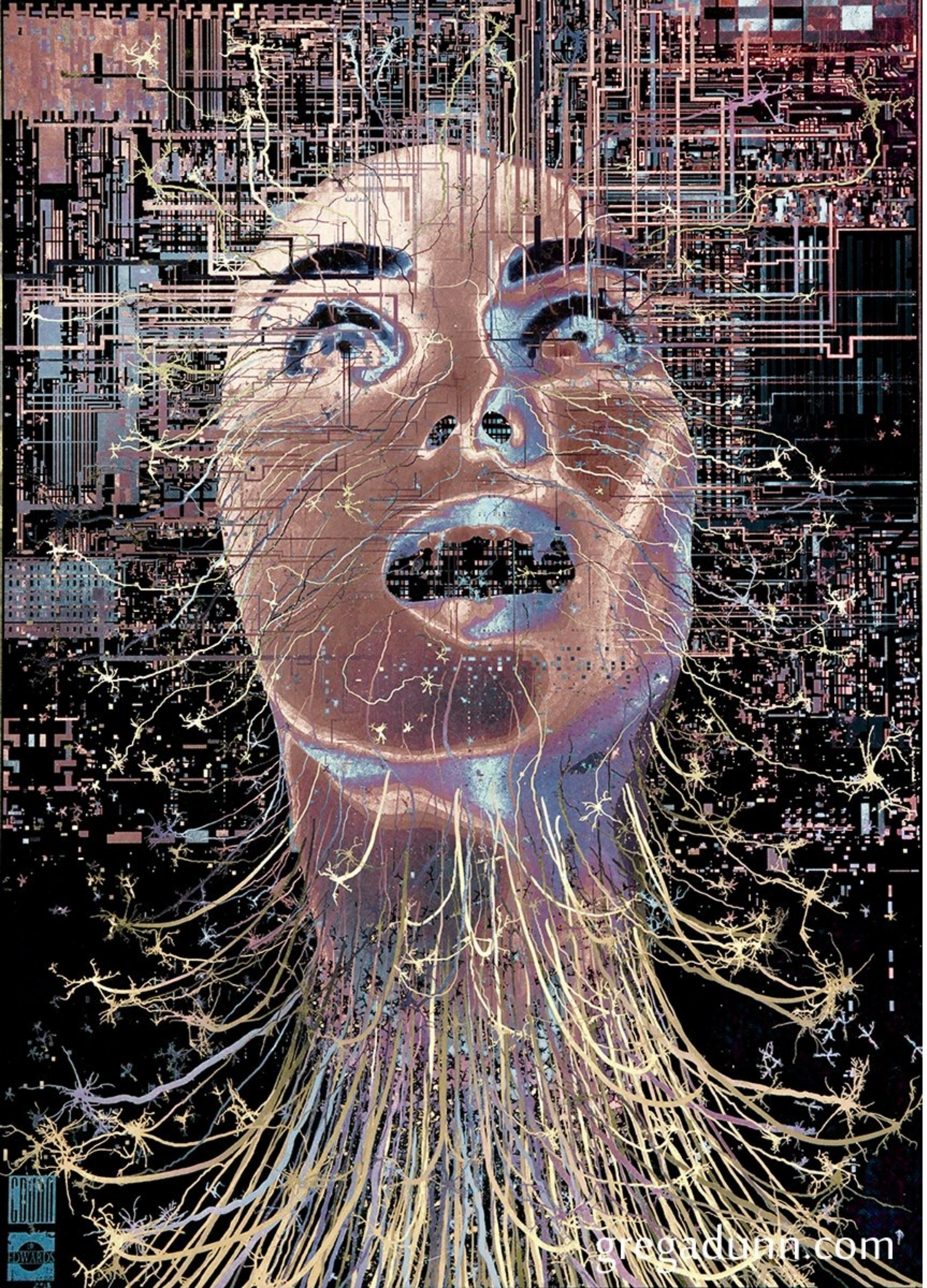
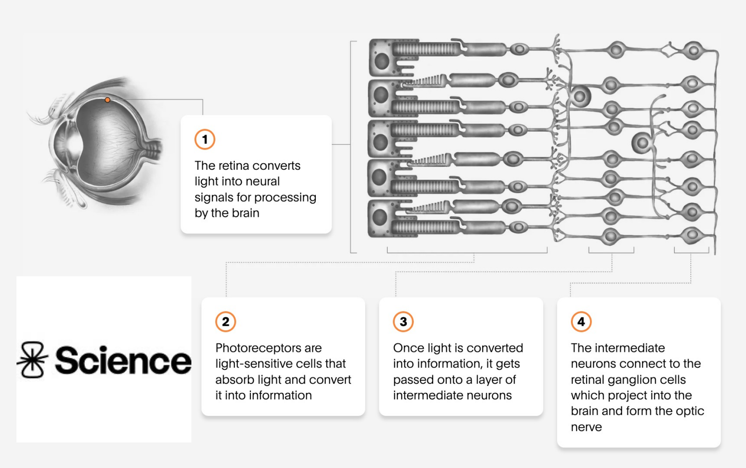
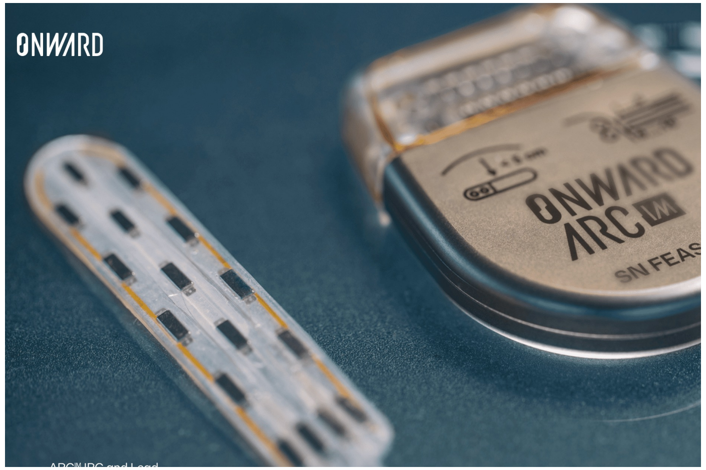


NX-435
Brain machine interfaces for systems neuroscience

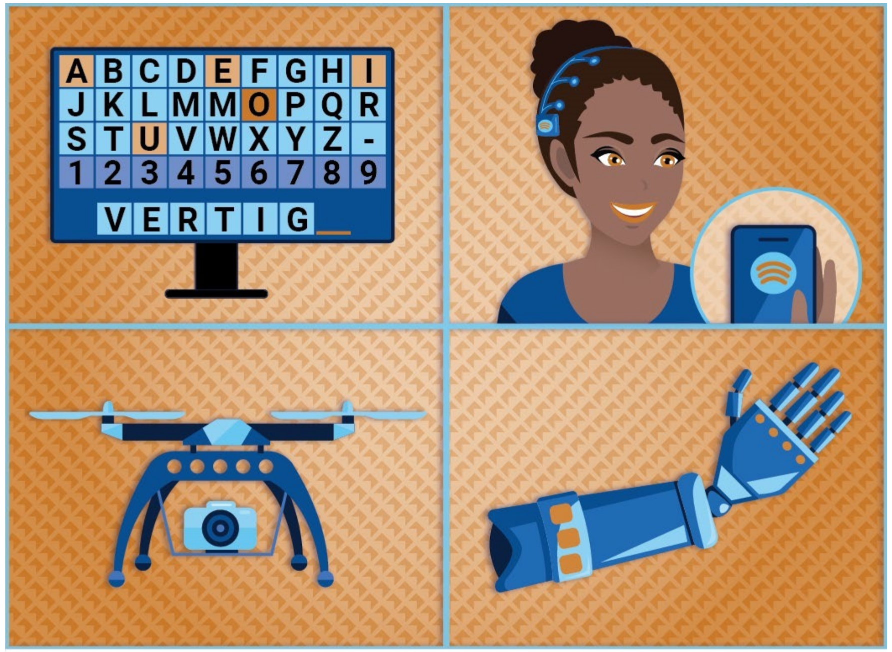
Prof. Mackenzie Mathis, PhD &
Spencer Bowles, PhD

Brain computer interfaces in industry





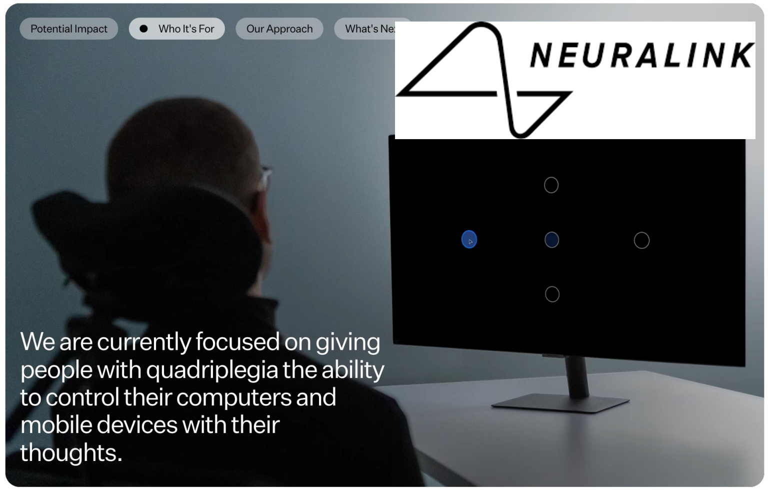
Simply put, a brain-computer interface (BCI) enables a person to control an external device using brain signals



Source: GAO analysis (data). emojoez/svitlana/titaporn/stock.adobe.com (images). | GAO-22-106118

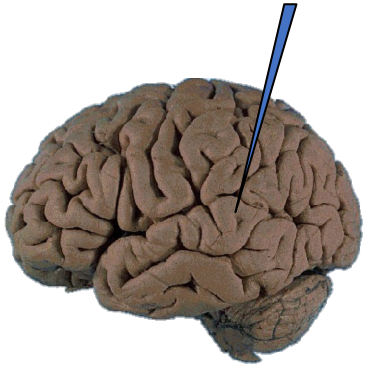
https://www.gao.gov/products/gao-22-106118

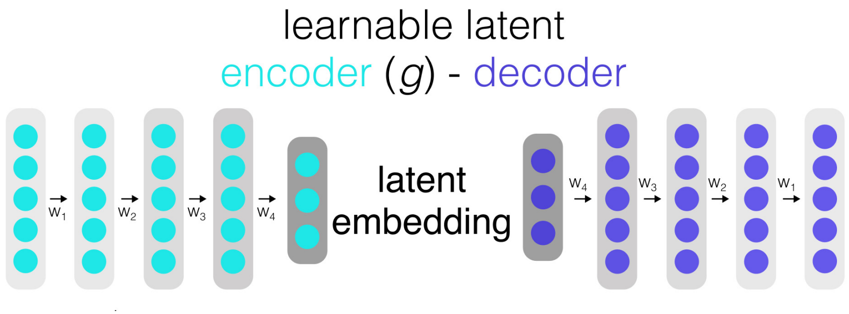
Tech at Meta



Simple overview

Record Neural Activity → Build a Decoder Algorithm → Calculate requisite control parameters for external device



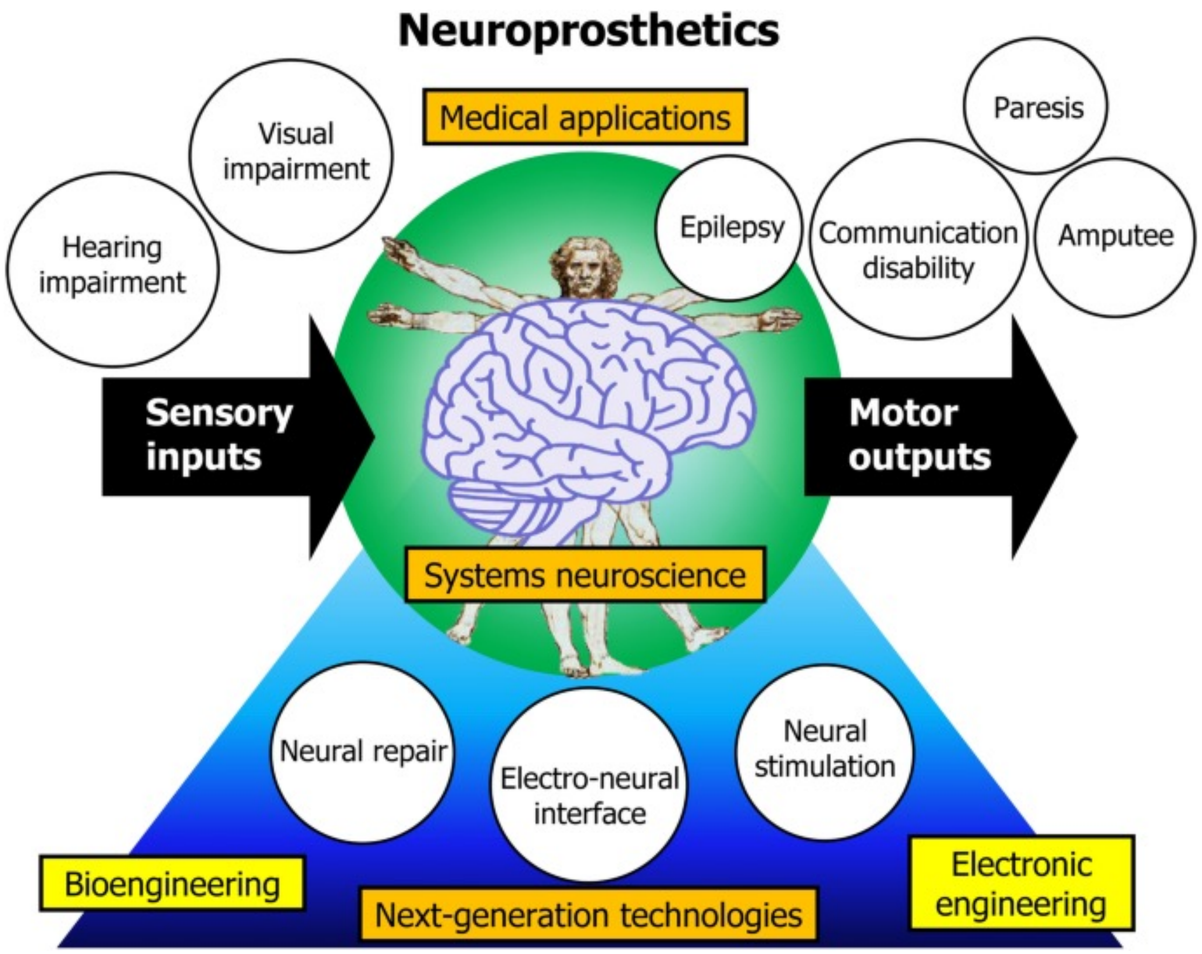


How systems neuroscience is enabling advancements in neuroprosthetics & BCIs

Neuroprosthetics in systems neuroscience and medicine

Our accumulating knowledge in systems neuroscience combined with the development of innovative technologies may enable brain restoration for patients with nervous system disorders. This Collection provides a platform for interdisciplinary research in neuroprosthetics. It will gather studies investigating medical applications of systems neuroscience, informatics, and engineering in the development of neural prostheses. Submissions with a clinical focus on nervous system diseases and brain repair in either humans or animals are also included.

https://www.nature.com/collections/hjcgcjcach



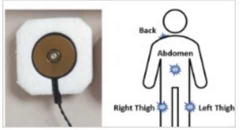
- Which brain areas to record from
- Need to understand neural subtypes
- How to give appropriate sensory feedback
- How do we enable adaptation and learning

Systems neuroscience and neuroprosthetics

Article
Open Access
17 Aug 2022
Scientific Reports

Identifying potential training factors in a vibrotactile P300-BCI

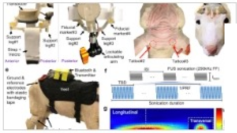
M. Eidel & A. Kübler



Article
Open Access
29 Sep 2021
Scientific Reports

Transcranial focused ultrasound modulates cortical and thalamic motor activity in awake sheep

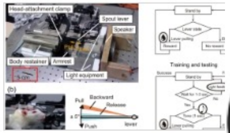
Hyun-Chul Kim, Wonhye Lee ... Seung-Schik Yoo



Article
Open Access
23 Sep 2021
Scientific Reports

Prepulse inhibition predicts subjective hearing in rats

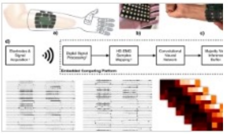
Naoki Wake, Kotaro Ishizu ... Hirokazu Takahashi



Article
Open Access
28 May 2021
Scientific Reports

Intuitive real-time control strategy for high-density myoelectric hand prosthesis using deep and transfer learning

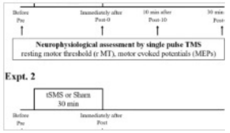
Simon Tam, Mounir Boukadoum ... Benoit Gosselin



Article
Open Access
8 Mar 2021
Scientific Reports

Transcranial static magnetic stimulation over the motor cortex can facilitate the contralateral cortical excitability in human

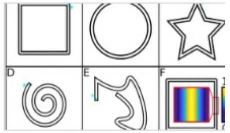
Yasuyuki Takamatsu, Satoko Koganemaru ... Tatsuya Mima



Article
Open Access
25 Feb 2021
Scientific Reports

Quantifying the alignment error and the effect of incomplete somatosensory feedback on motor performance in a virtual brain–computer-interface setup

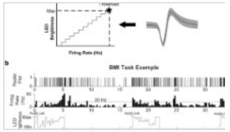
Robin Lienkämper, Susanne Dyck ... Christian Klaes



Article
Open Access
17 Nov 2020
Scientific Reports

Operant conditioning of motor cortex neurons reveals neuron-subtype-specific responses in a brain-machine interface task

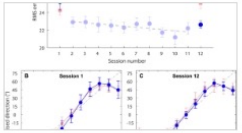
Martha Gabriela Garcia-Garcia, Cesar Marquez-Chin & Milos R. Popovic



Article
Open Access
25 Aug 2020
Scientific Reports

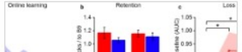
Haptic sound-localisation for use in cochlear implant and hearing-aid users

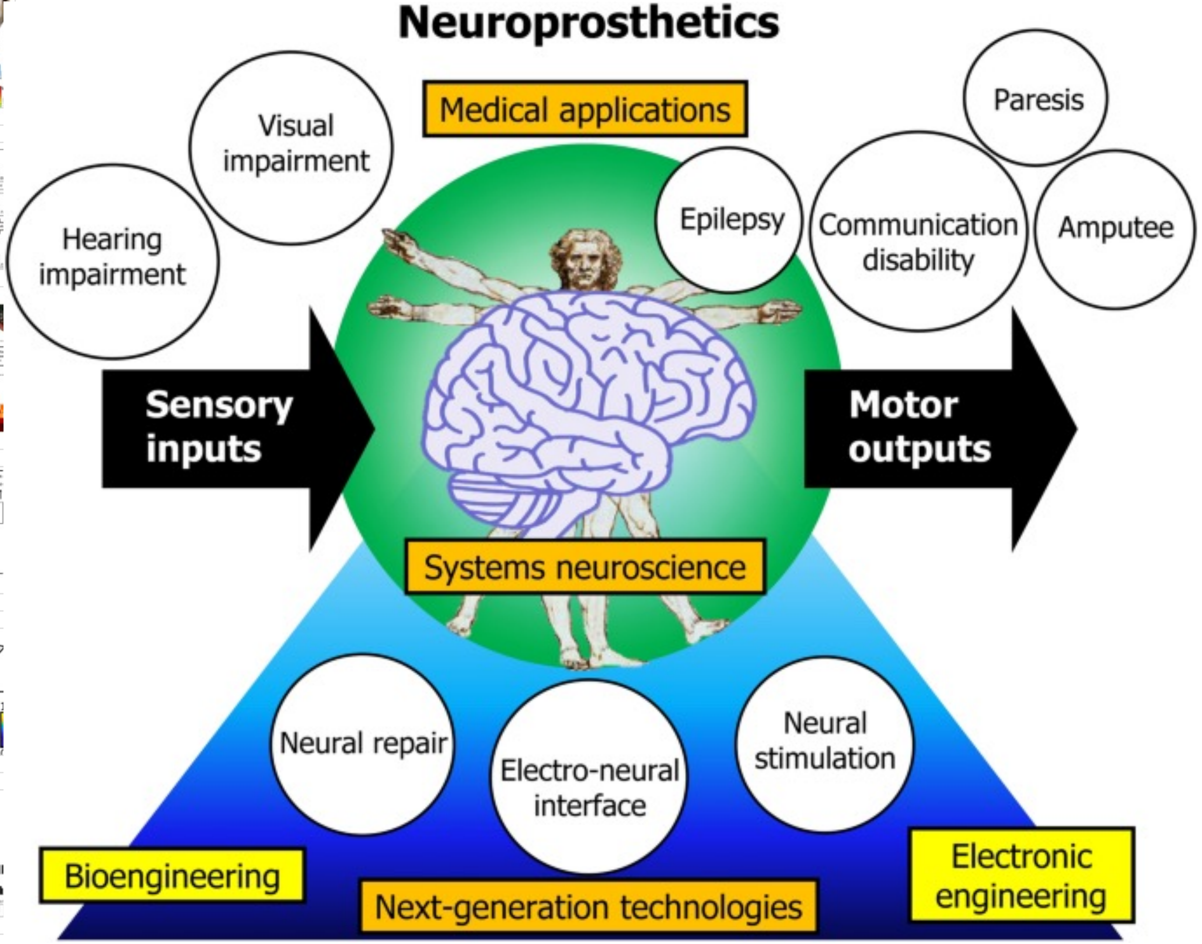
Mark D. Fletcher & Jana Zgheib



Article
Open Access

Cerebellar transcranial alternating current stimulation in the gamma range applied during the acquisition of a novel motor skill

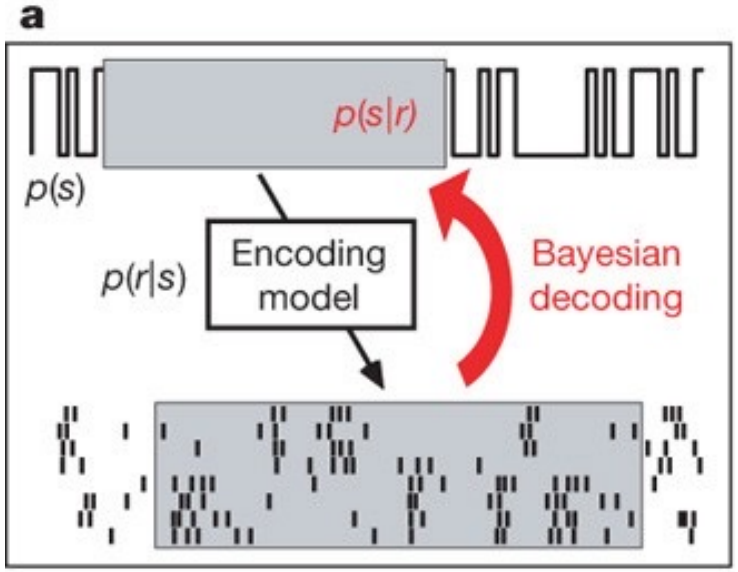




Brain computer interfaces: a primer in decoding

Stimulus

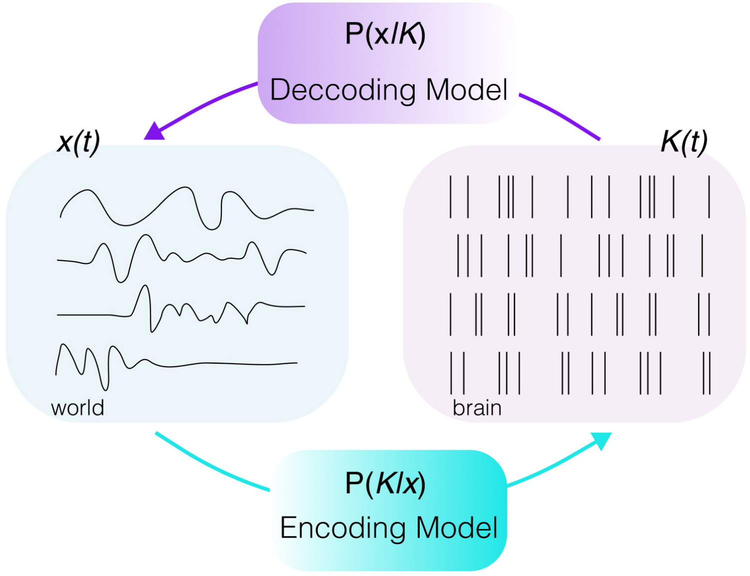
Spikes



- Our brain needs to determine what is going on in the real world from patterns of spikes.

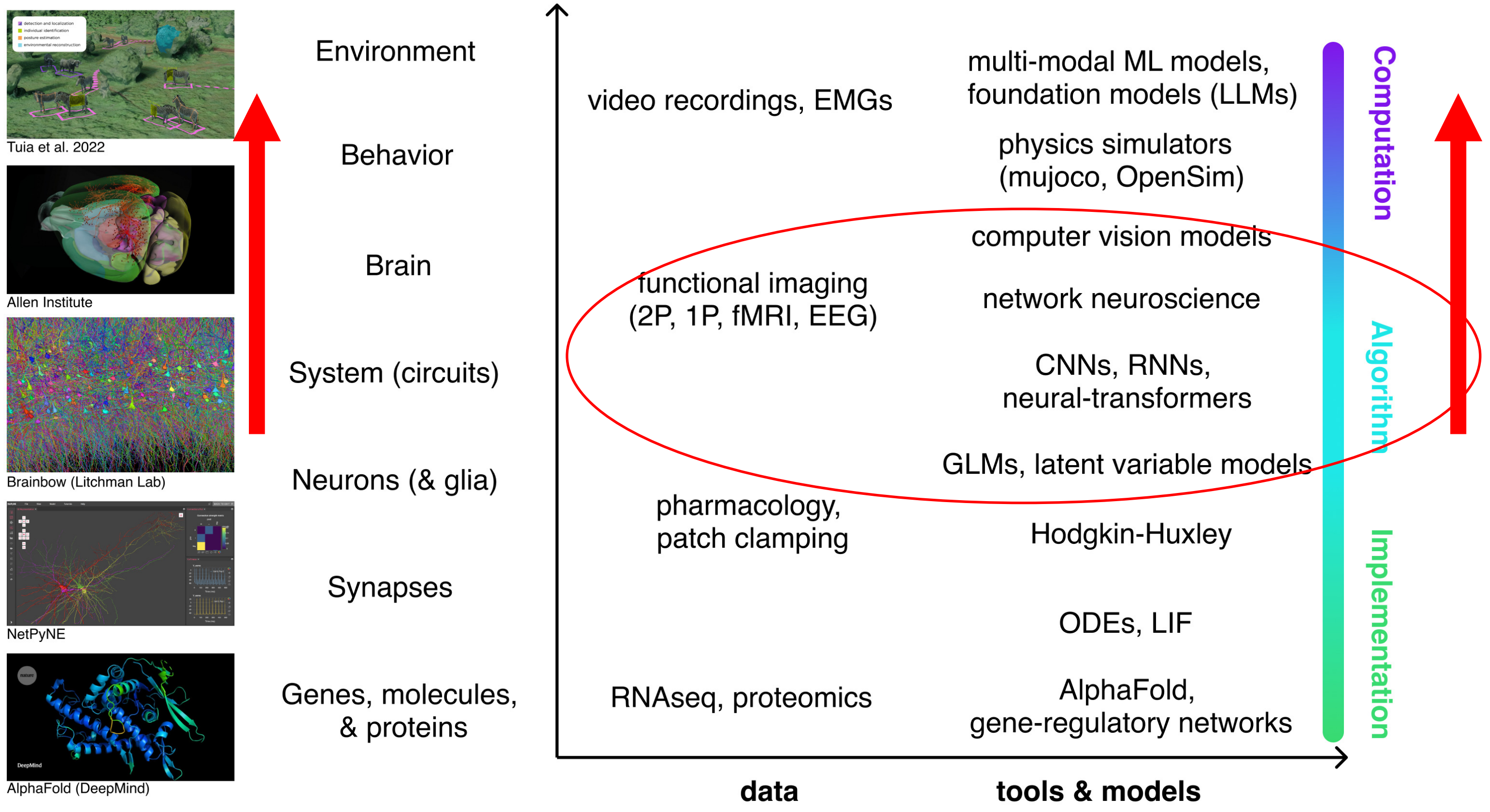
Brain computer interfaces: a primer in decoding

A encoding and decoding models



An encoder represents the neural response of population K(t) to stimulus x(t) via P (K|x), and a decoder aims to recover x(t) given the neural activity K(t) via P (x|K).

B levels of analysis

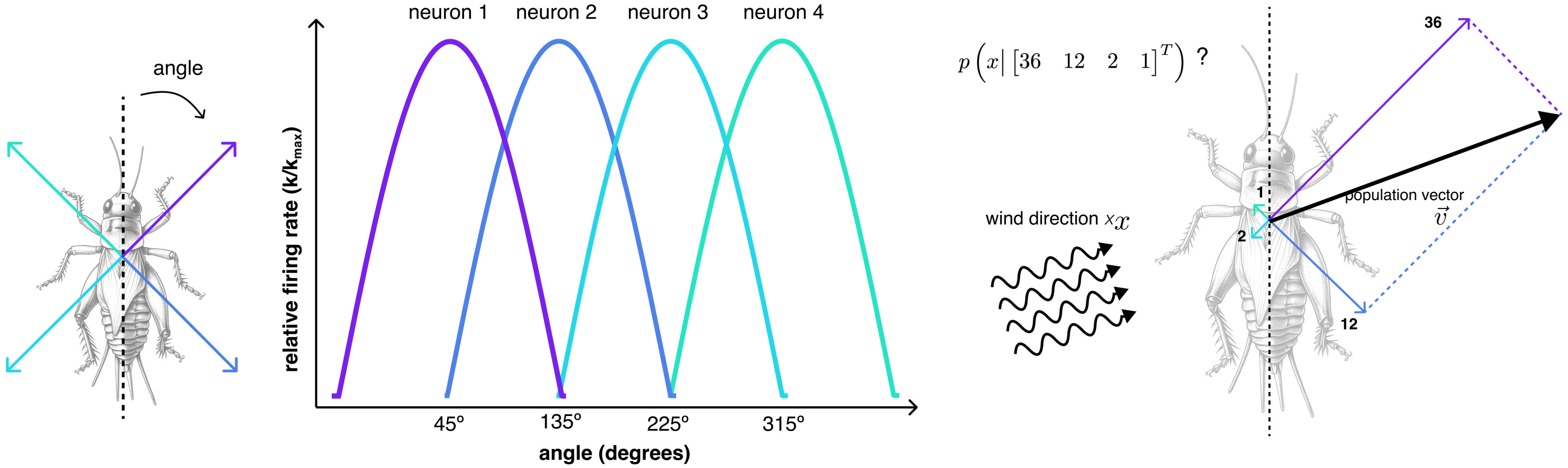


Systems neuroscience spans scales of descriptions and decoding algorithms can target any individual level, and even span across scales. Here, we outline example scales (from genes to environment), the types of data we can collect (from genetic sequencing to whole-animal video analysis), and the classes of models the field has developed. On the far right is our mapping of scales, example data, and example tools to levels of understanding (akin to Marr's 'three levels' (14), with a systems perspective)

Brain computer interfaces: a primer in decoding

A encoding model of wind direction

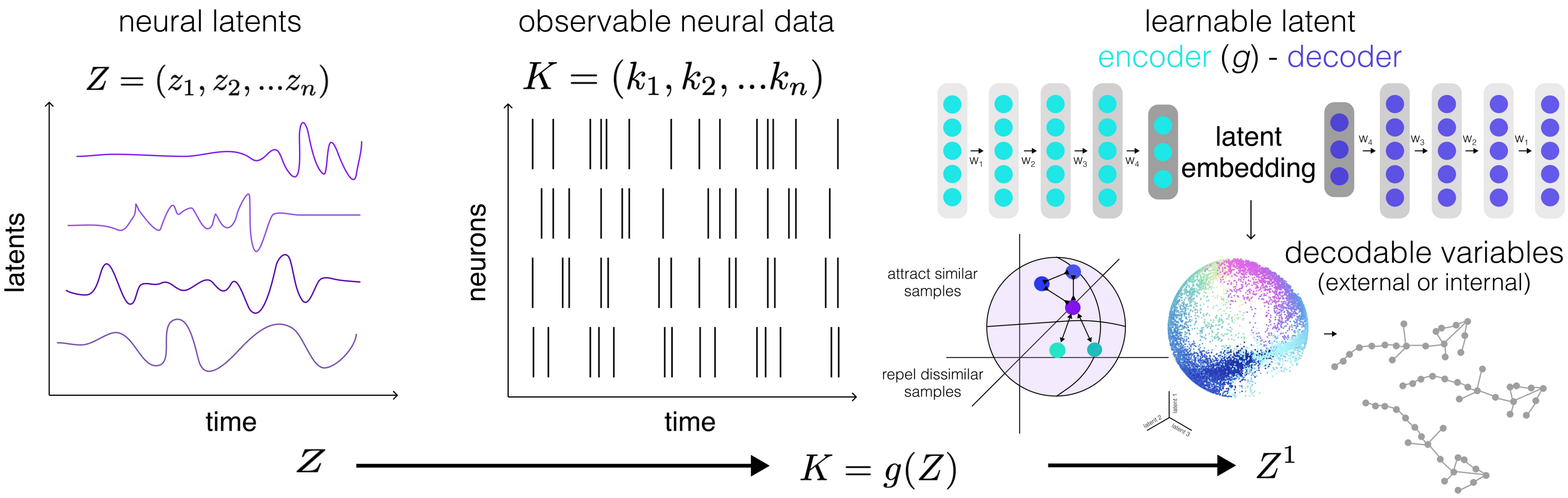
B decoding with population vector



A: The cercal system of the cricket has four interneurons that represent the wind direction. The preferred wind directions of the neurons are pointing in four cardinal directions and can be represented by orthogonal vectors (on the left). Each neuron responds with a firing rate approximated by a half-wave rectified cosine function. The maximum firing rate is elicited when the wind is blowing in the preferred direction.

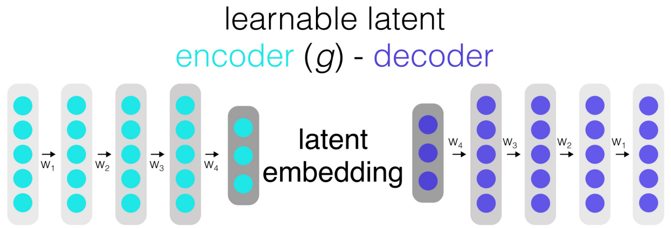
B: The wind direction x can be decoded as the direction of the population vector ˆx. This vector is the sum of the four preferred orientations scaled by their firing rate. An example is shown for neurons responding with activity [36, 12, 2, 1]T . Note how the population vector closely matches the wind direction

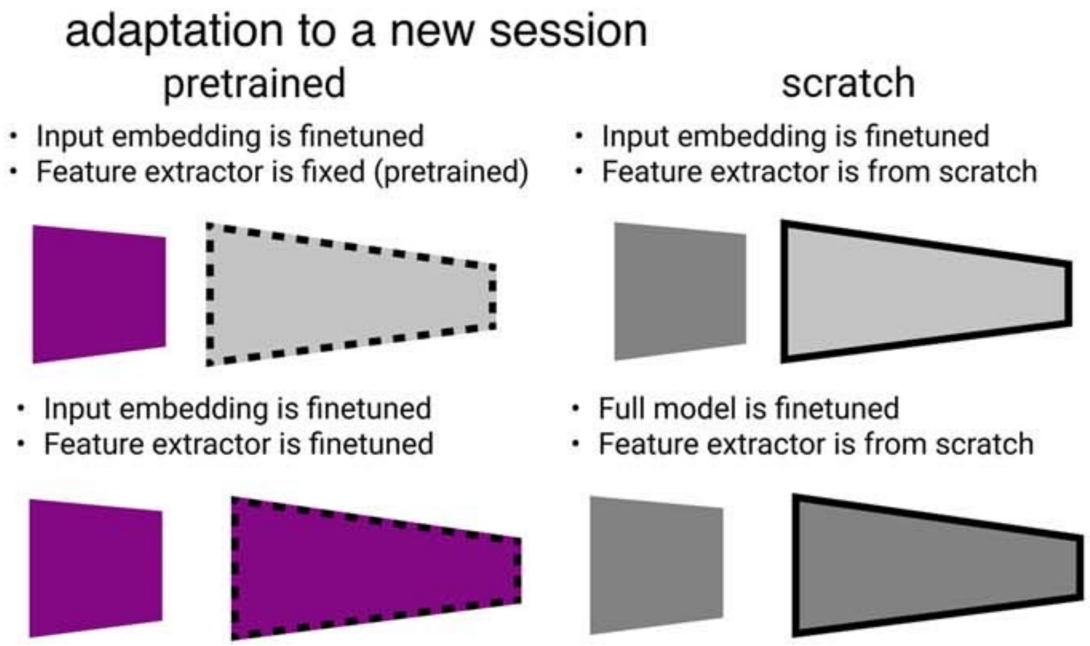
Brain computer interfaces: a primer in decoding

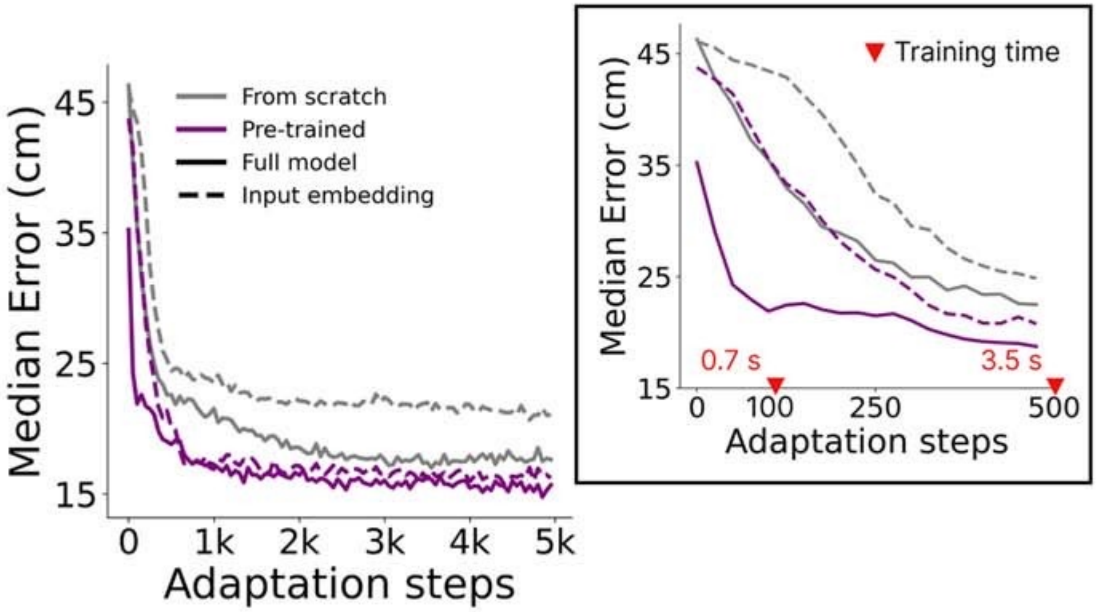


Learnable latent variable models. A: On the path to building more causal models are new frameworks, such as CEBRA (27), that allow for learning a mapping from the observable data K to the latent dynamics Z. Here, the aim is to use identifiable models with contrastive learning g(Z) (the encoder), then invert this model or use another decoder framework to probe the relationship between the estimated latents, Z1, and a variable such as an externally observable state (behavior), internal, or sensory (i.e., recover some stimulus space (x)).

Brain computer interfaces: a primer in decoding



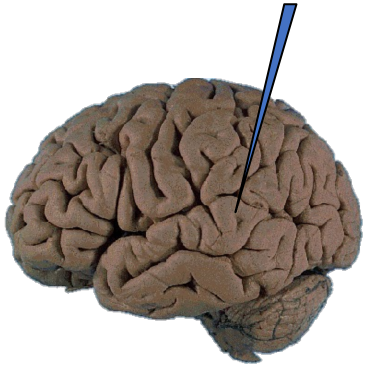


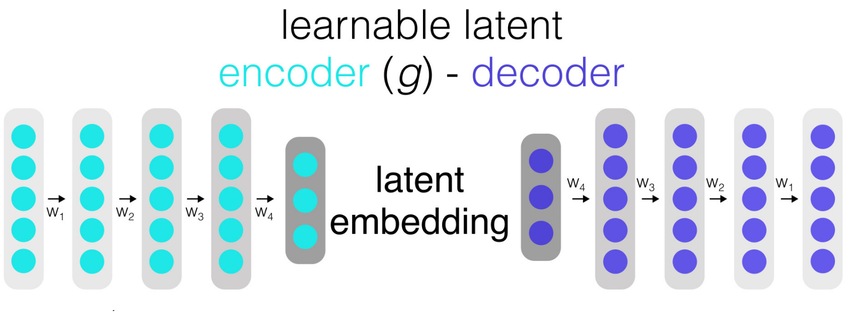


Schneider, Lee, Mathis 2023 Nature

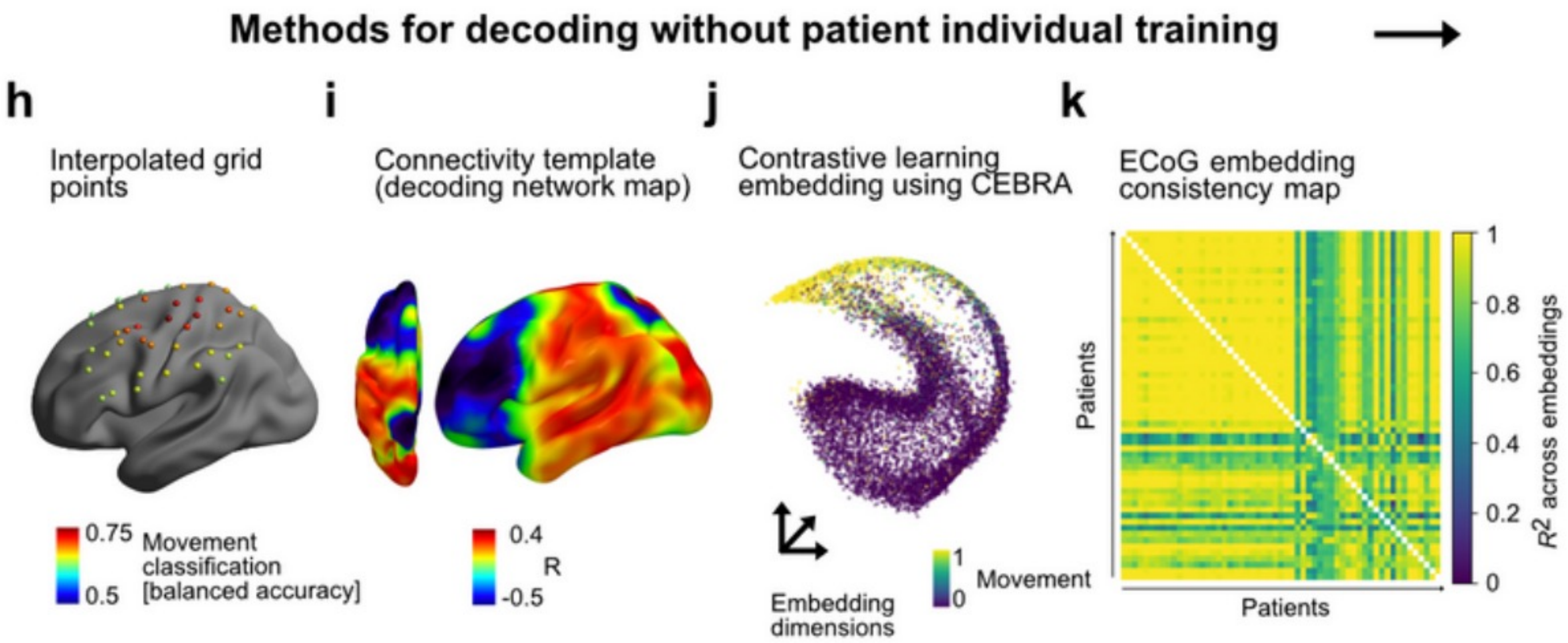
Simple overview

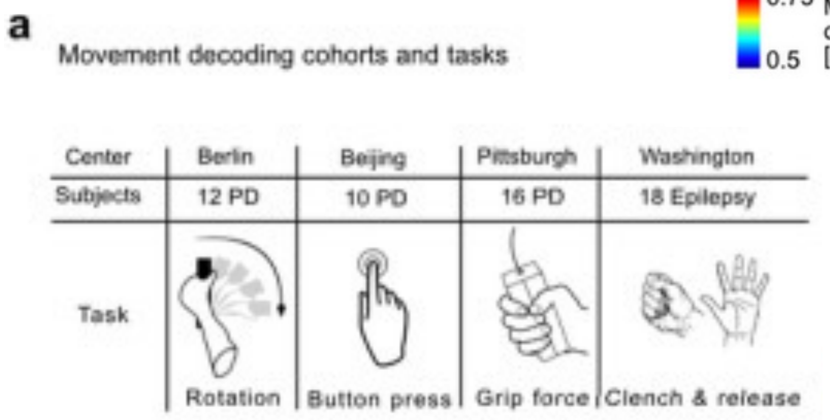
Record Neural Activity → Build a Decoder Algorithm → Calculate requisite control parameters for external device

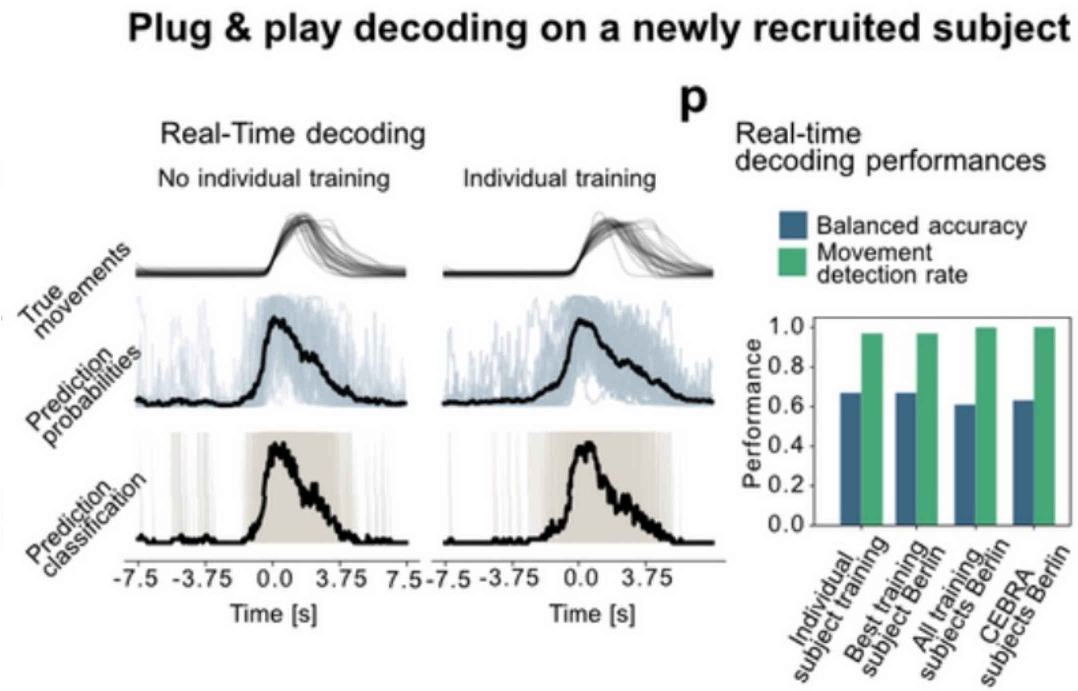




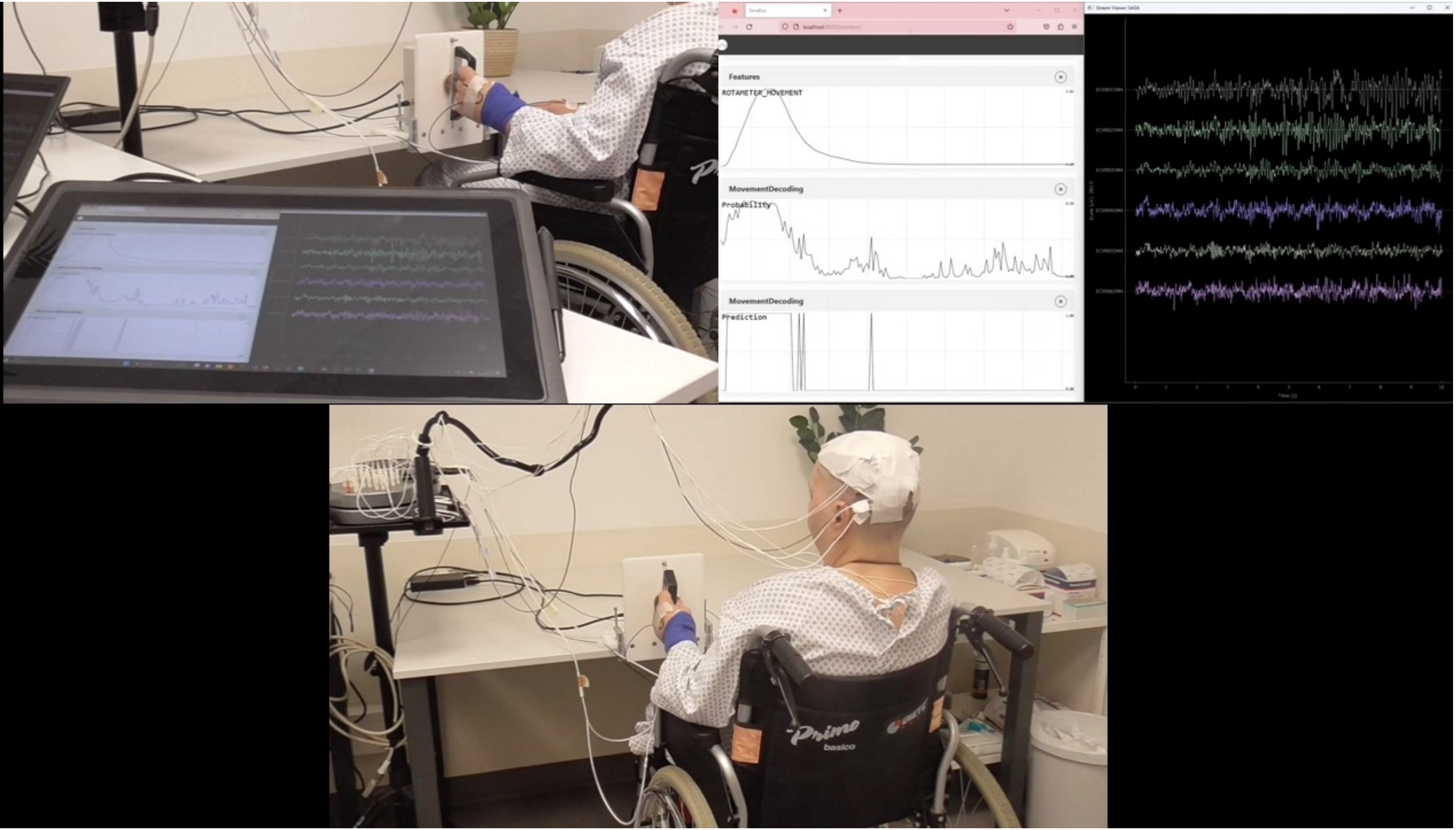
Record neural data → build a model → deploy







Merk et al. 2023
https://doi.org/10.21203/rs.3.rs-3212709/v1



Features
ROTAMETER_MOVEMENT
MovementDecoding
Probability
MovementDecoding
Prediction
Primo
basico

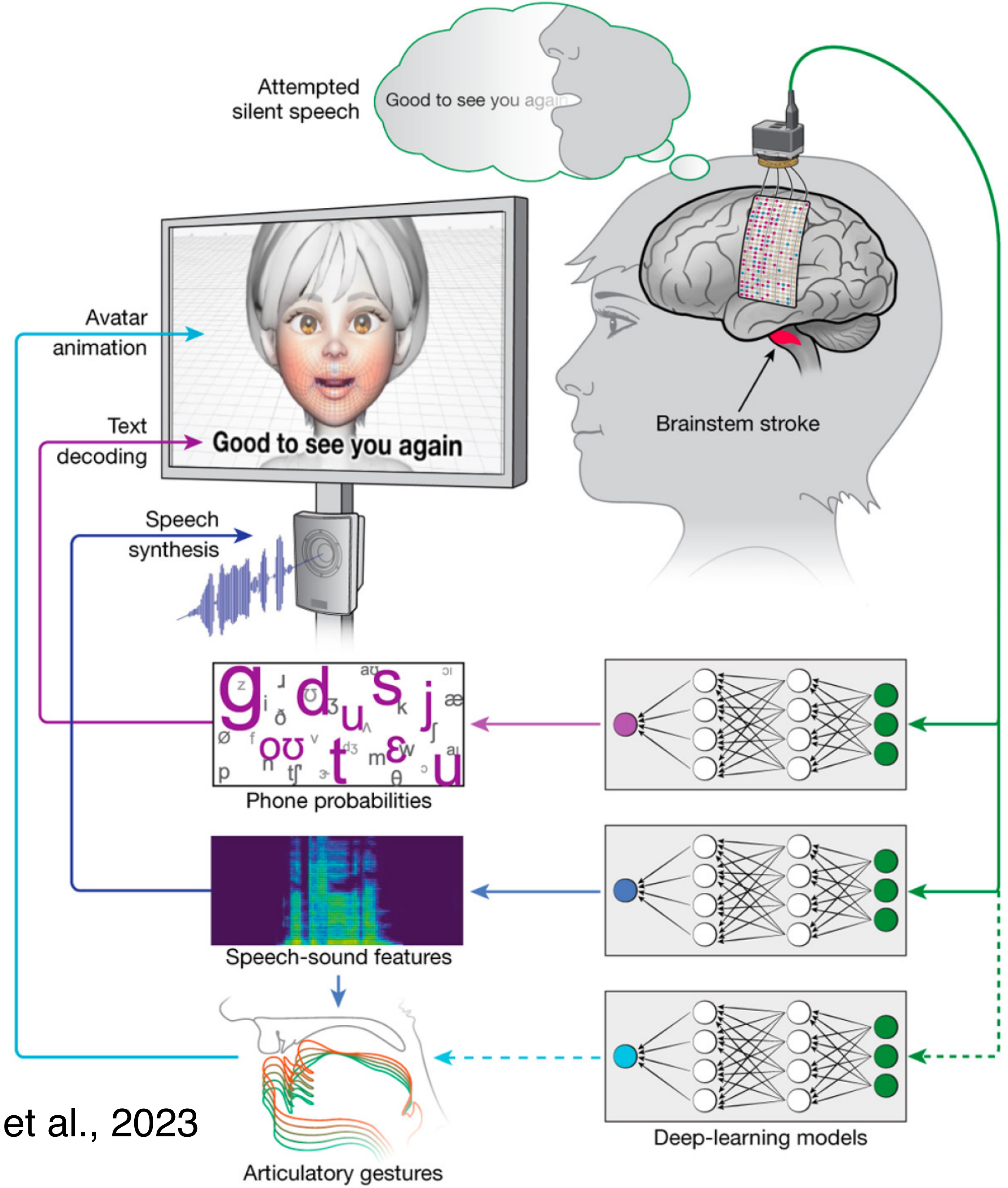
Brain computer interfaces: for language

Multi-modal speech decoding.

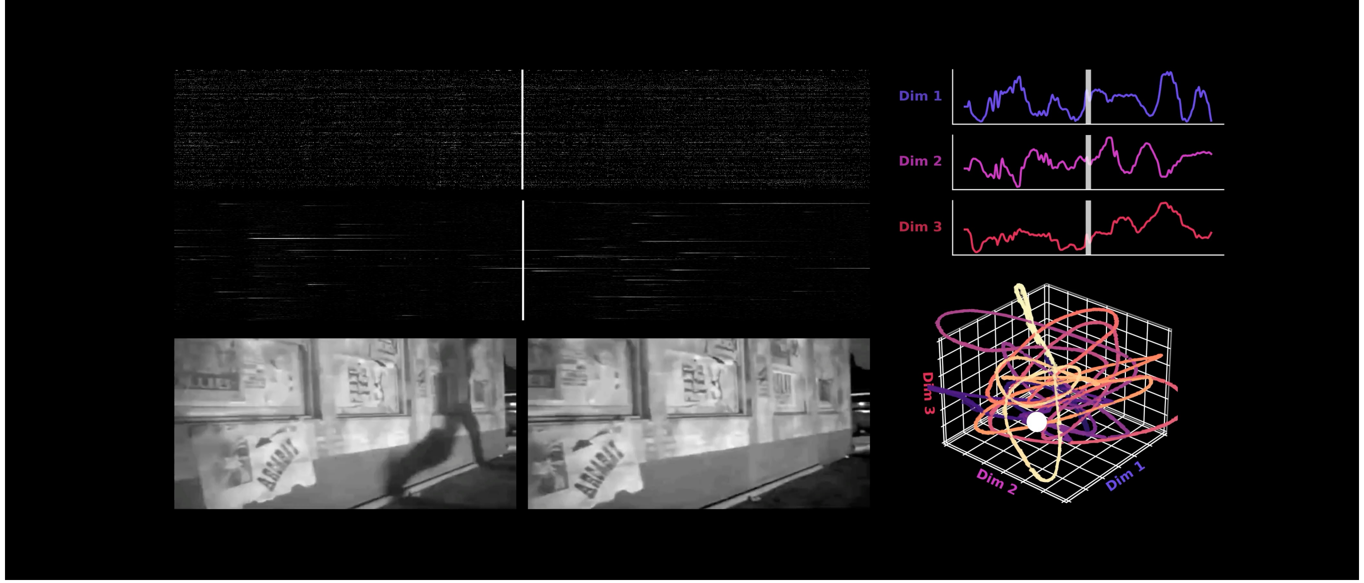
- Neural activity was used to train a ANN to predict phone probabilities, speech-sound features
- and articulatory gestures.

- **A decoder was then constructed to produce text, generate audible speech and animate an avatar,** respectively.

Metzger et al., 2023



Brain computer interfaces: for visual scene estimation and reconstruction



Movie frame prediction from V1 of mice (using CEBRA + kNN decoder)

Illustration of decoded images from fMRI using Diffusion Models.

Ground truth (GT) vs. decoded images generated by Chen et al. from human fMRI with a diffusion model. Note that decoded images share similar color, shape and semantics.

What’s next: BCIs also can be used to study neural dynamics of learning

BCIs not only have the potential to replace or augment motor function, **but also to be used as tools to study the direct and indirect neural circuits involved in learning as they adapt to new contingencies**

Garcia-Garcia et al. 2020

- Single neuron BCI!

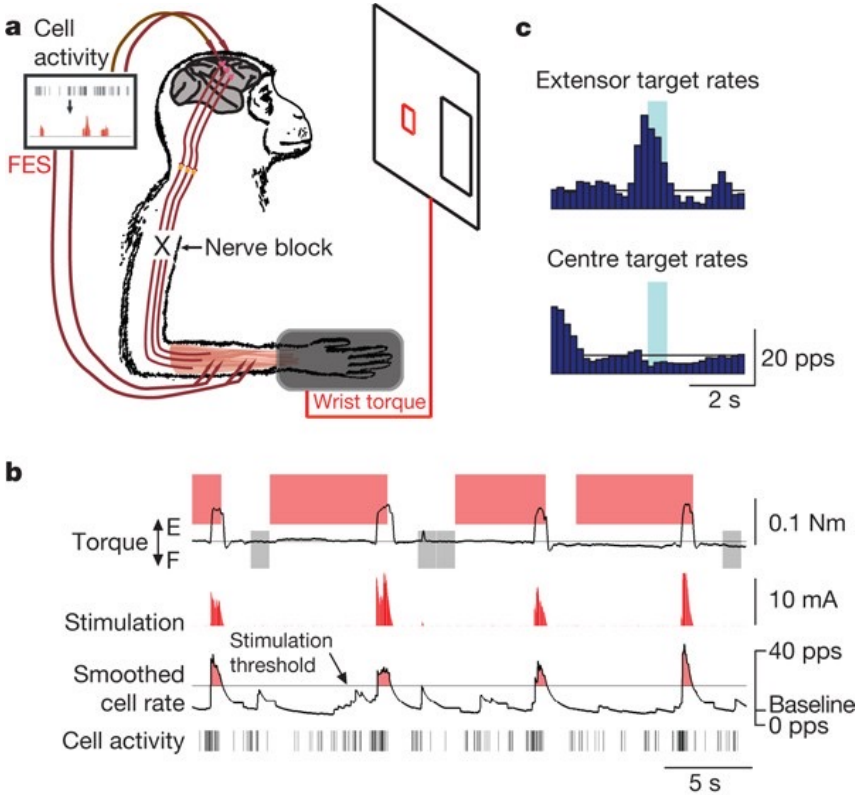
- Monkeys demonstrated volitional control of the discharge rates of nearly all cells tested within the first 10-min practice session

Letter | Published: 01 December 2008

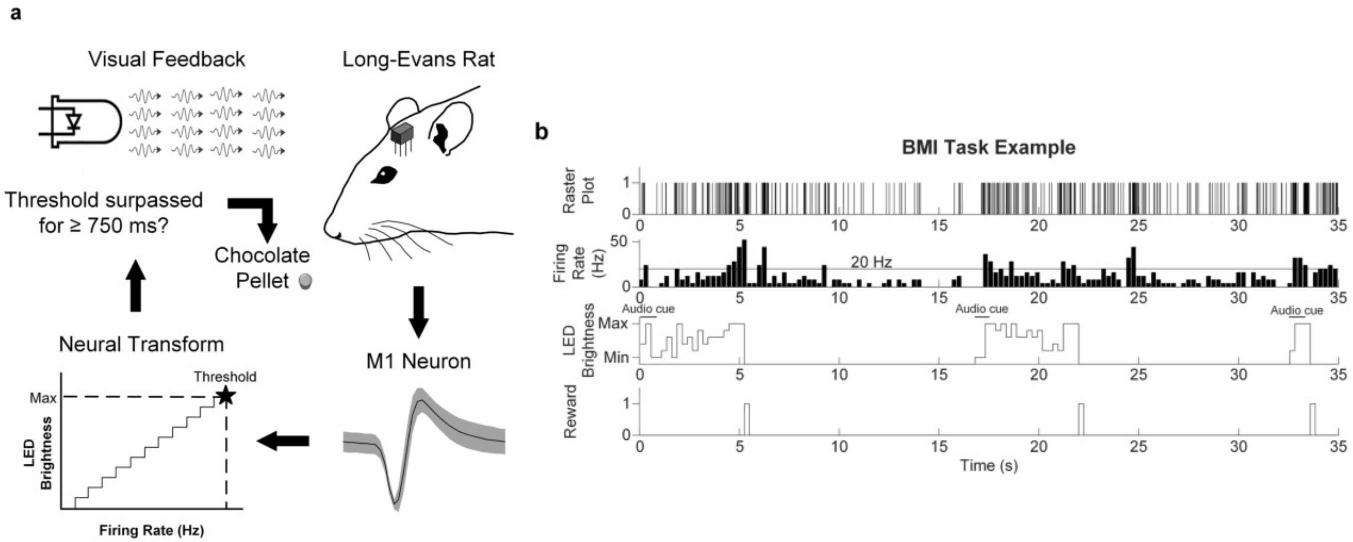
Direct control of paralysed muscles by cortical neurons

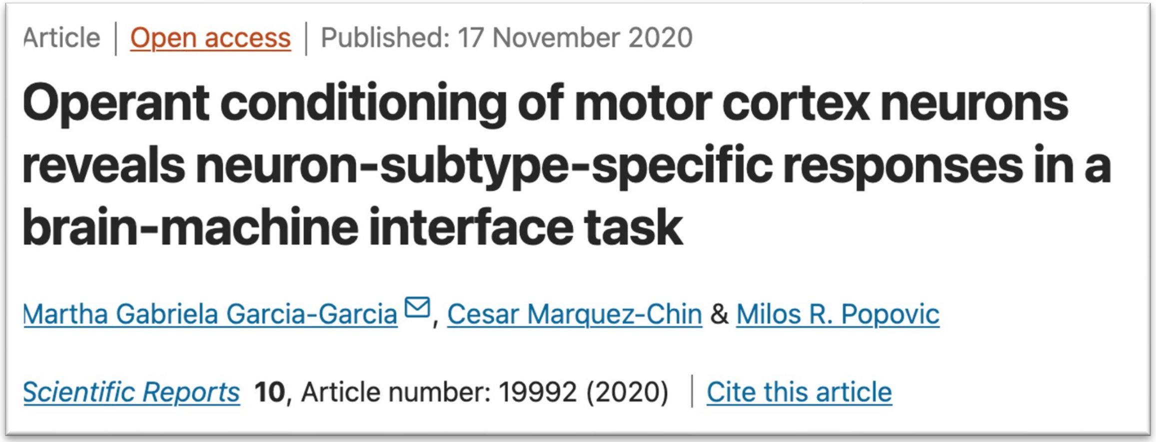
Chet T. Moritz, Steve I. Perlmutter & Eberhard E. Fetz

Nature **456**, 639–642 (2008) | Cite this article



Brain computer interfaces: considering neuron subtypes




Article | Open access | Published: 17 November 2020

Operant conditioning of motor cortex neurons reveals neuron-subtype-specific responses in a brain-machine interface task

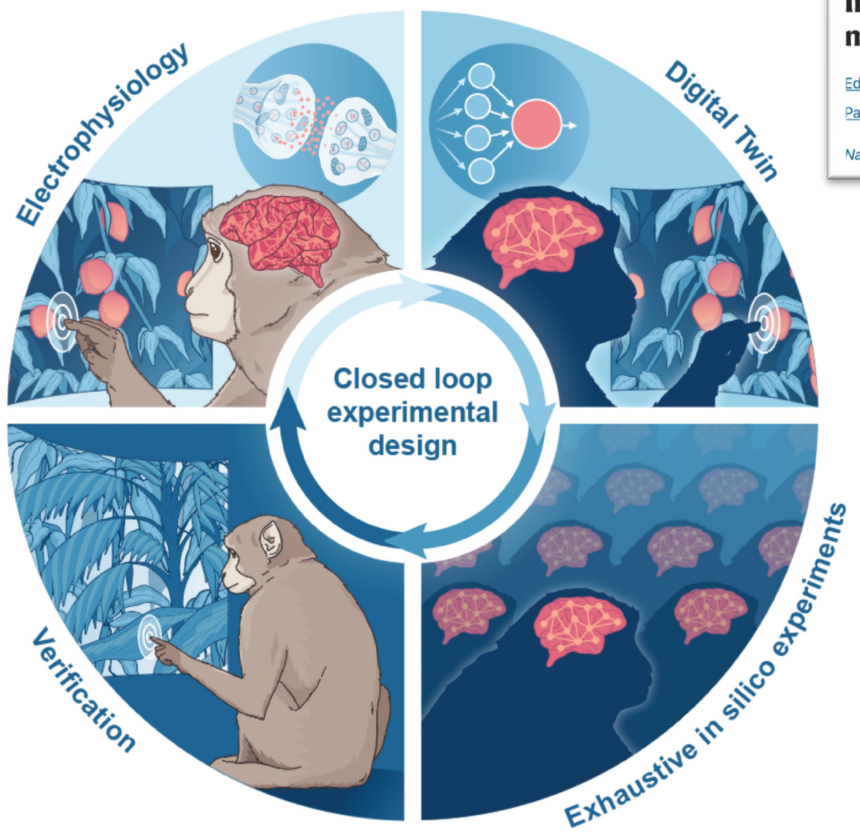
Martha Gabriela Garcia-Garcia, Cesar Marquez-Chin & Milos R. Popovic

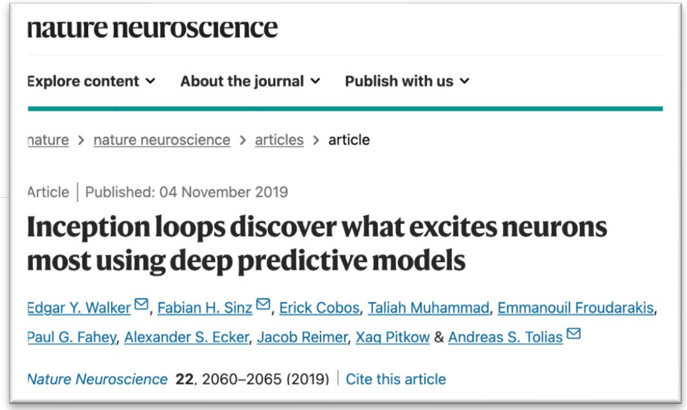
Scientific Reports **10**, Article number: 19992 (2020) | Cite this article

The authors investigated how neuron subtypes respond and adapt to a given BMI task.

- We conditioned single cortical neurons in a BMI task.
- Recorded neurons were classified into bursting and non-bursting subtypes based on their spike-train autocorrelation.
- Both neuron subtypes had similar improvement in performance and change in average firing rate.
- However, in bursting neurons, the activity leading up to a reward increased progressively throughout conditioning, while the response of non-bursting neurons did not change during conditioning.

Record neural data → build a model → deploy




nature neuroscience

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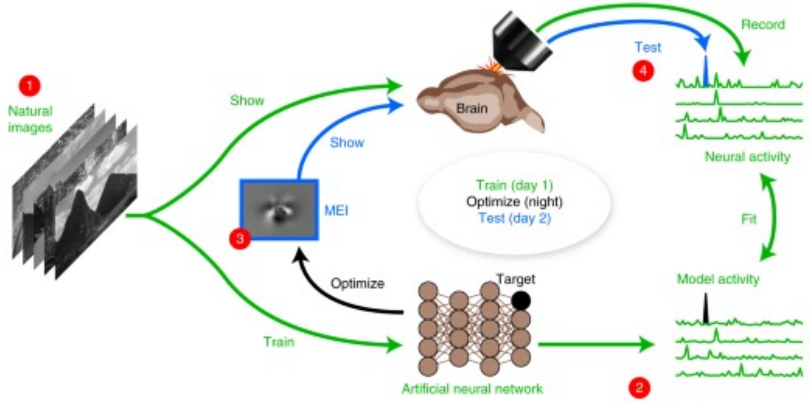
nature > nature neuroscience > articles > article

Article | Published: 04 November 2019

Inception loops discover what excites neurons most using deep predictive models

Edgar Y. Walker, Fabian H. Sinz, Erick Cobos, Taliah Muhammad, Emmanouil Froudarakis, Paul G. Fahey, Alexander S. Ecker, Jacob Reimer, Xaq Pitkow & Andreas S. Tolias

Nature Neuroscience **22**, 2060–2065 (2019) | Cite this article

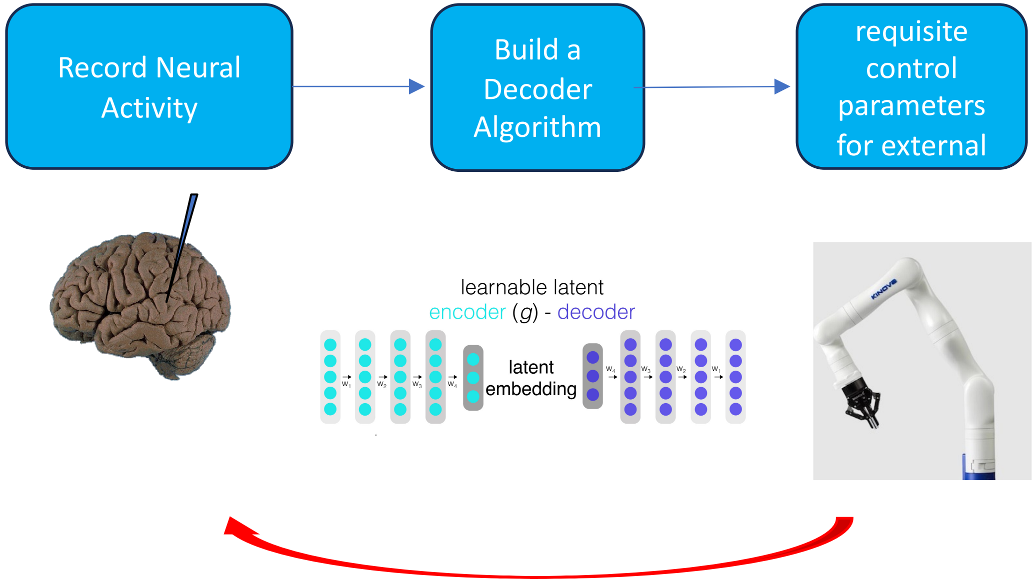


- Inception Loops are a great example of neural decoding and close-loop stimulus design.
- In part, this is a type of “BCI”, as we are designing neural control of “optimal” external stimuli to drive activity.
- However, the goal of BCIs is slightly different: we want to “read & write” into the brain.

What’s next: Reading & Writing into the brain

Current BCIs are mostly focused on allowing brain signals (neural activity) to be translated into controlling external devices. However, another critical goal is to give sensory feedback to the patient.

(imagine: if you are controlling a robotic arm, it would be very helpful to know when the arm touched the cup you want to pick up!)



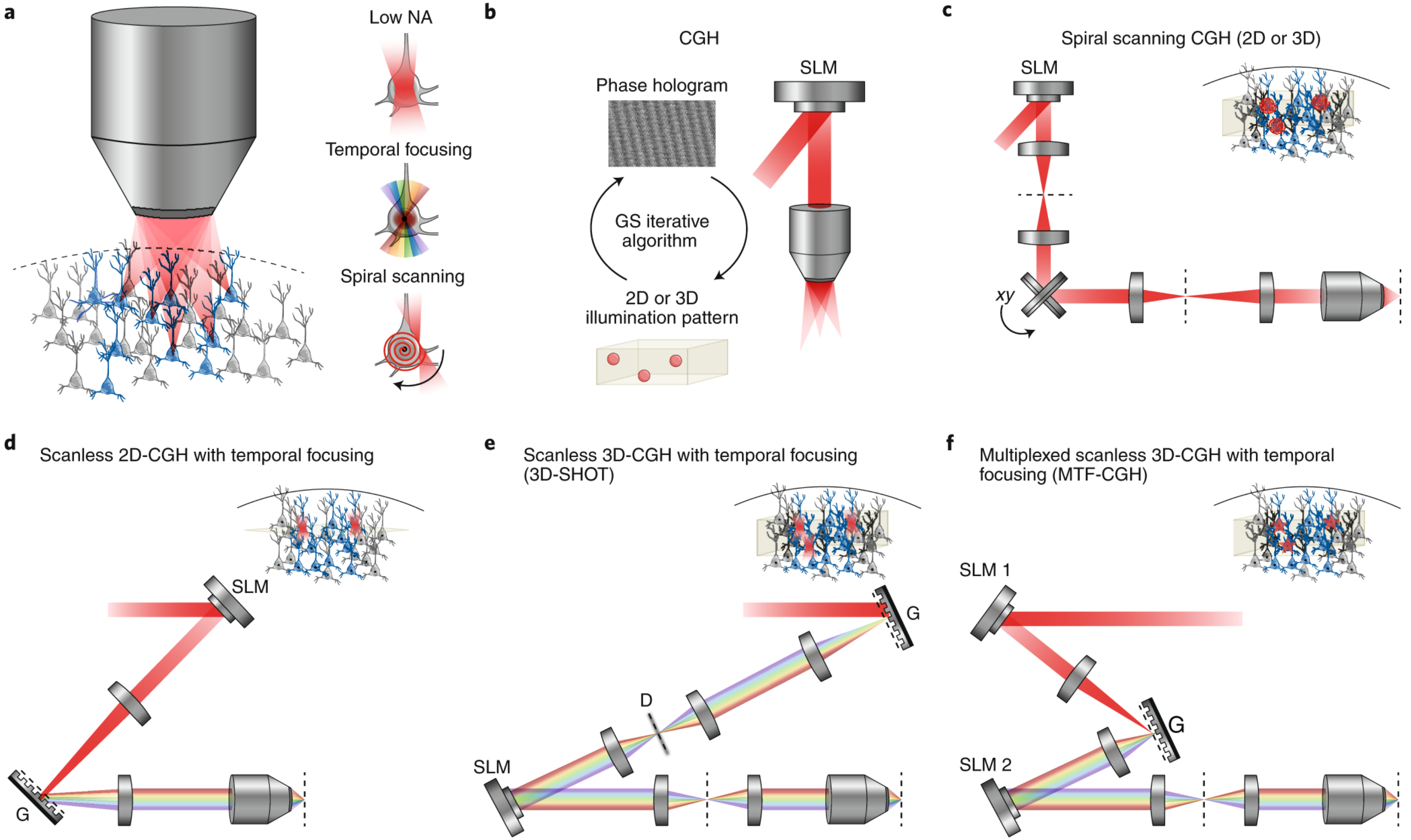
This requires us then being to DECODE the signals to create the MOVEMENTS in the external device, and GIVE SENSORY feedback to the BRAIN.

Do we know how to give the “right” patterns of activity to make it “feel, look, hear” real?

This is also where more scientific understanding is critical …

Reading & Writing into the brain: all optical studies

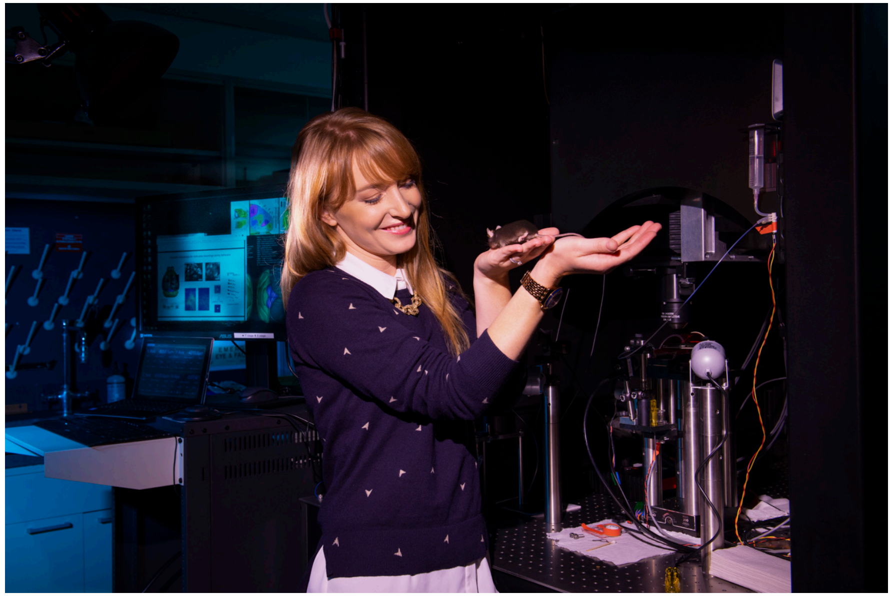
- **Calcium imaging + optogenetics allows for "all optical" access the neural circuits.**
- We can design closed-loop experiments to measure and perturb neural activity.
- We can design these such that we "closed-loop" record neural activity and have the animal use this activity to complete a task.



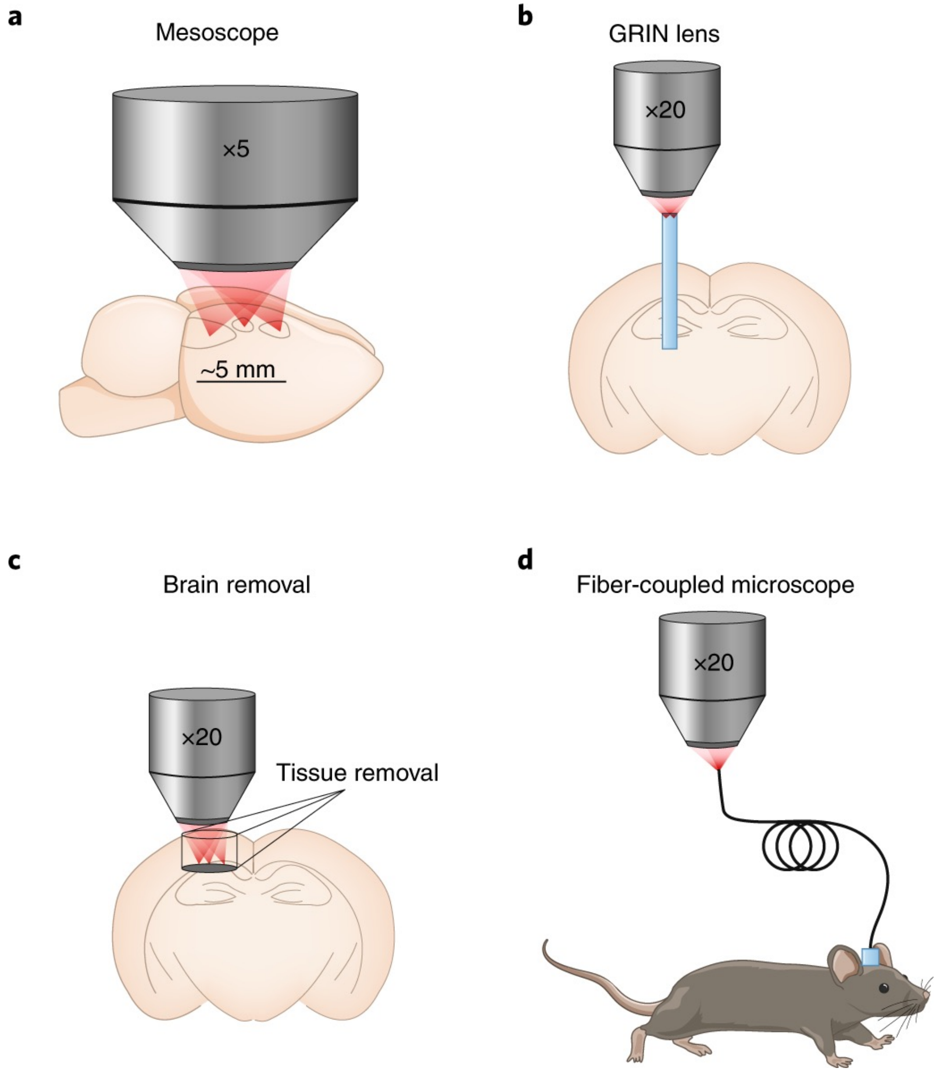
Adesnik, H., Abdeladim, L. Probing neural codes with two-photon holographic optogenetics. *Nat Neurosci* **24**, 1356–1366 (2021). https://doi.org/10.1038/s41593-021-00902-9

Reading & Writing into the brain: all optical studies

- Typical 2-photon imaging window is ~500 um in diameter in the cortex (layers ~2-5 most typical).
- Now, new approaches are enabling recording in deeper areas (GRIN lens) and larger areas (mesoscope)

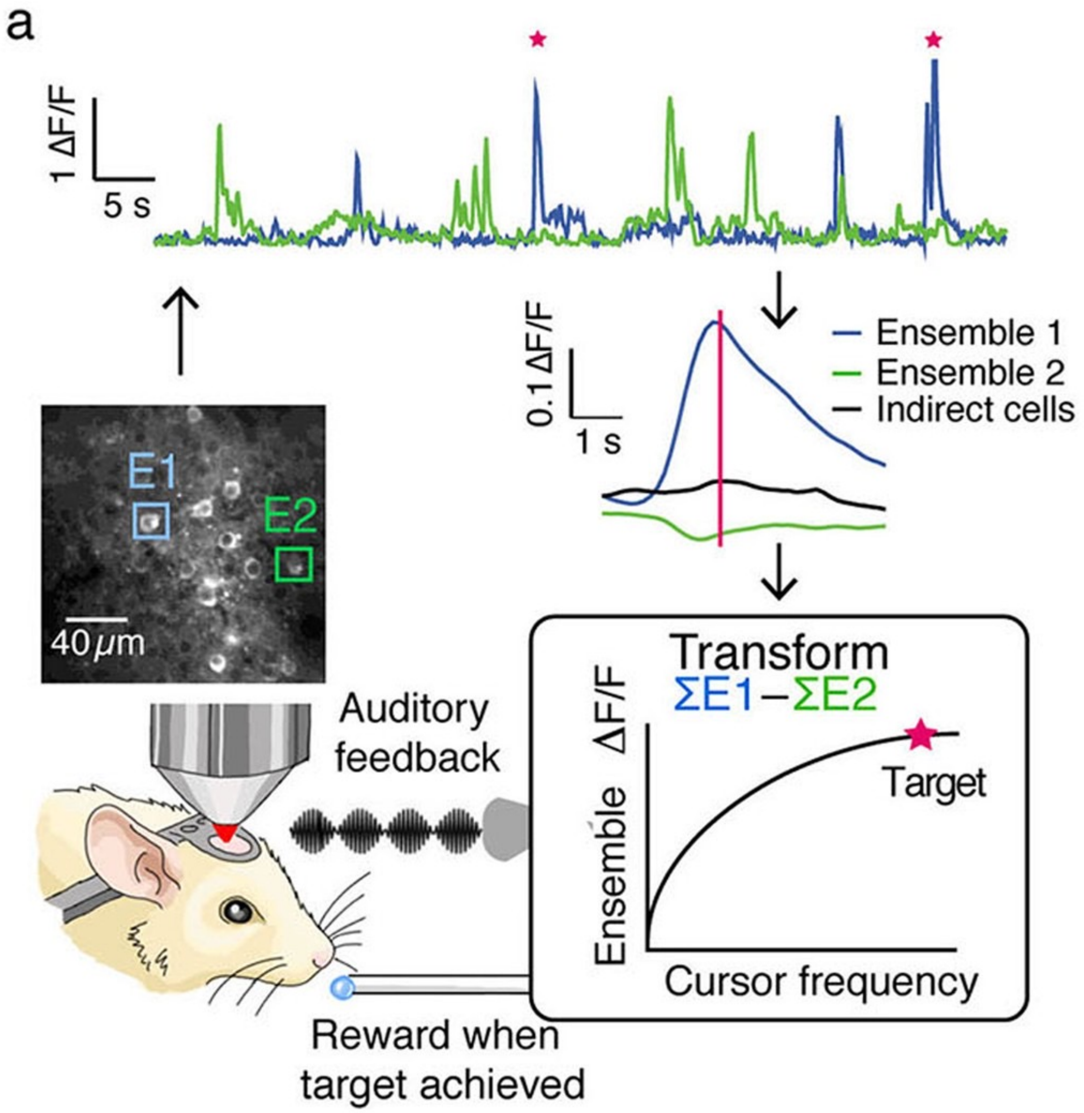


Our 2P mesoscope system at **EPFL**!
(not many in the world)



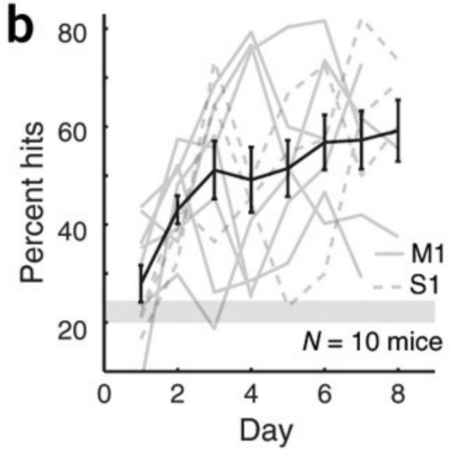
Adesnik, H., Abdeladim, L. Probing neural codes with two-photon holographic optogenetics. *Nat Neurosci* **24**, 1356–1366 (2021). https://doi.org/10.1038/s41593-021-00902-9

Brain computer interfaces: all optical studies

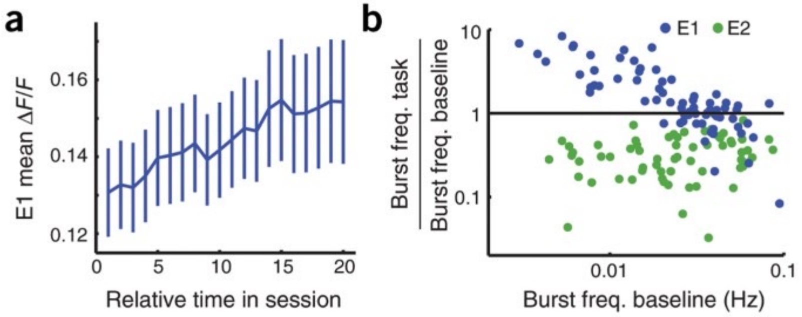


BMI tasks provide a powerful approach for studying sensorimotor learning, as they enable arbitrary mapping between neuronal activity, behavioral output and reward

Mice learn to intentionally modulate calcium dynamics.



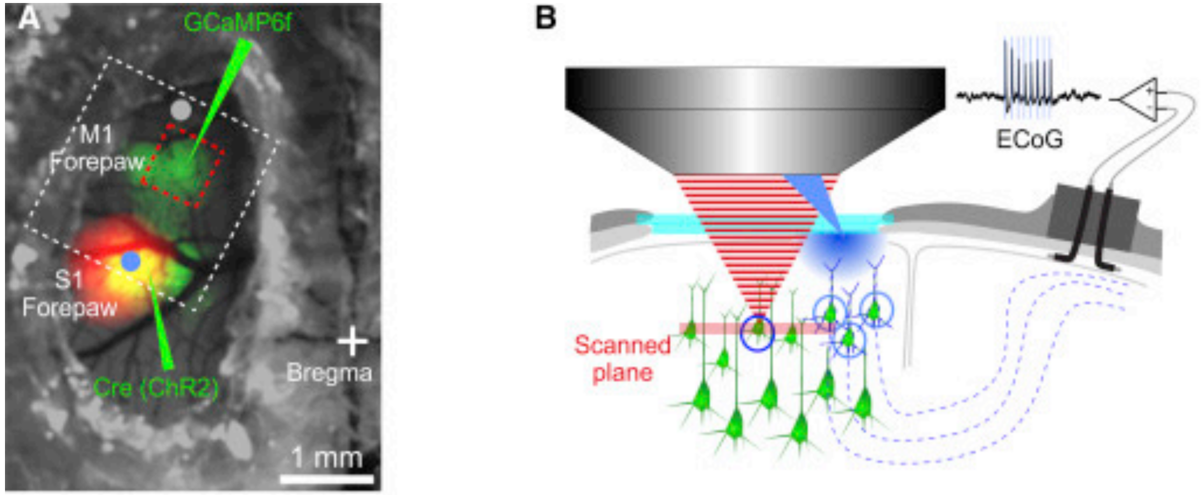
Local network reorganization accompanies learning



Clancy et al. 2014
https://www.nature.com/articles/nn.3712

Brain computer interfaces: all optical studies

Can mice learn to use a fabricated feedback channel to control single-neuron activity?
How do responses of the conditioned and neighboring cortical neurons change with learning?

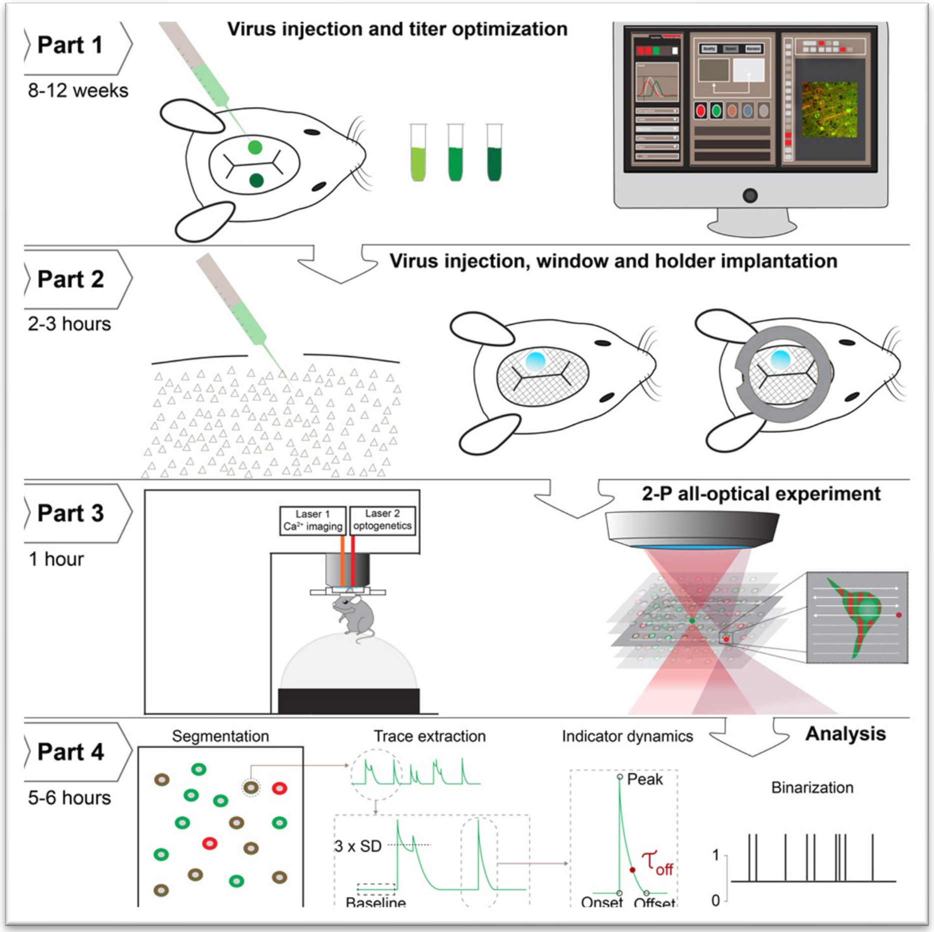


- They used 2P imaging, optogenetics, ECoG, real-time ROI selection, and a decoding algorithm*
- *(technical tour de force!)*

*general linear model with the threshold crossing rate (TCR) z score as the dependent and the z scores of the event rate (ER) and event amplitude (EA) as the independent variables was fit to each of the sessions as follows:

$$TCR = b_{Er}ER + b_{Ea}EA$$

Reminder: 2P imaging

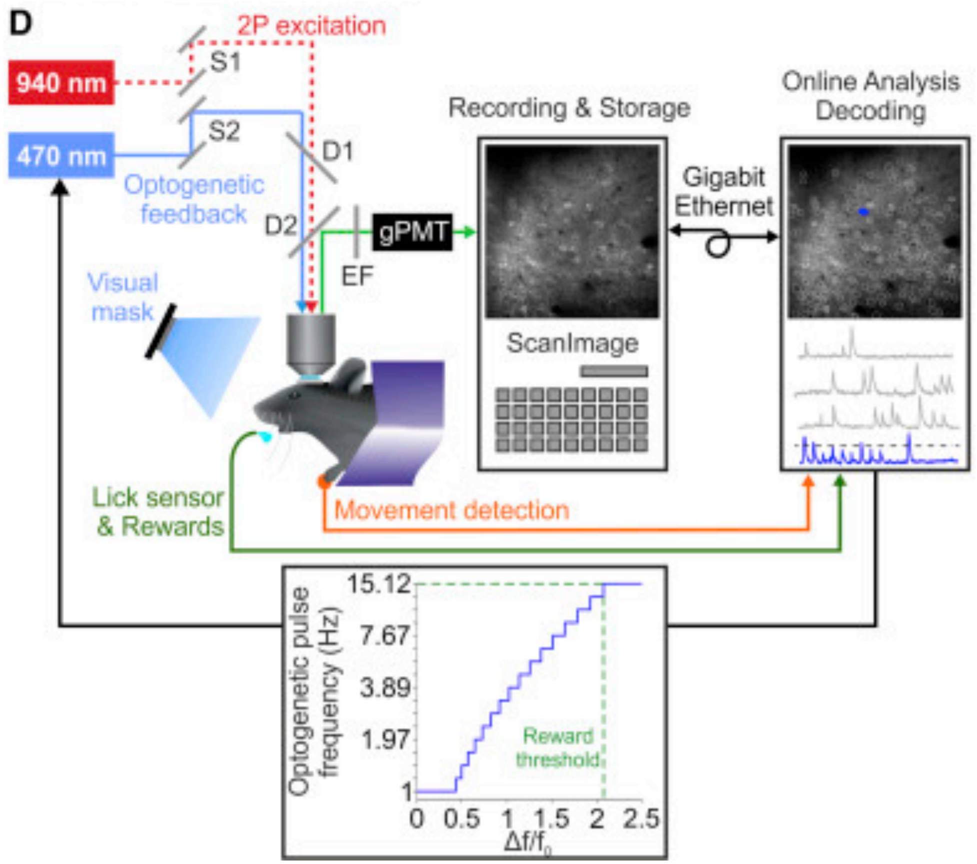


https://www.sciencedirect.com/science/article/pii/S2666166721007164

Prsa et al 2017 Neuron

Brain computer interfaces: all optical studies

Can mice learn to use a fabricated feedback channel to control single-neuron activity?
How do responses of the conditioned and neighboring cortical neurons change with learning?



Schematic of the experimental setup showing the head-fixed mouse under the two-photon microscope.

The two laser beams for imaging and stimulation were controlled independently, but focused through the same microscope objective.

To protect the sensitive photomultiplier tubes of the imaging system during the optogenetic blue light pulses, we combined optical filters and gated detection electronics.

Two-photon images were acquired on a PC running Scanimage and streamed to a control PC that extracted in real time:
- the Ca-dependent neural activity
- generated the feedback signal (inset: transfer function between neural activity and feedback pulse rate)
- acquired ECoG, lick, and forepaw movement sensor data
- controlled the blue light mask

S1, S2, scanning mirrors; D1, D2, dichroic mirrors; EF, emission filter; gPMT, gated photomultiplier tube.
A conditioned neuron (CN) (blue) was chosen among hundreds of simultaneously imaged neurons (gray).

Prsa et al 2017 Neuron

Brain computer interfaces: all optical studies

Can mice learn to use a fabricated feedback channel to control single-neuron activity?
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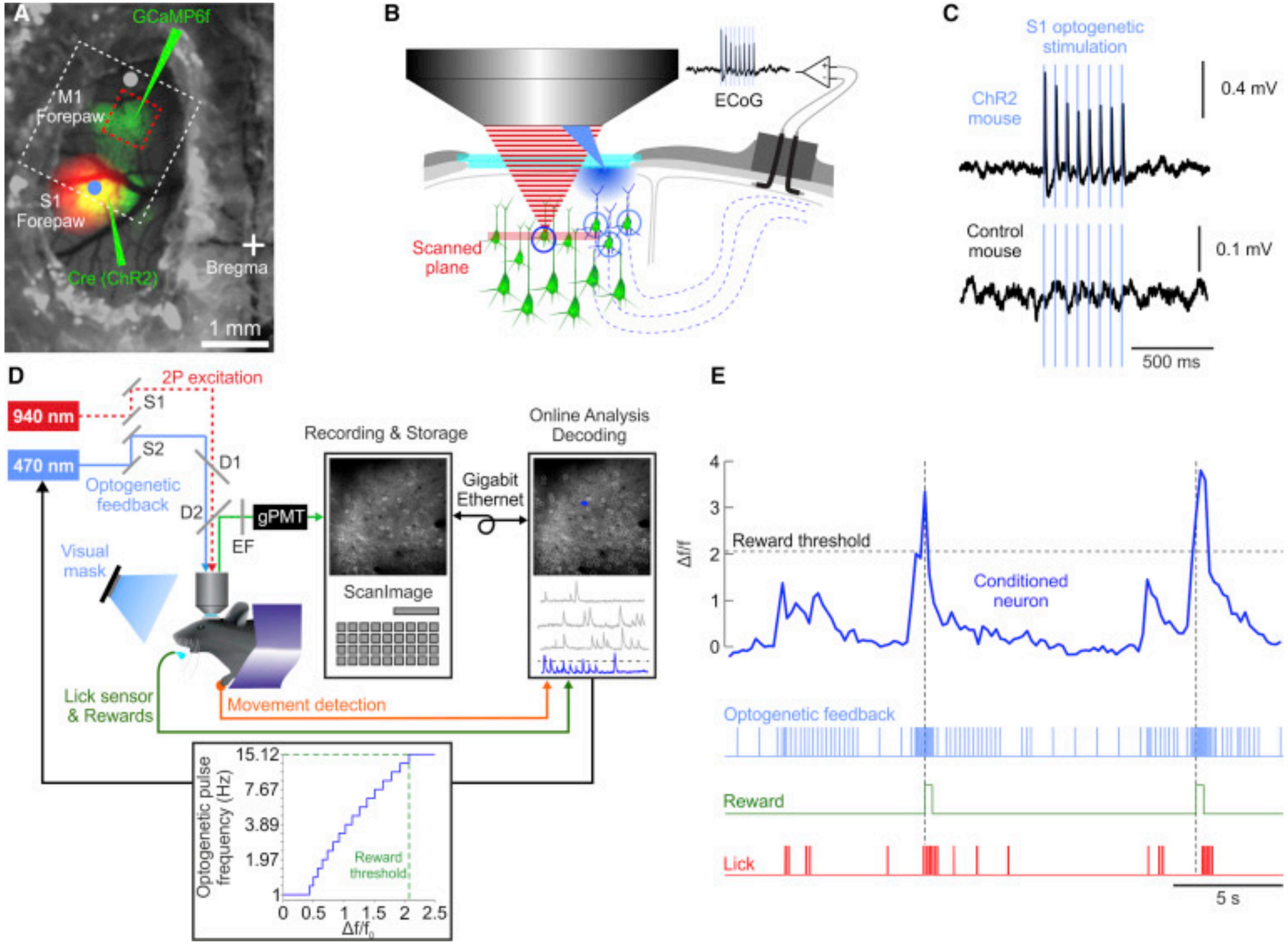

Prsa et al 2017 Neuron

- •All-optical brain-machine-brain interface for neuroprosthetic control
- •Mice rapidly learn to activate single neurons under optogenetically evoked feedback
- •Population imaging reveals that learning is restricted to the conditioned neuron

Note, no visual feedback was provided, only stimulation into S1!

Brain computer interfaces: all optical studies

Can mice learn to use a fabricated feedback channel to control single-neuron activity?
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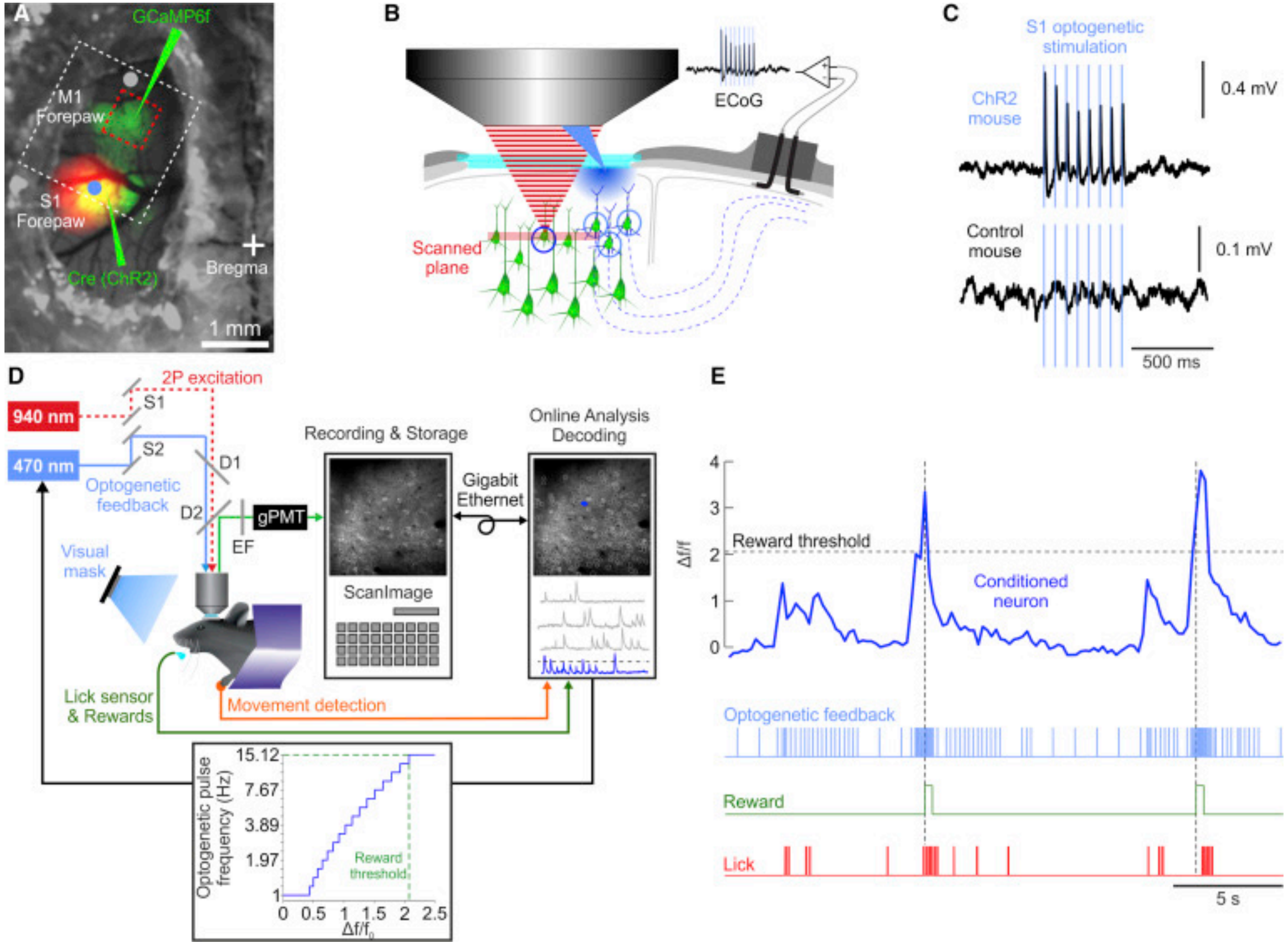


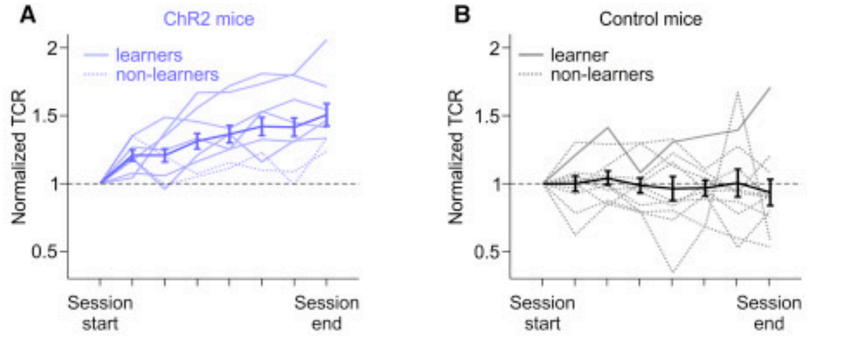
•All-optical brain-machine-brain interface for neuroprosthetic control

•Mice rapidly learn to activate single neurons under optogenetically evoked feedback

•Population imaging reveals that learning is restricted to the conditioned neuron

Note, no visual feedback was provided, only stimulation into S1:

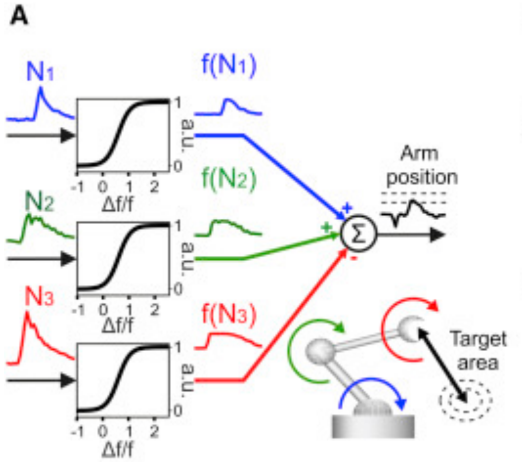
Importance of Artificial Sensory Feedback for Execution and Learning



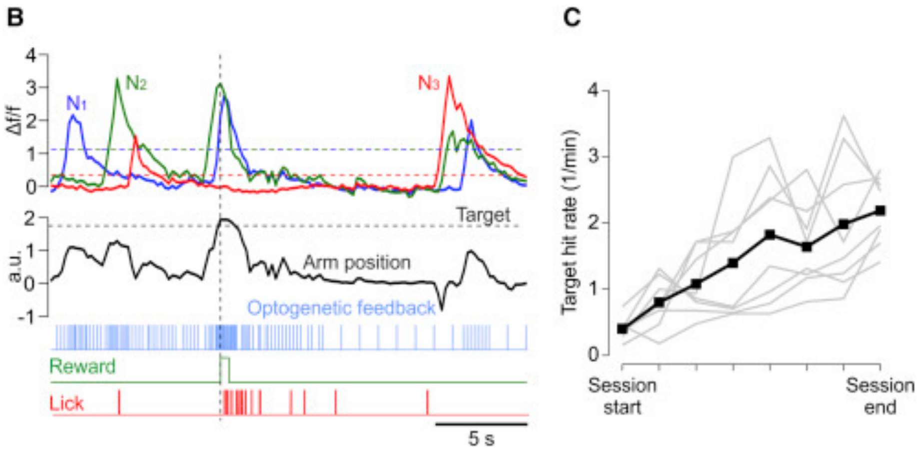
Prsa et al 2017 Neuron

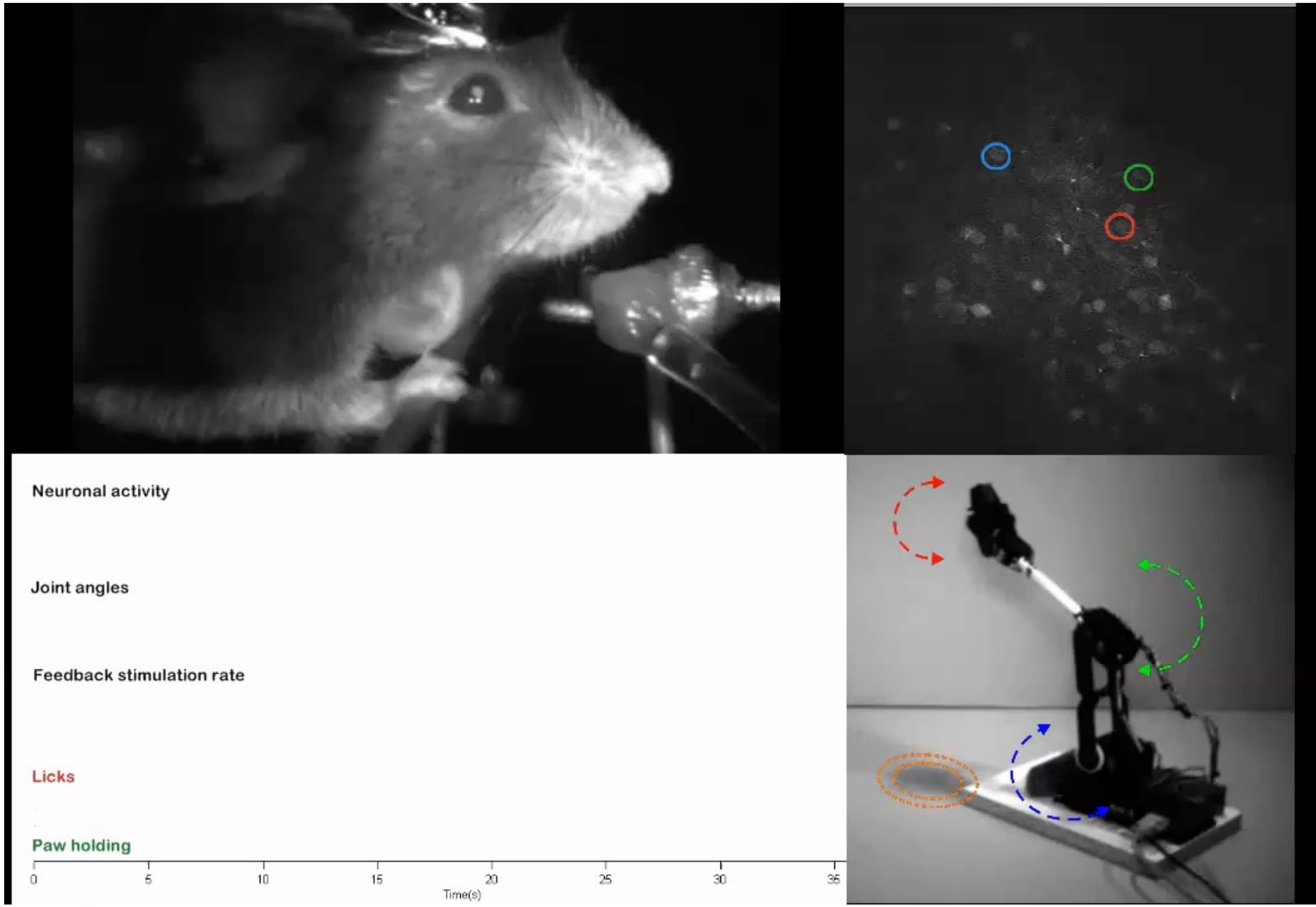
Brain computer interfaces: all optical studies

Multi-neuron Conditioning



The $\Delta f/f_0$ activities N_1, N_2, and N_3 of three CNs were first transformed by a logistic function into $f(N_1)$, $f(N_2)$, and $f(N_3)$, and the ensemble activity computed by adding $f(N_1)$ and $f(N_2)$ and subtracting $f(N_3)$. Each activity transform dictated the angular position of a robotic actuator and the ensemble activity was proportional to the effector distance to target.





Prsa et al 2017 Neuron

Designing experiments to test neural coding

a, Probing the role of neural synchrony.

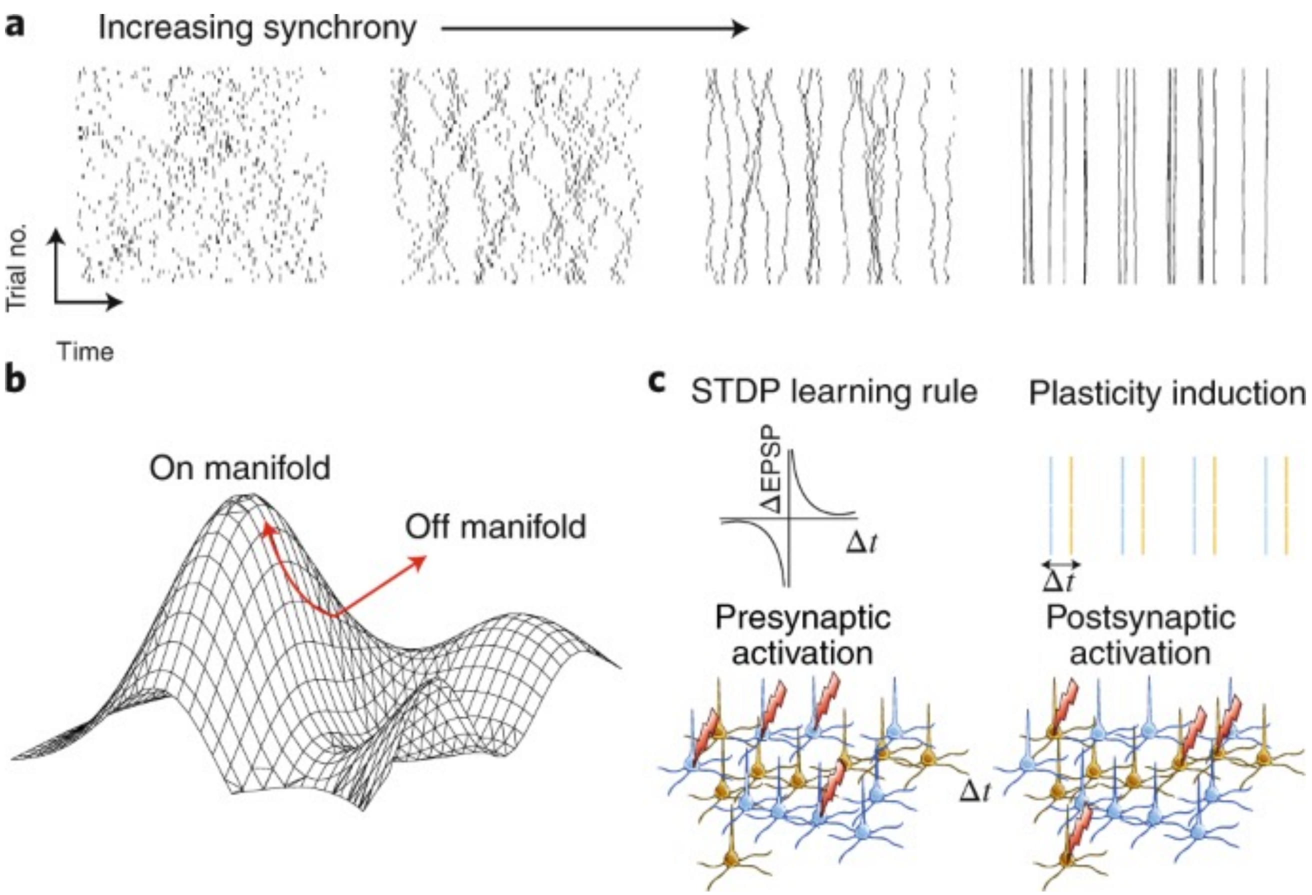
b, Schematic of two types of multiphoton holographic perturbations, one that obeys the intrinsic low-dimensional architecture of the neural activity patterns a group of neurons exhibits (‘on manifold’) and one that does not (‘off manifold’).

c, Schematic of using multiphoton holographic optogenetics to artificially induce Hebbian spike timing-dependent plasticity between two artificially chosen neural ensembles (indicated by the two colors).

Top left, schematic of the conventional STDP learning rule, plotting change in synaptic strength (ΔEPSP) versus the time delay between pre- and postsynaptic activation (*t*).

Top right, holographic stimulus pattern to induce STDP.

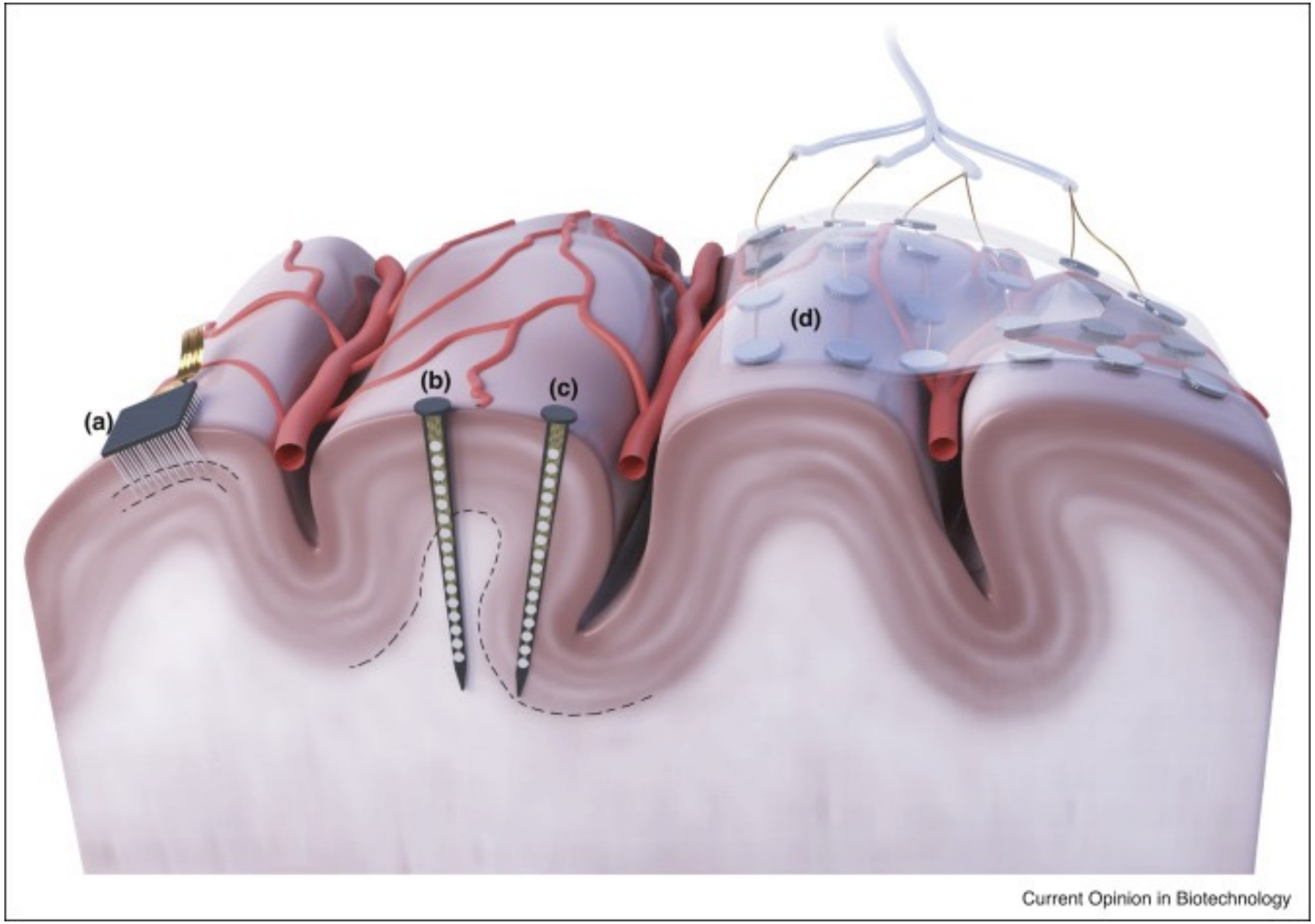
Bottom, schematic of fast interleaved photostimulation of two ensembles to drive STDP between them.



Adesnik, H., Abdeladim, L. Probing neural codes with two-photon holographic optogenetics. *Nat Neurosci* **24**, 1356–1366 (2021). https://doi.org/10.1038/s41593-021-00902-9

Brain computer interfaces: electrical implants

BMIs in humans and non-human primates are generally all electrical systems.

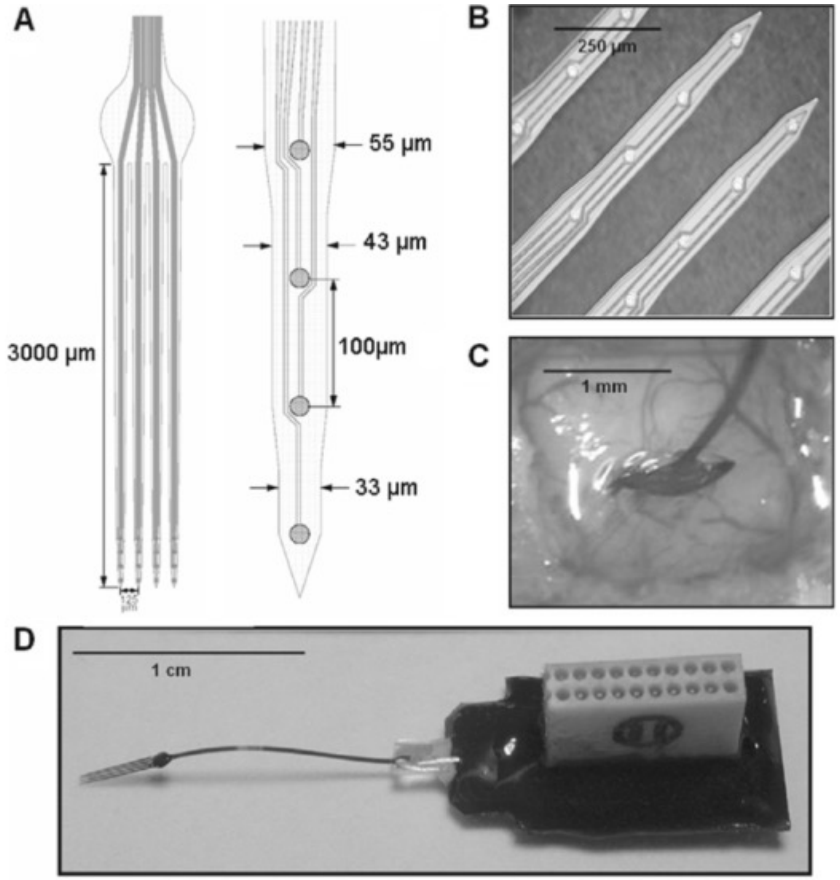


Rapeaux & Constandinou, 2021
Current opinion Biotech.

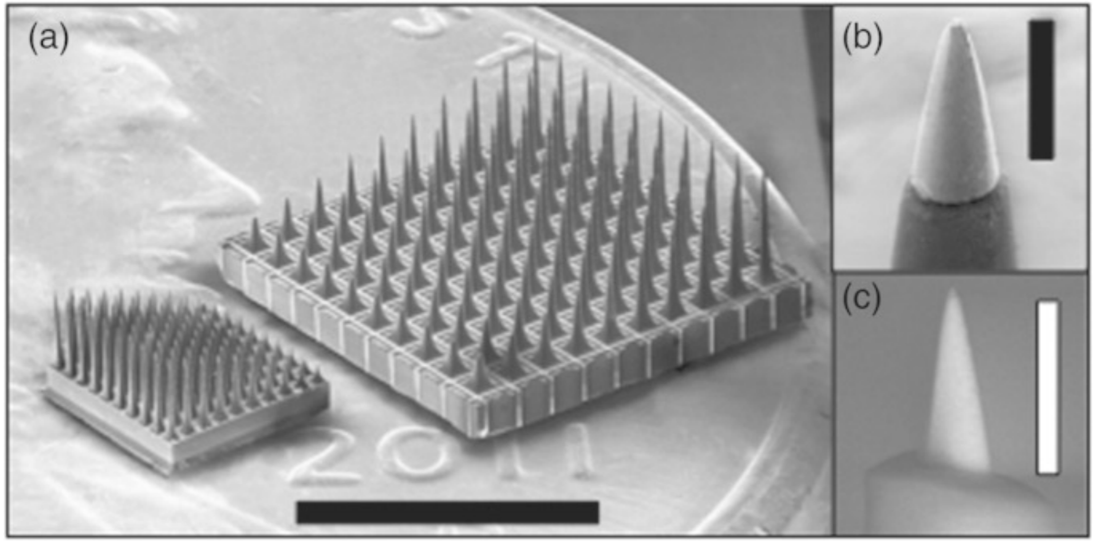
Implanted microelectrode arrays

Implanted microelectrode arrays are a common tool in systems neuroscience.

The size and number of recording sites vary with experimental goals and model organism.



Vetter et al., 2004 *Transactions on Biomed. Eng.*

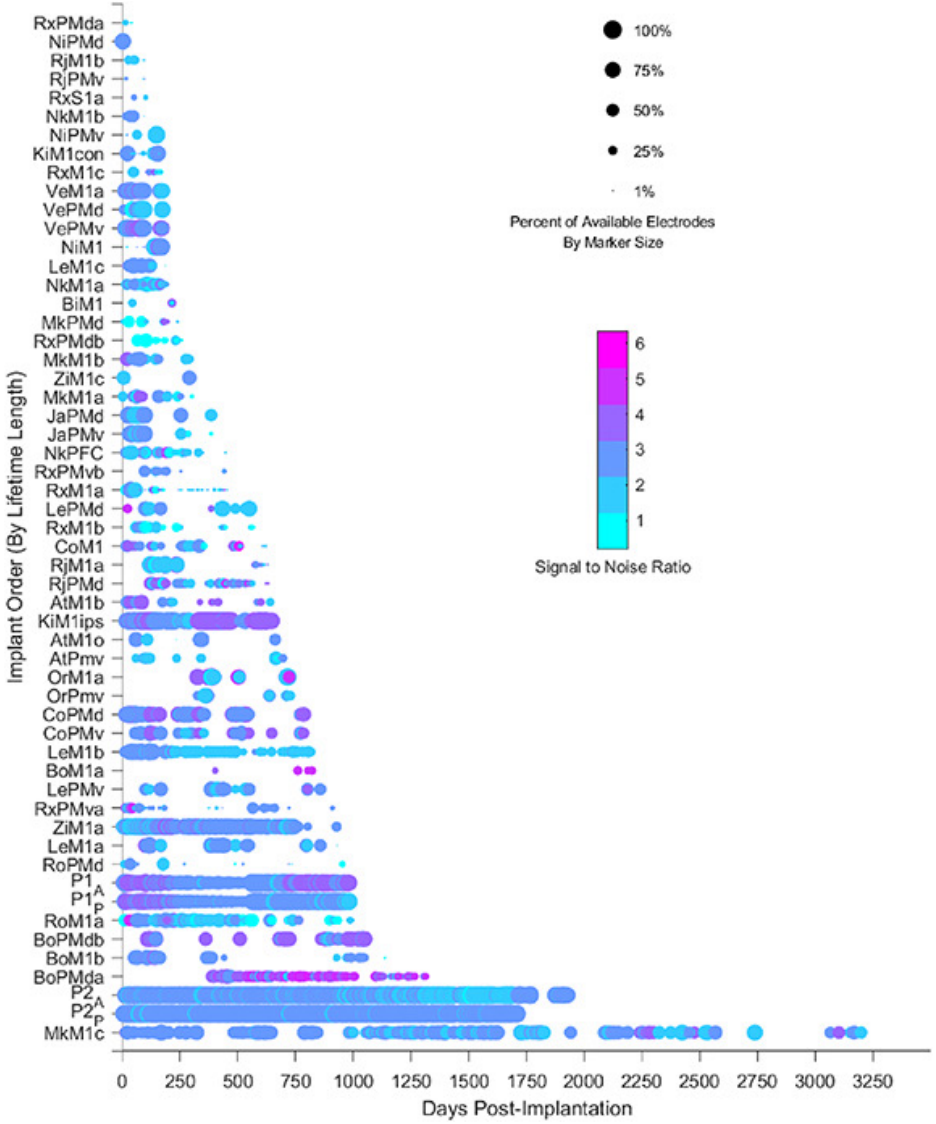


Wark et al., 2013 *J. Neural Eng.*

Microelectrode arrays

Implanted arrays can provide stable recordings for months or years.

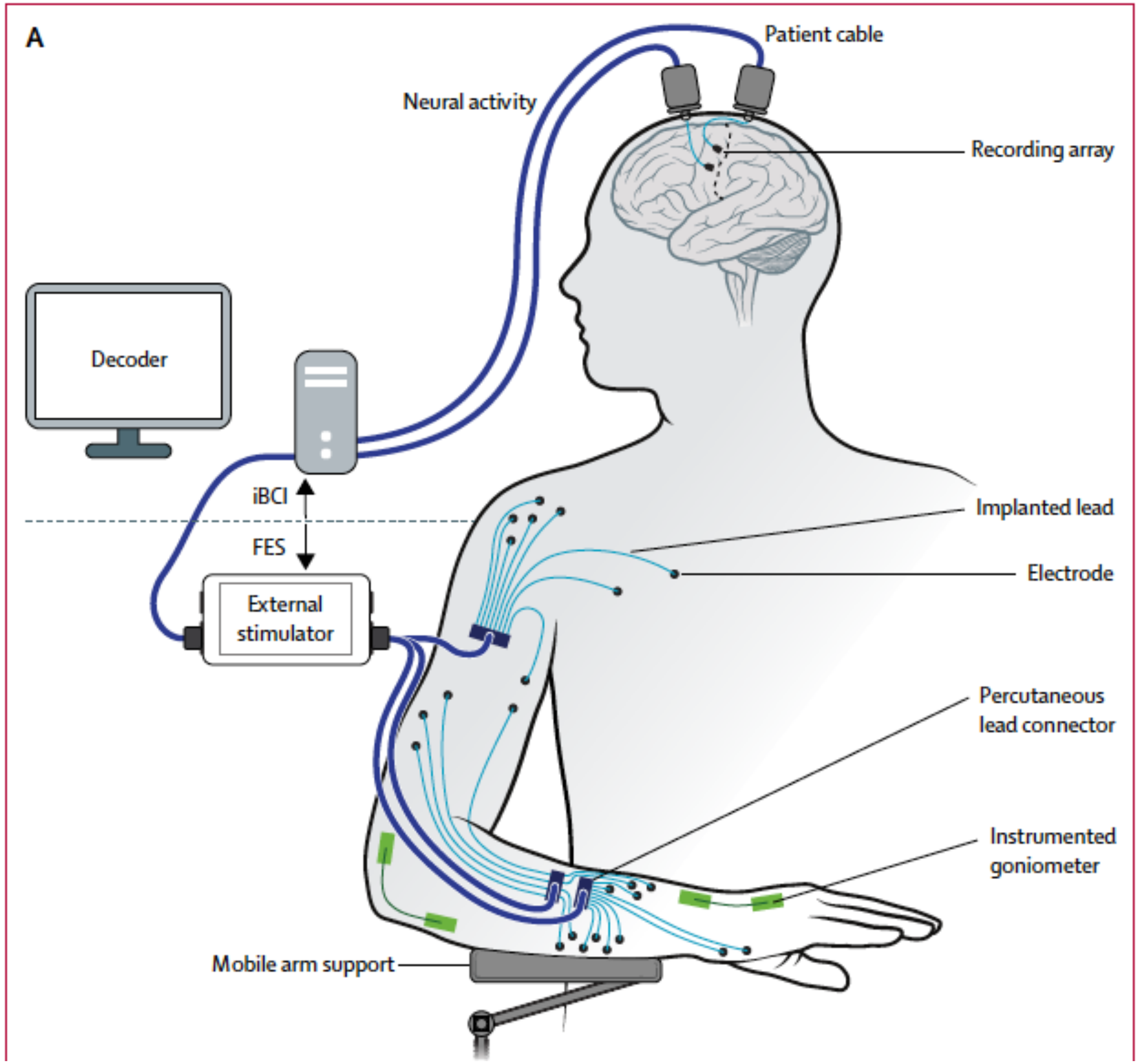
In primate research, research subjects often live with cortical implants for years, and perform multiple tasks with researchers.



Sponheim et al., 2021 *J. Neural Eng.*

Brain computer interfaces: electrical implants in humans

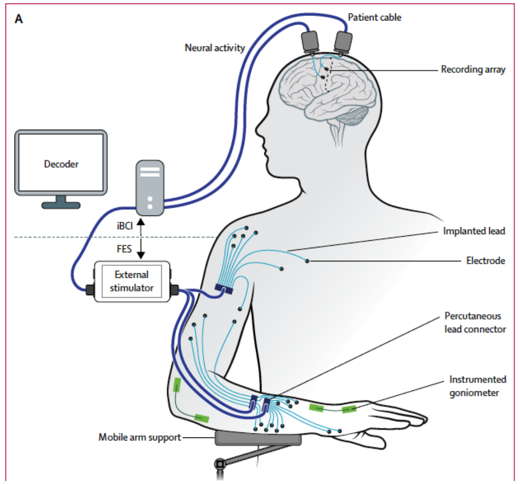
- Implanted arrays have also been tested in clinical settings.
  - They have been used to help quadriplegics regain some lost function.

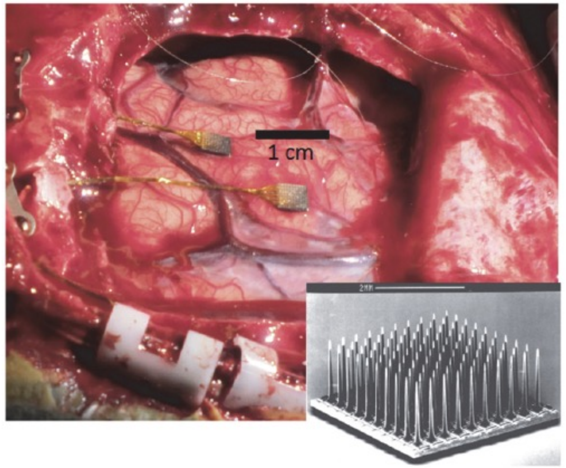


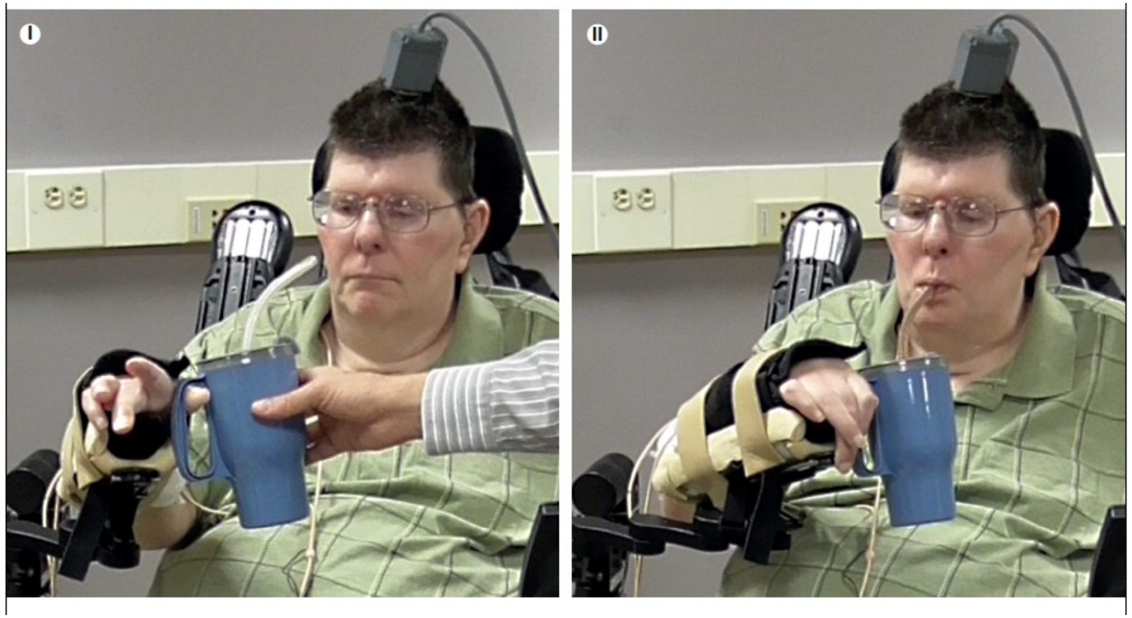
Ajiboye & Willet et al., 2017 *Lancet*

Brain computer interfaces: electrical implants in humans

- Implanted arrays have also been tested in clinical settings.
  - They have been used to help quadriplegics regain some lost function.
  - However, the use of cortical BMIs is almost entirely experimental







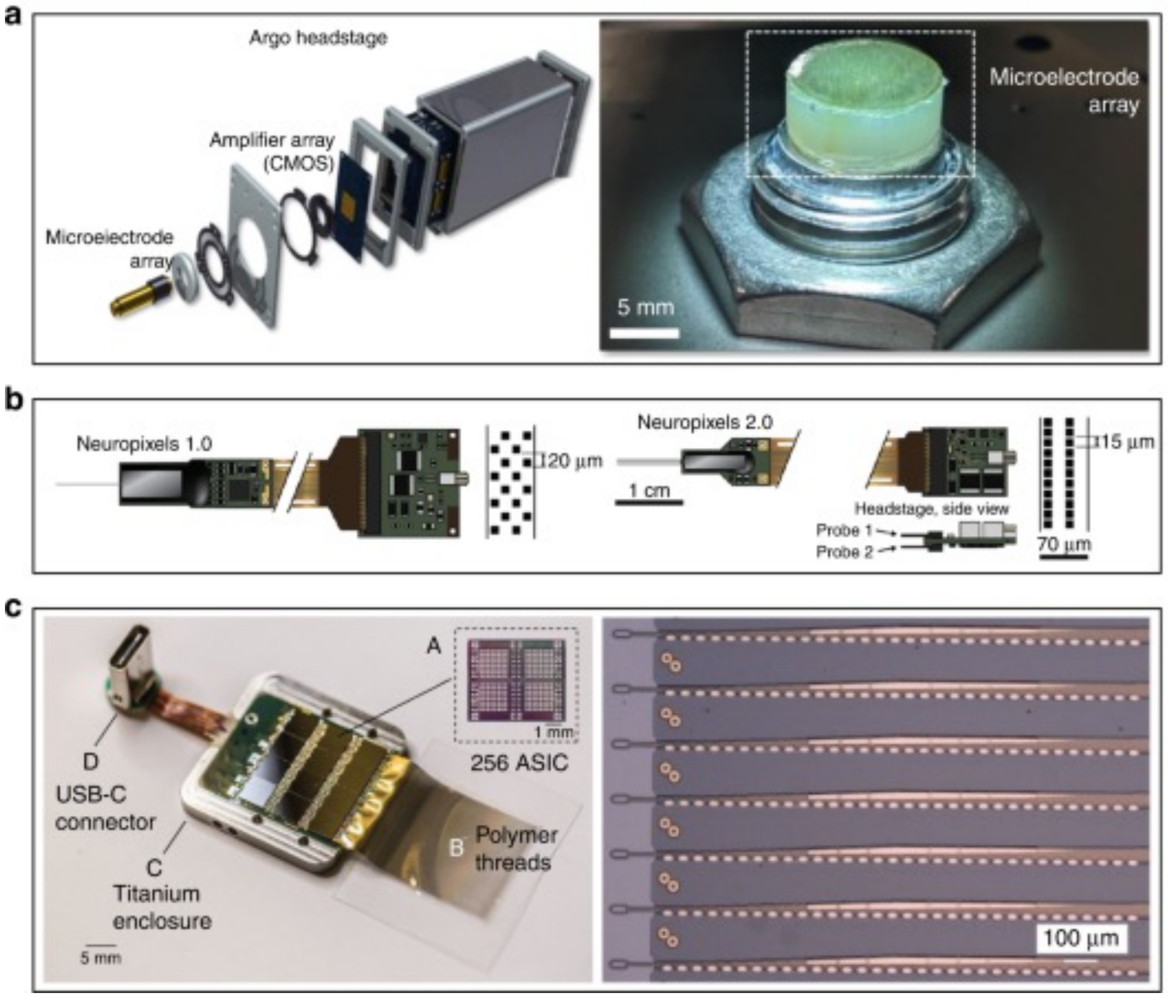
Ajiboye & Willet et al., 2017 *Lancet*

Next gen microelectrode arrays

- Modern microelectrodes tend to have increased throughput.
    - 1000-6000 contacts

- There is also a focus on more biocompatible materials.

- The electrode arrays used in research are several years ahead of their clinical counterparts due to safety testing requirements.



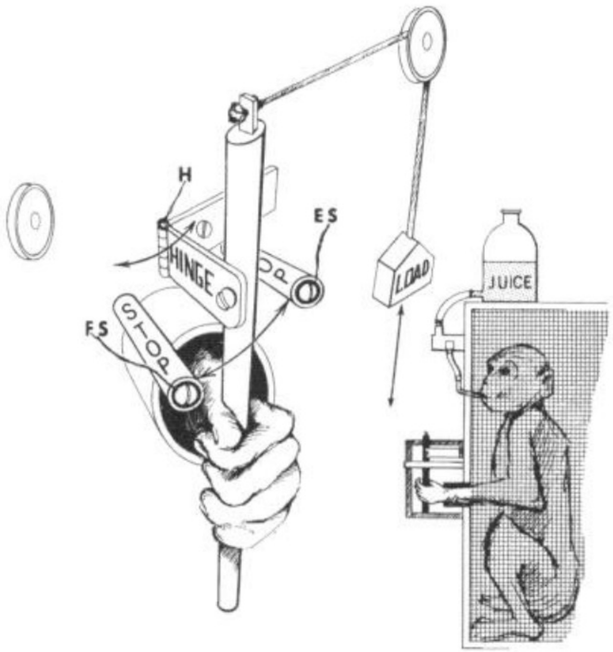
Wang et al., 2023 *Microsystems & NeuralEng.*

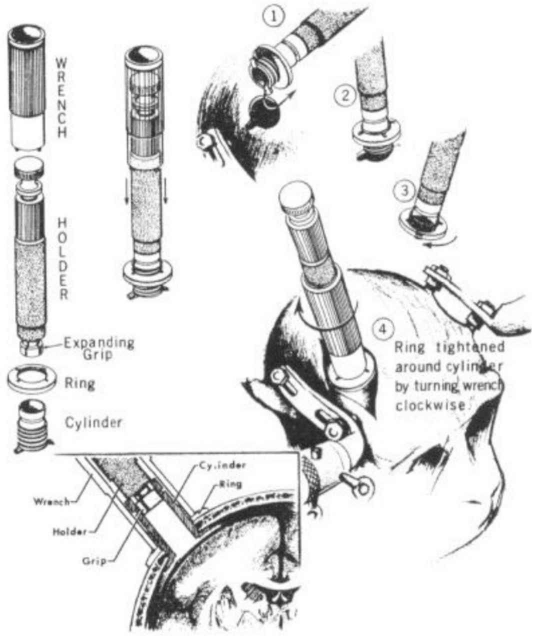
So we can record from motor cortex with BMIs, what have researchers found?

Movement research and primates

In vivo recordings of cortex in primates have been used to study movement for over 50 years.

Even the earliest studies demonstrated motor cortex encodes key features of movements.





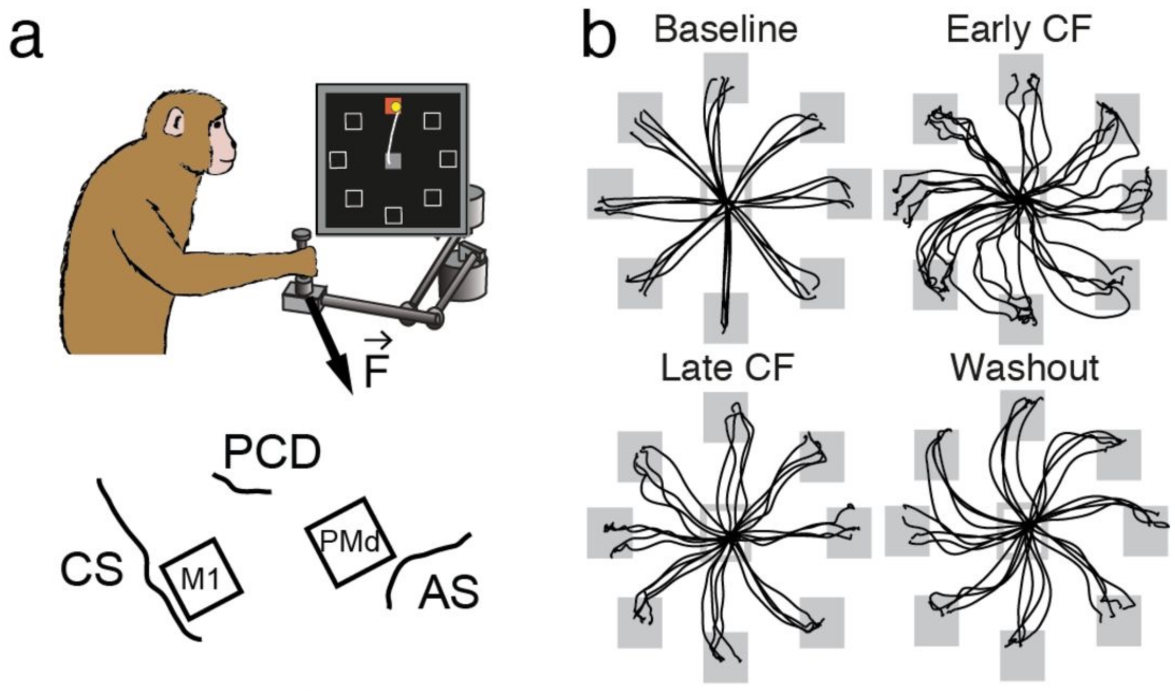
Evarts 1968, *J. Neurophysiology*

Center-out motor task

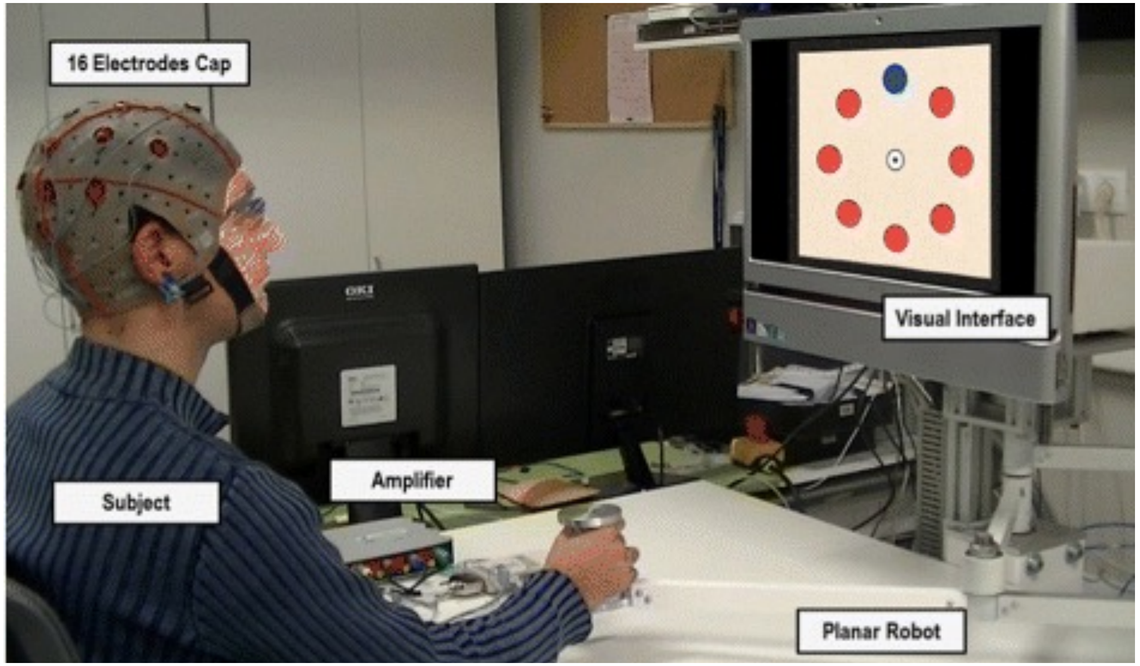
The center-out task is frequently used in motor control studies.

The task is very separatable yet constrained.

It can be performed with a limb, a cursor, or a robotic manipulandum.

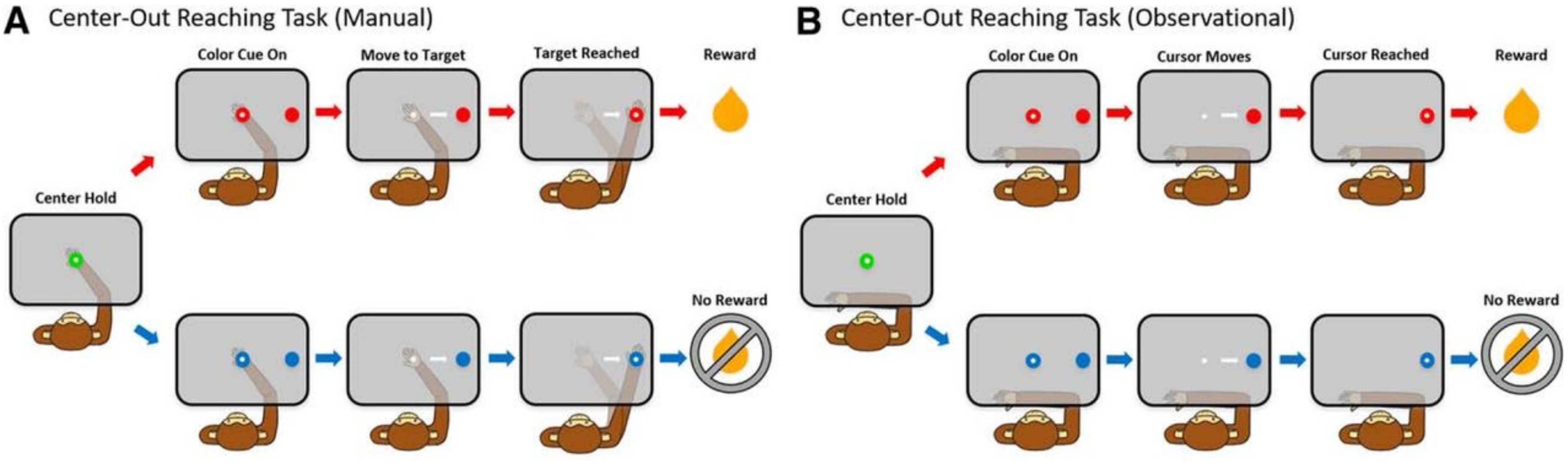


Perich, Gallego & Miller, 2018 *Neuron*



Úbeda et al., 2017 *J. NeuroEng & Rehab.*

Center-out motor task

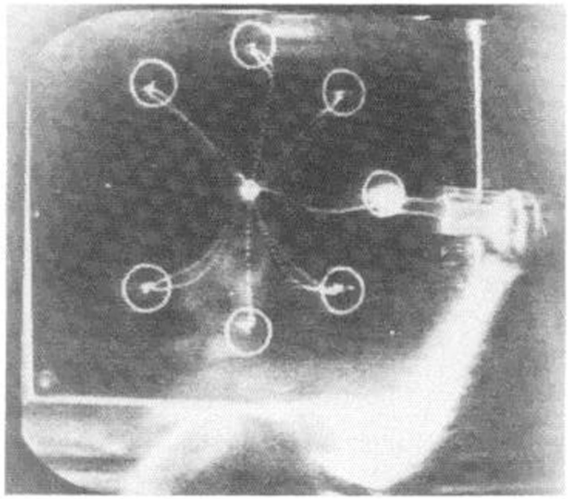


Observational version of the center out task are also used to train neural decoders.

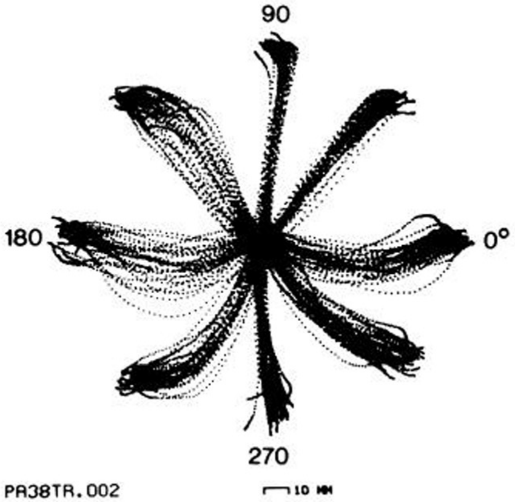
An et al., 2019 *eNeuro*

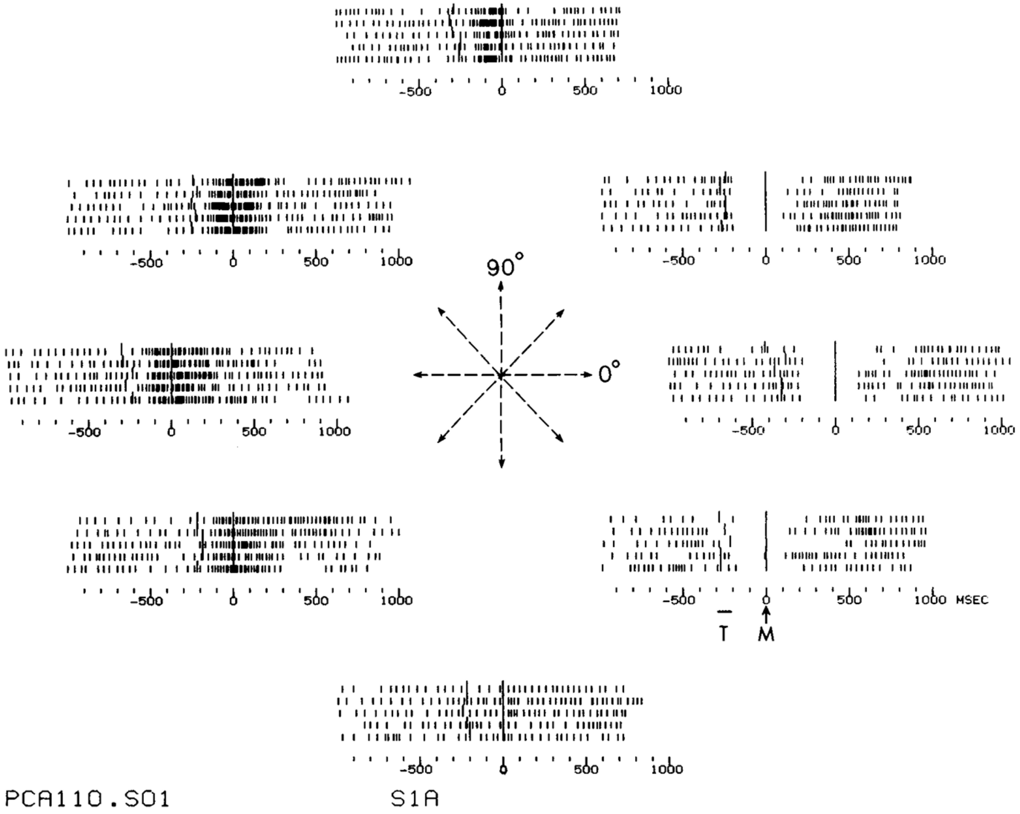
How does motor cortex encode movement?

B.



C.



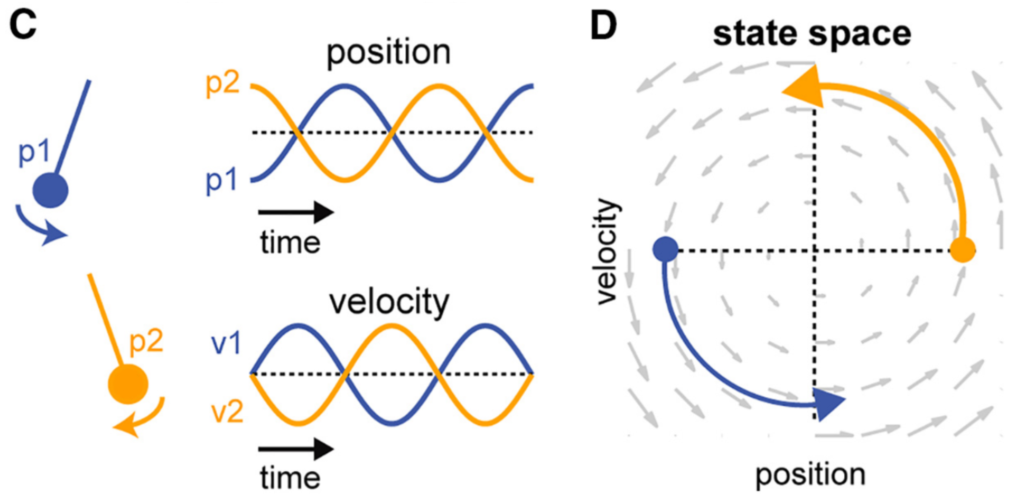


Georgopouloset al., 1982 *J. Neuroscience*

Review: what are dynamical systems?

"A set of coordinates, often represented as a vector, describing the instantaneous configuration of a dynamical system and that is sufficient to determine the future evolution of that system and its response to inputs."

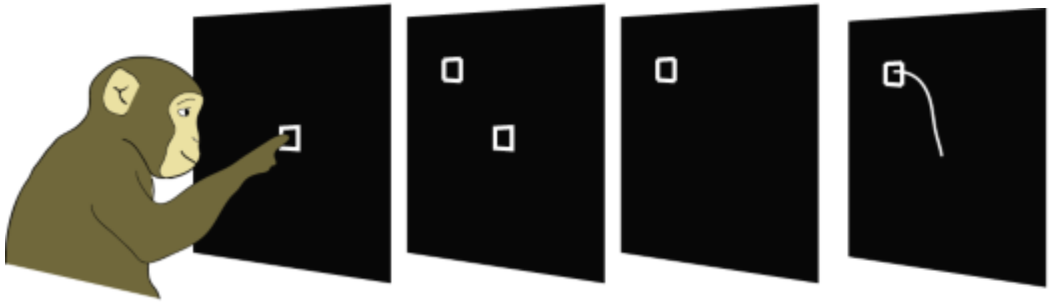
Churchland Shenoy 2013
Ann. reviews in neuroscience

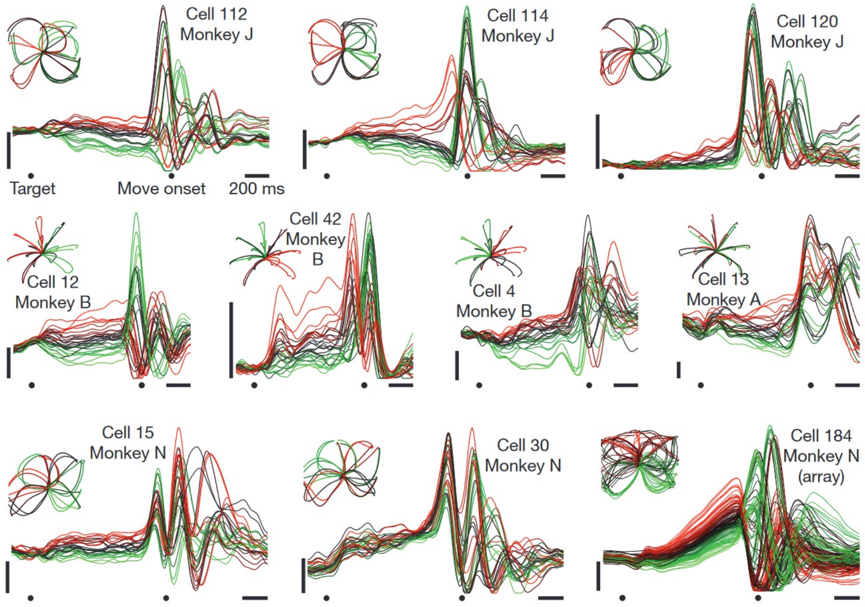


Pandarinath et al., 2018 *J neuroscience*

Discovery of rotational dynamics

- Monkeys performed a center out reaching task while neurons were recorded in primary motor cortex.
- Researchers also recorded from leeches swimming and walking monkeys.





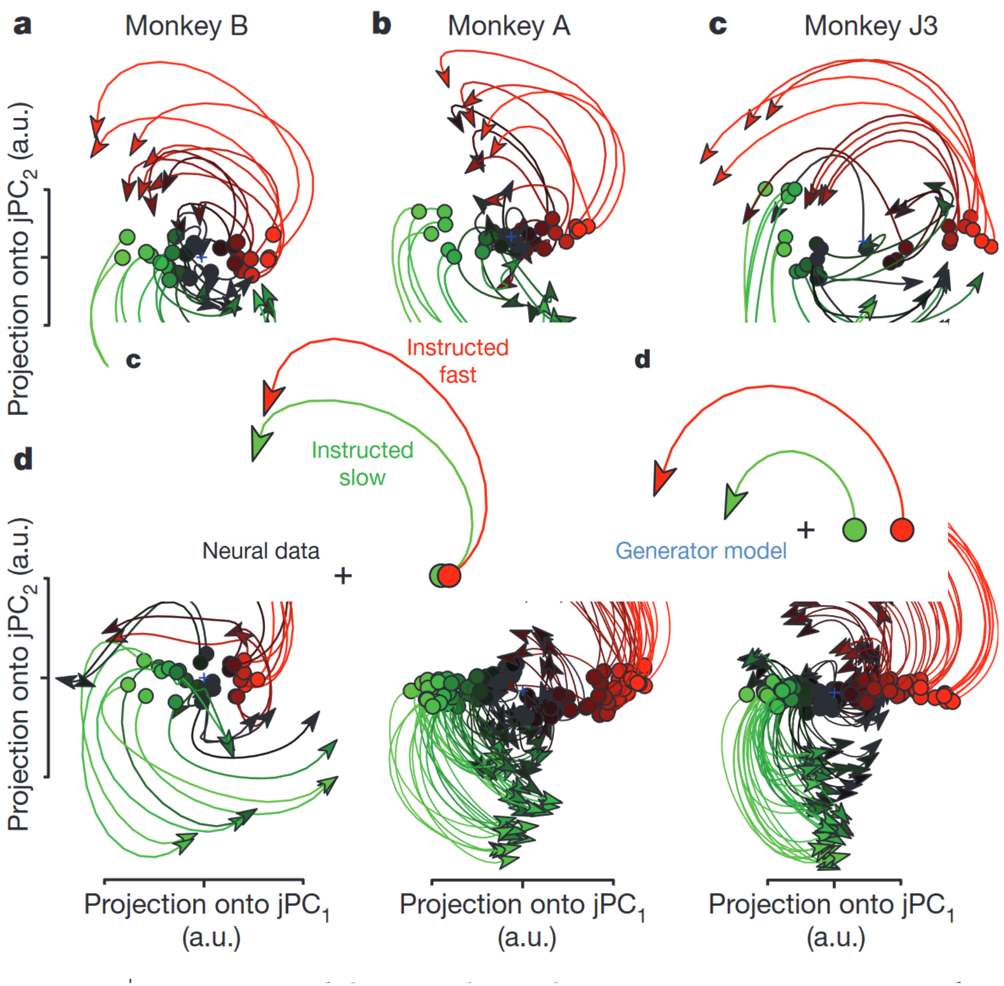
Chruchland et al., 2012 *Nature*

Rotational dynamics

- Low dimensional projections of neural activity during center-out reaching tasks produce highly consistent neural trajectories.

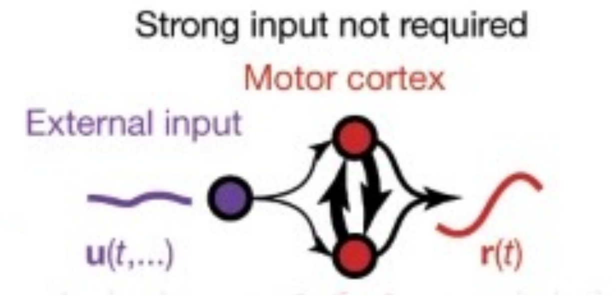
- These cyclical trajectories appear to show organization based on movement kinematics including direction and velocity of movements.

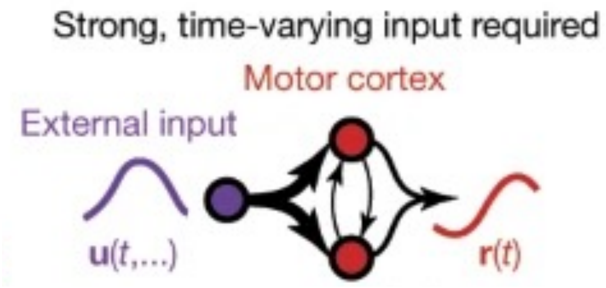
- This finding suggests that motor cortex acts as a dynamical system, with neural activity evolving over time based on local dynamics and external inputs.



Chruchland et al., 2012 *Nature*

Motor cortex as a dynamical system





There is ongoing research into the extent to which motor cortex is input-driven compared to intrinsically driven.

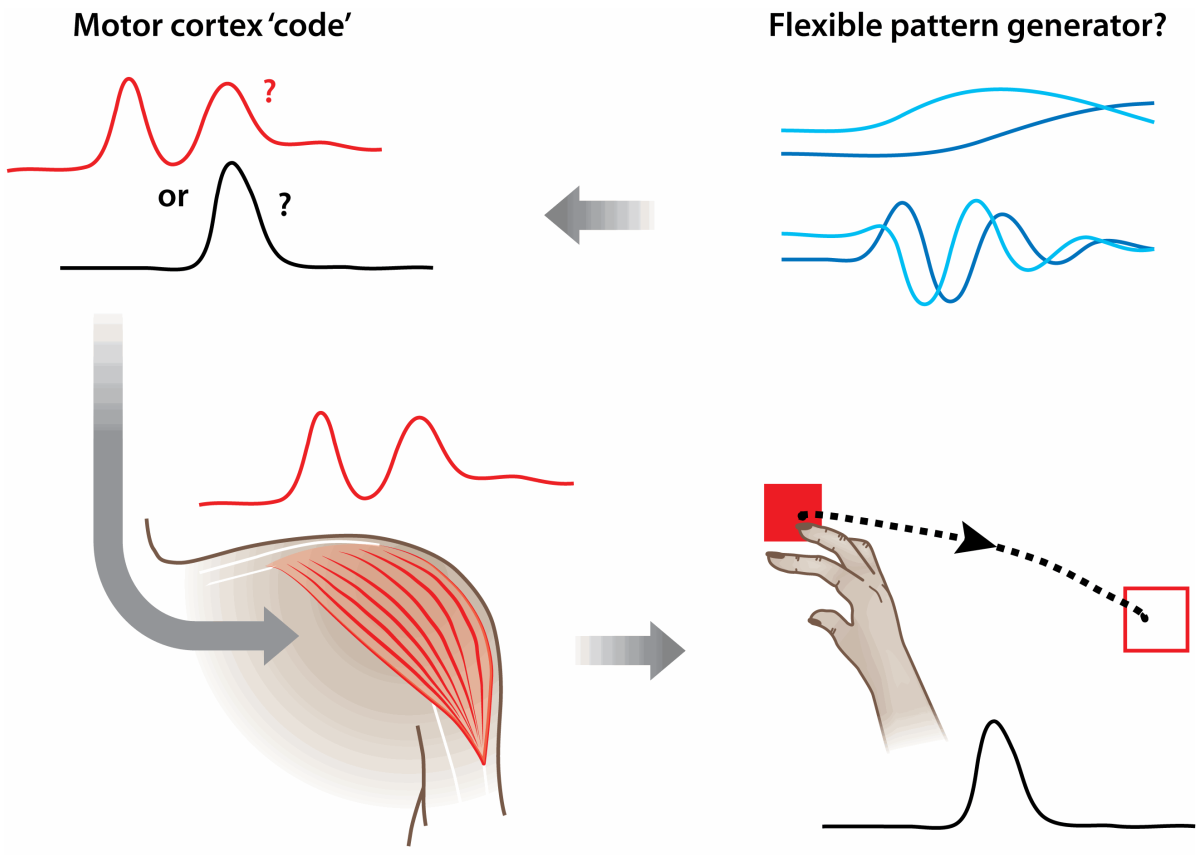
Sauerbrei et al., 2020 *Nature*

How does motor cortex encode movement?

- How cortical motor commands are transformed into motor movements is still an area of open debate.

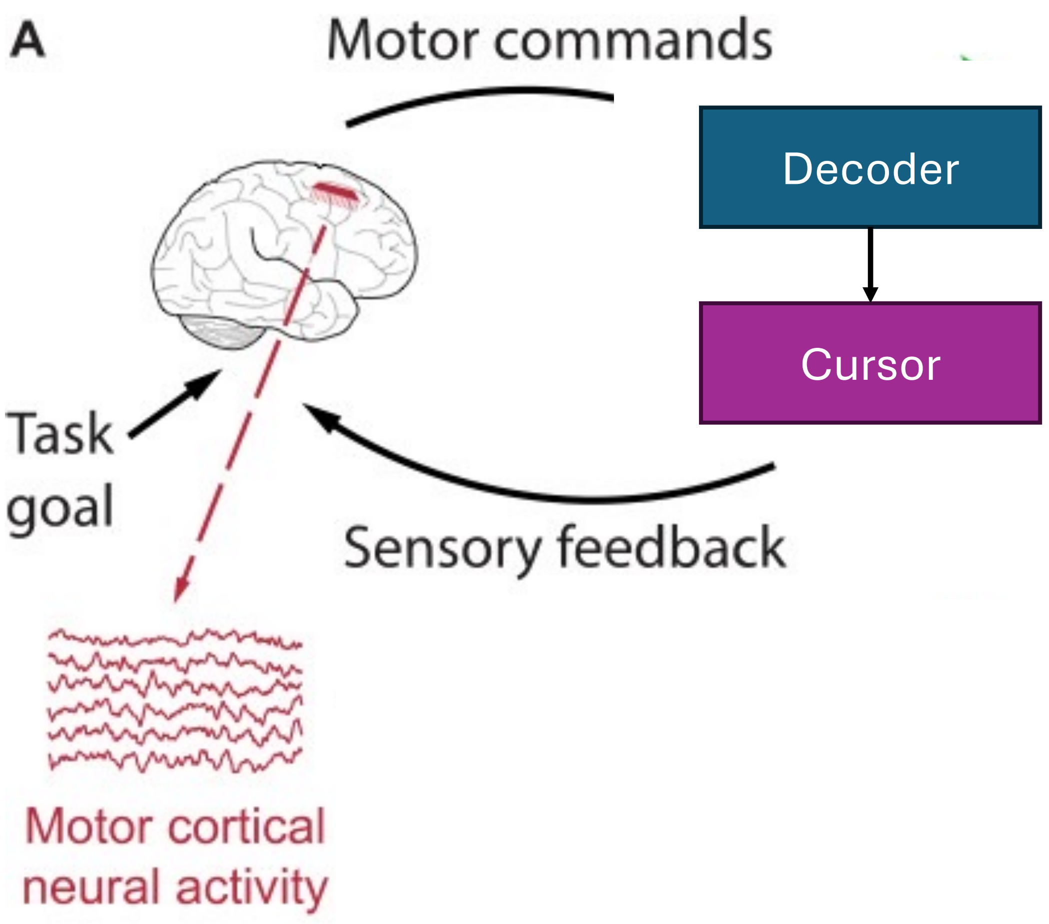
- Movement coding could be organized through muscle activations, movement kinematics, muscle synergies or some combination of factors.

- Since the precise transformation from neural cortical activity to movement is still under research, scientists can try to simplify cortical outputs to facilitate research.



Shenoy KV, et al. 2013.
Annu. Rev. Neurosci. 36:337–59

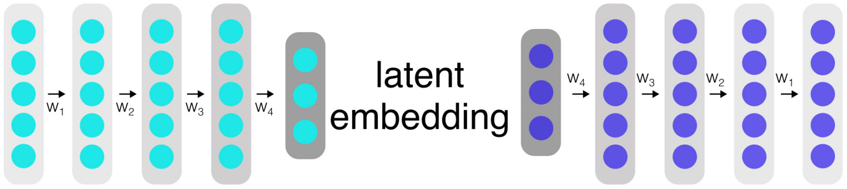
BMIs facilitate causal testing of the effect of neural activity on ‘movements’



Simple overview

Record Neural Activity → Build a Decoder Algorithm → Calculate requisite control parameters for external device

learnable latent
encoder (g) - decoder



Can we demonstrate a causal relationship between invariant dynamics in motor cortex and a task-relevant command?

Current Biology

CellPress
OPEN ACCESS

Article

Invariant neural dynamics drive commands to control different movements

Vivek R. Athalye,[1,7,9,14,*] Preeya Khanna,[2,7,10,*] Suraj Gowda,[4] Amy L. Orsborn,[3,11] Rui M. Costa,[1,8,12,*] and Jose M. Carmena[4,5,6,8,13,*]

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[2]Department of Neurology, University of California, San Francisco, San Francisco, CA 94158, USA
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[4]Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, Berkeley, CA 94720, USA
[5]Helen Wills Neuroscience Institute, University of California, Berkeley, Berkeley, CA 94720, USA
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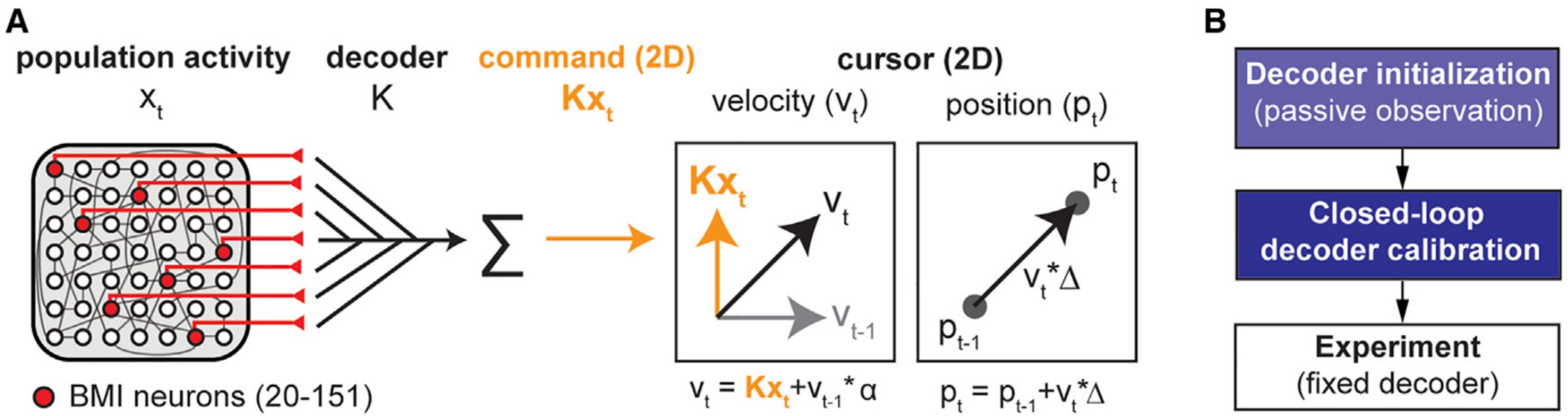
[7]These authors contributed equally
[8]Senior author

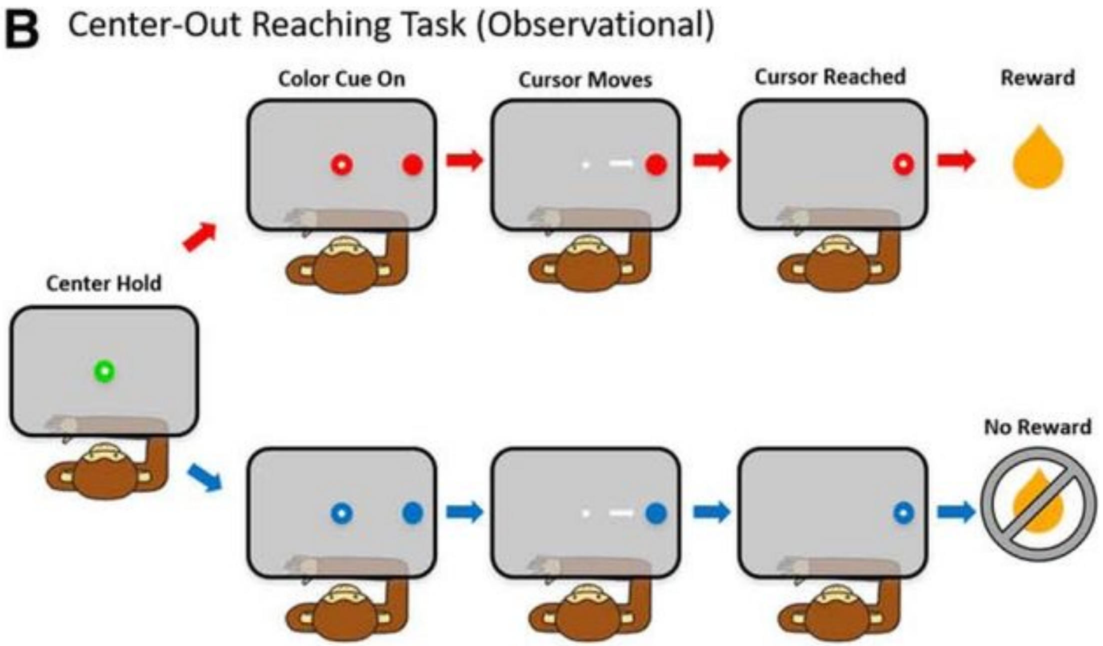
Experiment setup: training the BMI decoder

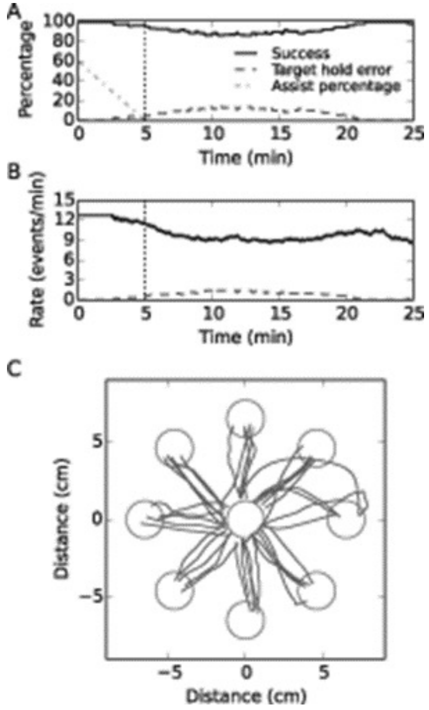


16x8 multi-shank arrays were implanted in the upper limb area of motor cortex.

Monkeys were trained to control a cursor using the implanted array, but without moving their arm.

Experiment setup: training the BMI decoder



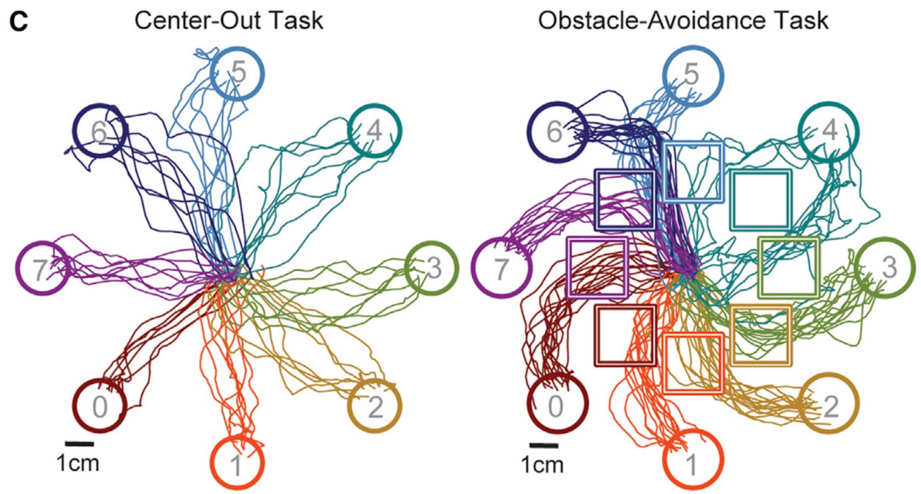


Monkeys first observed the center out cursor task so that decoder units could be identified.

After units were selected, monkeys began training to move the cursor though either a velocity Kalman filter (monkey G) or a velocity Point Process filter (monkey J).

The decoder was refined using ‘‘closed-loop decoder adaptation’’ or CLDA (Danhgi et al., 2014).

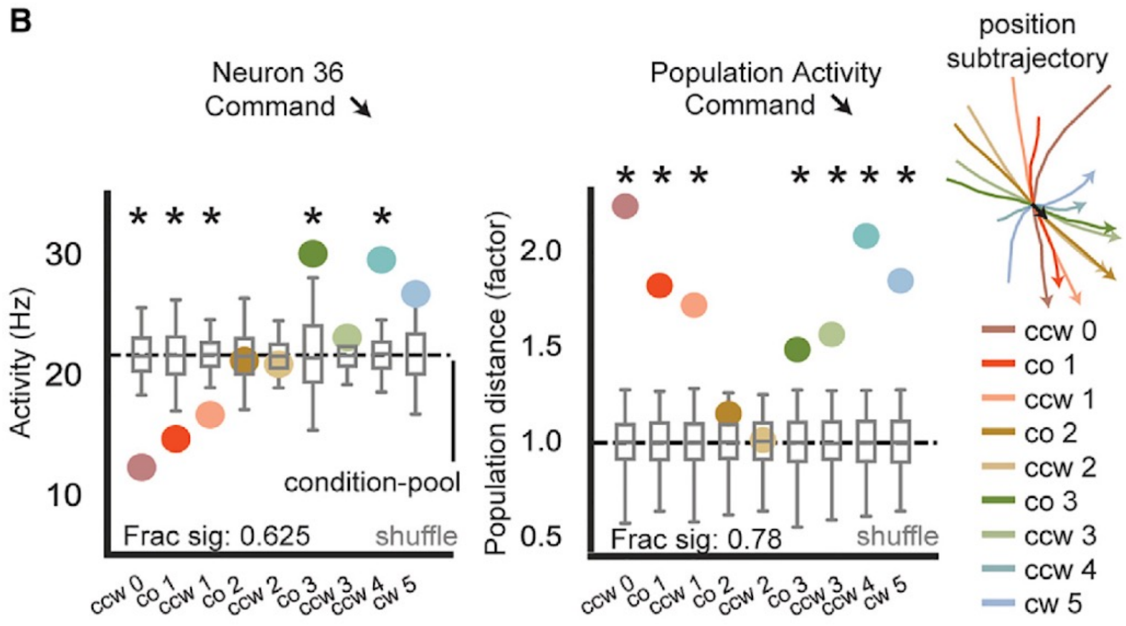
Different neural activity patterns can give rise to the same command.



Animals were trained on two tasks, center-out and obstacle avoidance.

Because the decoder is fixed for both tasks, the motor command produced by the neural activity could be compared across tasks and trials.

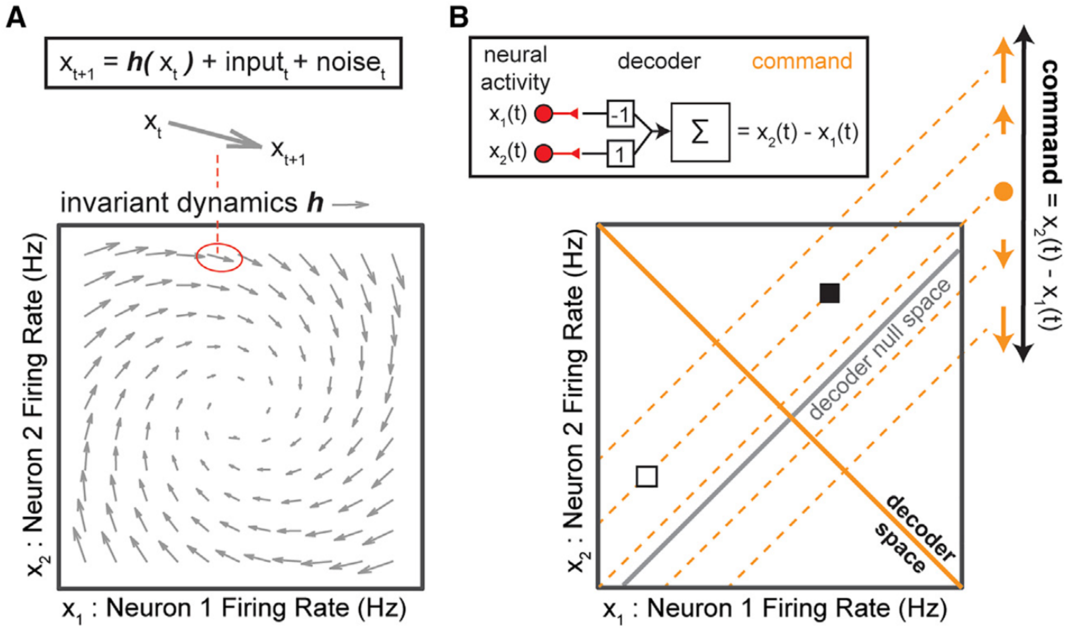
Command-relevant neural activity varies with sub-trajectory

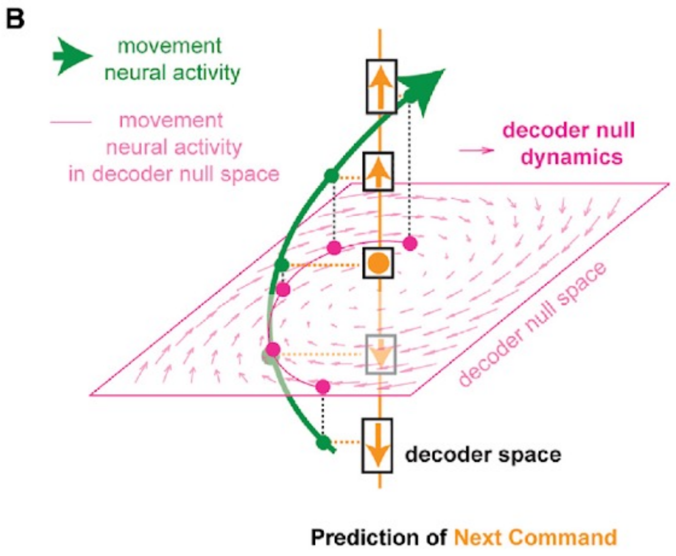


The further a sub-trajectory is from the middle of the trajectory distribution, the more the neural activity producing that command differs from the average activity to produce the command.

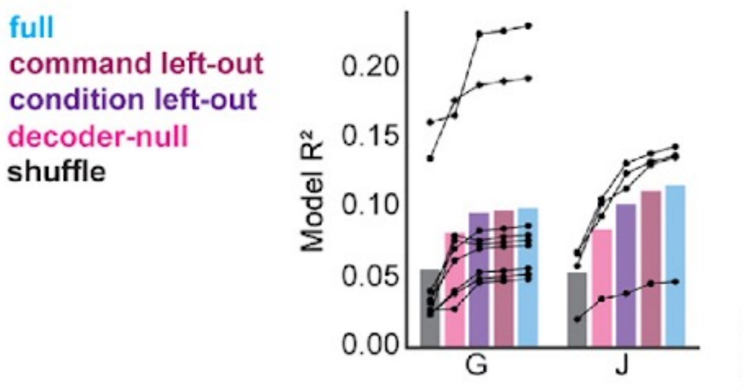
Do invariant dynamics are used to control different movements?

Researchers wanted to test whether the invariant dynamics in the neural activity they recorded produced subsequent motor commands in a way that was relevant to the task and condition of each trial.





“Invariant” dynamics predict motor commands in decoder-relevant space



Invariant dynamics can predict the neural activity that produced a motor command, even when task variables are removed.

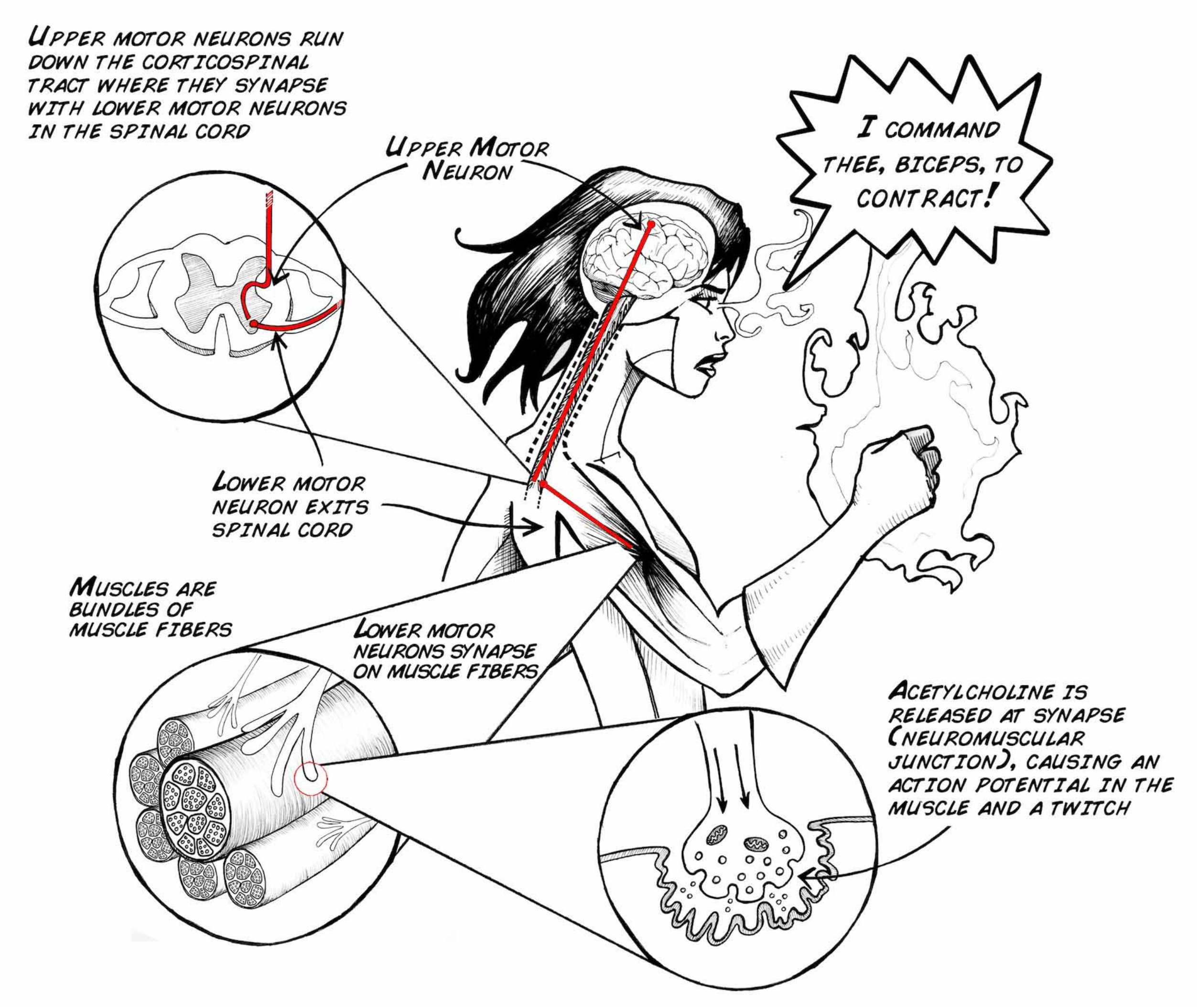
Invariant dynamics can predict the neural activity for the next motor command in a sequence, and the full model outperforms the null-decoder model.

Tomorrow:

Part 1: short (30 min) paper discussion

Part 2:

- **EMG recordings in your arm (30 min)**
- **Making a EMG-based "B"CI !**



https://backyardbrains.com/experiments/muscleSpikerBox

Summary

Overview:

- BCIs, or Brain Computer Interfaces, are systems that facilitate a **direct communication pathway between a brain and an external device.** This technology enables individuals to control devices using only their brain signals.
- **Recording neural activity is the foundation of how BCIs operate**. Specialized algorithms, known as decoders, are then employed to interpret these signals into commands that can control devices or computer systems.
- The importance of (**encoder-) decoder** algorithms lies in their ability to translate neural activity into actionable instructions for external devices, making them integral to the functionality of BCIs.

Systems Neuroscience Contributions:

- Instrumental in identifying optimal brain areas for signal recording, understanding neural subtypes, and designing effective sensory feedback within BCIs.
- Insights into neural dynamics, such as the relationship between neural firing and sensory stimuli or motor actions, thereby informing the development of more advanced BCIs.
- Current research in systems neuroscience contributes to BCIs by examining the principles of encoding sensory information into neural activity and decoding it back into the brain.

Current Technologies in BCIs:

- **Microelectrode arrays** are a key technology in BCIs, allowing for the stable recording of neural activity over extended periods. These arrays can be implanted and have been used in both research settings and, to a lesser extent, in clinical applications to assist individuals with paralysis.
- **Two-photon holographic optogenetics** represents a cutting-edge approach in BCI technology. It enables precise manipulation and recording of neural activity using light (calcium imaging and optogenetics).
- Technological advancements in BCI include increased recording stability and longevity, more biocompatible materials for implants, and higher throughput in signal recording. These improvements are crucial for the reliability and user-friendliness of BCIs, ultimately enhancing their applicability and integration into various aspects of life and healthcare. Ethics are also deeply important to consider.