.

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Zhang, S, Song, M, & **Yu, A J** (2015). Bayesian hierarchical model of local-global processing: Visual crowding as a case-study. Proceedings of the Cognitive Science Society Conference.

Ma, N & **Yu, A J** (2015). Variability in response time reveals statistical learning and adaptive decision-making. Proceedings of the Cognitive Science Society Conference.

Inhibitory Control

A growing thread of our recent work has been to understand the cognitive and neural computations underlying inhibitory control, the ability to stop or cancel inappropriate actions, which is known to be impaired in various psychiatric populations. Beginning with a rational learning and decision-making model (Shenoy & Yu, 2011) that explained a wide range of puzzling data related to inhibitory control, we then collaborated with Dr. C-S Li at Yale Medical School and Dr. M Paulus at UCSD Medical School to identify the neural correlates (in fMRI data) of probabilistic computation in the human brain (J. S. Ide, Shenoy, Yu*, & Li*, 2013), as well as investigating how the relevant cognitive and neural processes go awry psychiatric populations, in particular methamphetamine- and cocaine-users (Harlé et al., 2014, 2015; J. Ide, Hu, Zhang, Yu, & Li, 2015; Harlé, Zhang, Ma, Yu*, & Paulus*, 2016).

Shenoy, P & **Yu, A J** (2011). Rational decision-making in inhibitory control. Frontiers in Human Neuroscience 5:48. doi: 10.3389/fnhum.2011.00048.

Ma, N & **Yu, A J** (To appear). Inseparability of Go and Stop in Inhibitory Control: Go Stimulus Discriminability Affects Stopping Behavior. Frontiers in Neuroscience.

Ide, J S, Shenoy, P, **Yu*, A J**, & Li*, C-R (2013). Bayesian prediction and evaluation in the anterior cingulate cortex. Journal of Neuroscience, 33: 2039-2047. *Co-senior authors.

Harlé, K M, Shenoy, P, Steward, J L, Tapert, S, **Yu*, A J**, & Paulus*, M P (2014). Altered neural processing of the need to stop in young adults at risk for stimulus dependence. Journal of Neuroscience, 34(13): 4567-4580. *Co-senior authors.

Harlé, K M, Steward, J L, Zhang, S, Tapert, S, **Yu*, A J**, & Paulus*, M P (2015). Bayesian neural adjustment of inhibitory control predicts emergence of problem stimulant use. Brain, 138:3413-26. *Co-senior authors.

Harlé, K M, Zhang, S, Ma, N, **Yu*, A J**, & Paulus, M P* (under review). Reduced neural recruitment for Bayesian adjustment of inhibitory control in methamphetamine dependence. *Co-senior authors.

Neuromodulation, Learning, and Attention

Much of my earlier work (2002-2005), centered around my PhD research, dealt with the functional roles of the neuromodulators acetylcholine (ACh) and norepinephrine (NE) in perception, attention, and learning. The work contributed a quantitative theory of how ACh and NE respectively signal expected and unexpected uncertainty in cortical computations. Many subsequent experimental studies in electrophysiology, neuropsychology, and clinical neuroscience, done in various labs, have largely confirmed predictions of the theory. This work is not only important for its scientific contributions, but demonstrates that the theoretical approach taken in my research can have concrete and far-reaching impact on experimental and clinical neuroscience.

Yu, A J & Dayan, P (2002). Acetylcholine in cortical inference. Neural Networks, 15 (4/5/6): 719-730.

Yu, A J & Dayan, P (2005). Uncertainty, neuromodulation, and attention, Neuron, 46: 681-692.

Yu, A J & Dayan, P (2005). Inference, attention, and decision in a Bayesian neural architecture. In Advances in Neural Information Processing Systems 17: 1577-84. MIT Press, Cambridge, MA.

Dayan, P & **Yu, A J** (2006). Phasic norepinephrine: A neural interrupt signal for unexpected events. Network: Computation in Neural Systems, 17: 335-50.

Future Directions

While I intend to continue conducting research along all of the existing threads, I am particularly excited about two budding ares of research that my group has only begun to investigate: **affective cognition** and **social cognition**. Although various qualitative notions of how affect can and does influence cognitive processing have been put forth, I would like to formulate a quantitative theory of how affective state acts as a complementary source of information, along with immediate sensory inputs and retrieved memories, for cortical inference, decision-making, and planning. I am also interested in investigating how dysfunctions in the interaction between affective and cognitive processing may contribute to abnormal patterns of behavior in various psychiatric conditions, such as depression, substance abuse, anorexia, and autism. We have begun some preliminary work in this domain, by hypothesizing certain dysfunctions in learning and control in anxiety and depression (Paulus & Yu, 2012).

Paulus, M P & **Yu, A J** (2012). Emotion and decision-making: Affect-driven belief systems in anxiety and depression. Trends in Cognitive Sciences 16: 476-483.

In terms of social cognition, I am interested in how groups of individuals deliberately or accidentally share information while trying to achieve collective and/or individual goals in various competitive and cooperative settings. For example, we have begun examining the role of social information in competitive foraging (Ahmad & Yu, 2015), a scenario in which many decentralized agents competing for patches of resources can quickly converge onto the Nash equilibrium solution of matching reward-to-group-size ratio with limited social information (as have been observed in ducks and other animals). We intend to investigate a much broader class of problems in social decision-making, with implications for electoral voting, economic choice, dating, and social media networking.

Ahmad, S & **Yu, A J** (2014). A socially aware Bayesian model for competitive foraging. Proceedings of the Cognitive Science Society Conference.

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Ide, J., Hu, S., Zhang, S., Yu, A. J., & Li, C.-S. R. (2015). Impaired bayesian learning for cognitive control in cocaine dependence. *Drug and Alcohol Dependence*, *151*, 220–227.

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Ma, N., & Yu, A. J. (2015). Statistical learning and adaptive decision-making underlie human response time variability in inhibitory control. *Frontiers in Psychology*, *6*(1046). doi: 0.3389/fpsyg.2015.01046

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Shenoy, P., & Yu, A. J. (2011). Rational decision-making in inhibitory control. *Frontiers in Human Neuroscience*. (doi: 10.3389/fnhum.2011.00048)

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Yu, A. J. (2007). Optimal change-detection and spiking neurons. In B. Schölkopf, J. Platt, & T. Hoffman (Eds.), *Advances in Neural Information Processing Systems 19* (p. 1545-1552). Cambridge, MA: MIT Press.

Yu, A. J., & Cohen, J. D. (2009). Sequential effects: Superstition or rational behavior? *Advances in Neural Information Processing Systems*, *21*, 1873-80.

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Yu, A. J., & Huang, H. (2014). Maximizing masquerading as matching: Statistical learning and decision-making in choice behavior. *Decision*, *1*(4), 275-287.

Zhang, S., Song, M., & Yu, A. J. (2015). Bayesian hierarchical model of local-global processing: Visual crowding as a case-study. *Proceedings of the Thirty-Seventh Annual Conference of the Cognitive Science Society*.

Zhang, S., & Yu, A. J. (2013). Human active learning in a bandit setting. *Proceedings of the Thirty-Fifth Annual Conference of the Cognitive Science Society*.