Neuro 145 / MCB 145
Neurobiology of Perception and Decision-Making

COURSE SYLLABUS

2024 Fall / Full Term

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Lectures: Half course (fall term)
Tuesday & Thursday (10:30 – 11:45)
Location: TBA

Prerequisites: MCB80 Neurobiology of Behavior or with the instructor's permission.

Objectives: One of the foremost goals of neuroscience is to understand the neural circuits underlying perception and behavior. Recent advances have allowed us to record, image, and manipulate the brain, giving us unprecedented access to the neuronal processes that transform sensory stimuli into perception, and perception into behavior. How is sensory information processed in the brain? How does an animal choose its actions? How does an animal learn from ever-changing environments and adjust its behavior? The course will examine neurophysiological studies in perception and decision-making.

Website: https://canvas.harvard.edu/courses/140965

Goals:

1. To learn an exciting, multidisciplinary approach to decision science, encompassing not only neuroscience but also behavioral economics, psychology and machine learning.
2. To learn the tenets of electrophysiological experiments using animal models (mainly non-human primates but also rodents). We will cover some studies using functional imaging techniques in humans but will have less emphasis.
3. To develop critical reading skills to assess scientific literature.
4. To develop the tools to explore the subject further on your own.
5. To appreciate the scientific processes and have fun!

Format: The course consists of weekly lectures, and paper discussions. The lecture component (Thursdays) is followed by paper discussions (Tuesdays) where students read 1-2 papers relevant to the previous lecture, and discuss in the classroom. Before paper discussions, students are asked to write a short report on one of the assigned papers (750-1,200 words). The report should be sent to both the instructor and the teaching fellow via e-mail by midnight the day before class. In lieu of submitting a report, a student can present a paper in the discussion section. Presenting in class will make the student eligible for 5 extra-credit points (i.e., 105 points for that week).

Hours: By appointment.

Grading:

Weekly short reports (News & Views style)*	40 %
Class participation (discussions)**	20 %
Term paper (Grant proposal)***	40 %

* Reports should include background, pertinent results, an evaluation of the paper, and suggestions for future directions. (see the guideline for weekly reports). Reports will be graded based on their accuracy (30%), insights (30%), future experiments or suggestions (10%), and writing (30%). There will be 9 weekly reports, and we will use the 8 best reports for final grading. Students can either disregard their worst report or choose not to submit one report.

** Attendance and active participation are expected. Attendance in all classes and sessions is required. Two unexcused absences throughout the semester will result in the drop of a whole letter grade. Absences will only be excused if 1) you contact us in advance of the absence; and 2) you complete an additional assignment that we agree upon in lieu of your participation in that class.

*** Final reports will be graded based on creativity (30%), accuracy (30%), insight (10%) and writing/execution (30%).

Policy: We encourage you to discuss your assignments in study groups with your classmates, but the reports you submit must be written in your own words and reflect your own thinking. We expect students to know that it is never appropriate to copy text verbatim from any source. Please read the Guide to Using and Citing Sources (link below). We expect that you understand that turning in work not written in your own words constitutes plagiarism. Any cases of suspected plagiarism will be handled in accordance with University policy and referred to the Harvard College Administrative Board.

Writing guides: https://lifesciences.fas.harvard.edu/writing-guides

Contents:

0. Introduction: overview of the course

1. Early visual processing

What happens when sensory information enters the brain? Sensory systems "extract" particular features and "process" information. Using the early visual pathway, we study key concepts such as the receptive field and efficient coding. We also explore various illusions, and learn how they advance our understanding of the sensory system. How do receptive field properties of neurons relate to what we see?

2. Object recognition, artificial neural networks

Modern artificial neural networks (ANNs) achieve impressive performance in various complex tasks. Some of the ideas in ANNs come from how neurons and circuits work in the brain. A type of ANNs, called convolutional neural network (CNN) or deep learning, mimics the brain's visual system. How the ANNs work has also provided great insights into how the brain works. Here we learn the history of ANNs, focusing on CNN or deep learning, and compare them with the visual system in the brain.

3. Single neurons and perception

Electrophysiological recordings of single neurons in *awake* animals have provided a basis for linking neurons to perception. We will review classic studies that recorded neural activity while monkeys performed visual tasks. Using data as our backdrop, we will learn how signal detection theory provides a theoretical framework for the relationship between neural activity and psychophysics.

4. Neural mechanism of perceptual decisions

How is sensory information used to guide animals' actions? We will examine "decision"-related activity in higher brain areas such as the parietal cortex. We will also learn mathematical tools to study decision-making, including drift diffusion models or neural integrators.

5. Behavioral economics

Theoretical and experimental studies of decision-making developed in economics and psychology provide frameworks to explore the neural basis of decision-making. We will discuss utility theory, game theory, and prospect theory developed in economics. How do human behaviors differ from "normative" (rational) behavior? We will learn humans' intrinsic preferences in risk.

6. Reinforcement learning and dopamine neurons

Reinforcement learning theories, developed in the field of artificial intelligence or machine learning, explore algorithms to train machines (or "agents") to maximize reward based on trial-and-error. This type of learning algorithm provides a theoretical framework for reward-based learning in animals. We will examine how reward is processed in the brain. Studies of neurons that use dopamine as a neurotransmitter have provided a basis for bridging biological processes of reward-based learning with learning theories developed in machine learning.

7. Model-based reinforcement learning and planning

It is thought that the animal learns the structure of the environment, often referred to as internal models or cognitive maps of the environment. The ability to "simulate" based on these models allows the animal to efficiently learn and make decisions without directly observing the potential outcomes.

8. Neural circuit mechanisms: neural dynamics

How can we understand the mechanism of decision-making at the detailed neural circuit level? The brain consists of neurons that interact with one another through complex neural circuits.

There is an increasing interest in understanding the brain function as a result of emerging properties at the level of neuronal population. We will discuss concepts of attractor and dynamical systems approaches. We will also discuss new approaches for studying the neural circuits using detailed connectivity diagrams called connectomes.

9. Decision-making across time

Many of our decisions involve choosing actions across time. Should I go to a party now or prepare for the exam next week? May I eat chocolate or should I exercise? Should I stay in the party or leave and do something else? We will discuss experimental findings and theories on inter-temporal choice, foraging decisions, and self-control.

10. Neuroscience and society

Our understanding of how the brain selects actions and controls movements may help develop novel techniques for brain-computer interfaces to restore movements and communications in patients with motor and speech disorders. We will discuss how neuroscience has impacted on such technologies.

Reading list:

- Required readings for weekly reports and discussions are marked by asterisks (*).
- Other papers are recommended readings for deeper understanding of the subject.
- No textbook is required.

Books:

- Foundations of Neuroeconomic Analysis, by Paul Glimcher, Oxford University Press, 2010
- Thinking, Fast and Slow, by Daniel Kahneman, Farrar, Straus and Giroux, 2011
- Principles of Neural Science, by Eric Kandel, John D. Koester 1, Sarah H. Mark, Steven A. Siegelbaum, McGraw-Hill Medical; 6th edition, 2021
- Principles of Neurobiology, by Liqun Luo, CRC Press; 2nd edition, 2021
- Dreher, J. C., & Tremblay, L. (Eds.). (2016). Decision Neuroscience: An Integrative Perspective. Academic Press.

References:

0. Introduction

- Ruff, C. C., & Huettel, S. A. (2013). Experimental methods in cognitive neuroscience. Neuroeconomics: Decision making and the brain, 2, 77-108.

1. Early visual processing [No report is required]

*- Hubel DH, Wiesel TN., (1962) Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. J Physiol., 160:106-54.

*- Reid, R.C., and Alonso, J.M. (1995). Specificity of monosynaptic connections from thalamus to visual cortex. Nature 378, 281–284.

- Hubel DH, Wiesel TN. (1959) Receptive fields of single neurones in the cat's striate cortex. J Physiol., 148:574-91.

- Lien, A.D., and Scanziani, M. (2013). Tuned thalamic excitation is amplified by visual cortical circuits. Nat. Neurosci. 16, 1315–1323.

- Fukushima, K. (1980). Neocognitron: A self-organizing neural network model for a mechanism of pattern recognition unaffected by shift in position. Biol. Cybern. 36, 193–202.

- Olshausen and Field (1996) Emergence of simple-cell receptive field properties by learning a sparse code for natural images. Nature, 381(6583): 607-9.

- Carandini, M., and Heeger, D.J. (2012). Normalization as a canonical neural computation. Nat. Rev. Neurosci. 13, 51–62.

2. Object recognition, artificial neural networks [No report is required]

*- Quiroga, R.Q., Reddy, L., Kreiman, G., Koch, C., and Fried, I. (2005). Invariant visual representation by single neurons in the human brain. Nature 435, 1102–1107.

*- Chang, L., and Tsao, D.Y. (2017). The Code for Facial Identity in the Primate Brain. Cell 169, 1013-1028.e14.

- Tanaka, K. (1996). Inferotemporal cortex and object vision. Annu. Rev. Neurosci. 19, 109–139.

- Freiwald, W.A., Tsao, D.Y., and Livingstone, M.S. (2009). A face feature space in the macaque temporal lobe. Nat. Neurosci. 12, 1187–1196.

- Hesse, J.K., and Tsao, D.Y. (2020). The macaque face patch system: a turtle's underbelly for the brain. Nat. Rev. Neurosci. 21, 695–716.

- DiCarlo, J.J., Zoccolan, D., and Rust, N.C. (2012). How does the brain solve visual object recognition? Neuron 73, 415–434.

- LeCun, Y., Bengio, Y., and Hinton, G. (2015). Deep learning. Nature 521, 436–444.

- 3Blue1Brown Series. (2017) Neural Networks Series, S3, E1-E4. https://www.youtube.com/playlist?list=PLZHQObOWTQDNU6R1_67000Dx_ZCJB-3pi

- Yamins, D.L.K., Hong, H., Cadieu, C.F., Solomon, E.A., Seibert, D., and DiCarlo, J.J. (2014). Performance-optimized hierarchical models predict neural responses in higher visual cortex. Proc. Natl. Acad. Sci. U.S.A. 111, 8619–8624.

- Lindsay Grace (2018) Deep Convolutional Neural Networks as Models of the Visual System: Q&A. https://neurdiness.wordpress.com/2018/05/17/deep-convolutional-neural-networks-as-models-of-the-visual-system-qa/

3. Single neurons and perception

*- Salzman CD, Britten KH, Newsome WT. (1990) Cortical microstimulation influences perceptual judgements of motion direction. Nature, 346(6280):174-7.

*- Marshel, J.H., Kim, Y.S., Machado, T.A., Quirin, S., Benson, B., Kadmon, J., Raja, C., Chibukhchyan, A., Ramakrishnan, C., Inoue, M., et al. (2019). Cortical layer-specific critical dynamics triggering perception. Science 365, eaaw5202.

- Parker AJ, Newsome WT. (1998) Sense and the single neuron: probing the physiology of perception. Annu Rev Neurosci., 21:227-77. Review.

- Newsome WT, Britten KH, Movshon JA. (1989) Neuronal correlates of a perceptual decision. Nature, 341(6237):52-4.

- Britten, K.H., Shadlen, M.N., Newsome, W.T., and Movshon, J.A. (1992). The analysis of visual motion: a comparison of neuronal and psychophysical performance. J. Neurosci. 12, 4745–4765.

- Britten KH, Newsome WT, Shadlen MN, Celebrini S, Movshon JA. (1996) A relationship between behavioral choice and the visual responses of neurons in macaque MT. Vis Neurosci., 13(1):87-100.

- Shadlen MN, Britten KH, Newsome WT, Movshon JA. (1996) A computational analysis of the relationship between neuronal and behavioral responses to visual motion. J Neurosci., 16(4):1486-510.

- Heeger DH. Signal Detection Theory.

- Dayan and Abbott, Chapter 3. Neural decoding, Theoretical Neuroscience, Computational and Mathematical Modeling of Neural Systems, MIT Press.

4. Neural mechanisms of perceptual decisions

*- Stine, G.M., Trautmann, E.M., Jeurissen, D., and Shadlen, M.N. (2023). A neural mechanism for terminating decisions. Neuron 111, 2601-2613.e5.

*- Evans, D.A., Stempel, A.V., Vale, R., Ruehle, S., Lefler, Y., and Branco, T. (2018). A synaptic threshold mechanism for computing escape decisions. Nature 558, 590–594.

- Gold JI, Shadlen MN., (2007) The neural basis of decision making. Annu Rev Neurosci. 2007;30:535-74. Review.

- Uchida N, Kepecs A, Mainen ZF. (2006) Seeing at a glance, smelling in a whiff: rapid forms of perceptual decision making. Nat Rev Neurosci., 7(6):485-91.

- Hanks TD, Summerfield C. (2017) Perceptual decision making in rodents, monkeys, and humans. Neuron, 93(1):15-31.

- Najafi, F., and Churchland, A.K. (2018). Perceptual Decision-Making: A Field in the Midst of a Transformation. Neuron 100, 453–462.

5. Behavioral economics (decisions under risk)

*- Kahneman, D. and Tversky, A. (1979) "Prospect Theory: An Analysis of Decision under Risk", Econometrica, XLVII (1979), 263-291.

- De Martino B, Kumaran D, Seymour B, Dolan RJ. (2006) Frames, biases, and rational decision-making in the human brain. Science, 313(5787):684-7.

- Kahneman, D. (2002) Maps of bounded rationality: a perspective on intuitive judgment and choice. Nobel Prize Lecture.

- Kahneman, D. (2002) Prize Lecture video (http://nobelprize.org/mediaplayer/index.php?id=531).

- Camerer, CF. (1998) Prospect theory in the wild. Evidence from the field.

- Constantinople, C.M., Piet, A.T., and Brody, C.D. (2019). An Analysis of Decision under Risk in Rats. Curr. Biol. 29, 2066-2074.e5.

6. Reinforcement learning, reward and dopamine neurons

*- Waelti, P., Dickinson, A., and Schultz, W. (2001). Dopamine responses comply with basic assumptions of formal learning theory. Nature 412, 43–48.

*- Kim, H.R., Malik, A.N., Mikhael, J.G., Bech, P., Tsutsui-Kimura, I., Sun, F., Zhang, Y., Li, Y., Watabe-Uchida, M., Gershman, S.J., and Uchida, N. (2020). A Unified Framework for Dopamine Signals across Timescales. Cell 183, 1600-1616.e25.

- Schultz W, Dayan P, Montague PR. (1997) A neural substrate of prediction and reward. Science, 275(5306):1593-9. Review.

- Watabe-Uchida, M., Eshel, N., and Uchida, N. (2017). Neural Circuitry of Reward Prediction Error. Annu. Rev. Neurosci. 40, 373–394.

- Cohen JY, Haesler S, Vong L, Lowell BB, Uchida N. (2012) Neuron-type-specific signals for reward and punishment in the ventral tegmental area. Nature. Feb 2;482(7383):85–88.

- Eshel, N., Bukwich, M., Rao, V., Hemmelder, V., Tian, J., and Uchida, N. (2015). Arithmetic and local circuitry underlying dopamine prediction errors. Nature 525, 243–246

- Steinberg, E.E., Keiflin, R., Boivin, J.R., Witten, I.B., Deisseroth, K., and Janak, P.H. (2013). A causal link between prediction errors, dopamine neurons and learning. Nat. Neurosci. 16, 966–973.

- Menegas, W., Akiti, K., Amo, R., Uchida, N., and Watabe-Uchida, M. (2018). Dopamine neurons projecting to the posterior striatum reinforce avoidance of threatening stimuli. Nat. Neurosci. 21, 1421–1430.

- Lowet, A.S., Zheng, Q., Matias, S., Drugowitsch, J., and Uchida, N. (2020). Distributional Reinforcement Learning in the Brain. Trends Neurosci. 43, 980–997.

7. Model-based reinforcement learning and planning

*- Widloski, J., and Foster, D.J. (2022). Flexible rerouting of hippocampal replay sequences around changing barriers in the absence of global place field remapping. Neuron 110, 1547-1558.e8.

*- Harten, L., Katz, A., Goldshtein, A., Handel, M., and Yovel, Y. (2020). The ontogeny of a mammalian cognitive map in the real world. Science 369, 194–197.

- Balleine BW, Daw ND, O'Doherty JP. (2009) Multiple forms of value learning and the function of dopamine, in Neuroeconomics: Decision making and the brain

- Doya K. (2000) Complementary roles of basal ganglia and cerebellum in learning and motor control. Curr Opin Neurobiol., 10(6):732-9. Review.

- Johnson A, Redish AD. (2007) Neural ensembles in CA3 transiently encode paths forward of the animal at a decision point. J Neurosci., 27(45):12176-89.

- Pfeiffer, B.E., and Foster, D.J. (2013). Hippocampal place-cell sequences depict future paths to remembered goals. Nature 497, 74–79.

- Behrens, T.E.J., Muller, T.H., Whittington, J.C.R., Mark, S., Baram, A.B., Stachenfeld, K.L., and Kurth-Nelson, Z. (2018). What Is a Cognitive Map? Organizing Knowledge for Flexible Behavior. Neuron 100, 490–509.

- Mattar, M.G., and Lengyel, M. (2022). Planning in the brain. Neuron 110, 914–934.

Reading on additional topics:

Addiction:

*- Pascoli, V., Hiver, A., Van Zessen, R., Loureiro, M., Achargui, R., Harada, M., Flakowski, J., and Lüscher, C. (2018). Stochastic synaptic plasticity underlying compulsion in a model of addiction. Nature 564, 366–371.

Exploration / Novelty seeking:

*- Ogasawara, T., Sogukpinar, F., Zhang, K., Feng, Y.-Y., Pai, J., Jezzini, A., and Monosov, I.E. (2022). A primate temporal cortex-zona incerta pathway for novelty seeking. Nat. Neurosci. 25, 50–60.

8. Neural circuit mechanisms

*- Kaufman, M.T., Churchland, M.M., Ryu, S.I., and Shenoy, K.V. (2014). Cortical activity in the null space: permitting preparation without movement. Nat. Neurosci. 17, 440–448.

*- Li, N., Chen, T.-W., Guo, Z.V., Gerfen, C.R., and Svoboda, K. (2015). A motor cortex circuit for motor planning and movement. Nature 519, 51–56.

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

*- Kim, S.S., Rouault, H., Druckmann, S., and Jayaraman, V. (2017). Ring attractor dynamics in the Drosophila central brain. Science 356, 849–853.

- Strogatz, S.H., (2018) Nonlinear Dynamics and Chaos. 2nd Edition. CRC Press.

- Wang, X. J. (2013). Neuronal circuit computation of choice. In Neuroeconomics: Decision Making and the Brain: Second Edition. Elsevier Inc..

- Churchland, M.M., and Shenoy, K.V. (2024). Preparatory activity and the expansive null-space. Nat. Rev. Neurosci. 25, 213–236.

- Svoboda, K., and Li, N. (2018). Neural mechanisms of movement planning: motor cortex and beyond. Curr. Opin. Neurobiol. 49, 33–41.

- Inagaki, H.K., Chen, S., Daie, K., Finkelstein, A., Fontolan, L., Romani, S., and Svoboda, K. (2022). Neural Algorithms and Circuits for Motor Planning. Annu. Rev. Neurosci. 45, 249–271.

- Khona, M., and Fiete, I.R. (2022). Attractor and integrator networks in the brain. Nat. Rev. Neurosci. 23, 744–766.

9. Decision-making across time: inter-temporal choice, foraging etc.

- McGuire, J.T., and Kable, J.W. (2015). Medial prefrontal cortical activity reflects dynamic re-evaluation during voluntary persistence. Nat. Neurosci. 18, 760–766. https://doi.org/10.1038/nn.3994.

*- Bukwich, M., Campbell, M.G., Zoltowski, D., Kingsbury, L., Tomov, M.S., Stern, J., Kim, H.R., Drugowitsch, J., Linderman, S.W., and Uchida, N. (2023). Competitive integration of time and reward explains value-sensitive foraging decisions and frontal cortex ramping dynamics. BioRxiv Prepr. Serv. Biol., 2023.09.05.556267.

- Mischel, W., Shoda, Y., and Rodriguez, M.I. (1989). Delay of gratification in children. Science 244, 933–938.

- Kable, J. W. (2014). Valuation, intertemporal choice, and self-control. *Neuroeconomics*, 173-192.

- McGuire, J., and Kable, J. (2016). Deciding to curtail persistence. Handb. Self-Regul. Res. Theory Appl., 533–546.

- Stephens, D. W., & Krebs, J. R. (1986). *Foraging theory* (Vol. 6). Princeton University Press.

- Hayden, B.Y., Pearson, J.M., and Platt, M.L. (2011). Neuronal basis of sequential foraging decisions in a patchy environment. Nat. Neurosci. 14, 933–939.

10. Neuroscience and society [No report is required]

*- Sadtler, P.T., Quick, K.M., Golub, M.D., Chase, S.M., Ryu, S.I., Tyler-Kabara, E.C., Yu, B.M., and Batista, A.P. (2014). Neural constraints on learning. Nature 512, 423–426.

*- Willett, F.R., Avansino, D.T., Hochberg, L.R., Henderson, J.M., and Shenoy, K.V. (2021). High-performance brain-to-text communication via handwriting. Nature 593, 249–254.

- Fetz, E.E. (1969). Operant conditioning of cortical unit activity. Science 163, 955–958. https://doi.org/10.1126/science.163.3870.955.

- Fetz, E.E., and Baker, M.A. (1973). Operantly conditioned patterns on precentral unit activity and correlated responses in adjacent cells and contralateral muscles. J. Neurophysiol. 36, 179–204. https://doi.org/10.1152/jn.1973.36.2.179.

- Orsborn, A.L., and Pesaran, B. (2017). Parsing learning in networks using brain-machine interfaces. Curr. Opin. Neurobiol. 46, 76–83.

- Hennig, J.A., Oby, E.R., Losey, D.M., Batista, A.P., Yu, B.M., and Chase, S.M. (2021). How learning unfolds in the brain: toward an optimization view. Neuron 109, 3720–3735.

- Gupta, A., Vardalakis, N., and Wagner, F.B. (2023). Neuroprosthetics: from sensorimotor to cognitive disorders. Commun Biol 6, 14.

- Metzger, S.L., Littlejohn, K.T., Silva, A.B., Moses, D.A., Seaton, M.P., Wang, R., Dougherty, M.E., Liu, J.R., Wu, P., Berger, M.A., et al. (2023). A high-performance neuroprosthesis for speech decoding and avatar control. Nature 620, 1037–1046.

Schedule:

0	9/3	Tuesday	**Introduction**
1	9/5	Thursday	**Early visual processing**
	9/10	Tuesday	Hubel & Wiesel (1962); Reid & Alonso (1995)
2	9/12	Thursday	**Introduction to artificial neural networks**
	9/17	Tuesday	Quiroga et al. (2005); Chang and Tsao (2017)
3	9/19	Thursday	**Single neurons and perception**
	9/24	Tuesday	Salzman et al. (1990); Marshel et al. (2019)
4	9/26	Thursday	**Neural mechanism of perceptual decisions**
	10/1	Tuesday	Stine et al. (2023); Evans et al. (2018)
5	10/3	Thursday	**Behavioral economics**
	10/8	Tuesday	Kahneman and Tversky (1979)
6	10/10	Thursday	**Reinforcement learning (1)**
	10/15	Tuesday	Waelti et al. (2001); Kim et al. (2020)
	10/17	Thursday	**Reinforcement learning (2)**
7	10/22	Tuesday	**Model-based reinforcement learning and planning**
	10/24	Thursday	Widloski and Foster (2022); Harten et al. (2020)
	10/29	Tuesday	Pascoli et al. (2018); Ogasawara et al. (2022)
8	10/31	Thursday	**Neural circuits (1)**
	11/5	Tuesday	**Neural circuits (2)**
	11/7	Thursday	Kaufman et al. (2014); Li et al. (2015)
	11/12	Tuesday	Mante et al. (2013); Kim et al. (2017)
9	11/14	Thursday	**Decision making across time**
	11/19	Tuesday	McGuire & Kable (2015); Bukwich et al. (2023)
10	11/21	Thursday	**Neuroscience and society**
	11/26	Tuesday	Sadtler et al. (2014); Willett et al. (2021)
	11/28	Thursday	Thanksgiving (11/27-12/1)
	12/3	Tuesday	**Overview and synthesis**

Weekly reports: Summary of a paper (750 – 1,200 words)

You will be asked to write a short summary of one of the assigned papers. Your summary should contain the following:

1. **Background**. What are the major questions addressed by the paper? Why is this paper significant, and where does it fit relative to the state of the field? Try to link the questions of this paper to the lecture material discussed in class this week.

2. **Experimental design and results**. Explain the most important experiments described in the paper. What is the method used? What results did the authors get? How was the data analyzed? You do not have to describe all control experiments.

3. **Conclusions**. What are the major conclusions of the paper? Do the results support the conclusions?

4. **Caveats of the experiments and/or future experiments**. Please point out any weaknesses of the paper. What experiments would address remaining questions? What questions should be considered in the future?

5. **Questions.** If you have questions after reading the paper, please include them.

Final Project: Grant proposal

- Students write a grant proposal for future experiments that will advance our understanding of neurobiology of perception and/or decision-making.
- The goal of this assignment is to demonstrate that you understand the current state of the field and can devise creative experiments to advance the field. Feasibility should be considered (for example, if you propose imaging more than 1000 neurons simultaneously with the time resolution of 1 ms, the method should be clearly laid out), but the importance of the questions outweighs feasibility.
- Should contain Specific Aims, Research Strategy and References (see below).
- Students must obtain approval for their topics from the instructor or a TA by November 12.
- The term paper is due by December 9.

Specific Aims (1 page)

- Should include 1 or 2 specific aims (subgoals) of the proposal. These define the specific questions or hypothesis to be pursued.
- State concisely the goals of the proposed research and summarize the expected outcome(s), including the impact that results of the proposed research will exert on the research field(s) involved. The summary of impact can be captured as a paragraph (2-3 sentences) at the conclusion of the Specific Aim section.

Research Strategy (3-5 pages not including Bibliography and References cited)

- Should include Significance and Approach as explained below.
- Cite published studies in the Research Strategy and provide full reference in the References section.

(a) Significance

- Background (current status of the field). Explain importance of the problem or critical barrier to progress in the field that the proposed project addresses.
- Significance. Explain how proposal will improve scientific knowledge, technical capability in one or more broad fields.

(b) Approach

- Describe the overall experimental methods and strategy to be used to accomplish the specific aims of the project.
- Discuss data analysis, potential problems, alternative strategies and benchmarks for success anticipated to achieve the aim.
- It may contain Specific Aims, Rationale, Hypotheses, Methods, Expected outcomes, Pitfalls and Solutions.