

Elizabeth E. Steinberg
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Summary of Research Accomplishments

I seek to understand how psychological processes such as motivation, emotion and learning are implemented and integrated in the brain to produce seamless, flexible behavior. The long-term goal of this research is to generate mechanistic insights that can be leveraged to improve treatments for addiction and other forms of mental illness.

As a graduate student in Patricia Janak's lab at UCSF, I identified causal roles for dopamine neurons in reinforcement learning. I demonstrated that enhancing dopamine neuron activity during a reward-predictive cue, mimicking a natural prediction error, is sufficient to drive Pavlovian learning (*Steinberg*, Keiflin* et al., Nat. Neuro. 2013*), bridging a critical gap between influential theoretical frameworks and experimental evidence. I also showed that dopamine neuron activation could drive instrumental learning (*Witten*, Steinberg* et al., Neuron 2011*), an effect that requires D1 and D2 receptor activation in ventral striatum (*Steinberg et al., PLoS ONE 2014*).

As a postdoctoral fellow in Robert Malenka's lab at Stanford University, I study how interactions between the central amygdala and substantia nigra contribute to motivation and emotion. I found that artificial activation of amygdalonigral projections engages strong motivational drives and supports reinforcement learning. During natural behavior, amygdalonigral neurons and nigral dopamine neurons are excited by rewarding and aversive events. Collectively, my data indicate that amygdalonigral salience signals instruct instrumental learning via disinhibition (*Steinberg et al., in preparation*), revealing a novel circuit mechanism for linking emotion, motivation and action.

Education and Postgraduate Training

Postdoctoral Fellowship Present
Stanford University, Department of Psychiatry and Behavioral Sciences
Research advisor: Dr. Robert Malenka

Ph.D., Neuroscience 2013
UCSF, Ernest Gallo Clinic and Research Center
Research advisor: Dr. Patricia Janak
Thesis committee: Drs. Howard Fields, Loren Frank, Linda Wilbrecht, Antonello Bonci

B.A., Neuroscience, Summa Cum Laude 2004
Columbia University
Major: Neuroscience and Behavior, Minor: Philosophy

Research Fellowships

National Institutes of Health Pathway to Independence Award (K99/R00), NIMH 2018 – 2023
A.P. Giannini Foundation Postdoctoral Research Fellowship – Accepted 2015 – 2018
National Research Service Award Individual Postdoctoral Fellowship (F32), NIDA – Awarded 2015 – 2018
Stanford University Dean's Postdoctoral Fellowship 2014
National Science Foundation Graduate Research Fellowship 2007 – 2010

Honors and Awards

Society for Neuroscience Trainee Professional Development Award 2017
Poster Prize, Gordon Research Conference: Amygdala Function in Emotion, Cognition and Disease 2017
Allison Doupe Travel Fellowship to attend McKnight Endowment Fund Annual Conference 2016
Helena Anna Henzl-Gabor Postdoctoral Travel Grant 2015
UCSF Graduate Research Award 2012
Poster Prize, FENS-IBRO School "Causal Neuroscience: Interacting with Neural Circuits" 2011
Earle C. Anthony Travel Award 2011
Summa Cum Laude, Columbia College 2004
Phi Beta Kappa Honor Society, Columbia College 2004
Honors in Biological Science, Columbia College 2004
Dean's List, Columbia College 2000 – 2004

Research Experience

- Stanford University, Laboratory of Dr. Robert Malenka** 2013 – Present
Postdoctoral fellow
Research interests: Amygdala and dopamine-dependent mechanisms of emotion and motivation
Key techniques: Fiber photometry, *ex vivo* physiology, single-cell qPCR, viral-genetic tracing, behavioral optogenetics and pharmacology
- Cold Spring Harbor Laboratory, Ion Channels and Synaptic Transmission** 2013
Course participant
Key techniques: *In vitro* and *ex vivo* physiology
- UCSF, Laboratory of Dr. Patricia Janak** 2007 – 2013
Graduate student
Research interests: Functional role of VTA dopamine neurons in reinforcement learning
Key techniques: Behavioral optogenetics and pharmacology, *in vivo* physiology
- UCSF, Laboratory of Dr. Michael Stryker** 2007
Rotation student
Research interests: Molecular determinants of experience-dependent visual cortical plasticity
Key techniques: Intrinsic signal optical imaging
- UCSF, Laboratory of Dr. Allison Doupe** 2007
Rotation student
Research interests: Role of activity-regulated cytoskeleton-associated protein (ARC) in vocal learning
Key techniques: Avian behavior, immunohistochemistry
- UCSF, Laboratory of Dr. Nirao Shah** 2006
Rotation student
Research interests: Role of Aromatase in sexually dimorphic behaviors
Key techniques: Cloning
- University of Auckland, Laboratory of Drs. Deborah Young and Matthew During** 2004 – 2006
Research technician
Research interests: Gene therapy interventions for Parkinson's disease
Key techniques: *In vivo* viral gene transfer, rat behavior, histology
- Columbia University, Laboratory of Dr. Eric Kandel** 2002 – 2004 (academic year)
Volunteer
Research interests: Neural abnormalities associated with fragile X mental retardation 1 (FMR1) mutation
Key techniques: Immunohistochemistry, *in situ* hybridization, cloning
- UCSF, Laboratory of Dr. Michael Merzenich** 2002 – 2003 (summers)
Volunteer
Research interests: Role of attention in directing auditory cortical map plasticity
Key techniques: Rat behavior

Publications

* Denotes equal contribution

Research articles

Steinberg EE, Gore F, Heifets BD, Beier KT, Taylor MD, Földy C, Lerner TN, Luo L, Deisseroth K, Malenka RC. Amygdala nigral salience signals shape instrumental learning. *In preparation*.

Berndt A*, Lee SY*, Wietek J, Ramakrishnan C, **Steinberg EE**, Rashid AJ, Kim H, Park S, Santoro A, Frankland PW, Iyer SM, Pak S, Åhrlund-Richter S, Delp SL, Malenka RC, Josselyn SA, Carlén M, Hegemann P, Deisseroth K. Structural foundations of optogenetics: Determinants of channelrhodopsin ion selectivity. *PNAS*. 2015 Dec 22. PMID: 26699459.

Beier KT, **Steinberg EE**, DeLoach KE, Xie S, Miyamichi K, Schwarz L, Gao XJ, Kremer EJ, Malenka RC, Luo L. Circuit Architecture of VTA Dopamine Neurons Revealed by Systematic Input-Output Mapping. Cell. 2015 Jul 30; 162(3):622-34. PMID: 26232228.

Lammel S*, **Steinberg EE***, Földy C*, Wall NR, Beier K, Luo L, Malenka RC. Diversity of transgenic mouse models for selective targeting of midbrain dopamine neurons. Neuron. 2015 Jan 21; 85(2):429-38. PMID: 25611513.

Recommended by F1000

Steinberg EE, Boivin JR, Saunders BT, Witten IB, Deisseroth K and Janak PH. Positive reinforcement mediated by midbrain dopamine neurons requires D1 and D2 receptor activation in the nucleus accumbens. PLoS ONE. 2014 April 14; 9(4): e94771. PMID: 24733061.

Steinberg EE*, Keiflin R*, Boivin JR, Witten IB, Deisseroth K, Janak PH. A causal link between prediction errors, dopamine neurons and learning. Nature Neuroscience. 2013 July; 16(7): 966-73. PMID: 23708143.

Recommended by F1000

**News and Views by Schoenbaum, Esber and Iordanova,
Spotlight article by Eshel, Tian and Uchida in Trends in Cog. Sci.**

Witten IB*, **Steinberg EE***, Lee SY, Davidson TJ, Zalocusky KA, Brodsky M, Yizhar O, Cho SL, Gong S, Ramakrishnan C, Stuber GD, Tye KM, Janak PH, Deisseroth K. Recombinase-driver rat lines: tools, techniques, and optogenetic application to dopamine-mediated reinforcement. Neuron. 2011 Dec 8; 72(5):721-33. PMID: 22153370.

Recommended by F1000

Polley DB, **Steinberg EE**, Merzenich MM. Perceptual learning directs auditory cortical map reorganization through top-down influences. Journal of Neuroscience. 2006 May 3; 26(18): 4970-82. PMID: 16672673.

Review articles and commentary

Eshel N, **Steinberg EE**. Learning what to approach. PLoS Biology. 2018 Oct; 16(10). PMID: 30307969.

Steinberg EE, Christoffel DJ, Deisseroth K, Malenka RC. Illuminating circuitry relevant to psychiatric disorders with optogenetics. Current Opinion in Neurobiology. 2015 Feb; 30C: 9-16. PMID: 25215625.

Steinberg EE, Janak PH. Establishing causality for dopamine in neural function and behavior with optogenetics. Brain Research. 2013 May 20; 1511:46-64. PMID: 23031636.

Presentations

Invited Talks

Gordon Research Conference on Optogenetic Approaches to Understanding Neural Circuits and Behavior. "Amygdalonigral salience signals shape instrumental learning" (2018).

Northwestern University, Department of Physiology. "Linking emotion, motivation and action with amygdalonigral circuits" (2018).

University of Zurich Brain Research Institute. "A selective role for amygdalonigral projections in reward learning" (2016).

Ernest Gallo Clinic and Research Center Annual Retreat. "Exploiting individual differences in incentive cue responding" (2012).

Ernest Gallo Clinic and Research Center Annual Retreat. "Techniques for optical stimulation in awake behaving rats" (2009).

Selected Posters

Steinberg EE, Gore F, Heifets BD, Beier KT, Földy C, Lerner TN, Taylor MD, Luo L, Deisseroth K, Malenka RC. Amygdalonigral salience signals drive instrumental learning. POSTER, *Society for Neuroscience Annual Meeting* (2017).

Steinberg EE, Gore F, Heifets BD, Beier KT, Földy C, Lerner TN, Taylor MD, Luo L, Deisseroth K, Malenka RC. Amygdalonigral salience signals shape action-outcome associations. POSTER, *Gordon Research Conference on Amygdala Function in Emotion, Cognition and Disease* (2017).

Steinberg EE, Beier KT, Taylor MD, Földy C, Lerner TN, Deisseroth K, Luo L, Malenka RC. A selective role for amygdalonigral projections in reward learning. POSTER, *Dopamine Triennial Meeting* (2016).

Steinberg EE, Beier KT, Taylor MD, Földy C, Luo L, Malenka RC. Anatomical, genetic and behavioral dissection of an amygdala-midbrain circuit. POSTER, *McKnight Fund Annual Conference* (2016).

Lammel S, **Steinberg EE**, Földy C, Wall NR, Beier K, Malenka RD. Optogenetic dissection of the mesohabenular projection system in mice. POSTER, *Society for Neuroscience Annual Meeting* (2014).

Steinberg EE, Keiflin R, Witten IB, Margolis EB, Tye KM, Deisseroth K, Janak PH. Optogenetics in transgenic rats: establishing causal roles for VTA dopamine neurons in learned appetitive behaviors. POSTER, *Society for Neuroscience Annual Meeting* (2012).

Steinberg EE, Keiflin R, Witten IB, Margolis EB, Tye KM, Deisseroth K, Janak PH. Establishing causal roles for VTA DA neurons in learned appetitive behaviors. POSTER, *Optogenetics and Pharmacogenetics in Neuronal Function and Dysfunction Elsevier Brain Research Conference* (2012).

Steinberg EE, Witten IB, Keiflin R, Cho SL, Tye KM, Zalocusky K, Brodsky M, Olsman M, Gong S, Stuber GD, Deisseroth K, Janak PH. Establishing causal roles for VTA DA neurons in learned appetitive behaviors. POSTER, *Gordon Research Conference on Catecholamines* (2011).

Steinberg EE, Witten IB, Keiflin R, Cho SL, Tye KM, Zalocusky K, Brodsky M, Olsman M, Gong S, Stuber GD, Deisseroth K, Janak PH. Establishing causal roles for VTA DA neurons in learned appetitive behaviors. POSTER, *FENS-IBRO School: Causal Neuroscience: Interacting with Neural Circuits* (2011).

Teaching, Mentoring and Service

Ad-hoc Reviewer

Journal of Neuroscience, Behavioral Brain Research, Pharmacology, Biochemistry and Behavior, PLoS ONE

Rotation Supervisor, Neuroscience Graduate Program 2018
Stanford University

Volunteer, Brain Day Outreach Program 2015 – 2018
Stanford University

Rotation Supervisor, Neuroscience Graduate Program 2010, 2012
UCSF

Teaching Assistant, School of Dentistry 2008
UCSF

Volunteer Instructor, Science and Health Education Partnership 2007 – 2008
UCSF