Models of the Mind and Brain

Instructor: Hayoung Song, Ph.D.

Models are essential tools in cognitive neuroscience because they allow us to formalize theories of the mind and brain, generate falsifiable hypotheses, and test those hypotheses against empirical data. Rather than relying only on descriptive accounts, models force us to specify mechanisms and evaluate how well they explain observed phenomena. This course introduces students to historically influential models as well as recent ones across domains such as attention, memory, decision making, and cognitive control. Through readings and discussions, students will learn what questions models can answer and how models can complement empirical findings. By the end of the semester, students will be able to formulate their own theoretical framework and design a computational model to formally test the theory of their interests. This course will serve as a prerequisite for the **Computational Models of Cognition** course, in which students will gain hands-on experience coding models and running simulations.

Course Description

This course will be taught as a **graduate seminar**. Each week, students will read 2-3 articles on a selected topic, submit a discussion post, and come to class prepared for active discussion. Each paper will be assigned to a student for in-class presentation, while all students are expected to contribute to the discussion. Students will design a computational model to test a theory or hypothesis about the mind and/or brain function, which will be submitted as a 2-page mock grant proposal due at the end of the semester. Model ideas will be discussed with the instructor at least once during office hours.

Grading

Class Participation: 30%
Discussion Questions: 10%
Class Presentation: 20%
Mock Grant Proposal - Idea Development: 10%
Mock Grant Proposal - Final paper: 30%

Class Participation

This class is discussion-based; therefore, you are expected to actively participate in the class discussion. Please let the instructor know if you have difficulty participating in the discussions.

Class Presentations

Each student is expected to take a lead in discussing 1-2 papers during the semester. The format will be that of a typical journal club presentation. Presentations should be prepared assuming that everyone has already read the paper, meaning it shouldn't be about summarizing the contents of the paper but about leading discussions. Discussion posts on Canvas should be reviewed before the class and incorporate into the presentation. The presenters are encouraged to incorporate outside materials to provide additional context. Sign-ups will open in the first week of class.

Discussion Questions

For each paper, students should come up with 1-5 questions that they think are worth discussing. These discussion questions should be posted on Canvas 12 hours prior to the start of the class.

Mock Grant Proposal

Each student will construct a theory based on empirical findings from their own graduate work or from existing studies. They will then write a grant proposal (2-page) outlining models that can formally test the theory. The proposal should include: comparison models with varying architectures, explanations of how the model accounts for existing empirical findings, proposals for empirical studies to test the theory, falsifiable hypotheses, and expected outcomes. During the semester, each student must attend at least one office hour with the instructor to discuss their proposed ideas, and the feedback received should be incorporated into the final mock grant proposal.

Course Schedule

Week 1. What are models and why do we need them?

- Marr, D. (1982). Vision: A computational investigation into the human representation and processing of visual information. Ch. 1: Introduction.
- Guest, O., Martin, A. E. (2021) How computational modeling can force theory building in psychological science. *Perspective on Psychological Science*, 16(4), 789-802.

Week 2. Models of Arousal and Vigilance

- Raut, R. V., Rosenthal, Z. P., Wang, X., Miao, H., Zhang, Z., Lee, J. -M., Raichle, M. E., Bauer, A. Q., Brunton, S. L., Brunton, B. W., Kutz, J. N. (2025). Arousal as a universal embedding for spatiotemporal brain dynamics. *Nature*.
- Rosenberg, M. D., Finn, E. S., Scheinost, D., Papademetris, X., Shen, X., Constable, R. T., Chun, M. M. (2015). A neuromarkers of sustained attention from whole-brain functional connectivity. *Nature Neuroscience*, 19, 165-171.
- Song, H., Chen, R., Botch, T. L., Braver, T. S., Rosenberg, M. D., Zacks, J. M., Ching, S. (2025) Geometry of neural dynamics along the cortical attractor landscape reflects changes in attention. *bioRxiv*.

Week 3. Models of Selective Attention

- Treisman, A. M. (1969). Strategies and models of selective attention. *Psychological Review, 76*(3), 282–299.
- Lee, J., Maunsell, J. H. R. (2009) A normalization model of attentional modulation of single unit responses, *PLoS ONE*, 4(2), e4651.

Week 4. Models of Working Memory

- Bayes, P. M., Husain, M. (2008) Dynamic shifts of limited working memory resources in human vision. *Science*, 321 (5890), 851-854.
- Awh, E., Barton, B., Vogel, E. K. (2007). Visual working memory represents a fixed number of items regardless of complexity. *Psychological Science*, 18 (7), 622-628.
- Wimmer, K., Nykamp, D. Q., Constantinidis, C., Compte, A. (2014). Bump attractor dynamics in prefrontal cortex explains behavioral precision in spatial working memory. *Nature Neuroscience*, 17, 431-439.

Week 5. Models of Episodic Memory I

- Hopfield, J. J. (1982). Neural networks and physical systems with emergent collective computational abilities. *PNAS*, 79(8), 2554-2558.
- Polyn, S. M., Norman, K. A., & Kahana, M. J. (2009). A context maintenance and retrieval model of organizational processes in free recall. *Psychological Review*, 116(1), 129–156.
- Lu, Q., Hasson, U., Norman, K. A. (2022). A neural network model of when to retrieve and encode episodic memories. *eLife*.

Week 5. Models of Episodic Memory II

- Whittington, J. C. R., Muller, T. H., Mark, S., Chen, G., Barry, C., Burgess, N., Behrens, T. E. J. (2020). The Tolman-Eichenbaum Machine: Unifying Space and Relational Memory through Generalization in the Hippocampal Formation. *Cell*, 183(5), 1249-1263.
- Chandra, S., Sharma, S., Chaudhuri, R., Fiete, I. (2025). Episodic and associative memory from spatial scaffolds in the hippocampus. *Nature*, 638 (8051), 739-751.

Week 6. Models of Event Cognition

- Franklin, N. T., Norman, K. A., Ranganath, C., Zacks, J. M., & Gershman, S. J. (2020). Structured Event Memory: A neuro-symbolic model of event cognition. *Psychological Review, 127*(3), 327–361.
- Langston, M., & Trabasso, T. (1999). Modeling causal integration and availability of information during comprehension of narrative texts. In H. van Oostendorp & S. R. Goldman (Eds.), *The construction of mental representations during reading* (pp. 29–69).

Week 7. Models of Perceptual Decision Making

- Luo, T. Z., Kim, T. D., Gupta, D., Bondy, A. G., Kopec, C. D., Elliott, V. A., DePasquale, B., Brody, C. D. (2025). Transitions in dynamical regime and neural mode during perceptual decisions. *Nature*.
- Brunton, B. W., Botvnick, M. M., Brody, C. D. (2013). Rats and humans can optimally accumulate evidence for decision-making. Science, 340 (6128), 95-98.

Week 8. Models of Value-based Decision Making

- Lak, A., Costa, G. M., Romberg, E., Koulakov, A. A., Mainen, Z. F., Kepecs, A. (2014). Orbitofrontal cortex is required for optimal waiting based on decision confidence. *Neuron*, 84(1), 190-201.
- Stachenfeld, K. L., Botvinick, M. M., Gershman, S. J. (2017). The hippocampus as a predictive map. *Nature Neuroscience*, 20, 1643-1653.s

Week 9. Models of Cognitive Control

- Mante, V., Sussillo, D., Shenoy, K. V., Newsome, W. T. (2013). Context-dependent computation by recurrent dynamics in prefrontal cortex. *Nature*, 503 (7474), 78-84.

- Yang, G. R., Joglekar, M. R., Song, H. F., Newsome, W. T., Wang, X. -J. (2019). Task representations in neural networks trained to perform many cognitive tasks. *Nature Neuroscience*, 22, 297-306.

Week 10. Models of Reasoning and Problem Solving

- Mnih, V., Kavukcuoglu, K., …, Hassabis, D. (2015). Human-level control through deep reinforcement learning. *Nature*, 518, 529-533.
- Song, H., Lu, Q., Nguyen, T. T., Chen, J., Leong, Y. C., Rosenberg, M. D., Ching, S., Zacks, J. M. (2025). A neural network with episodic memory learns causal relationships between narrative events. *bioRxiv*.

Week 11. Models of Social Interaction

- Park, S. A., Miller, D. S., Boorman, E. D. (2021). Inferences on a multidimensional social hierarchy use a grid-like code. *Nature Neuroscience*, 24, 192-1301.
- Zada, Z., Nastase, S., Speer, S., Mwilambwe-Tshilobo, L., Tsoi, L., Burns, S., Falk, E., Hasson, U., & Tamir, D. (2025). Linguistic coupling between neural systems for speech production and comprehension during real-time dyadic conversations. *bioRxiv*.

Week 12. Students' Choice

- TBD
- TBD

Week 13. Students' Choice

- TBD
- TBD