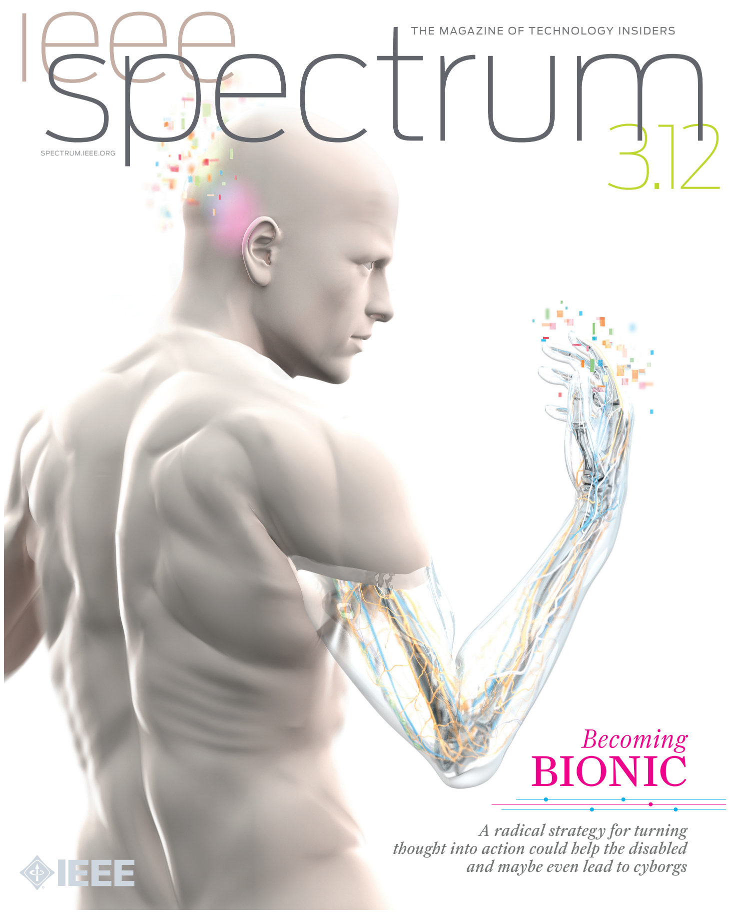
Brain-Machine Interfaces

LEVERAGING PLASTICITY, MACHINE LEARNING & NEUROTECHNOLOGY FOR BRAIN DYSFUNCTION AND AUGMENTATION



Jose M. Carmena, Ph.D.

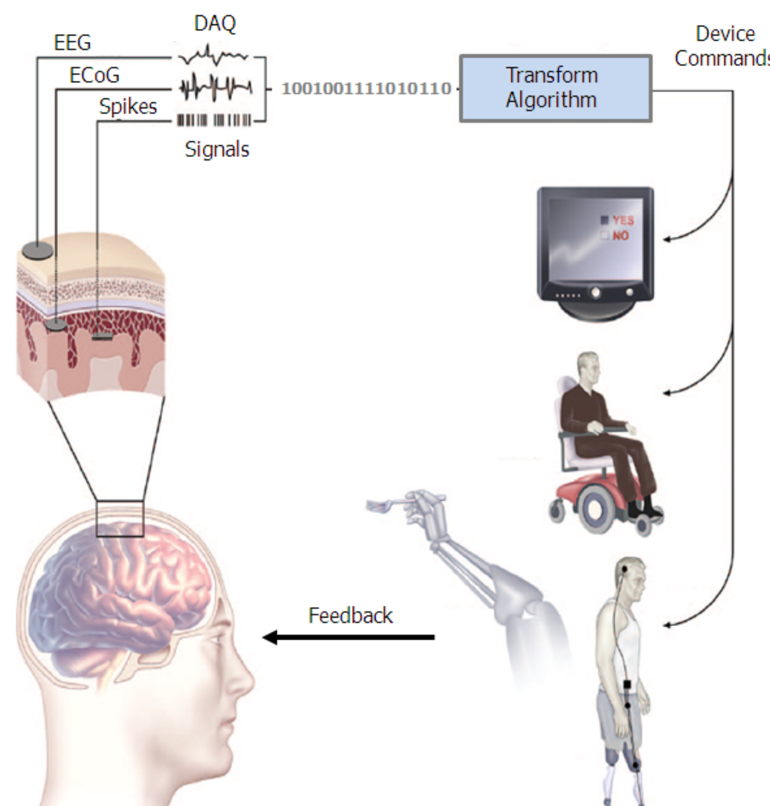
Professor
Dept. of Electrical Eng. & Computer Sciences
Helen Wills Neuroscience Institute

Co-Director
Center for Neural Engineering & Prostheses

University of California, Berkeley

Target: Restoring **motor function** (spinal cord injury, stroke, ALS…)

Approach:
Brain-Machine Interfaces
Translating thought into action



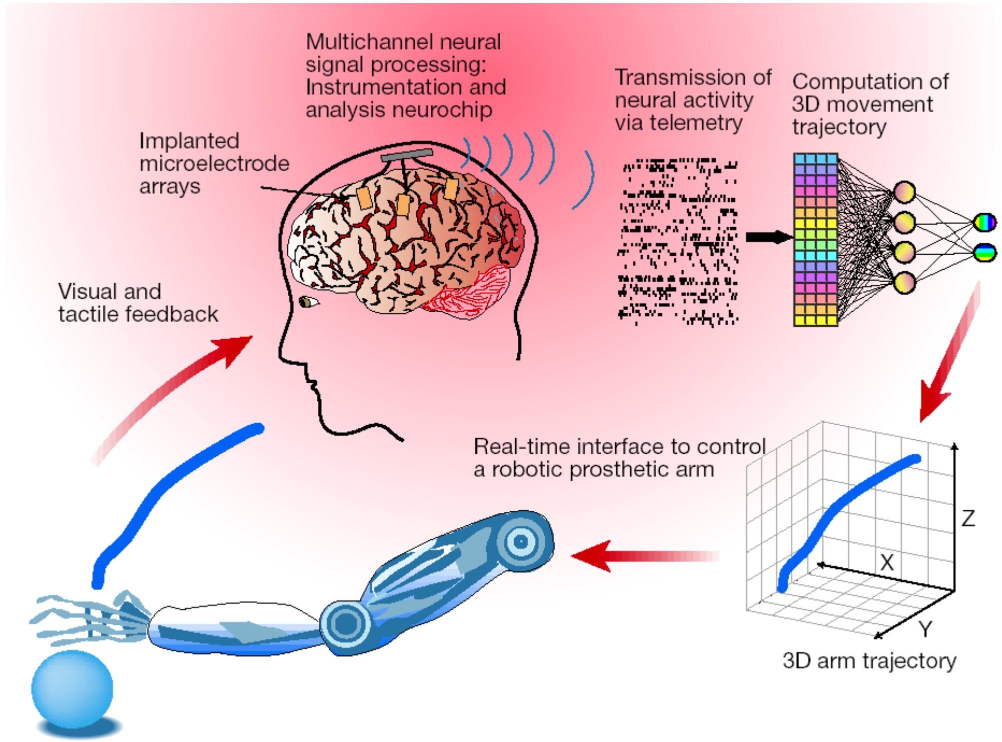
Leuthard et al., 2006

Impact:

- Patient population: Millions
- e.g. 1.3M SCI patients in the US alone

[Source: Christopher and Dana Reeve Foundation]

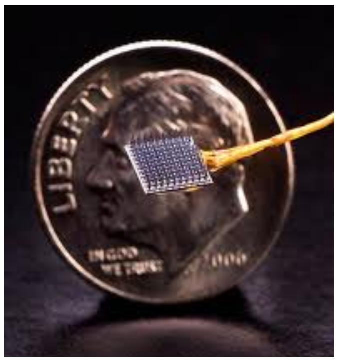
Significant progress in the past 15+ years…

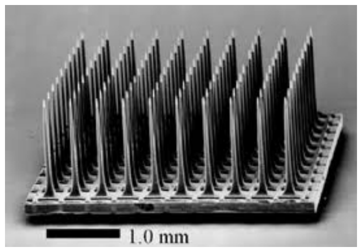


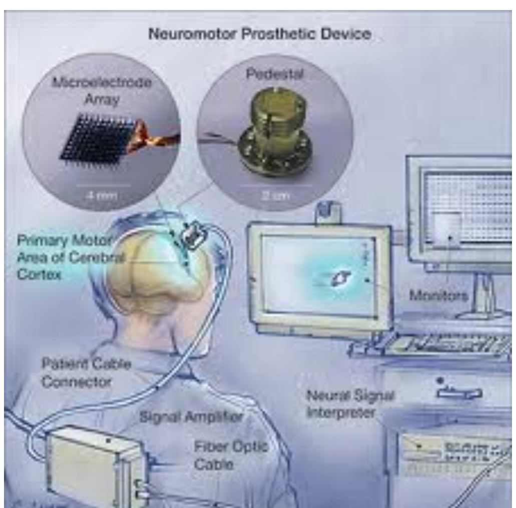
Some closed-loop BMI studies in rodents and (human/non-human) primates: Chapin et al, 1999; Serruya et al, 2002; Taylor et al, 2002; Carmena et al, 2003; Musallam et al, 2004; Wahnoun et al, 2006; Santhanam et al, 2006; Hochberg et al, 2006; Velliste et al., 2008; Mulliken et al., 2008; Truccolo et al, 2008; Kim et al, 2008; Jarosiewicz et al, 2008; Moritz et al, 2008; Ganguly & Carmena, 2009; Suminski et al, 2010; Ganguly et al, 2011; Mahmoudi and Sanchez, 2011; O'Doherty et al, 2011; Gilja et al, 2012; Koralek et al, 2012; Ethier et al, 2012; Hochberg et al, 2012; Collinger et al, 2013; Wander et al, 2013; Engelhard et al, 2013; Hwang et al., 2013; Shanechi et al., 2014; Sadtler et al, 2014; Orsborn et al, 2014; Gulati et al, 2014; Aflalo et al., 2015; Bouton et al., 2016; Shanechi et al., 2017…

What are the challenges?

- Bulky, tethered, wired implants (challenge 1)





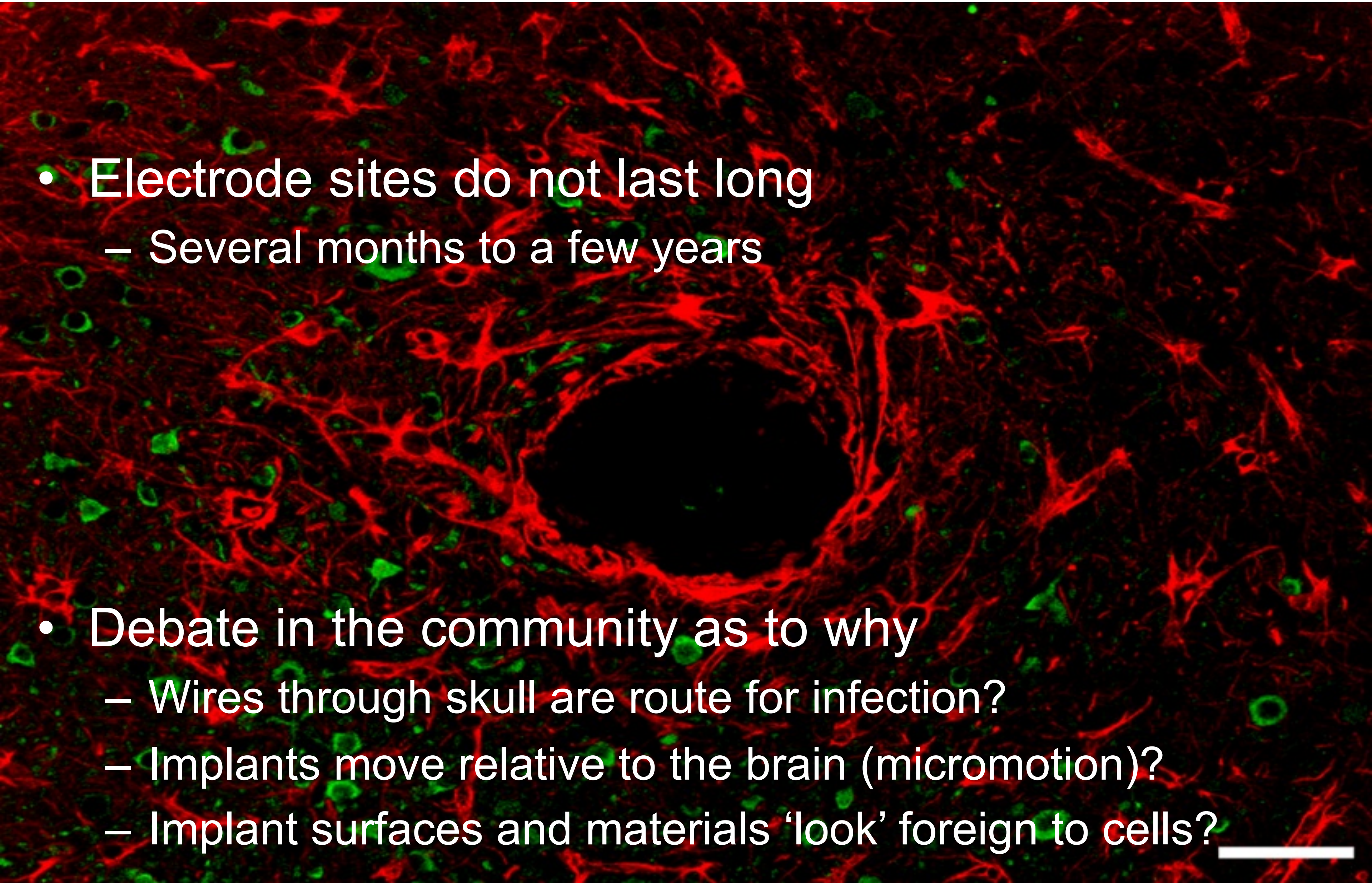


Goal: to dramatically extend the lifetime of clinically viable neural interfaces

Wish list: Ultra-small, high-density, compliant, tetherless wireless implants…**but**

- It's all about size & energy
- Scaling limited due to shank size

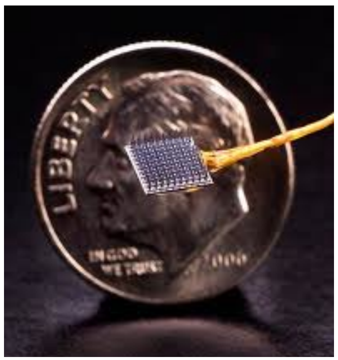
Problems at the biophysical interface

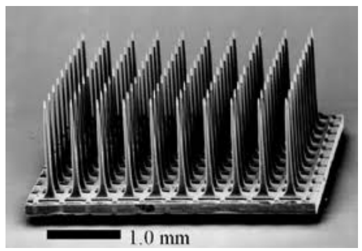


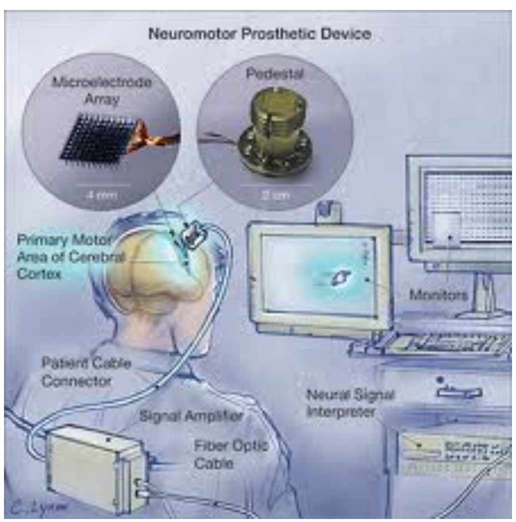
- Electrode sites do not last long
  - Several months to a few years
- Debate in the community as to why
  - Wires through skull are route for infection?
  - Implants move relative to the brain (micromotion)?
  - Implant surfaces and materials ‘look’ foreign to cells?

What are the challenges?

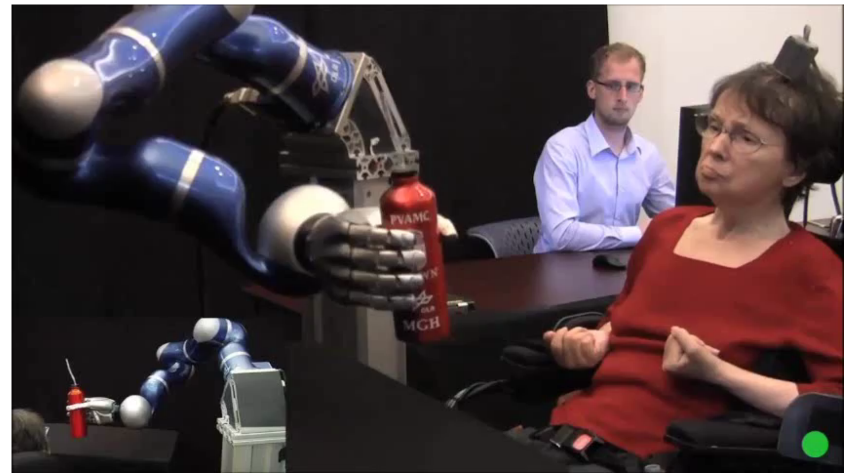
- Bulky, tethered, wired implants (challenge 1)



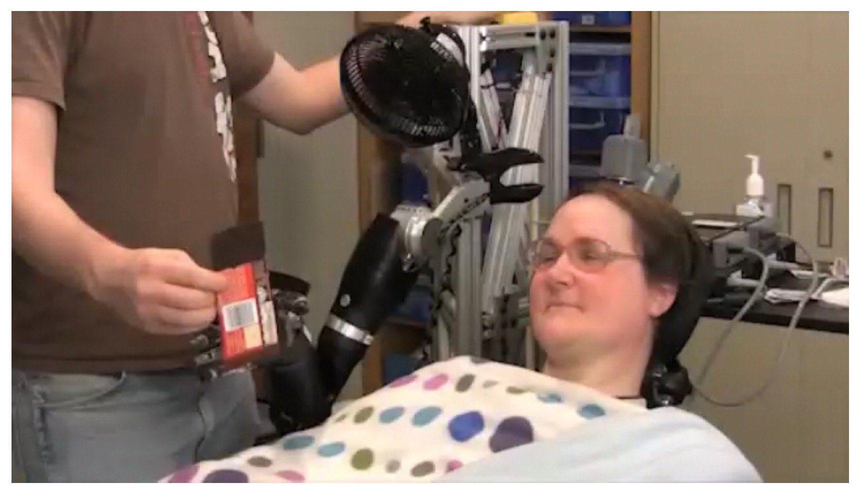




- Scaling up in performance/ tasks of daily living (challenge 2)

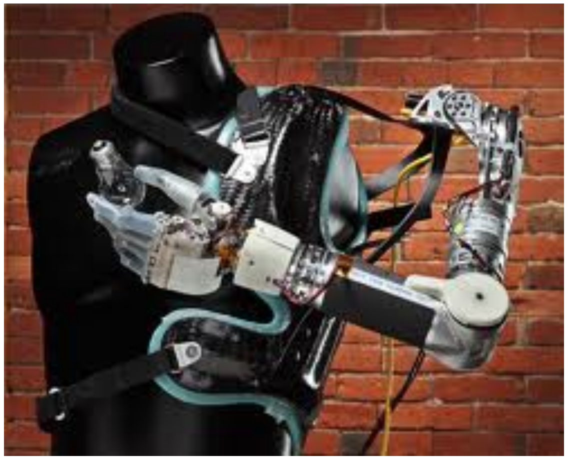


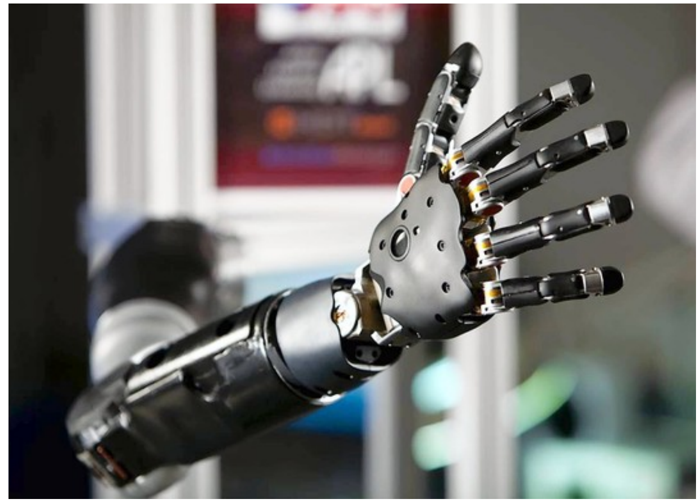
[Hochberg et al, 2012]

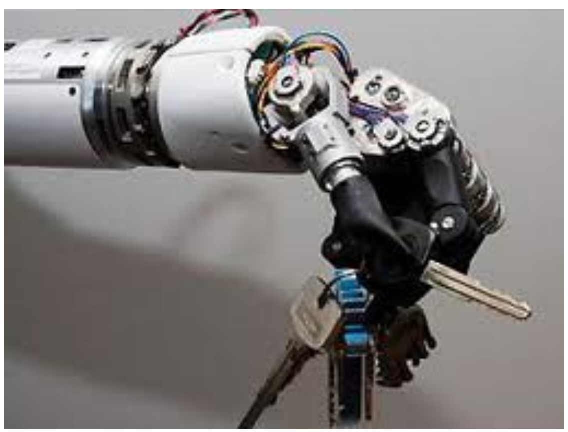


[Collinger et al, 2013]

Existing robotic solutions exceed the ability of BMIs to control them







DEKA’s 18-DOF arm

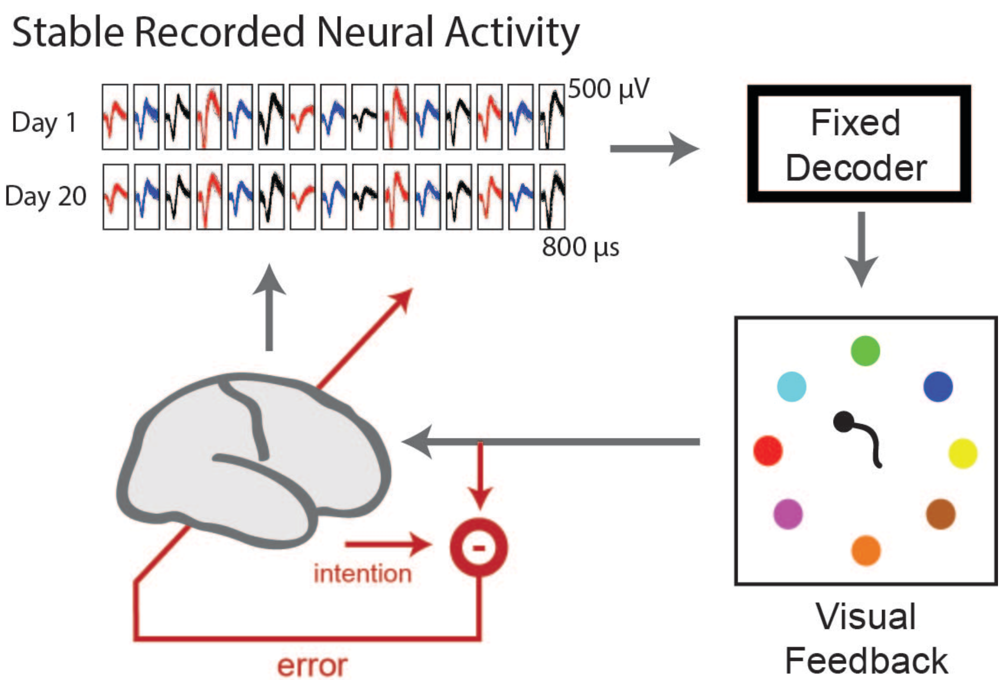
DARPA’s
22-DOF
prosthetic arm

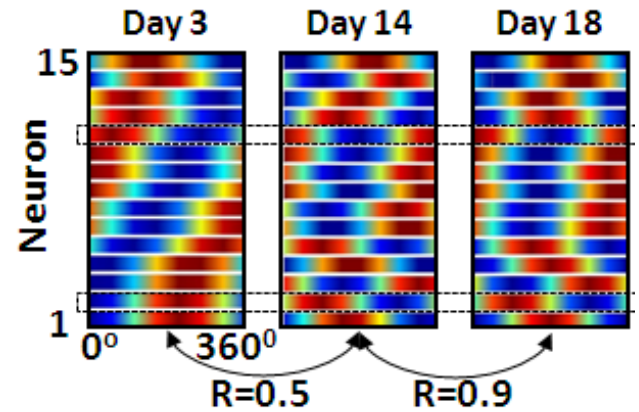
“We should focus on the brain, not on the robot” (N. Hogan)

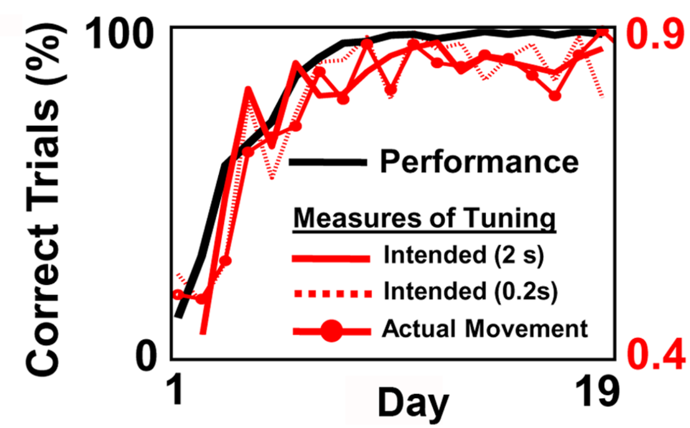
Outline

- **Neuroprosthetic control** in a closed-loop, 2-learner system
- **Modulation of emotional state** in mesolimbic and mesocortico networks
- Wireless recordings in the PNS with **ultrasonic neural dust**

Neural basis of neuroprosthetic skill learning







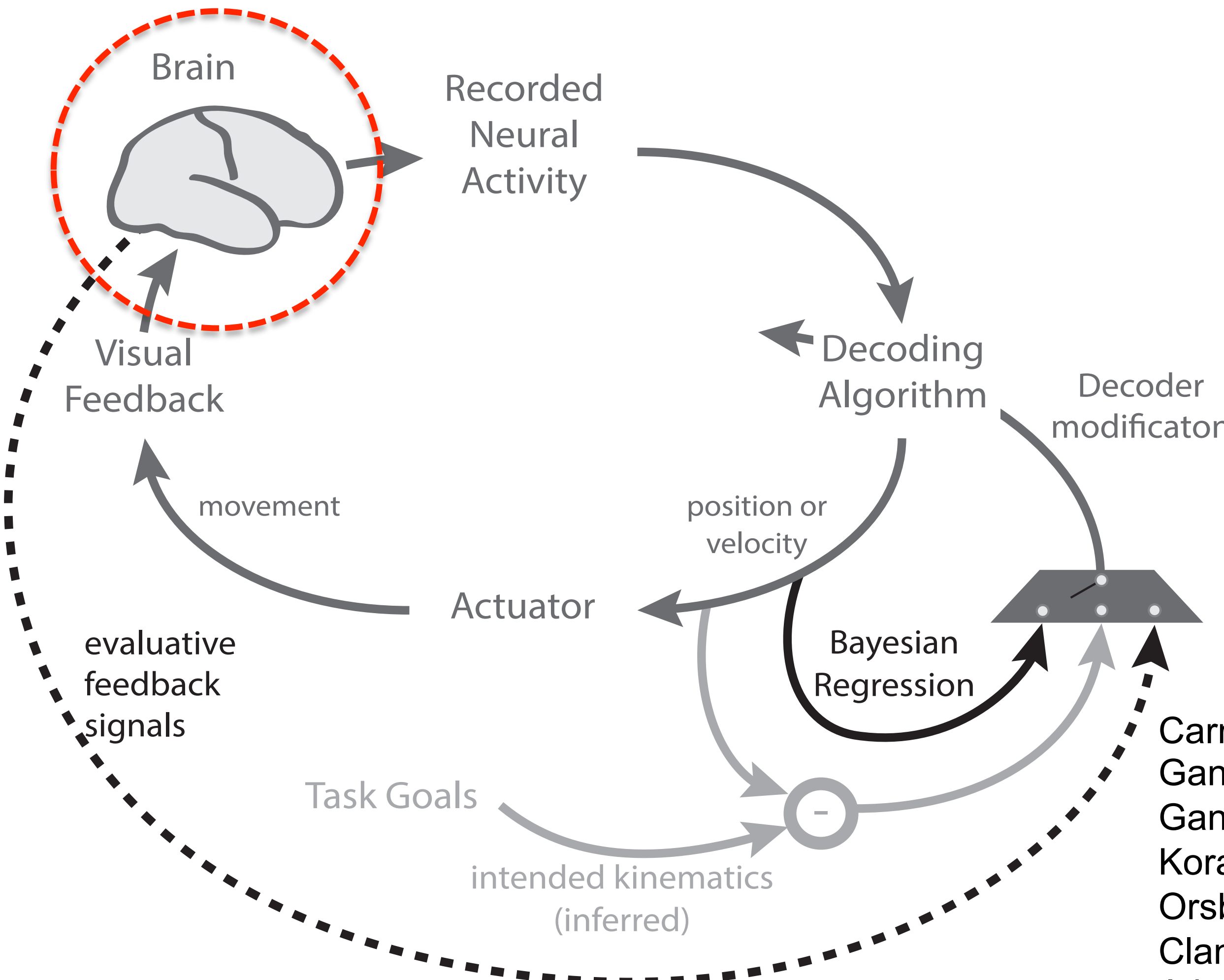
The brain can consolidate ***neuroprosthetic* motor skill** as in natural motor learning

➡ **Motor memory**: readily recalled, stable across time, and resistant to interference

Ganguly & Carmena, PLoS Biology, 2009

BMI is a 2-learner system

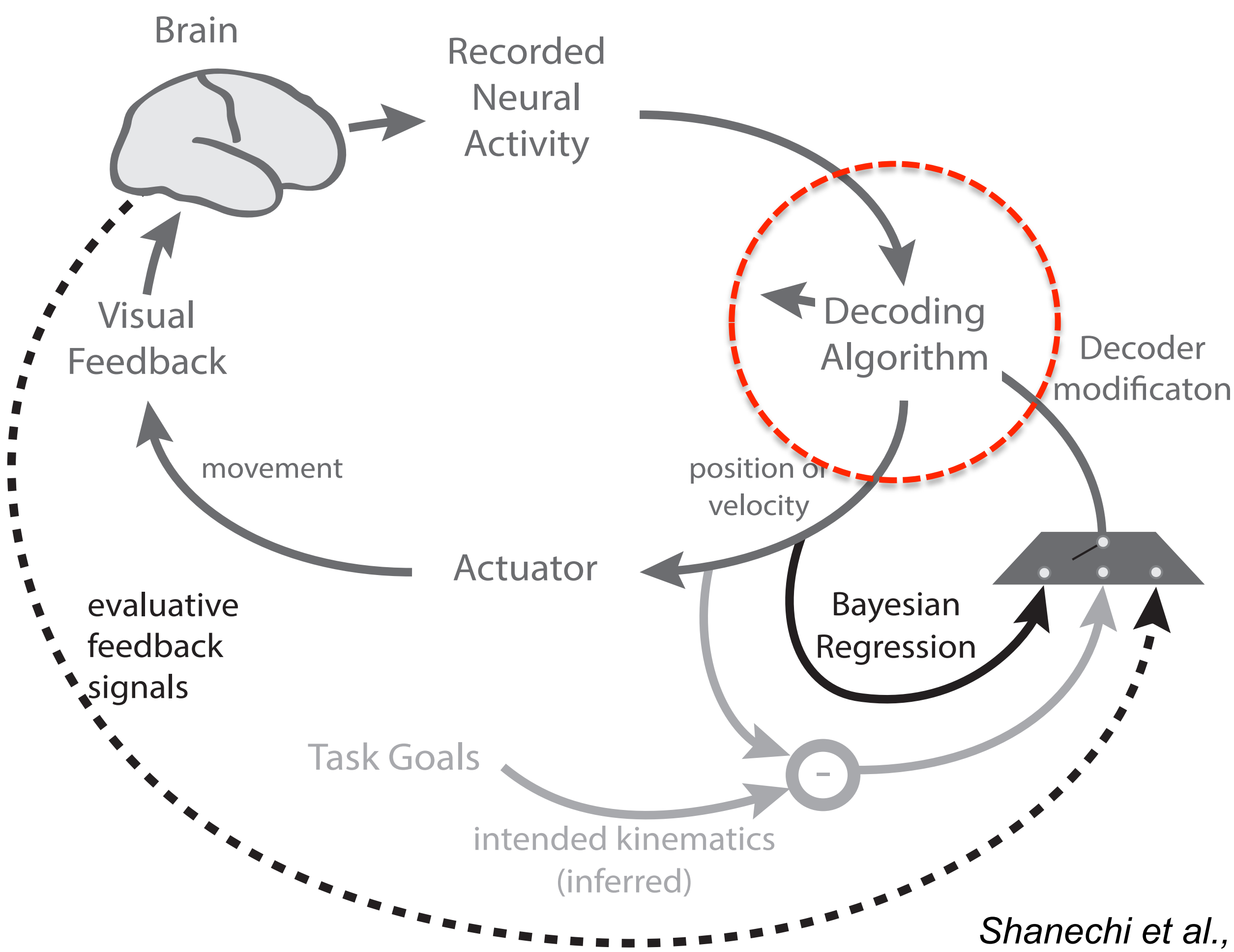
- The brain learns to control the BMI



Carmena et al., *PLoS Biology*, 2003
Ganguly & Carmena, *PLoS Biology*, 2009
Ganguly et al., *Nature Neurosc*, 2011
Koralek et al., *Nature*, 2012
Orsborn et al., *Neuron*, 2014
Clancy et al., *Nature Neurosc*, 2014
Athalye et al., *Neuron*, 2017
Neely et al., *Neuron*, 2018

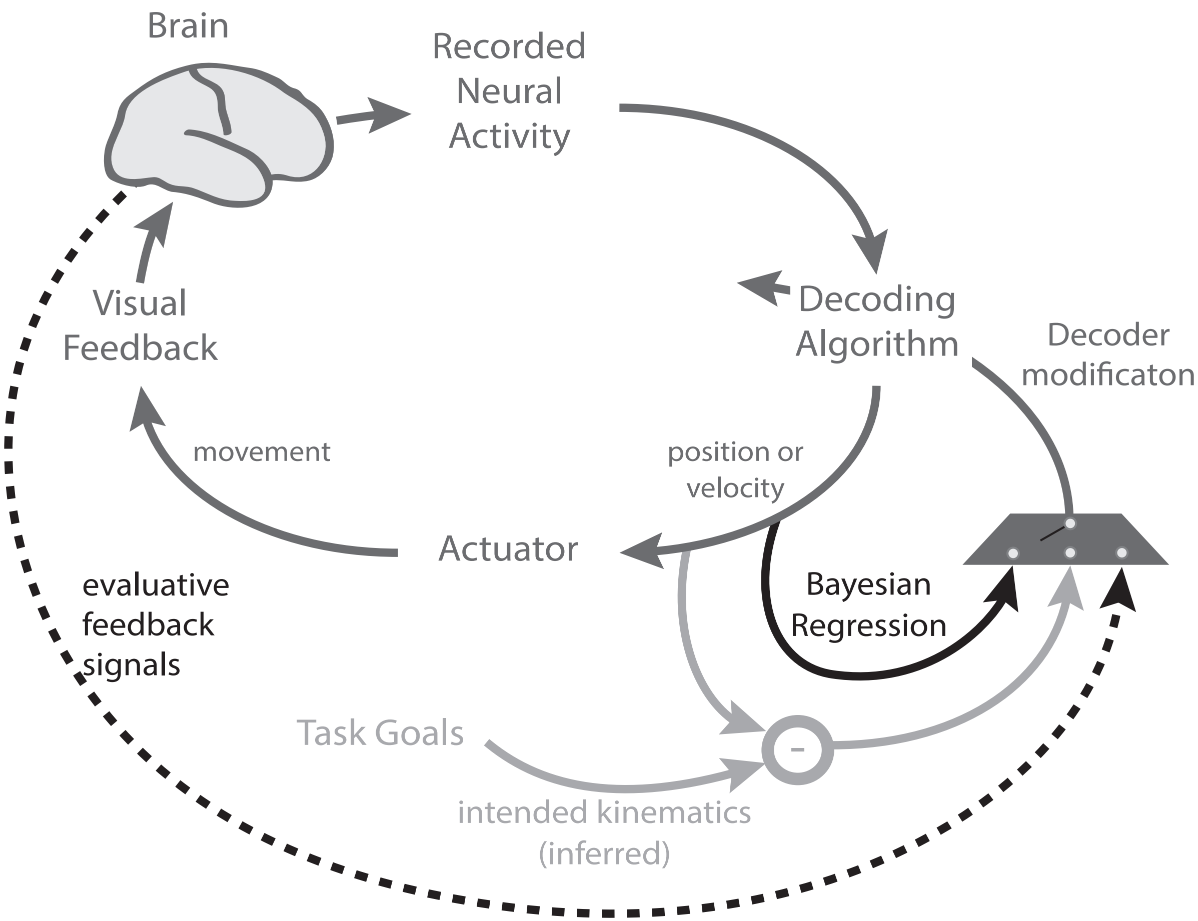
BMI is a 2-learner system

- The brain learns to control the BMI
- What about learning in the machine?



Shanechi et al., PLoS Comp Bio, 2016
Shanechi et al., Nature Comm., 2017

Closed-Loop Decoder Adaptation (CLDA)



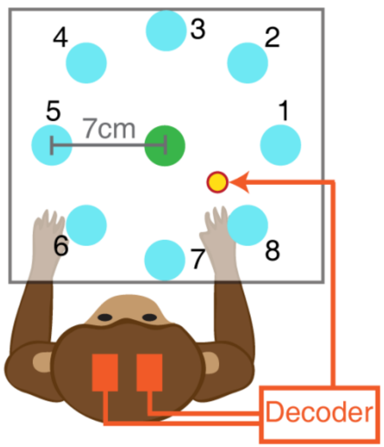
- Updating the decoder during closed-loop operation to **accelerate learning** and **boost** and **maintain performance.**
- ***When, which*** and ***how*** to update the parameters matters

Taylor et al., 2002
Schpigelman et al., 2008
DiGiovanna et al., 2009
Gilja et al., 2010; 2012
Li et al., 2011
Mahmoudi et al., 2011
Gurel and Mehring, 2012
Orsborn et al., 2012
Merel et al., 2013
…

Dangi, Orsborn*, et al., Neural Computation, 2013*
Dangi et al., Neural Computation, 2014
Shanechi et al., PLoS Comp Bio, 2017

Closed-Loop Decoder adaptation
(using smoothBatch algorithm)

Closed-loop BMI Operation



Collect Observation (1-2min batches)

Spikes (***Y***)

Intended kinematics (***X***$_{in}$)

Inferred from task using ReFIT algorithm (Gilja et al., 2012)

Update Decoder

ML Update

$$\hat{C} = YX_{in}^{T}(X_{in}X_{in}^{T})^{-1}$$

$$\hat{Q} = \frac{1}{N}(Y - \hat{C}X_{in})(Y - \hat{C}X_{in})^{T}$$

Sliding average

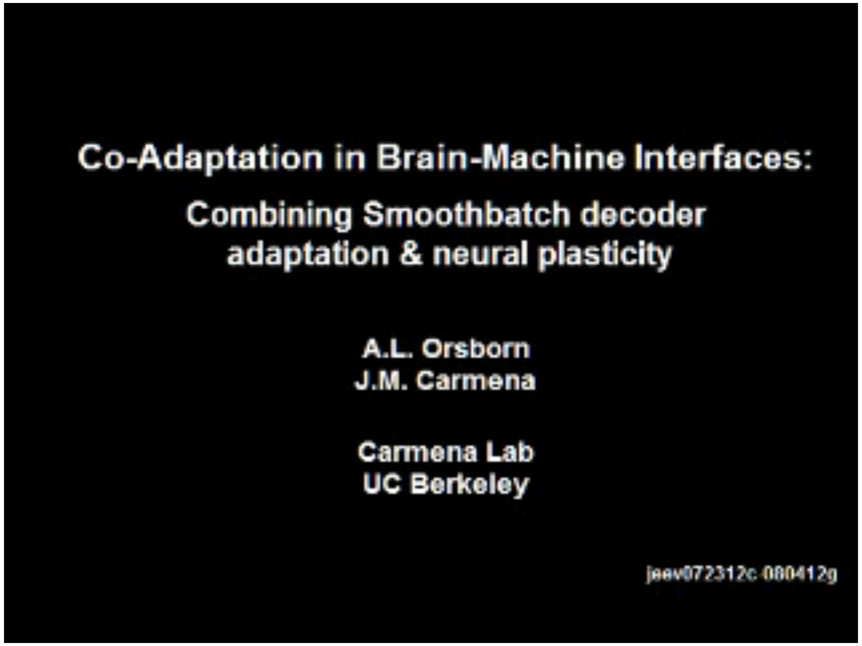
$$C^{(i+1)} = \beta C^{(i)} + (1-\beta)\hat{C}$$

$$Q^{(i+1)} = \alpha Q^{(i)} + (1-\alpha)\hat{Q}$$

Repeat as needed (until adequate performance)

Orsborn et al, *IEEE TNSRE*, 2012

Combining Neural and Decoder Adaptation



Decoder initialization
(independent of movement)

→

Decoder adaptation
(CLDA)

→

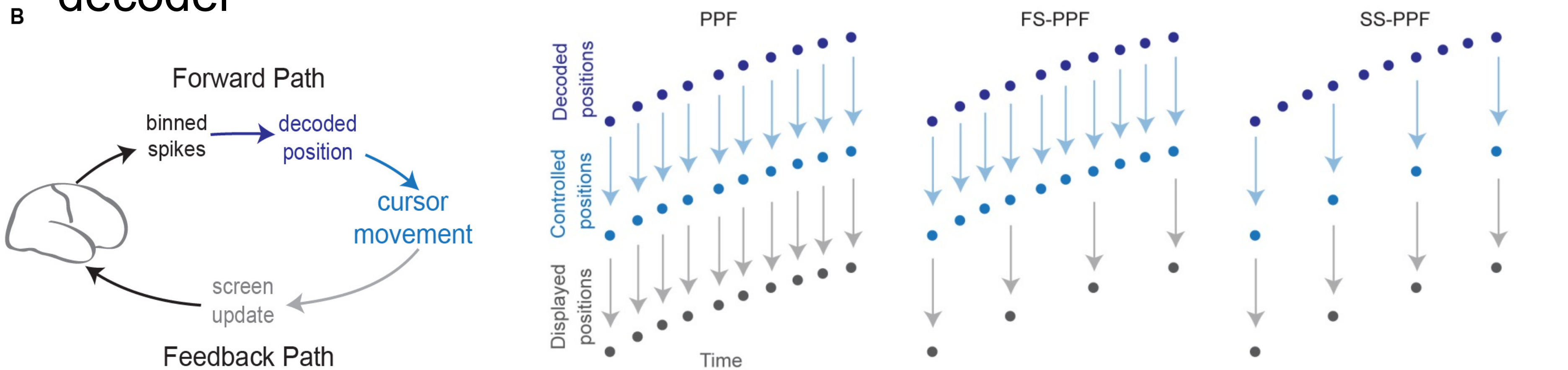
Fixed decoder & ensemble

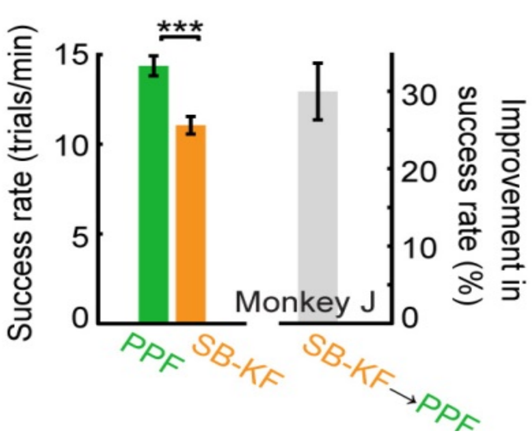
Decoder adaptation as needed
(e.g. shift in recordings)

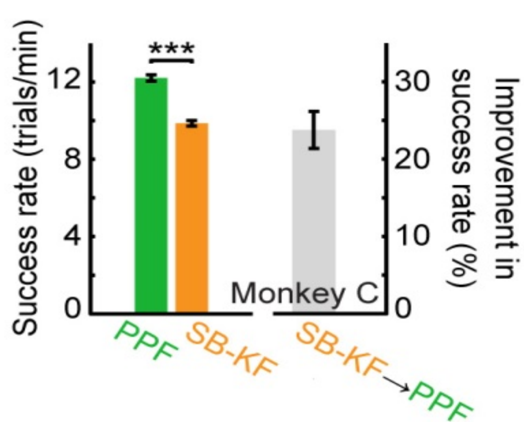
Rapid control and feedback rates in the sensorimotor pathway enhance neuroprosthetic control

- Using an adaptive optimal feedback-controlled point process decoder

B







30% improvement of BMI Performance over state of the art Kalman filter

Shanechi et al., PLoS Comp Bio, 2016
Shanechi et al., Nature Comm., 2017

Outline

- **Neuroprosthetic control** in a closed-loop, 2-learner system

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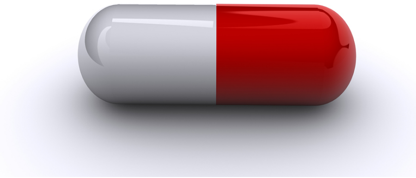
Samantha Santacruz, PhD

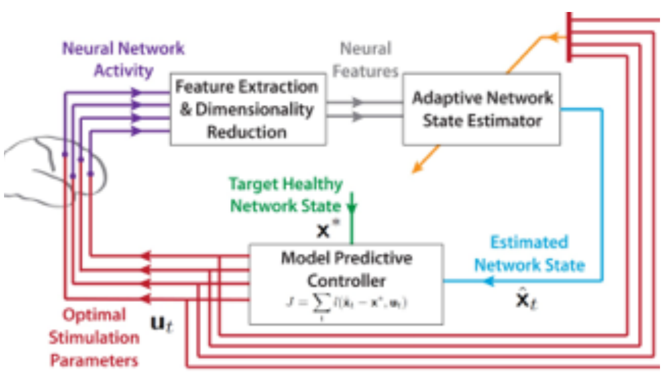
Mental Health: the Unchartered Territory

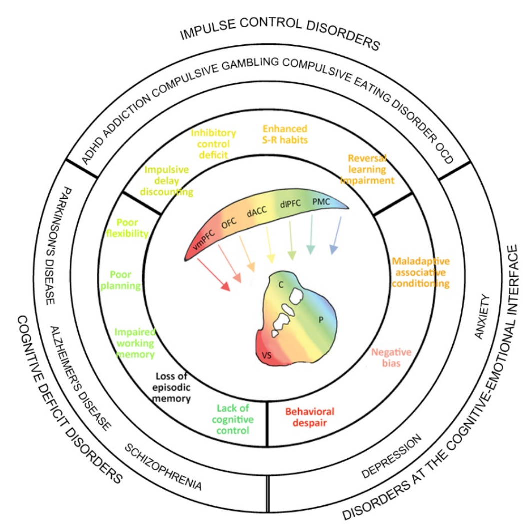
- Current pharmacological model is not good enough
  - Need targeted, personalized treatment



Mental Health: the Unchartered Territory

- **Goal**: to develop systems-based closed-loop therapy for neuropsychiatric disorders
  - Depression, anxiety, PTSD, TBI…
- Measuring how disorders are manifested in brain **systems**
- Modulating precise interventions based on neurophysiological **feedback**.





Mental Health: the Unchartered Territory

- Current pharmacological model is not good enough
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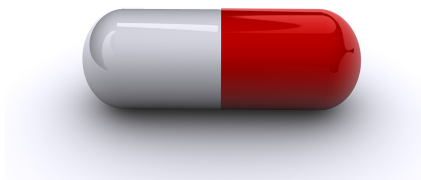
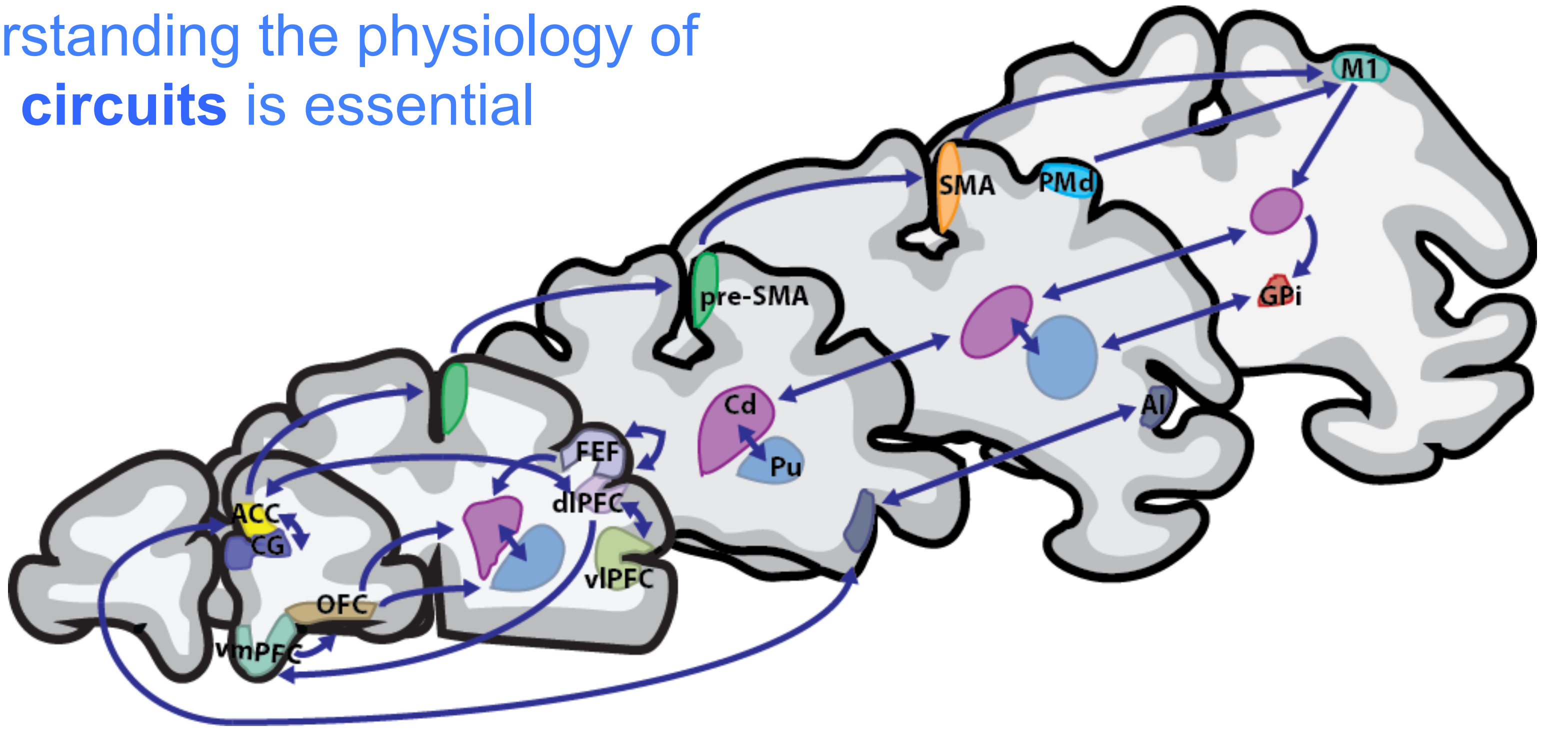
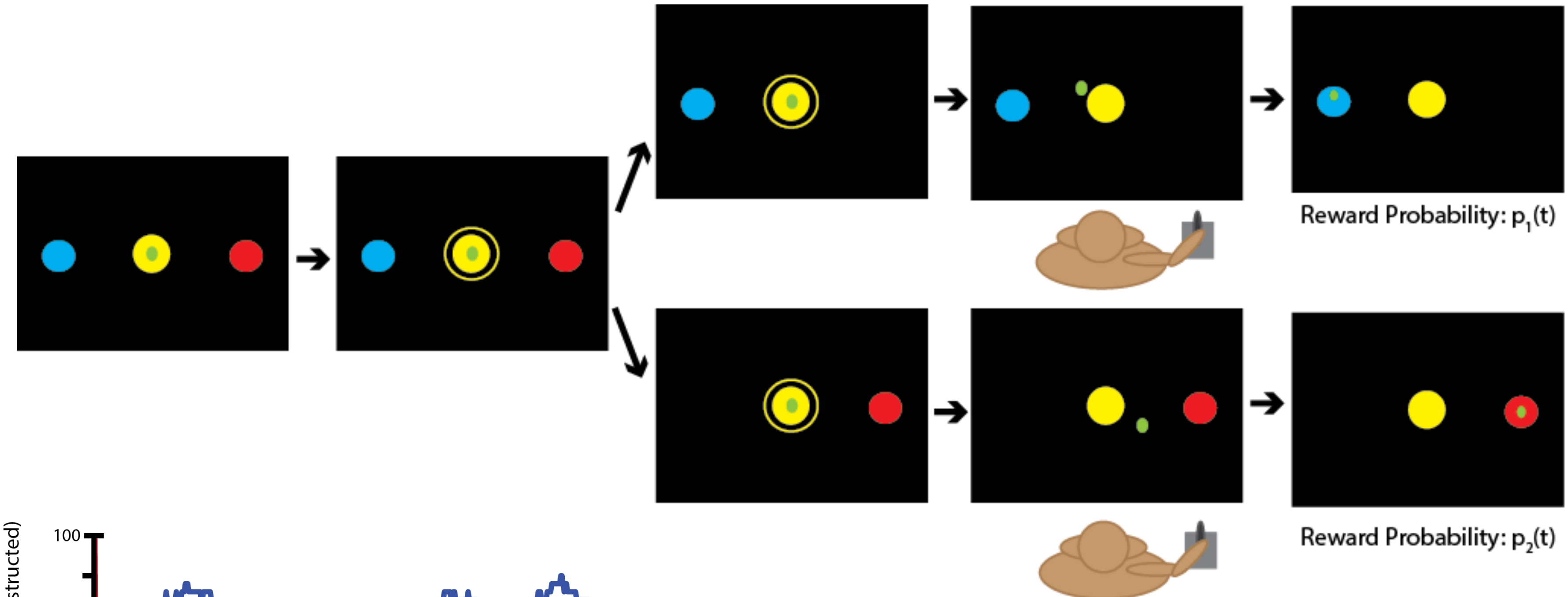
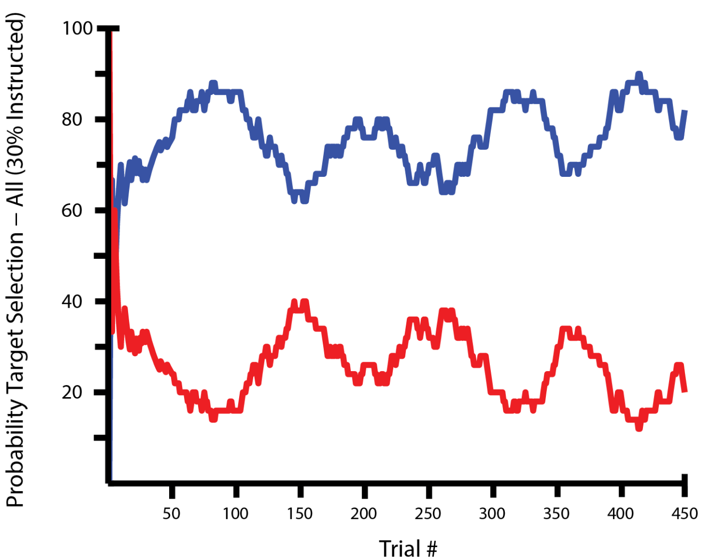


- Understanding the physiology of **brain circuits** is essential



Free-choice probabilistic reward task



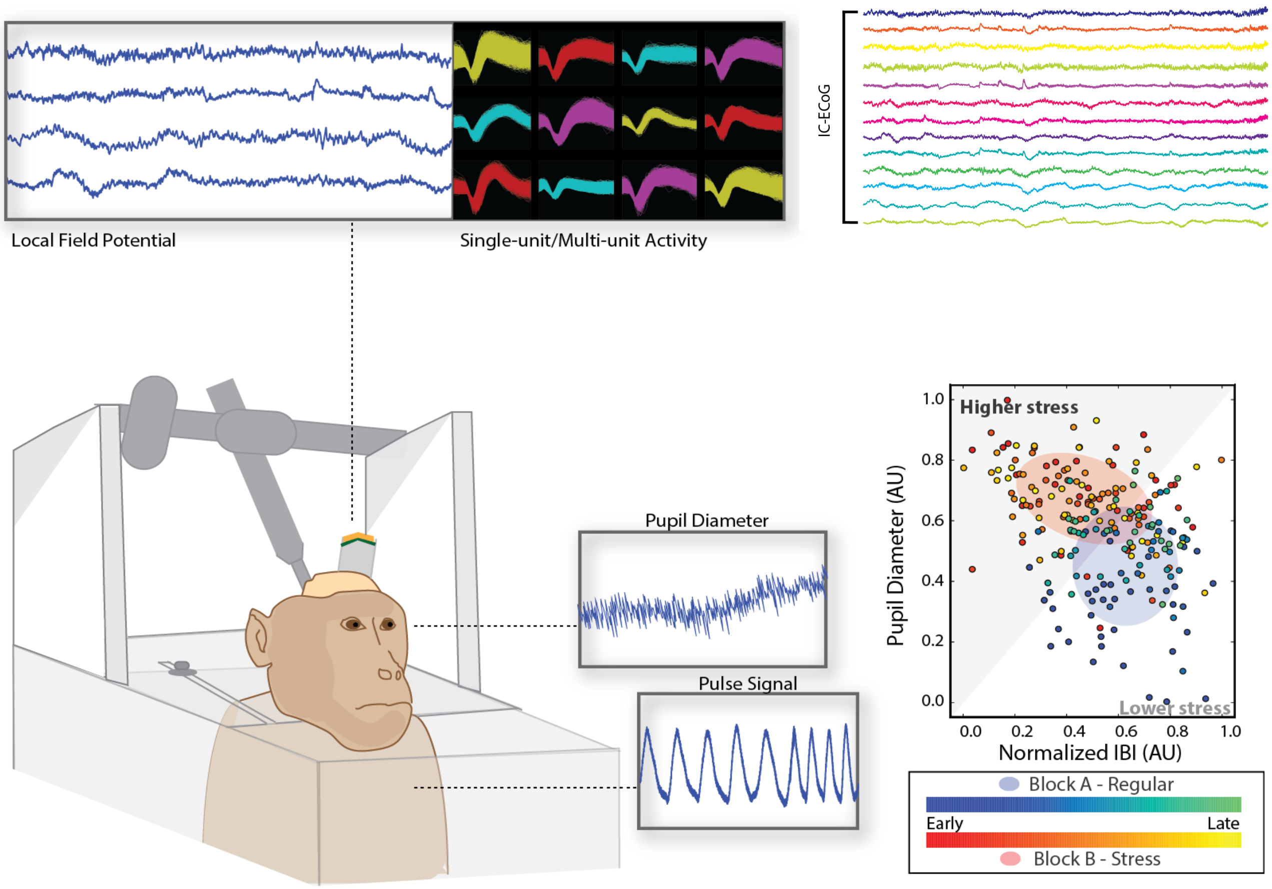


- ➢ Reward probabilities drift over time
- ➢ Subject’s target selection policy reflects local variations in reward probability.

NHP stress/anxiety animal model

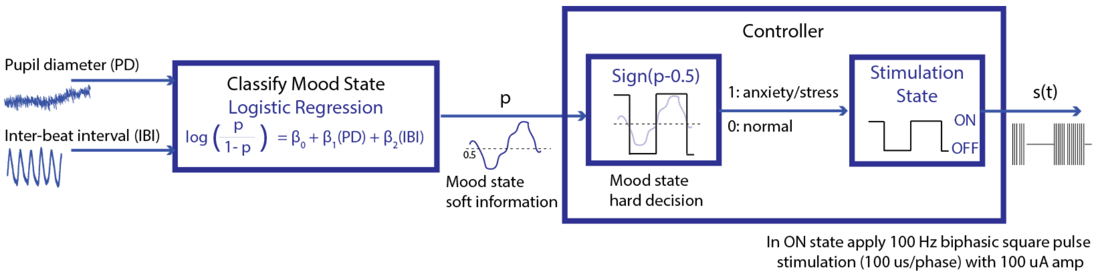
Physiological markers are good predictors of stress state

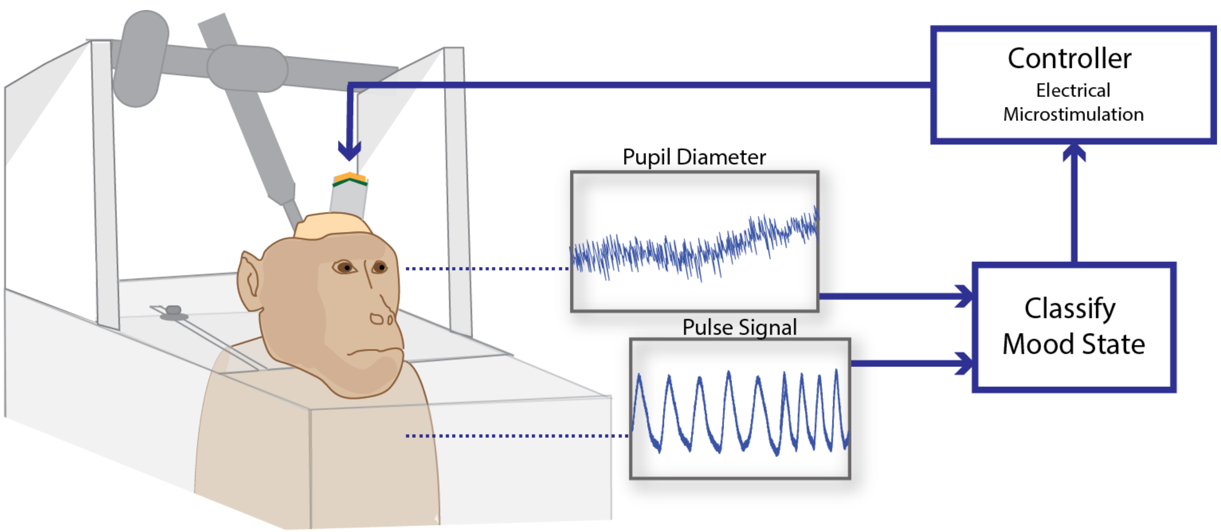
- Heart inter-beat interval (IBI) decreases and pupil diameter increases in stress trials compared to regular trials.

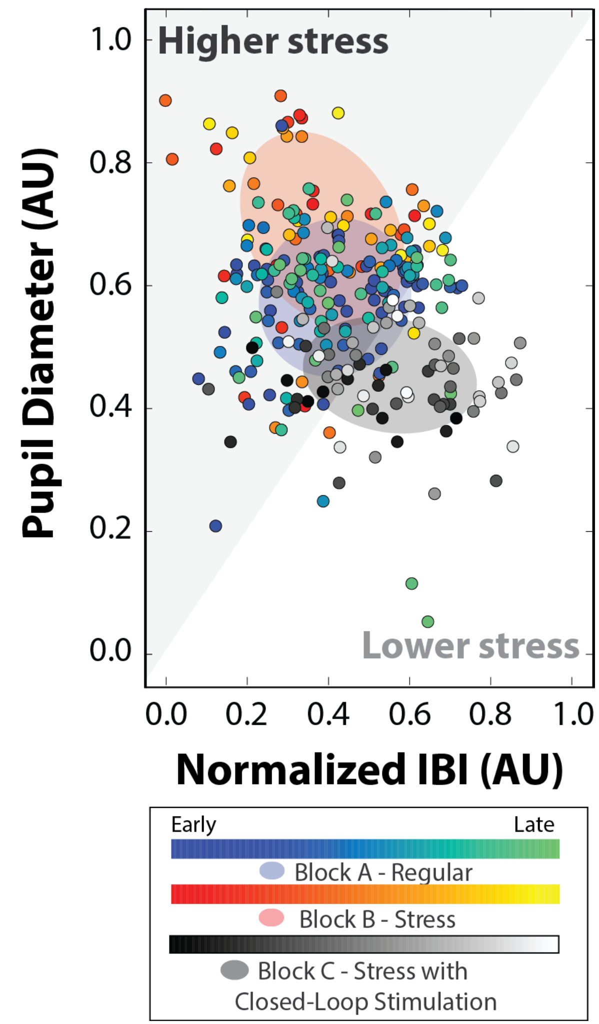


Identifying emotional state shifts with closed-loop stimulation

High-frequency stimulation in OFC/vmPFC during stress trials reduces stress response







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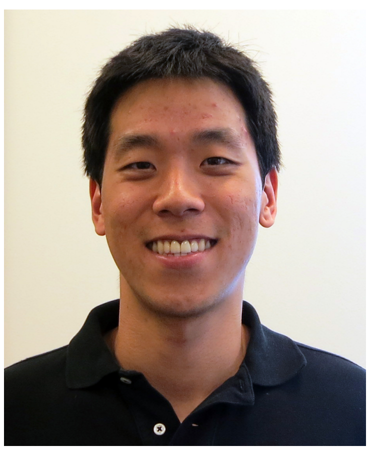


DJ Seo

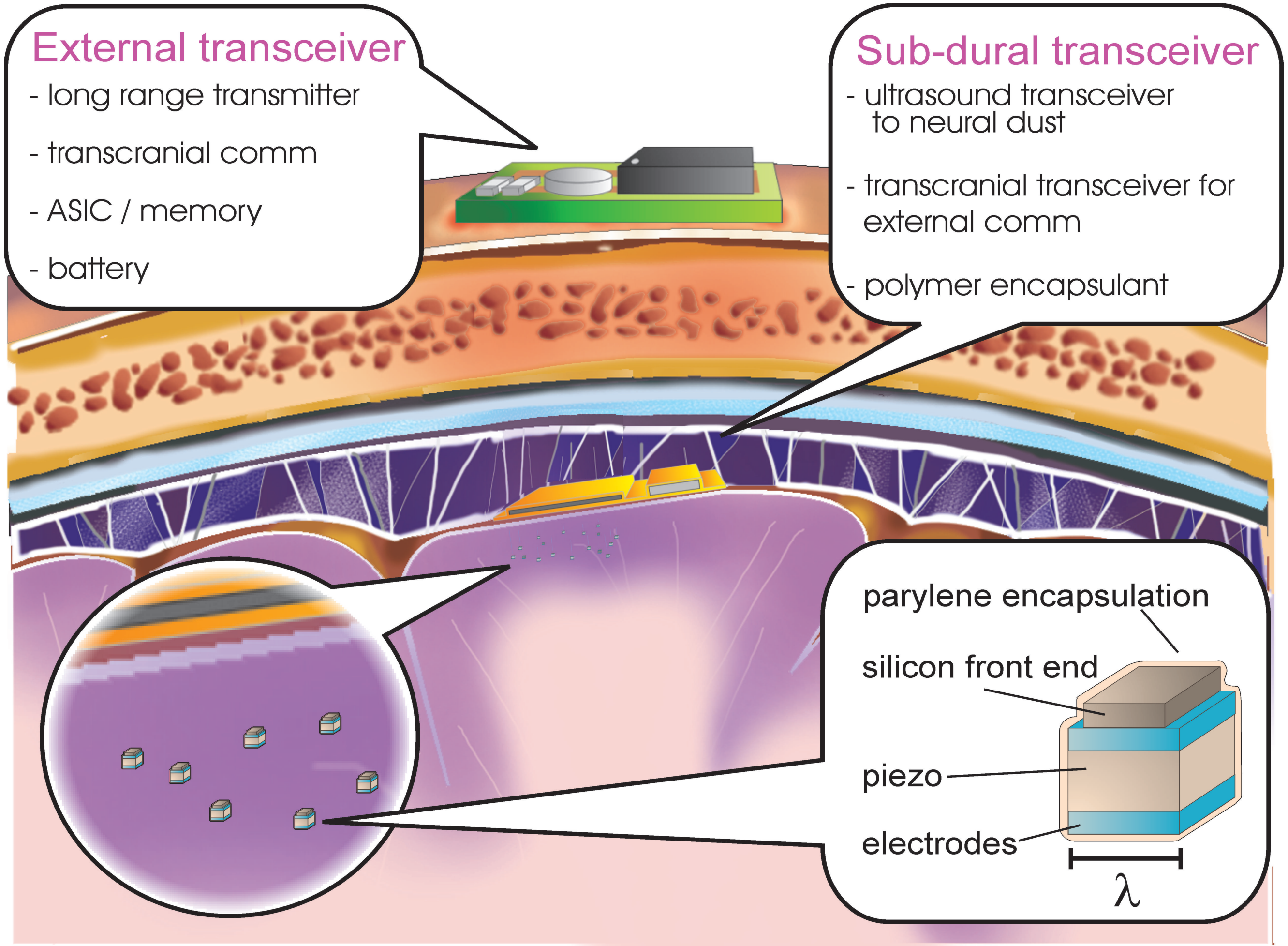
Ryan Neely

Michel Maharbiz

w/ Jan Rabaey and Elad Alon (UC Berkeley)

Neural Dust

An Ultrasonic, Low Power Solution for Chronic BMIs



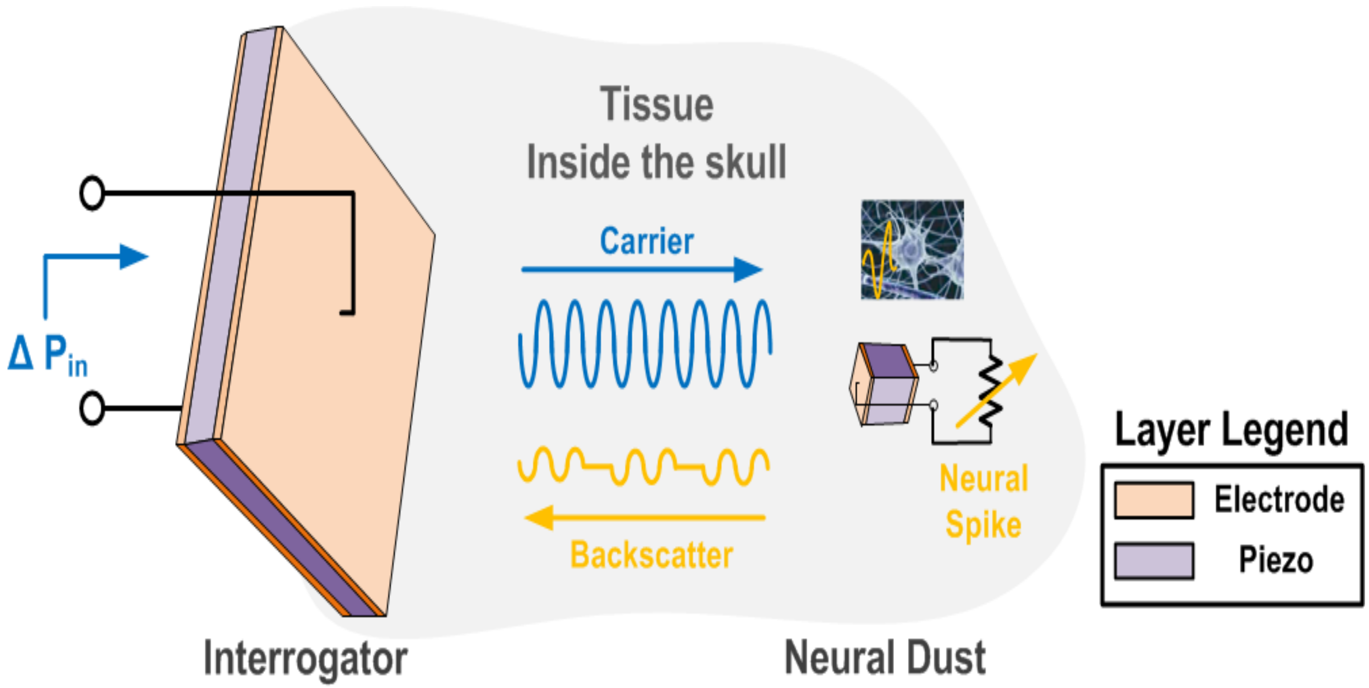
D.J. Seo
R. Neely
J. Carmena
J. Rabaey
E. Alon
M. Maharbiz

EECS
Berkeley
UNIVERSITY OF CALIFORNIA

Towards 1000+ unanchored, free-floating neural dust motes

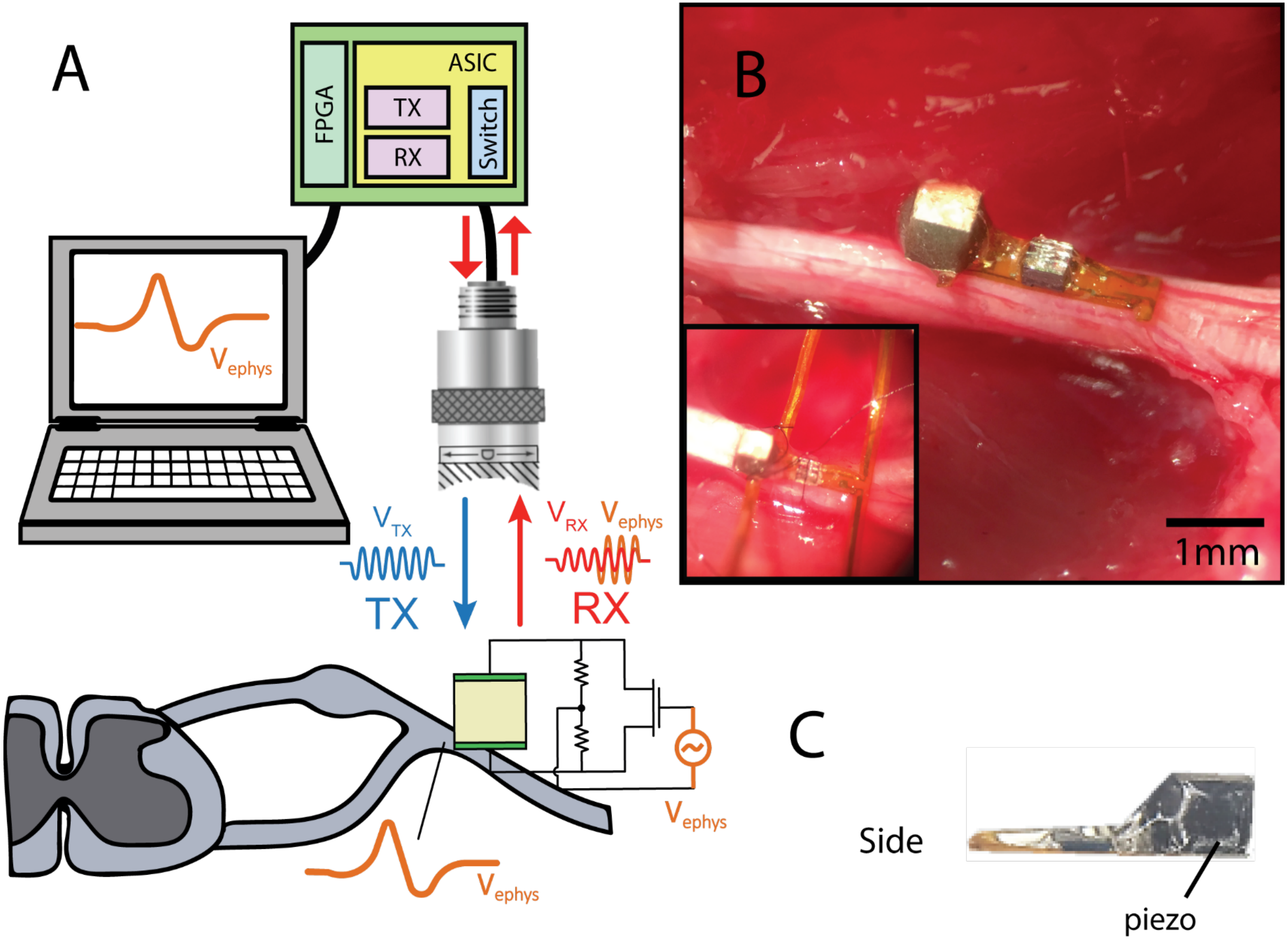
http://arxiv.org/abs/1307.2196 *Seo et al., Neuron, 2016*

Basic **Neural Dust** Operation



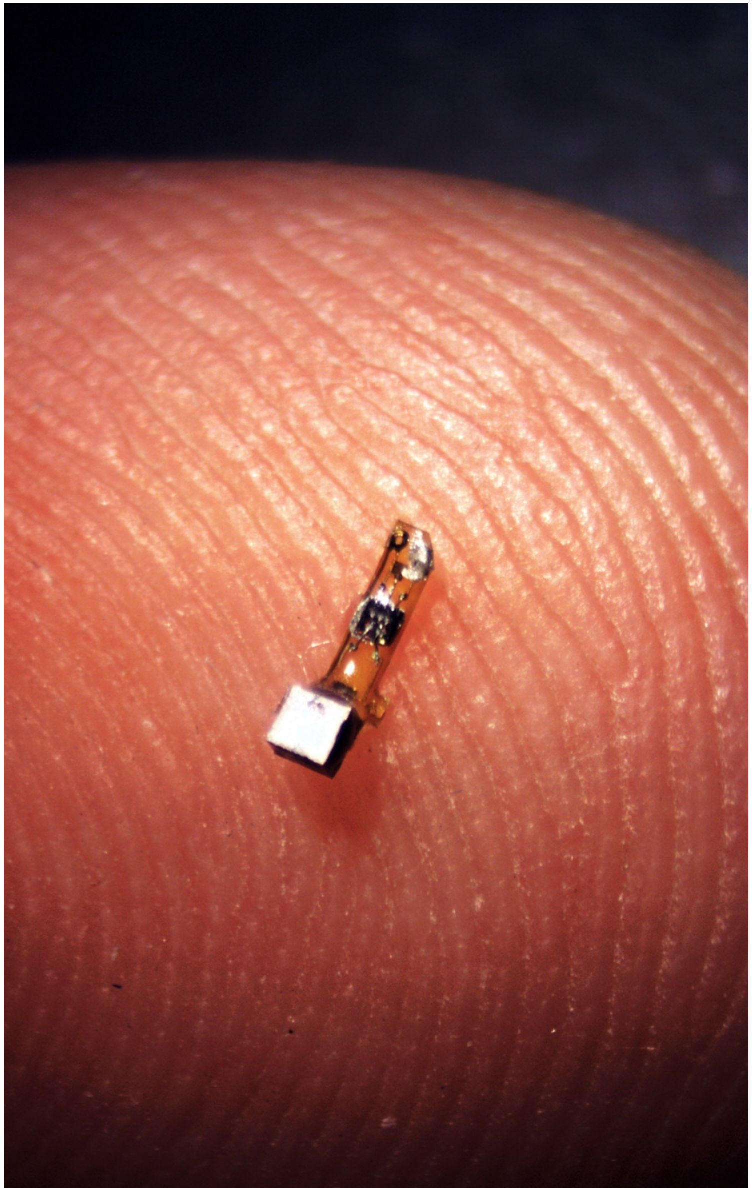
- the **interrogator** couples ultrasound energy to the **motes** with sufficient bandwidth/resolution to interrogate each mote
- each mote consists of a **piezoelectric transducer**, surface electrodes for signal acquisition, and electronics for signal amplification/conversion.
- motes **backscatter** the modulated amplitude, frequency, and/or phase of the impinging ultrasound wave.

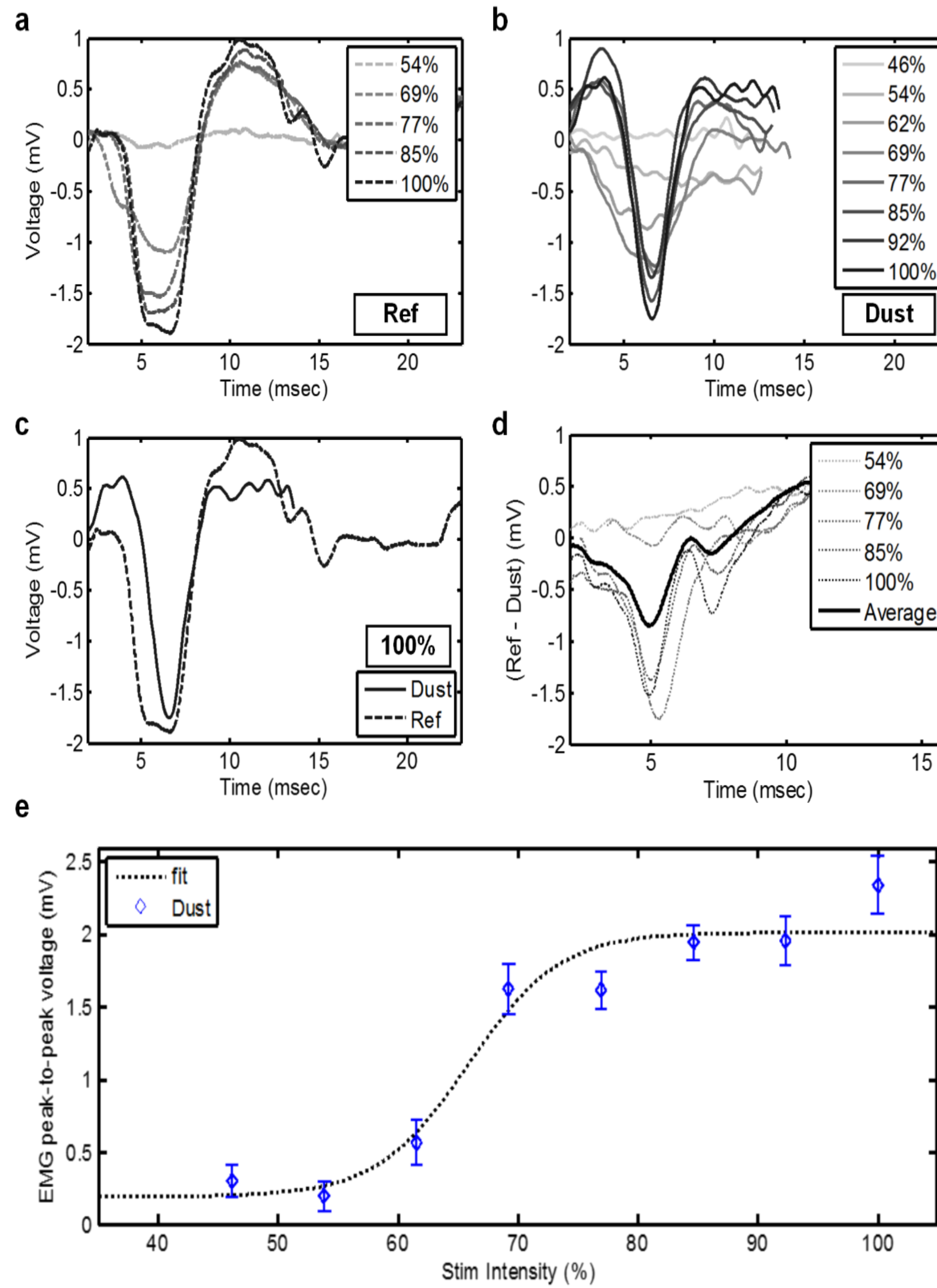
Neural Dust system overview



Seo et. al., *Neuron*, 2016

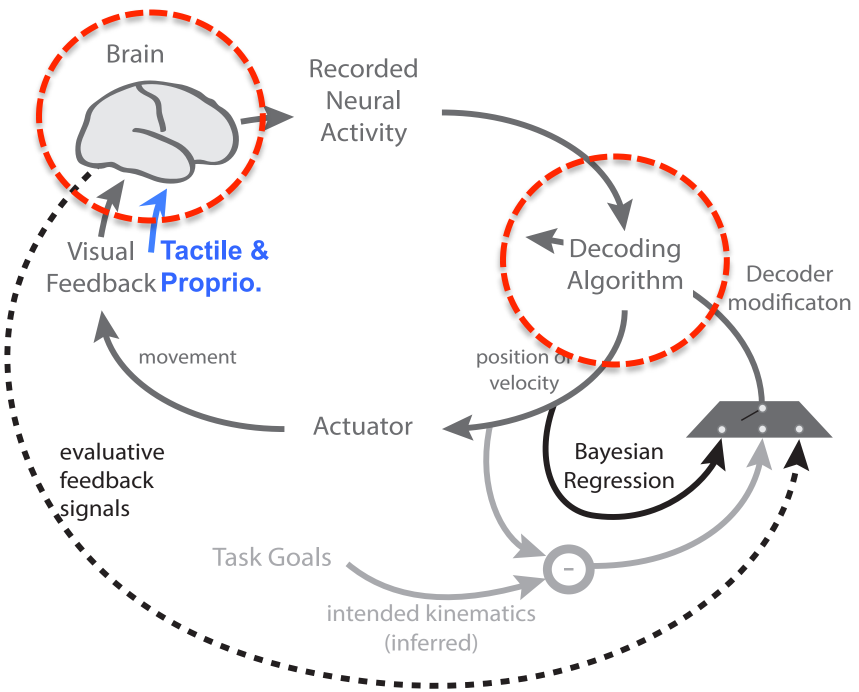
Neural Dust EMG recordings





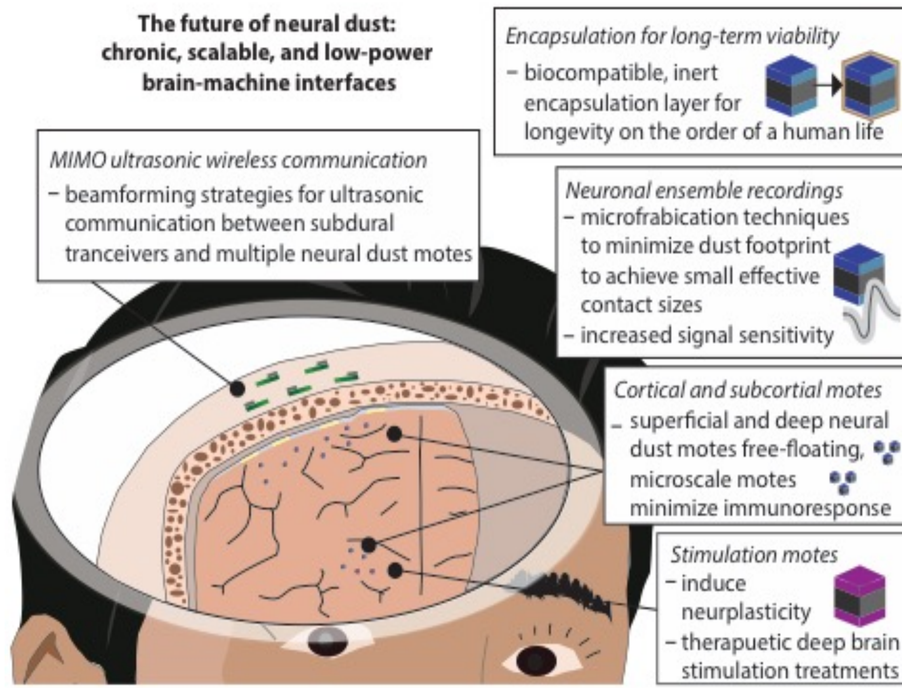
The Road Ahead…
Towards Skillful, Natural BMI Control

BMIs are 2-learner systems



- Exploiting **neuroplasticity** & **machine learning** to boost and consolidate performance
- "Write-in" **tactile** and **propioceptive** feedback from the BMI

The Road Ahead…
Mental Health Prosthetics



- Towards **closed-loop deep brain stimulation therapies**
  - From coarse electrical stimulation to precise chemical sensing and stimulation
  - Minimally invasive solutions

Thank you!

Carmena Lab

- Samantha Santacruz, PhD
- Nuria Vendrell-Llopis, PhD
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- Bing Liu, PhD
- Preeya Khanna, PhD
- Tanner Dixon, BS
- Albert You, BS
- David Piech, BS
- Vivek Athalye, PhD
- Ryan Neely, PhD
- Suraj Gowda, PhD
- Helene Moorman, PhD
- Siddharth Dangi, PhD
- Kelvin So, PhD
- Aaron Koralek, PhD
- Maryam Shanechi, PhD
- Amy Orsborn, PhD
- Simon A. Overduin, PhD
- Ryan Canolty, PhD
- Karunesh Ganguly, MD, PhD
- John Long, PhD
- Rodolphe Heliot, PhD
- Subramaniam Venkatraman, PhD

Collaborators

- Rui Costa (Columbia)
- Michel Maharbiz (UC Berkeley)
- Rich Ivry (UC Berkeley)
- Robert Knight (UC Berkeley)
- Joni Wallis (UC Berkeley)
- Reza Shadmehr (JHU)
- Dan Feldman (UC Berkeley)