Speech Brain-Computer Interfaces for Restoring Natural Communication

Past, now, and future

STANFORD UNIVERSITY

N·P·T·L

Neural Prosthetics Translational Laboratory

BRAINGATE

TURNING THOUGHT INTO ACTION

Providence VA Medical Center · Massachusetts General Hospital · Brown University · Carney Institute for Brain Science · Emory University · Harvard Medical School · Stanford University · University of California, Davis

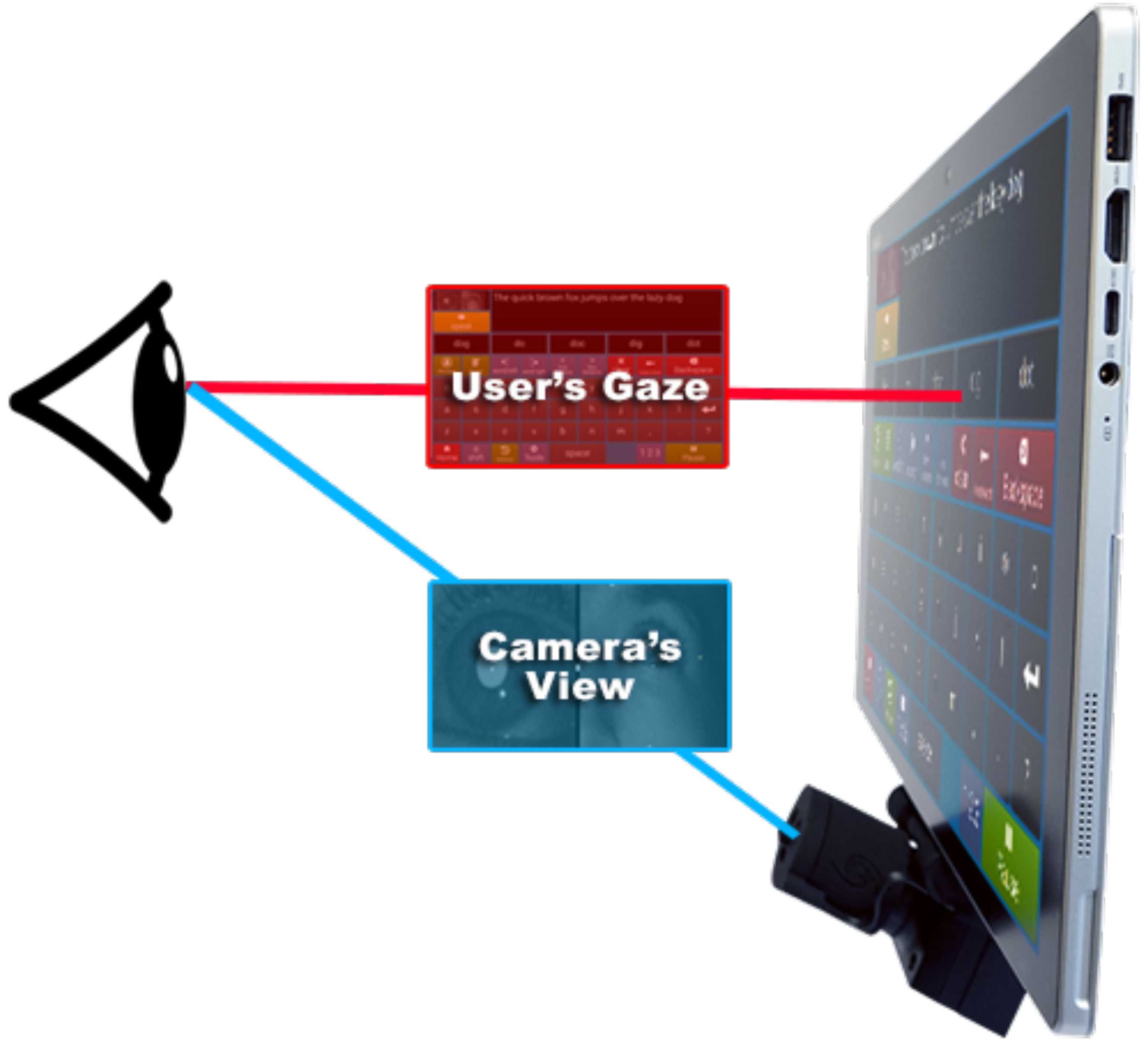
Chaofei Fan, CS224N


DOING ACTIVITIES HAVING LESS ON YOUR MIND

What we take for granted is lost for some individuals

- Howard Wicks, 21, lost all his dreams after a sever stroke.
- Neurological disorders like brainstem stroke or Amyotrophic Lateral Sclerosis (ALS) can cause speech and motor impairment and even complete loss of speech.
- These individuals are facing extreme challenges in their lives.
- Communication with loved ones and caretakers is one of their most desperate needs.

Assistive communication devices



Neuralink Prime Study

Tap into the intact mind with brain-computer interfaces (BCIs)

“[The Link] has helped me reconnect with the world, my friends, and my family. It's given me the ability to do things on my own again without needing my family at all hours of the day and night.”

— Noland Arbaugh, PRIME Study participant

A Brief History of BCI

How does BCI work? Start from the beginning...

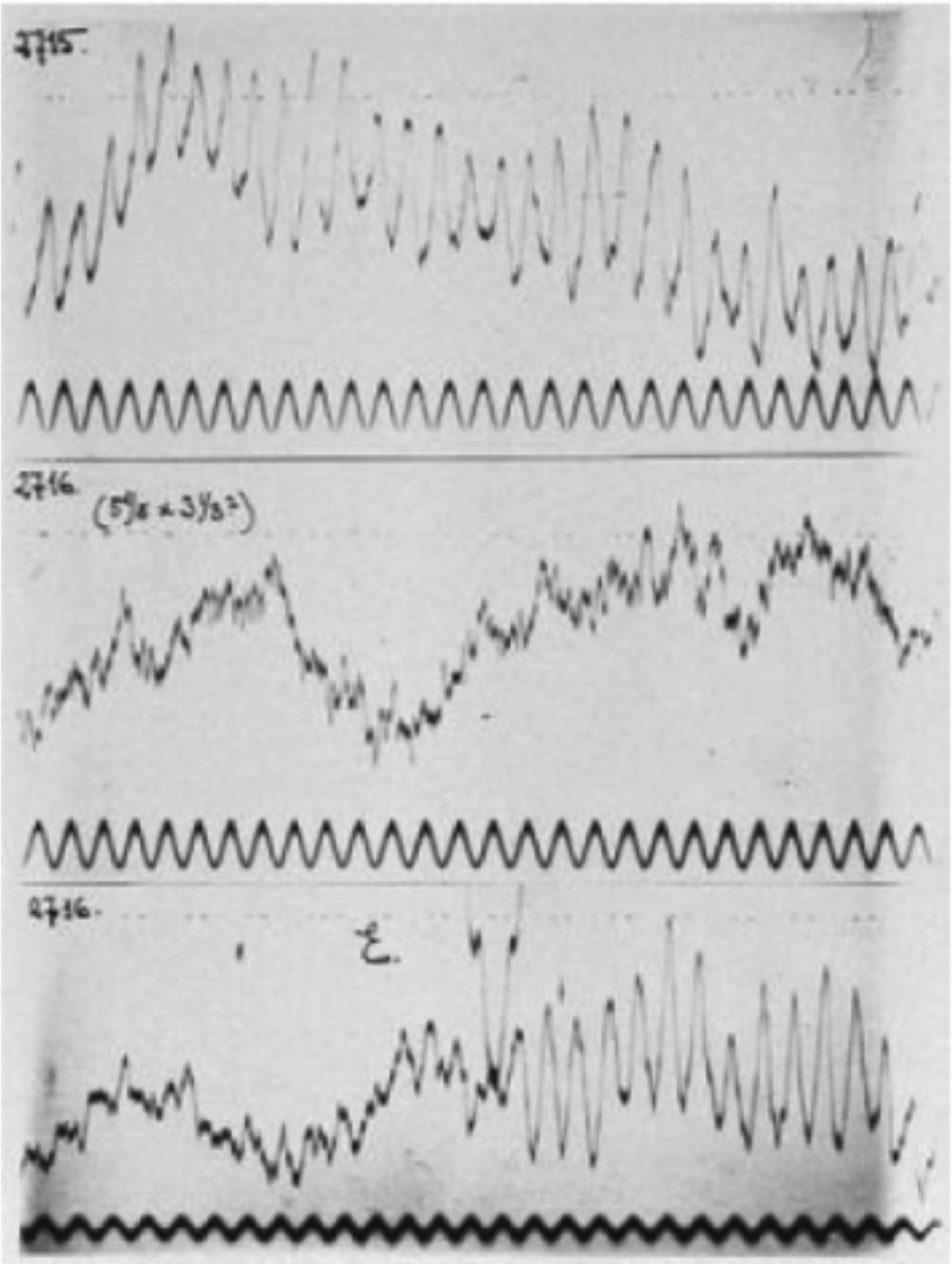
Electricity in the brain

The Electric Currents of the Brain. By RICHARD CATON, M.D., Liverpool.—After a brief *résumé* of previous investigations, the author gave an account of his own experiments on the brains of the rabbit and the monkey. The following is a brief summary of the principal results. In every brain hitherto examined, the galvanometer has indicated the existence of electric currents. The external surface of the grey matter is usually positive in relation to the surface of a section through it. Feeble currents of varying direction pass through the multiplier when the electrodes are placed on two points of the external surface, or one electrode on the grey matter, and one on the surface of the skull. The electric currents of the grey matter appear to have a relation to its function. When any part of the grey matter is in a state of functional activity, its electric current usually exhibits negative variation. For example, on the areas shown by Dr. Ferrier to be related to rotation of the head and to mastication, negative variation of the current was observed to occur whenever those two acts respectively were performed. Impressions through the senses were found to influence the currents of certain areas; *e. g.*, the currents of that part of the rabbit's brain which Dr. Ferrier has shown to be related to movements of the eyelids, were found to be markedly influenced by stimulation of the opposite retina by light.

Listen to the brain from the outside

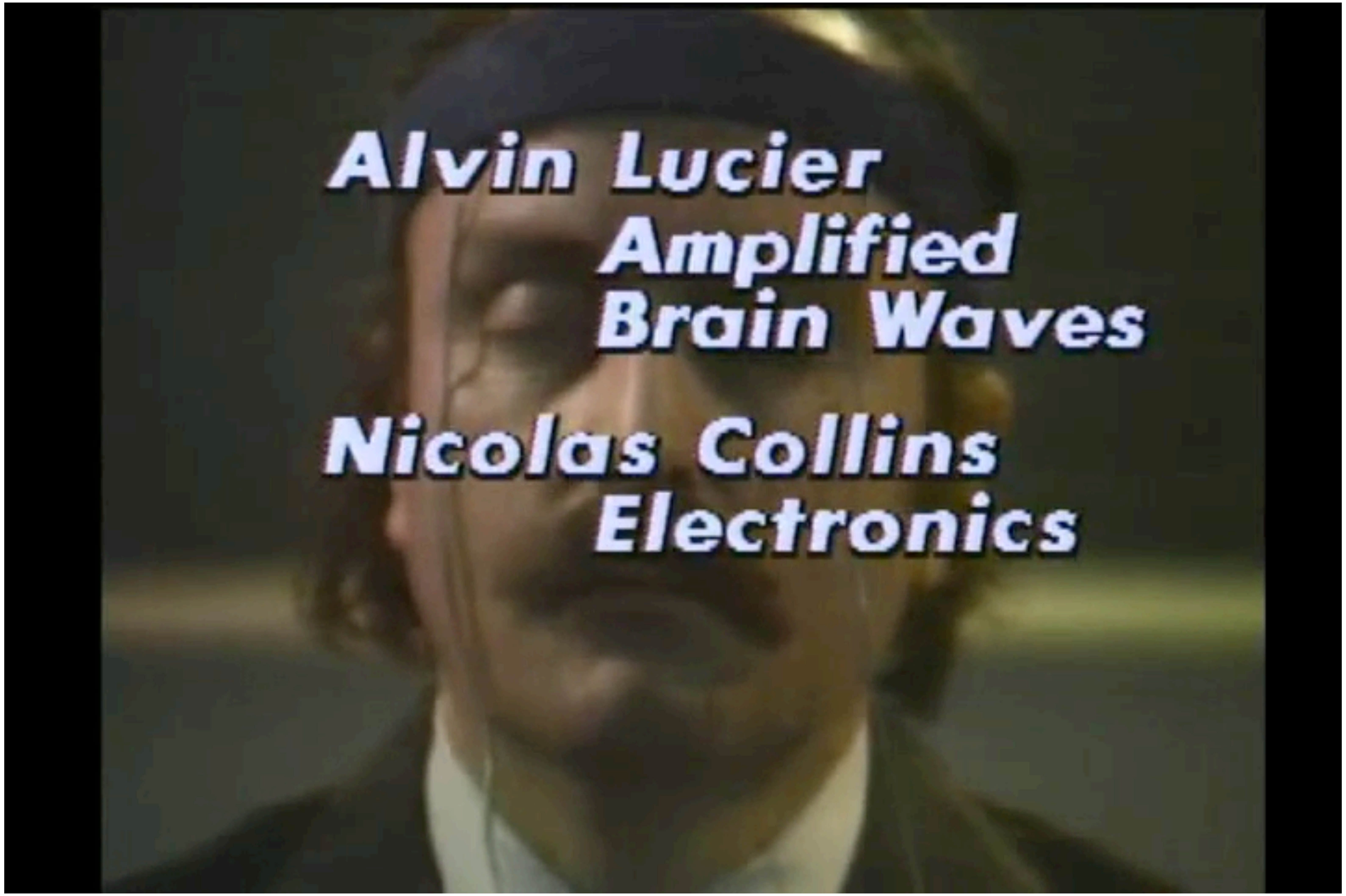
Electroencephalogram (EEG)

Hans Berger, a German psychiatrist, invented EEG and succeeded in recording the first human EEG in 1924.

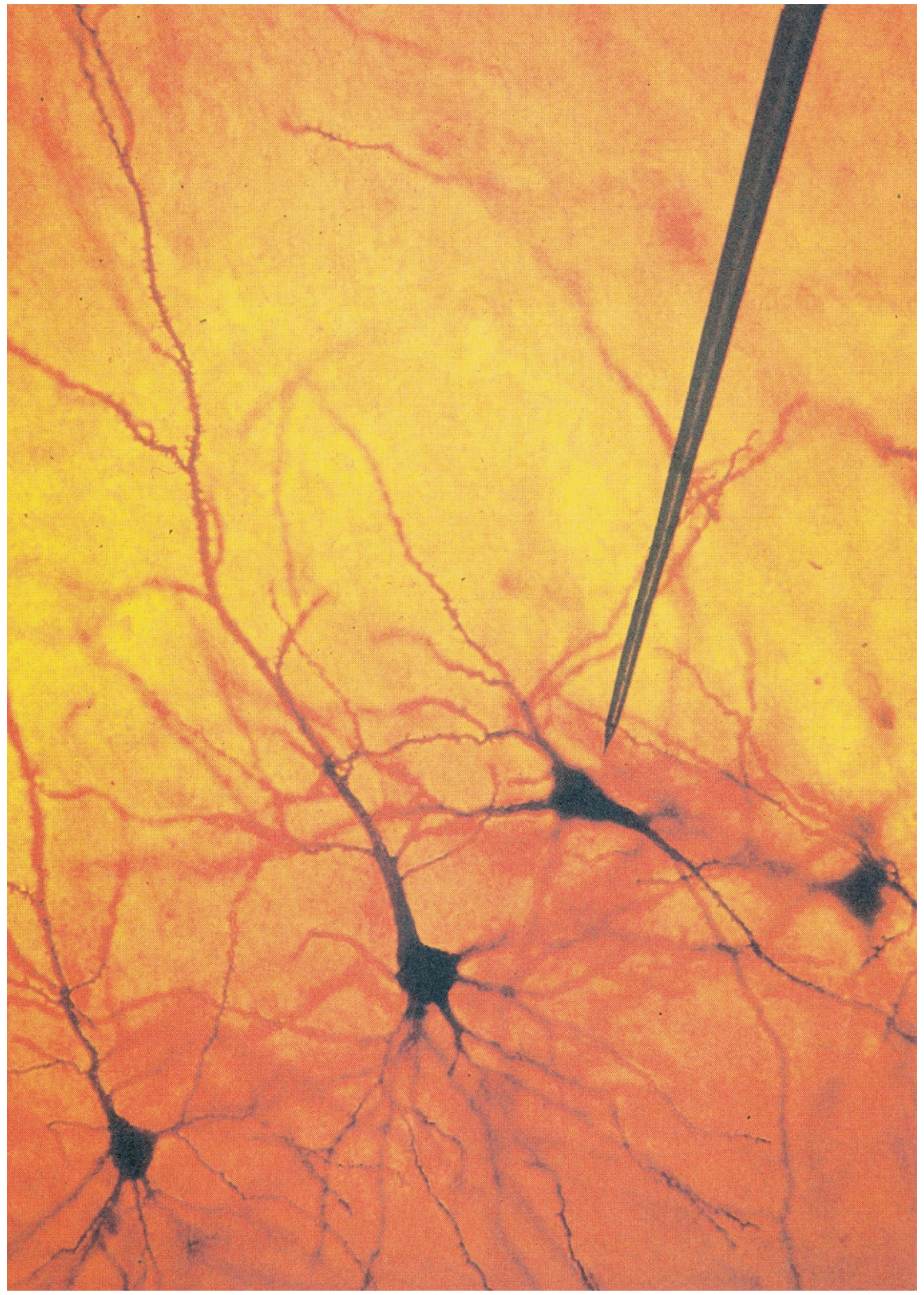


Perform with brain waves

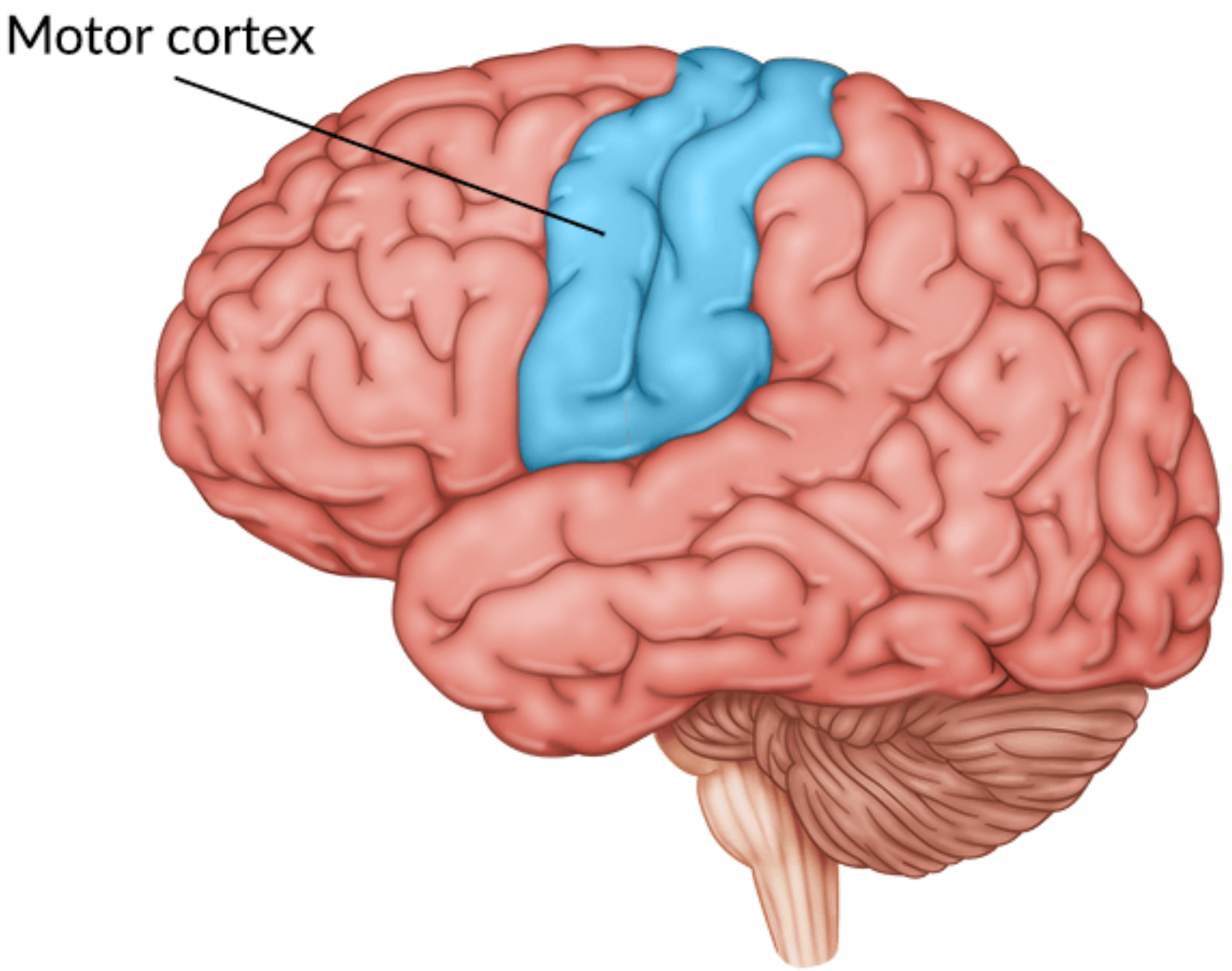
Electroencephalogram (EEG)



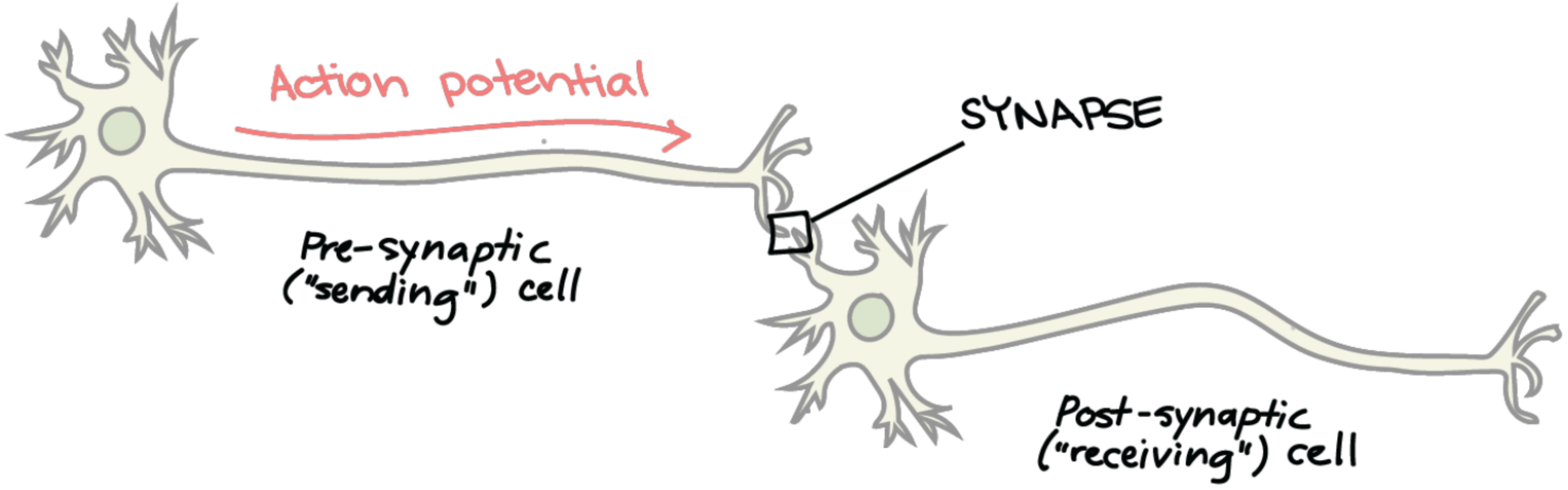
Listen to single neurons in motor cortex



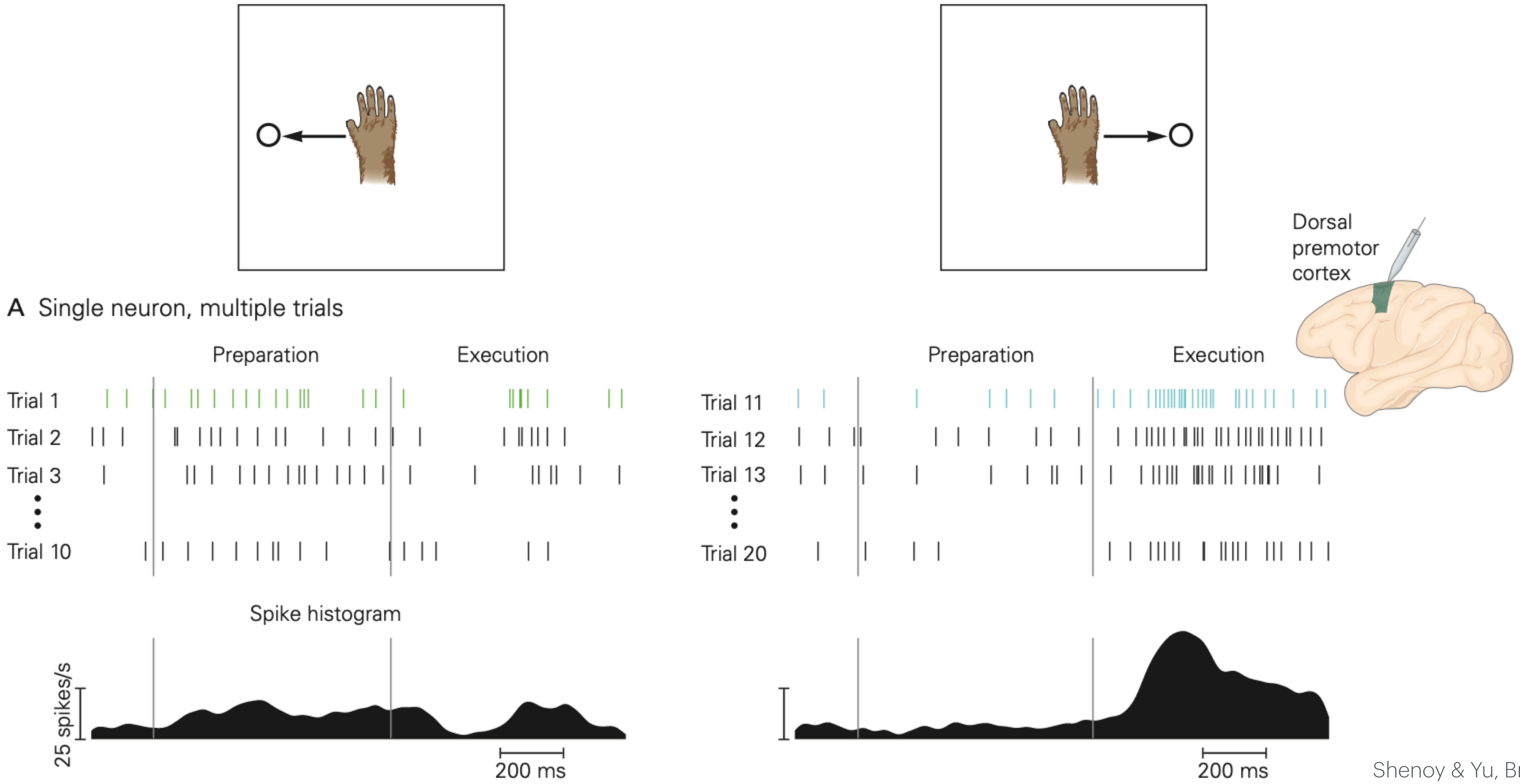
Hubel 1988



Neurons communicate with spikes



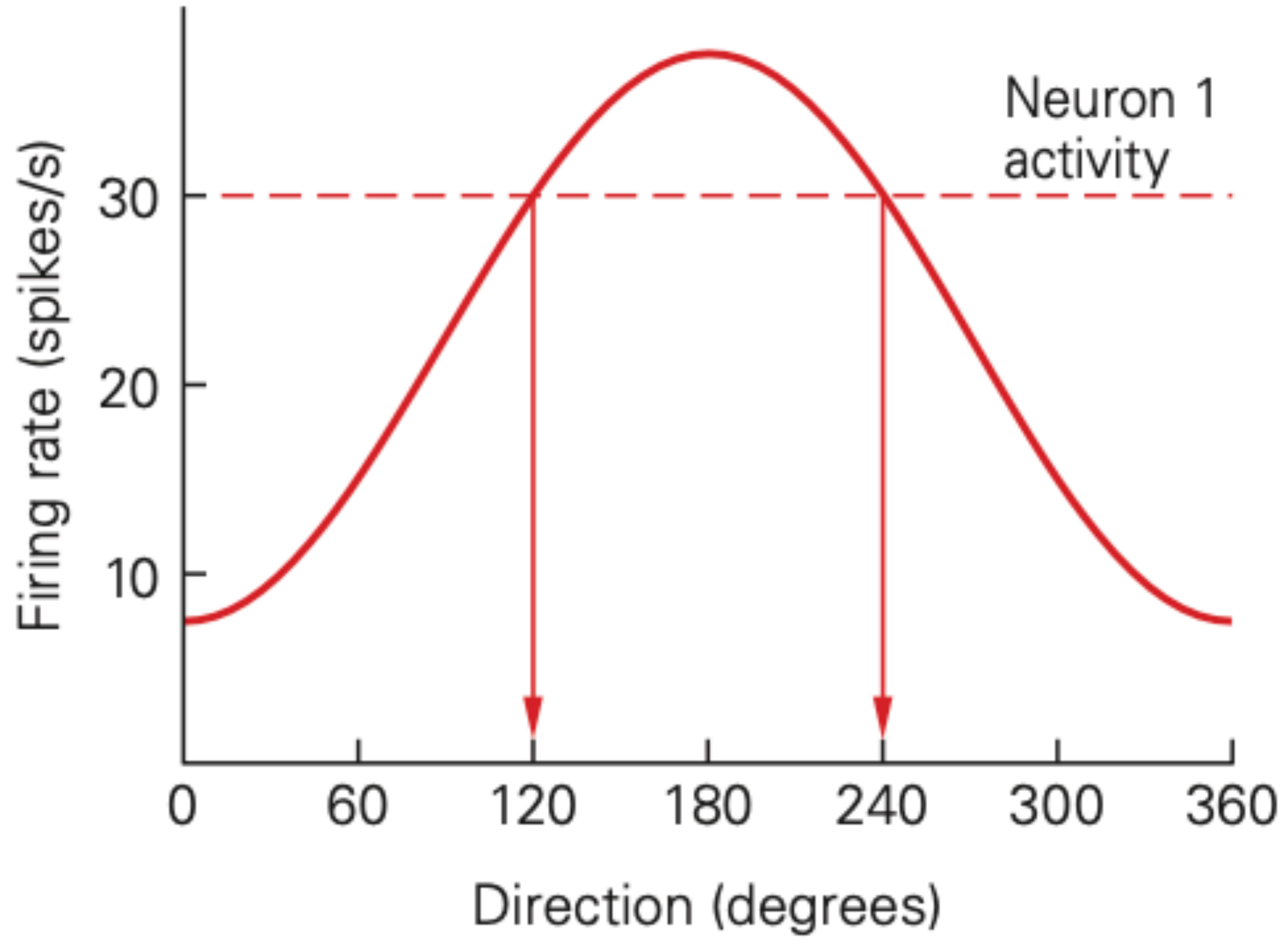
Single neurons encode movement directions



Shenoy & Yu, Brain Machine Interfaces

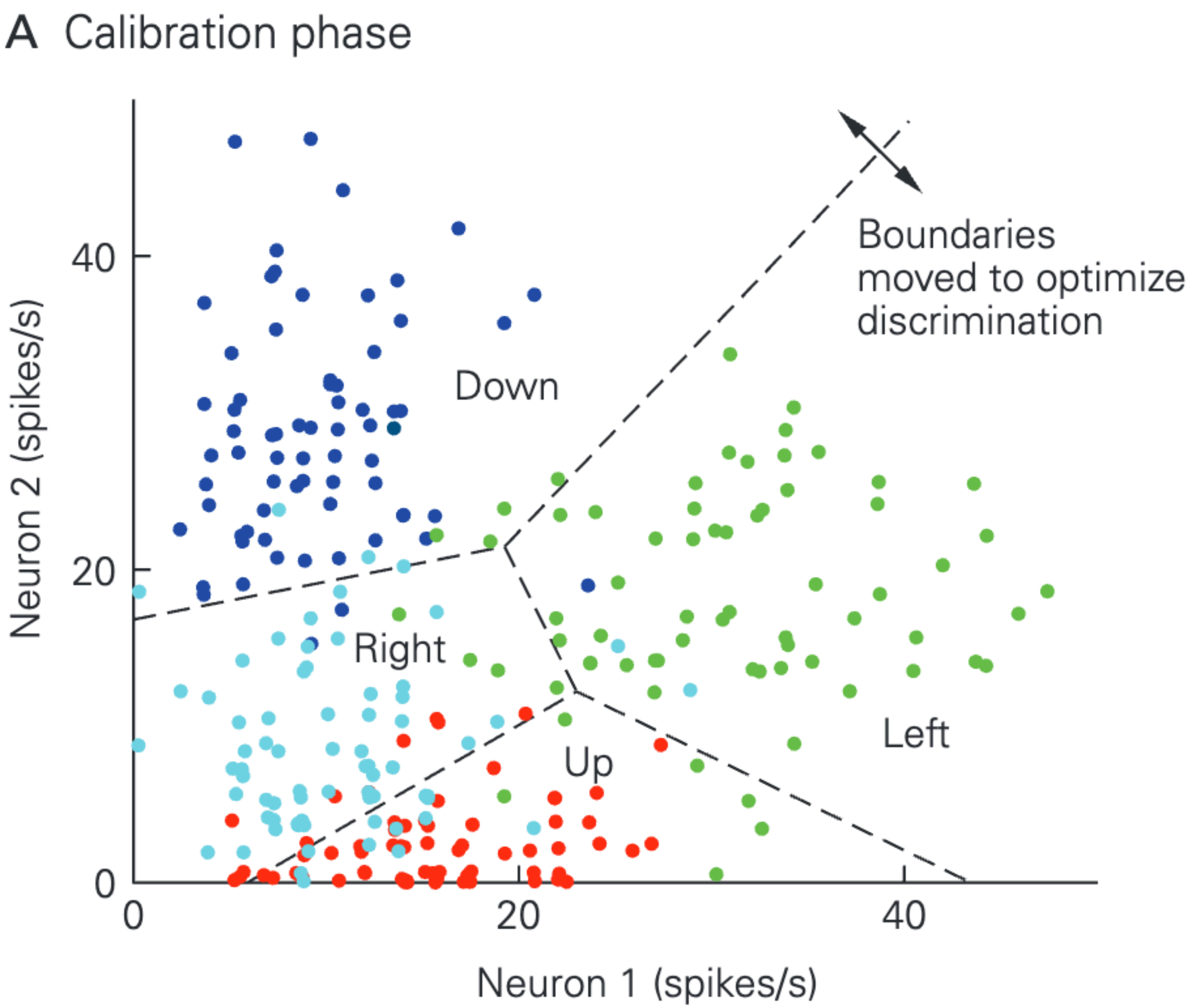
Multiple neurons for accurate decoding

A One neuron



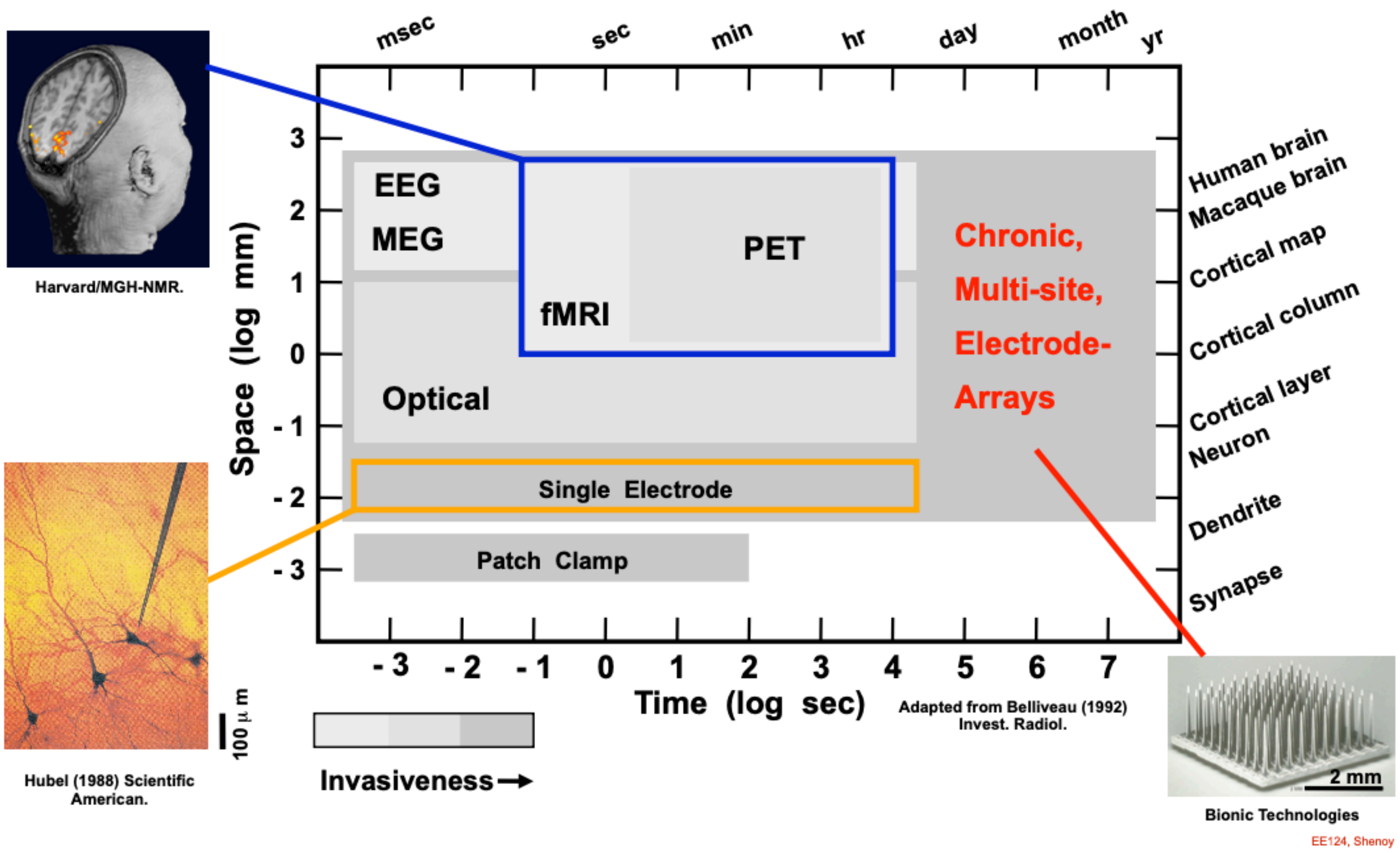
Shenoy & Yu, Brain Machine Interfaces

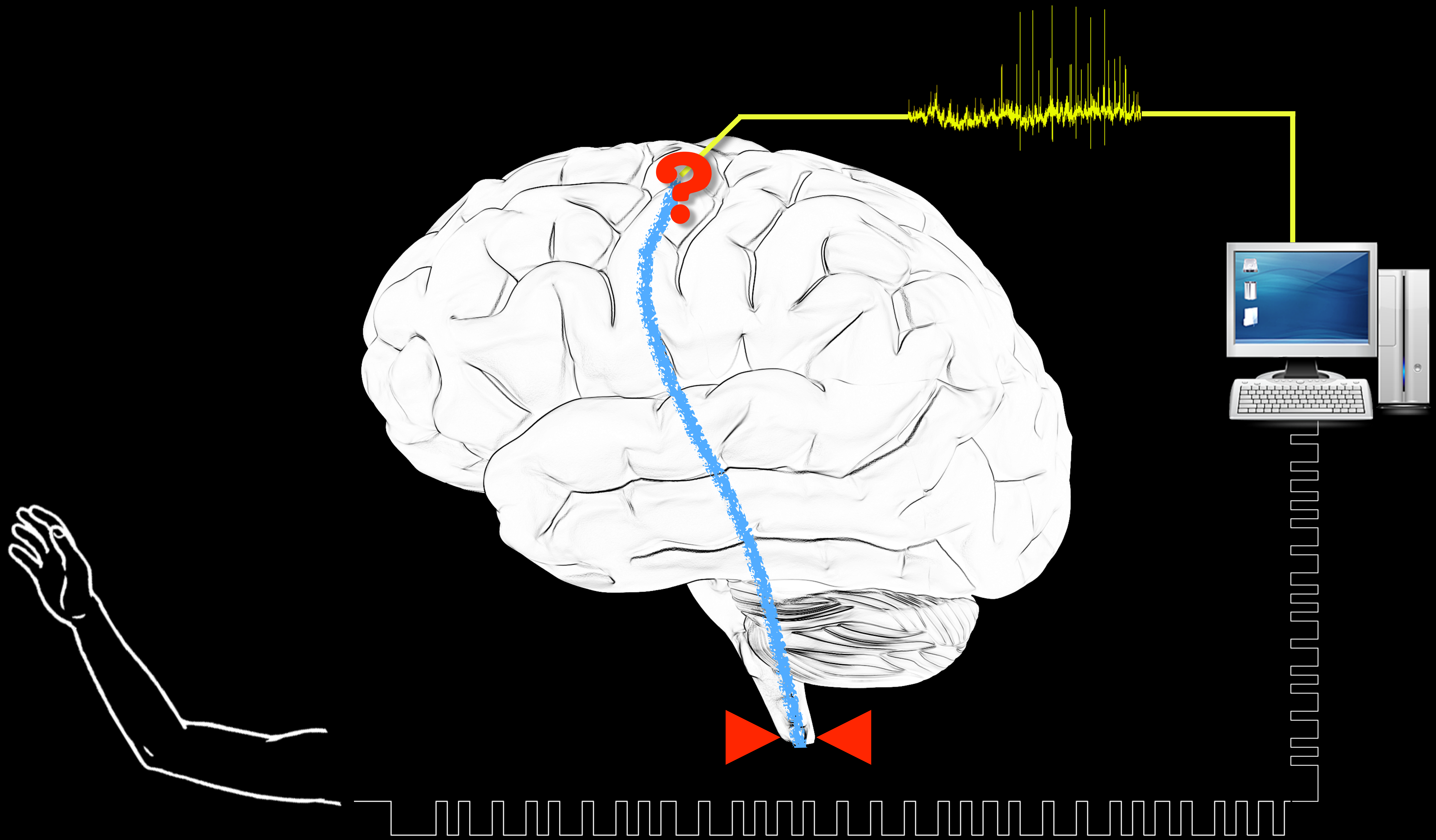
Multiple neurons for accurate decoding



Shenoy & Yu, Brain Machine Interfaces

Techniques for measuring neural activity



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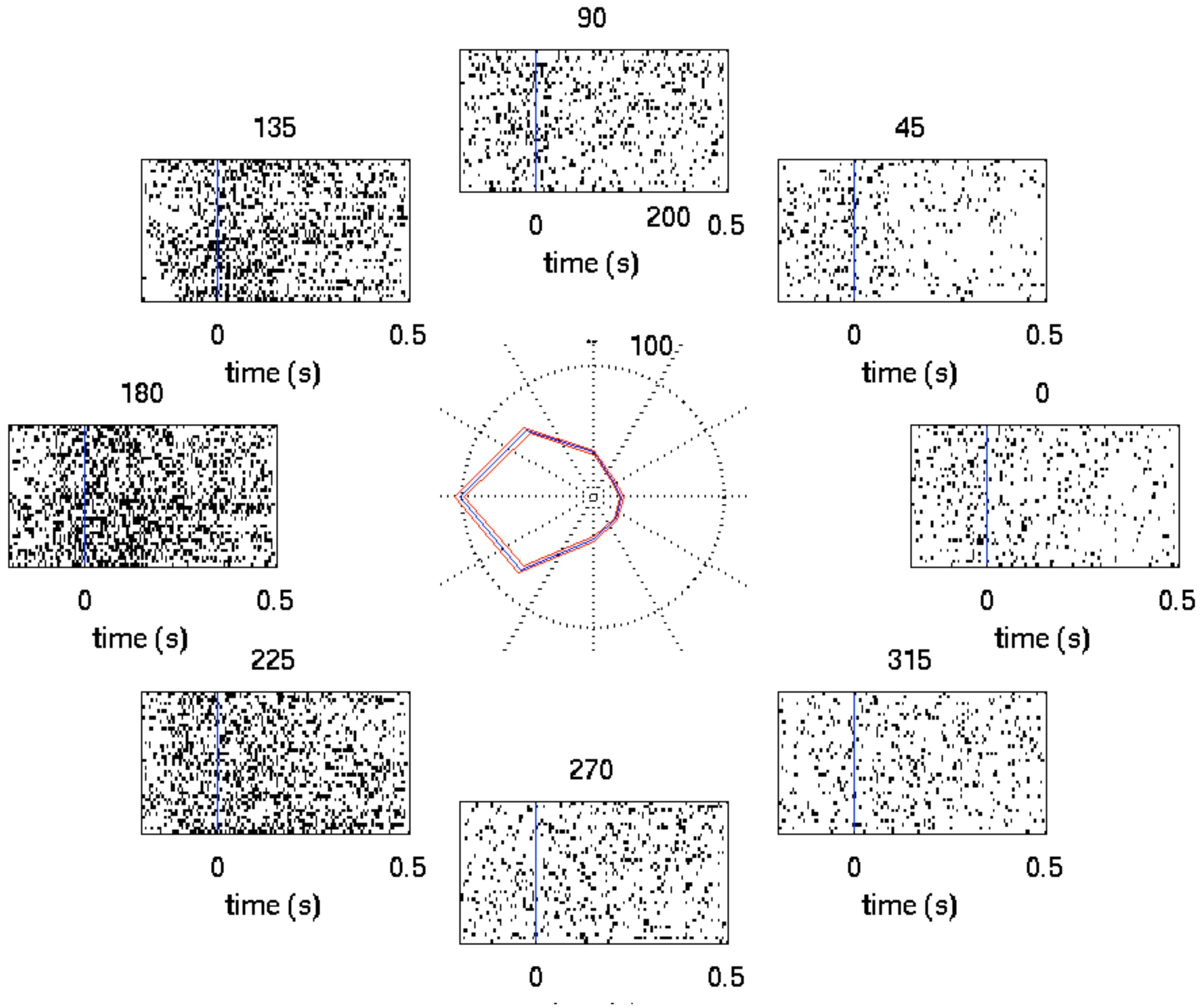
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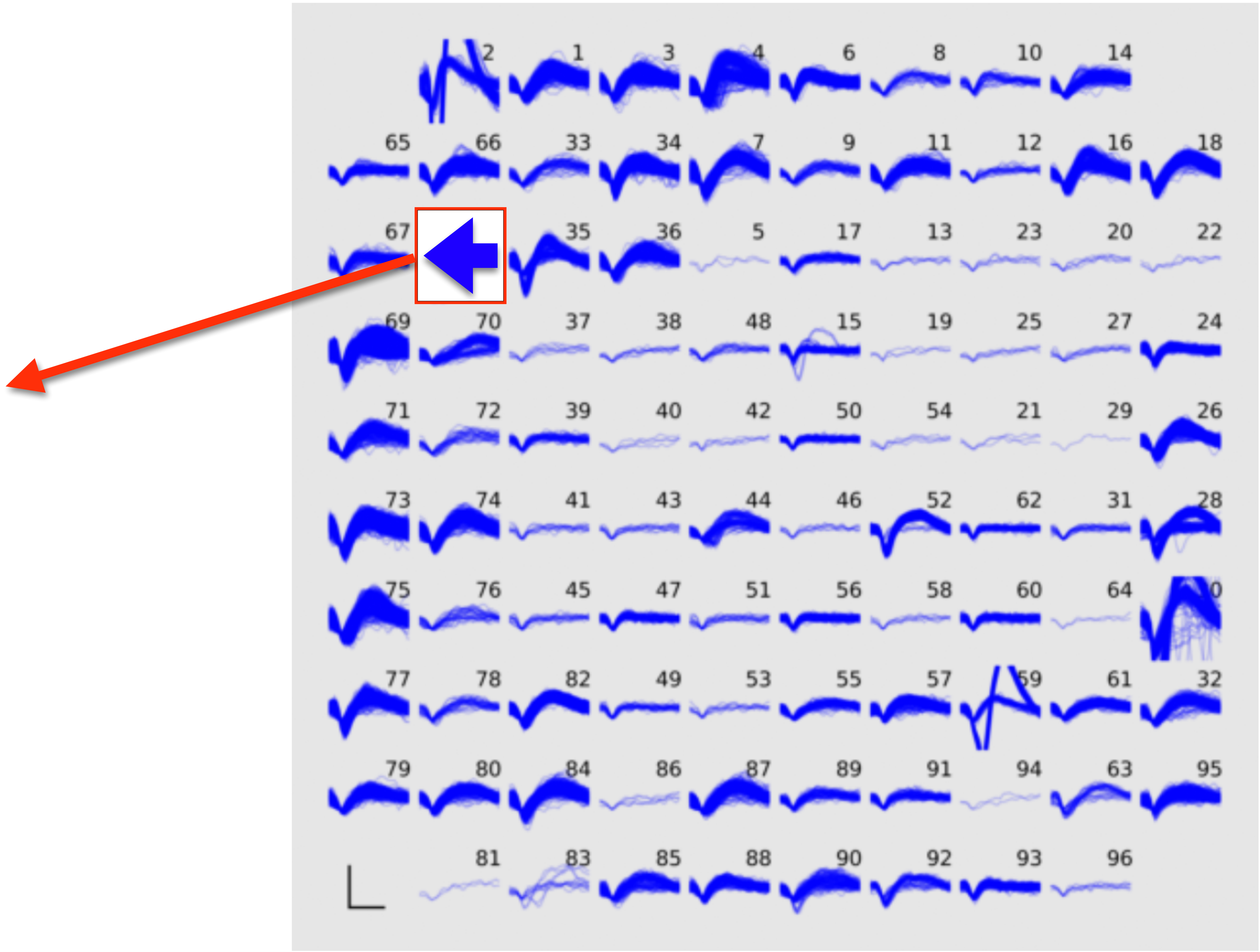
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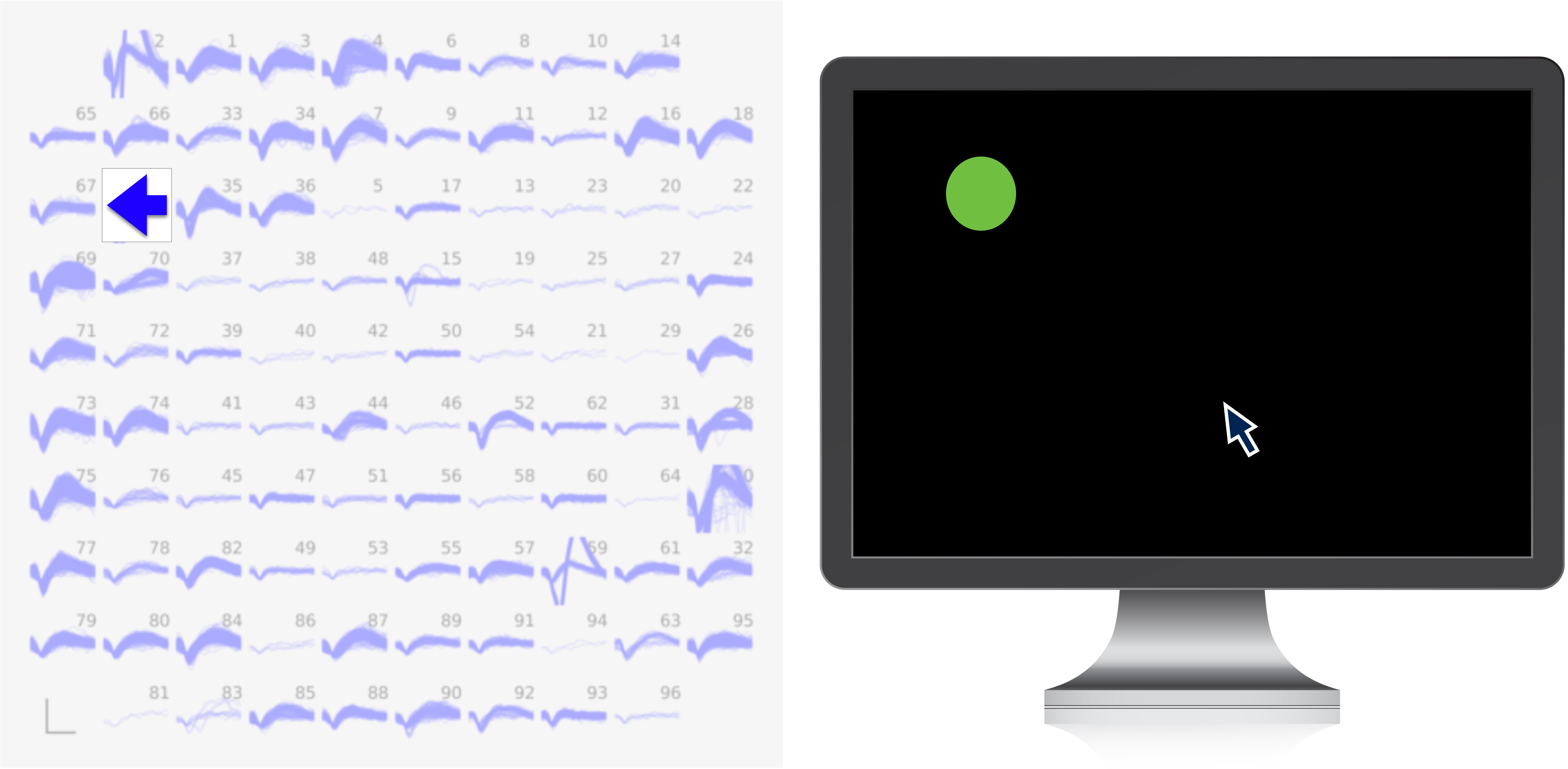
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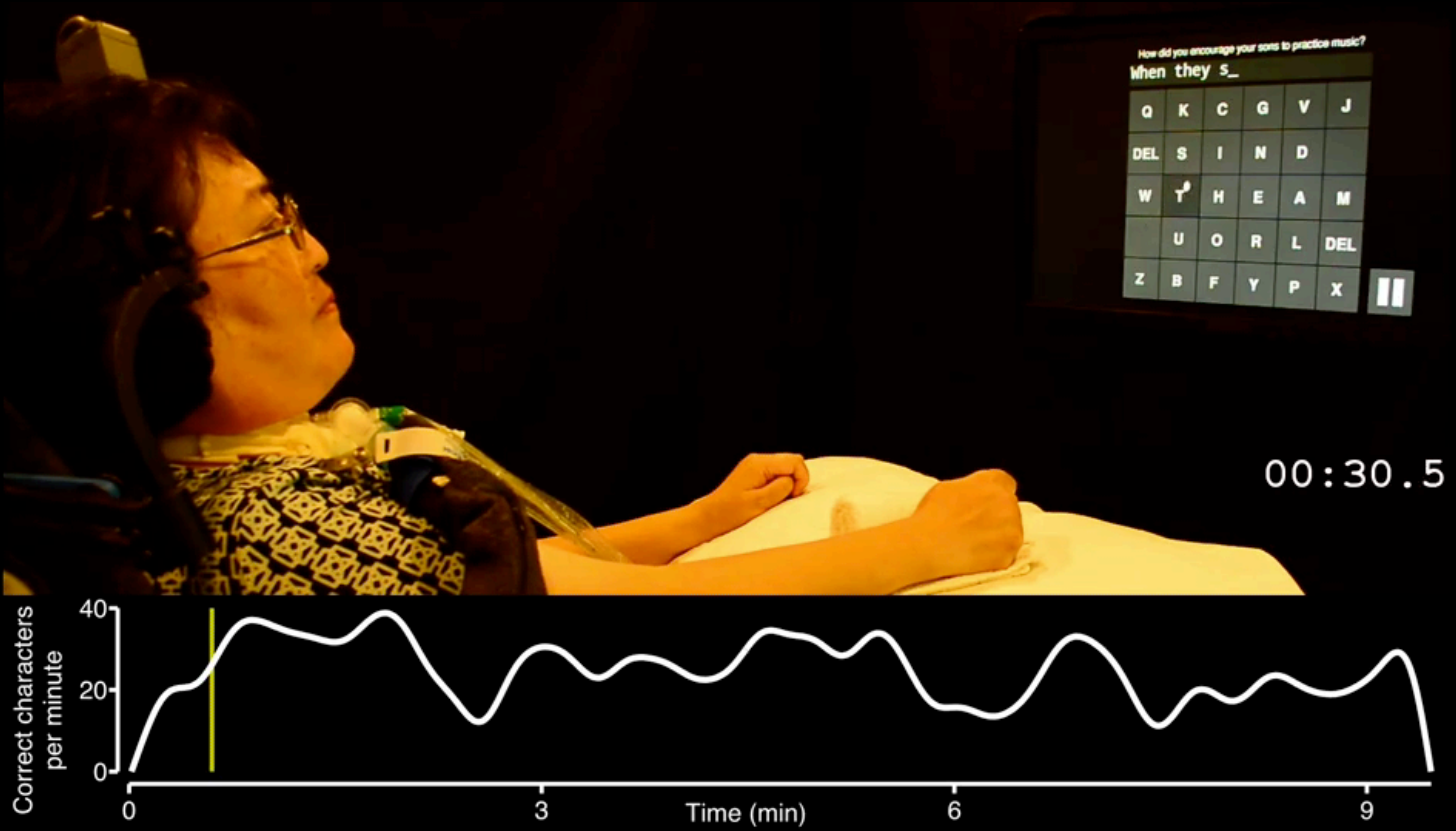


Pandarinath*, Nuyujukian*, et al. (2017) *eLife*

BrainGate2 Neural Interface System. CAUTION: Investigational Device. Limited by US Federal Law to Investigational Use

Beyond 2D control

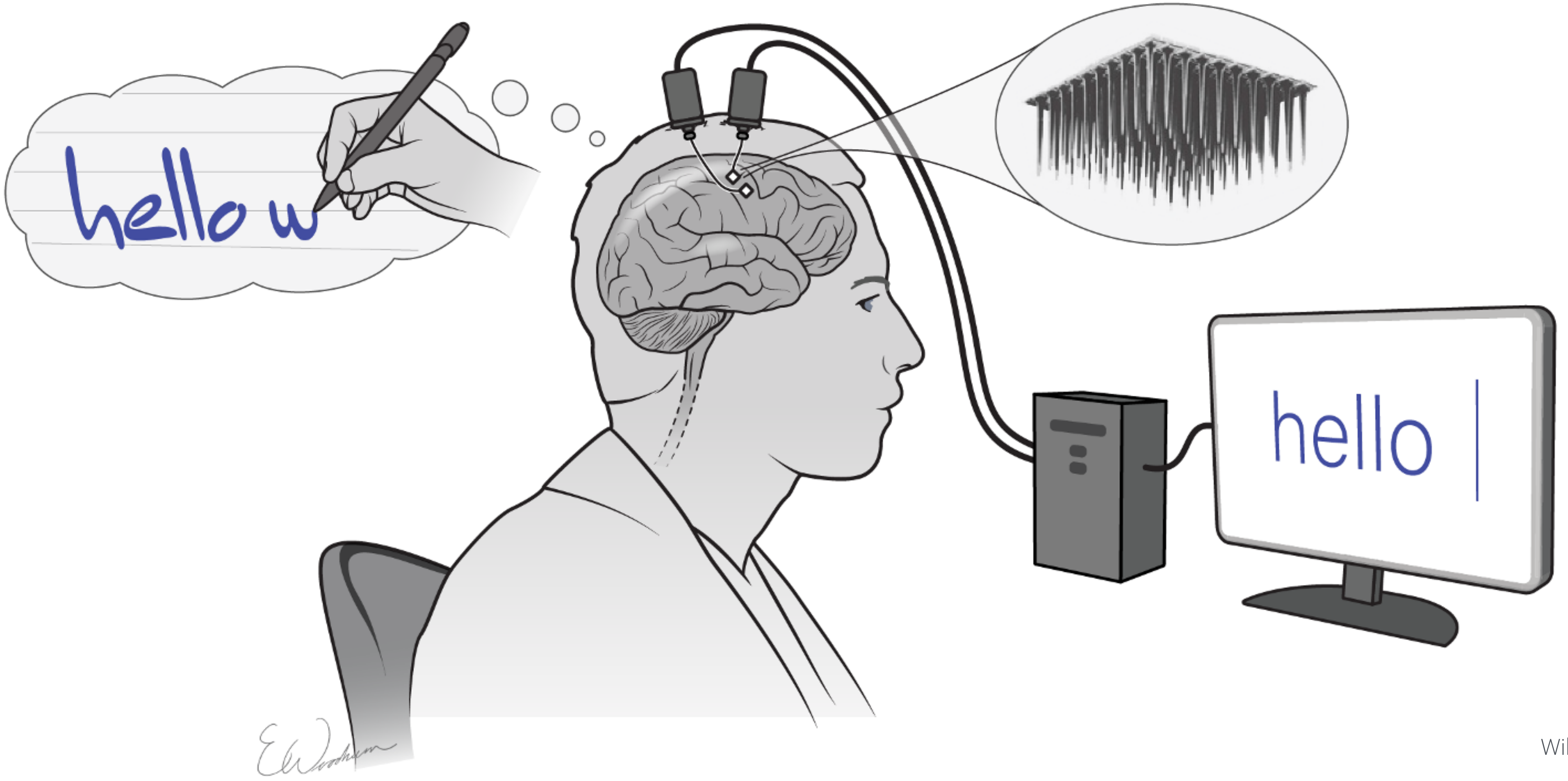
Control robotic arms

Beyond 2D control

Restore walking

Beyond 2D control

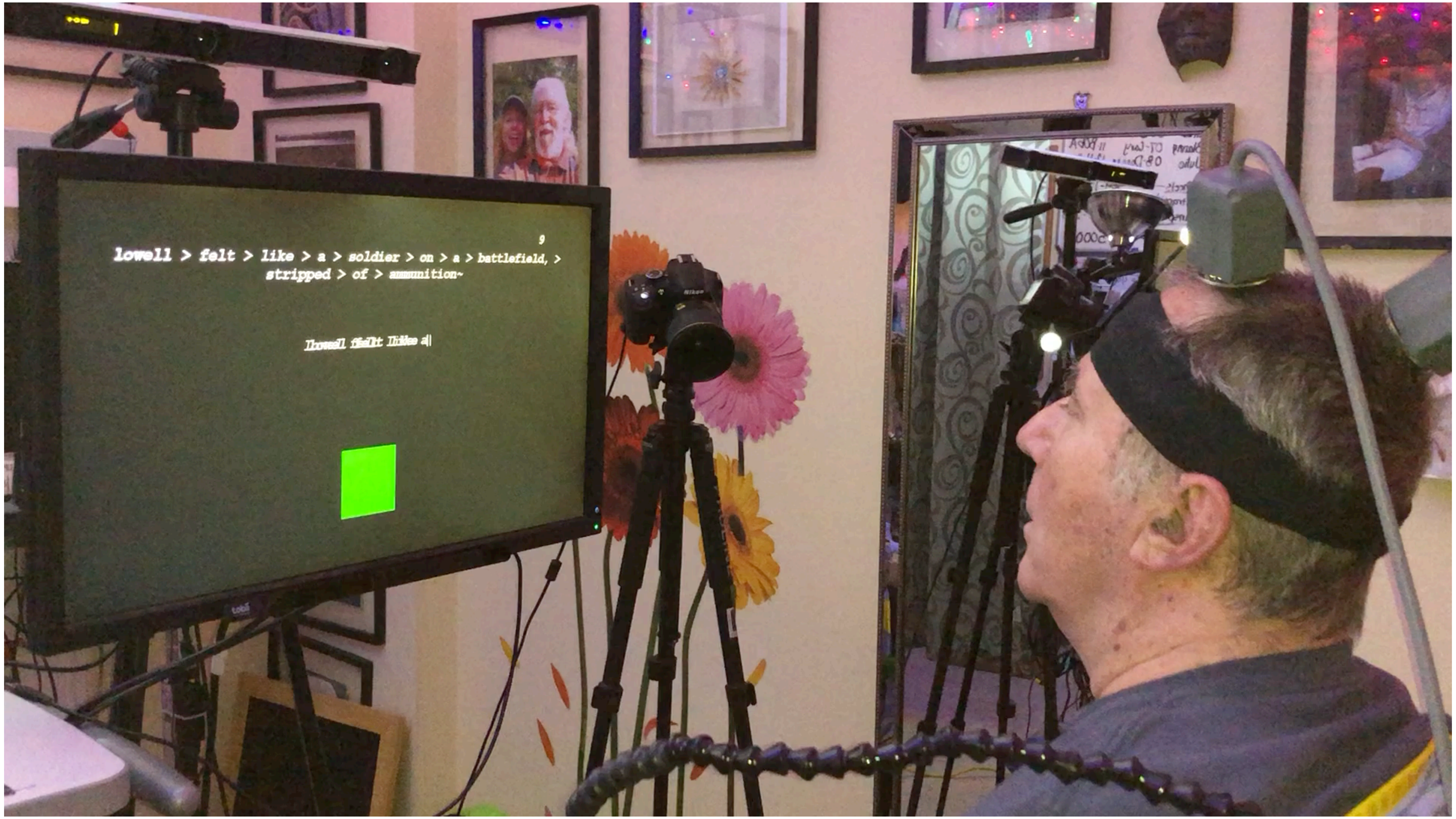
Communication through handwriting



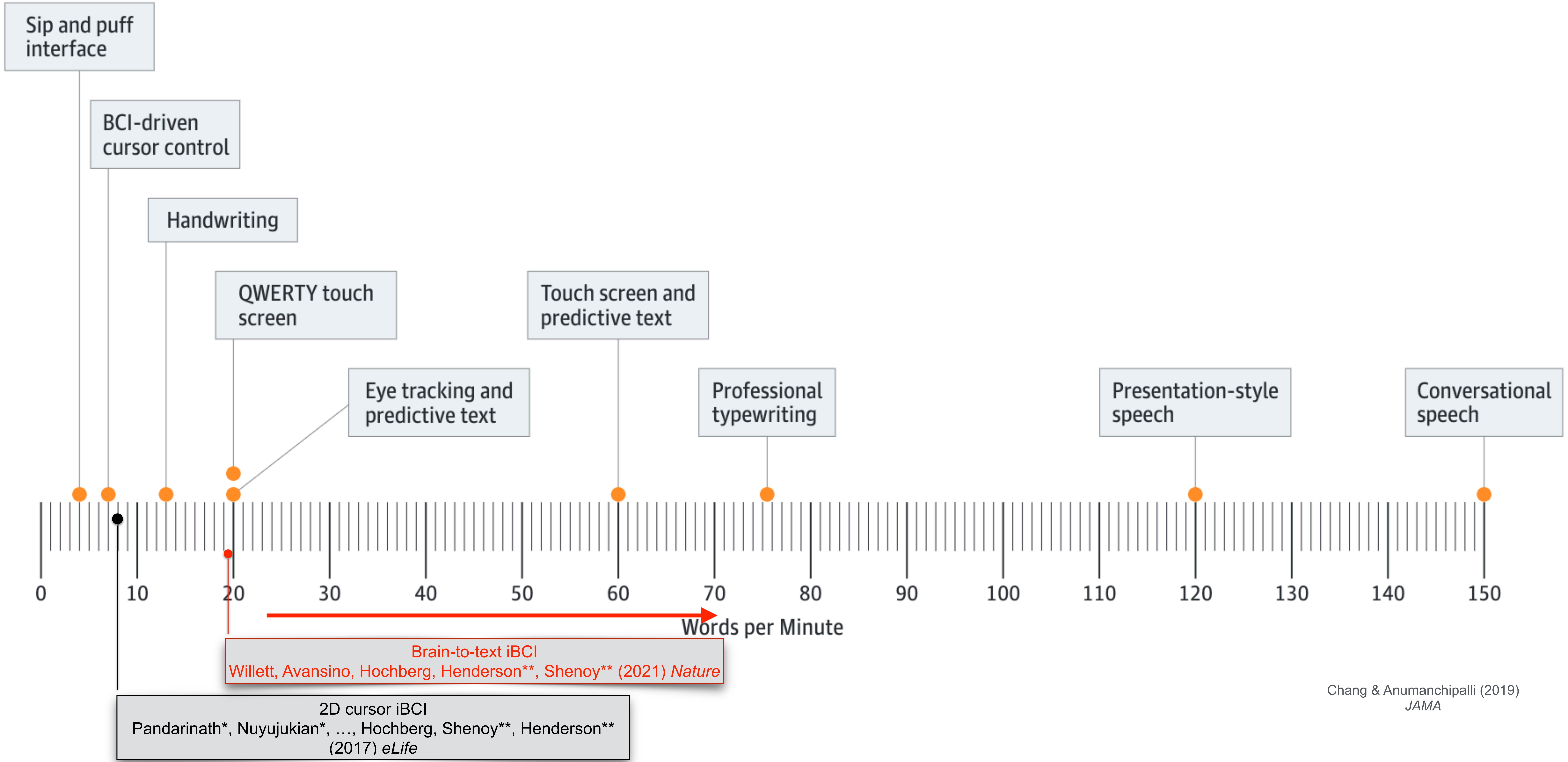
Willett et al. 2021

90 char/min with 95% accuracy

Communication through handwriting

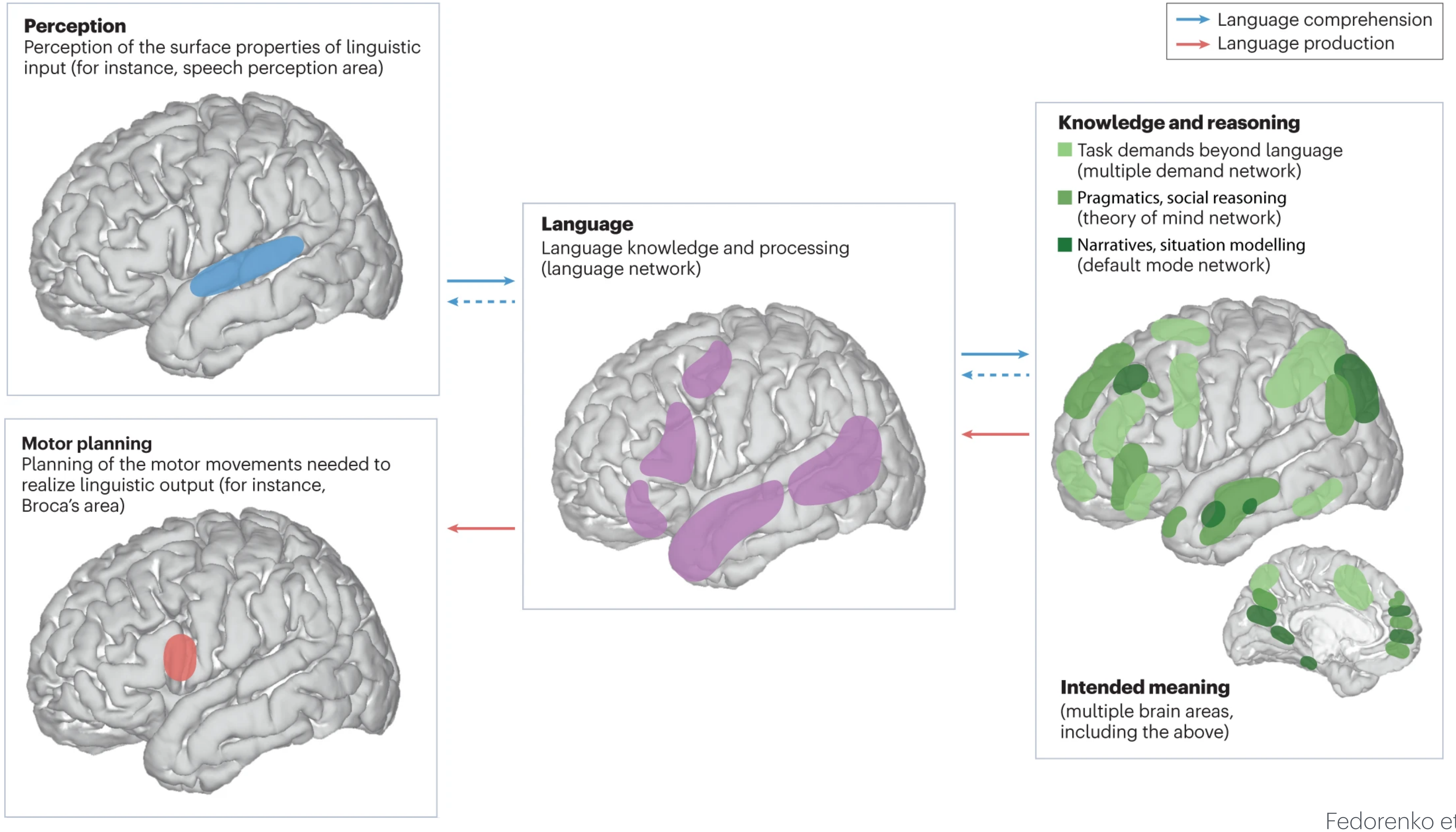


Restore natural speech?



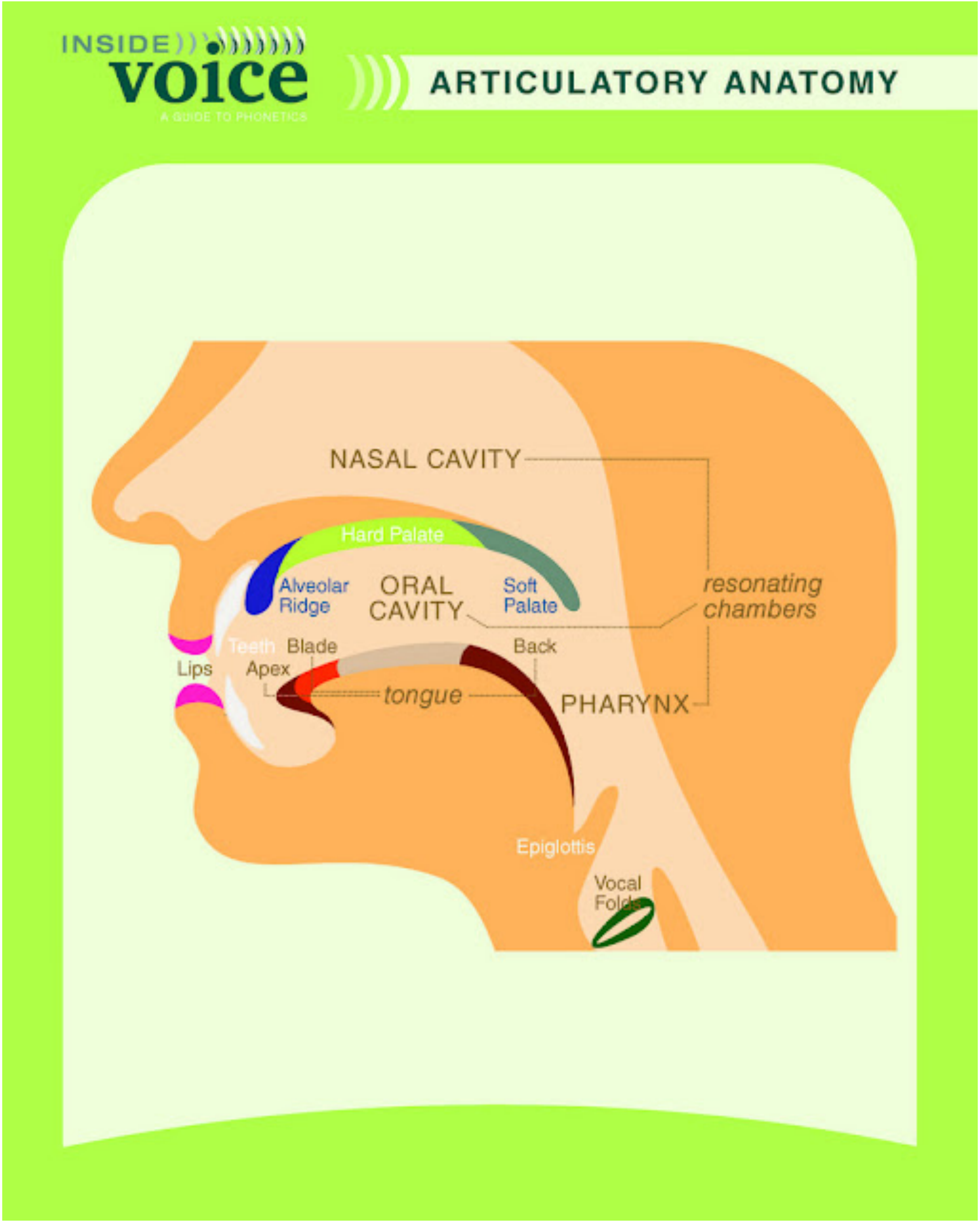
Chang & Anumanchipalli (2019)
JAMA

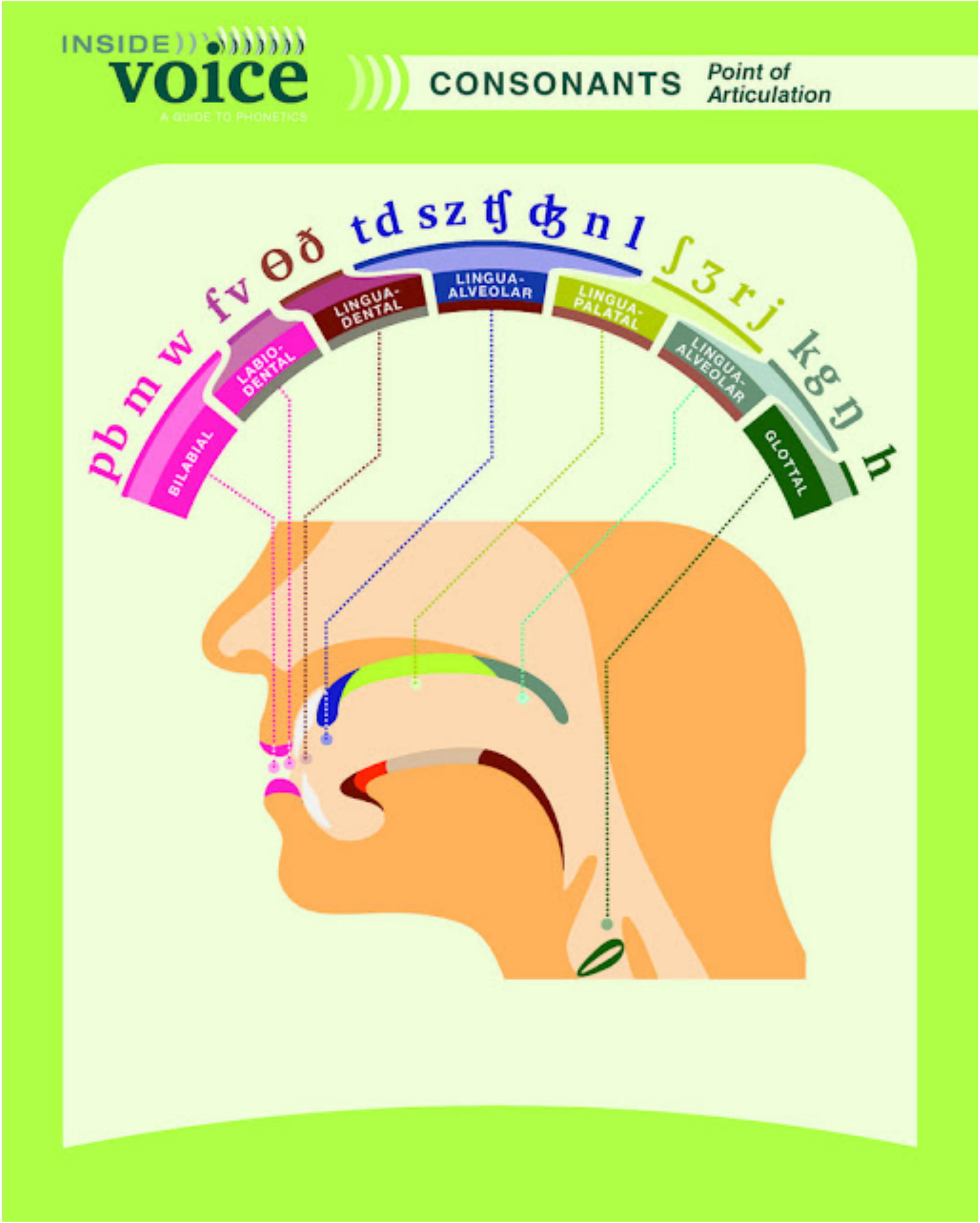
Language processing in the brain



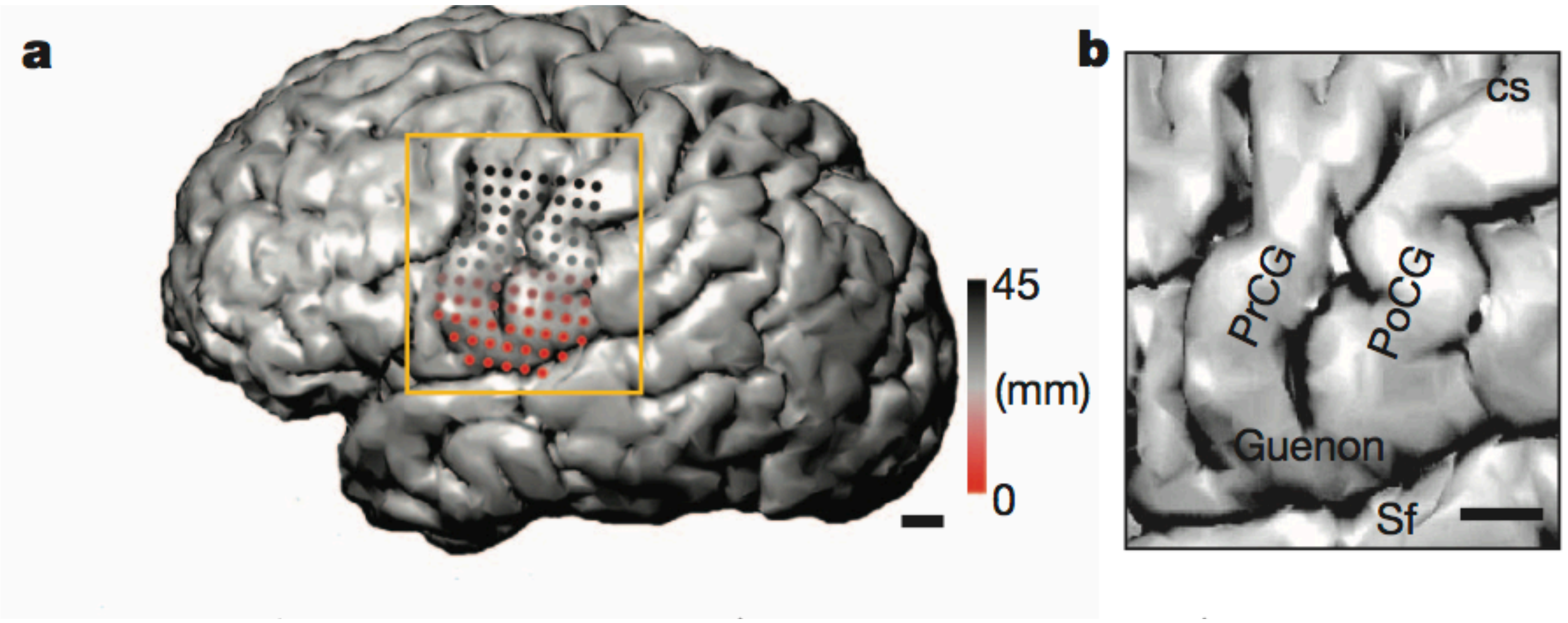
Fedorenko et al. 2024

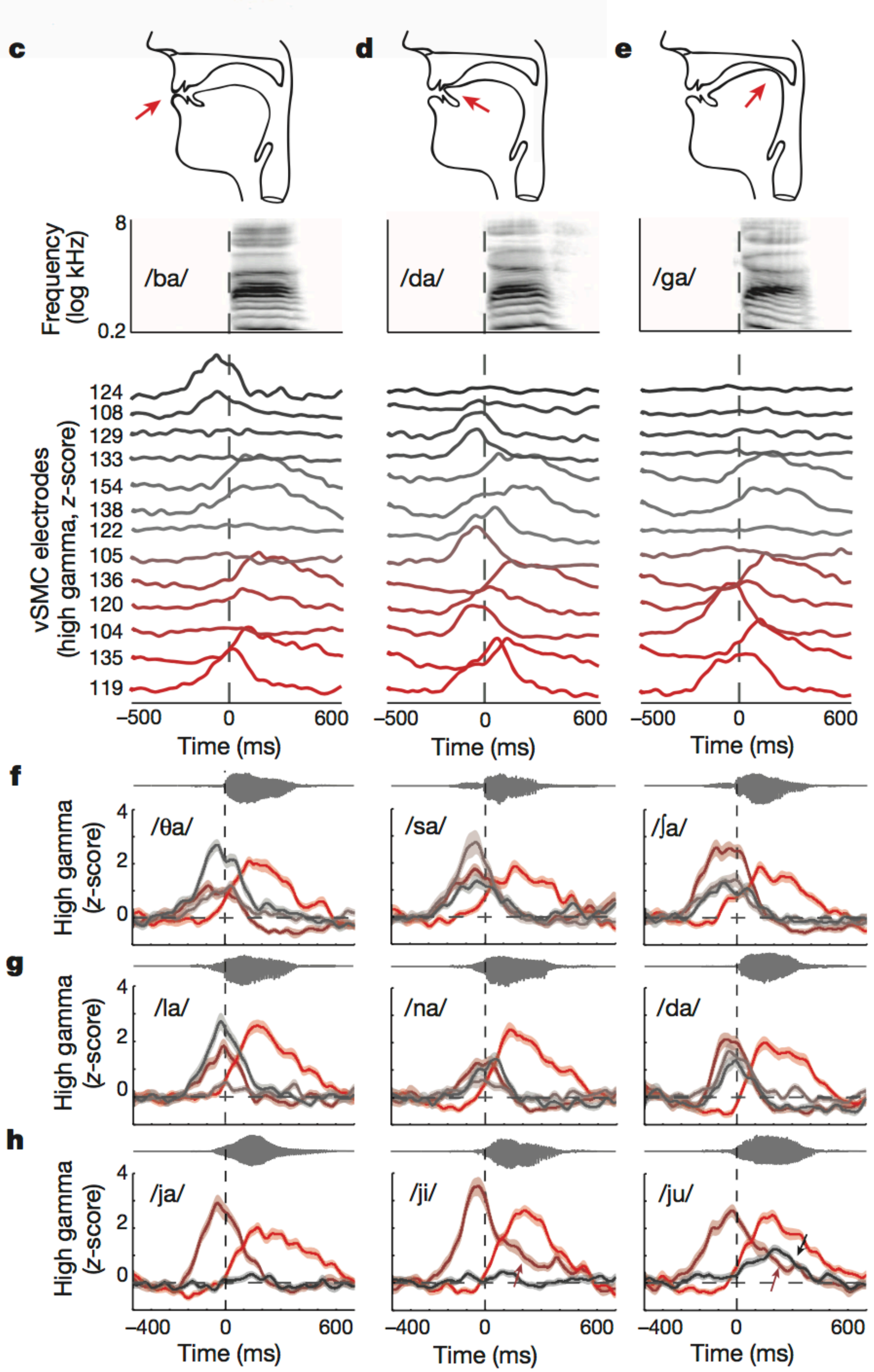
How do we produce speech sound





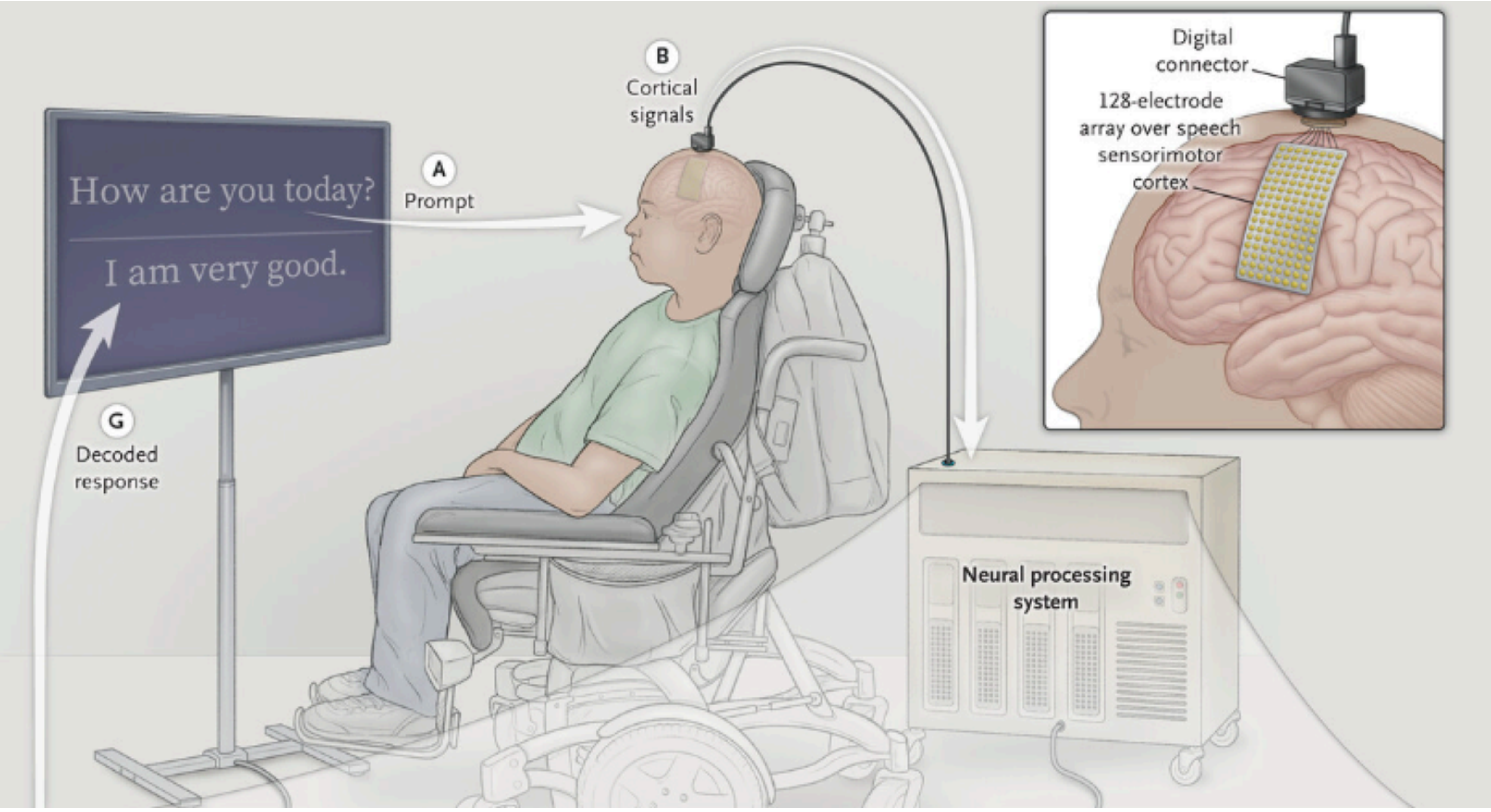
Motor cortex encodes articulatory and phonemic information

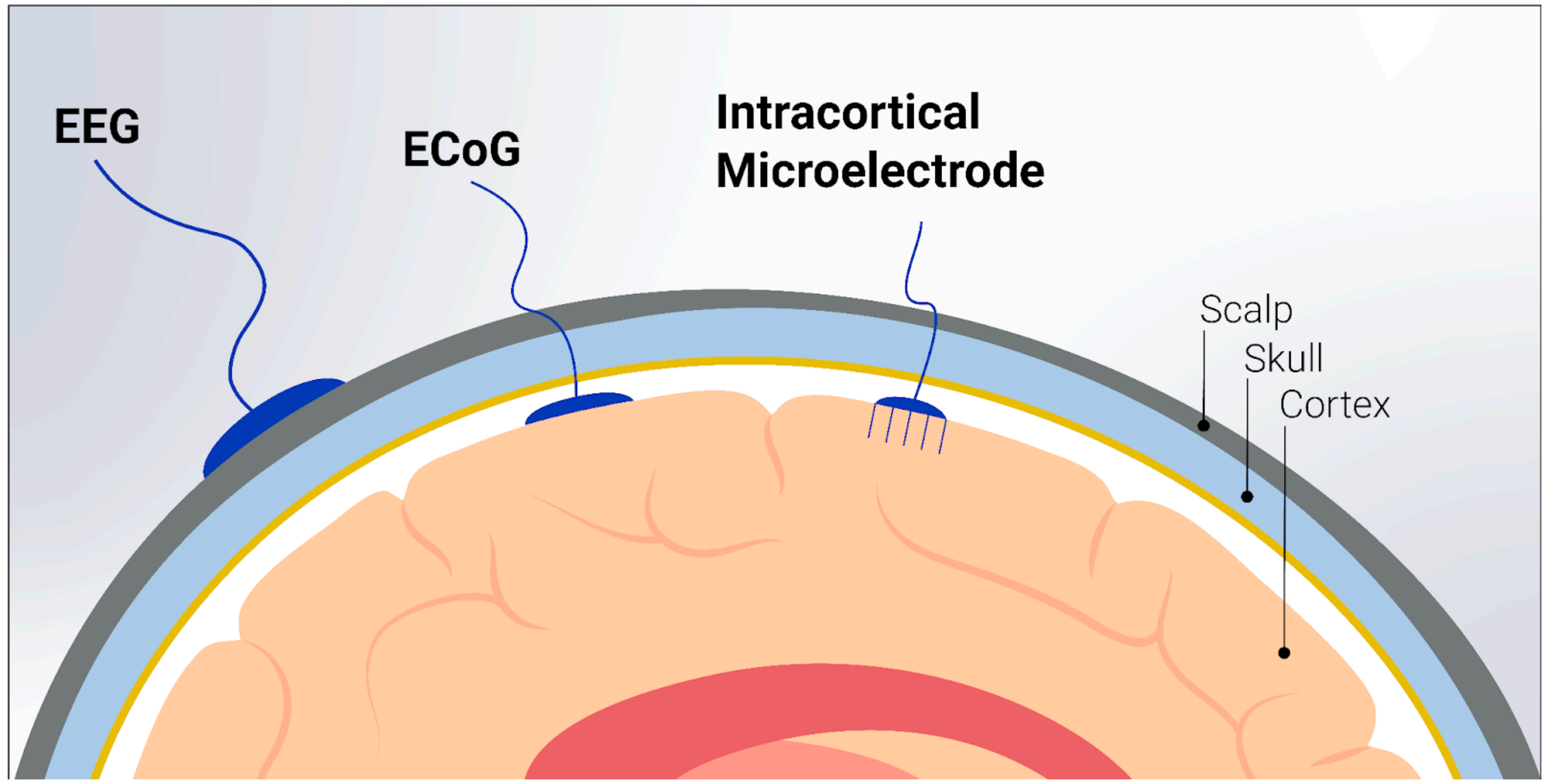




Bouchard et al. 2013

Small vocabulary speech BCI with ECoG





Moses et al. 2021

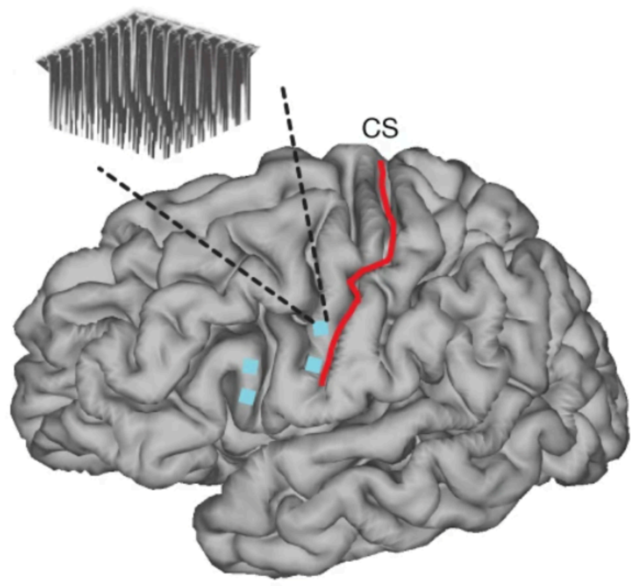
A High-Performance Speech Neuroprosthesis

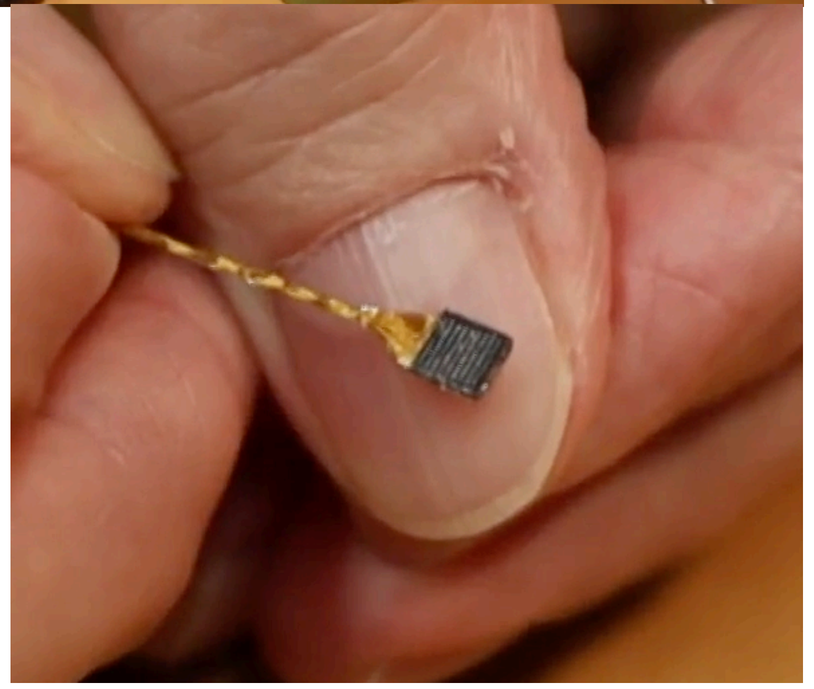
Implanting microelectrode arrays into BrainGate2 clinical trial participant T12

- T12 has bulbar-onset Amyotrophic Lateral Sclerosis (ALS)

- She retains some limited orofacial movement and an ability to vocalize, but is unable to produce intelligible speech.

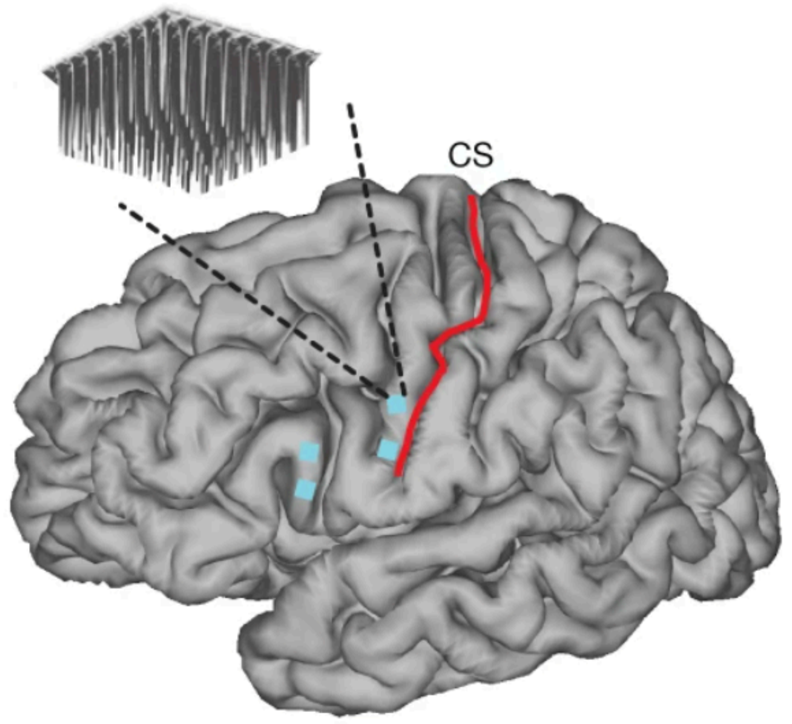
- Four 64-channel Utah arrays
  - Two in area 6v (ventral motor cortex)
  - Two in area 44 (part of Broca's area)

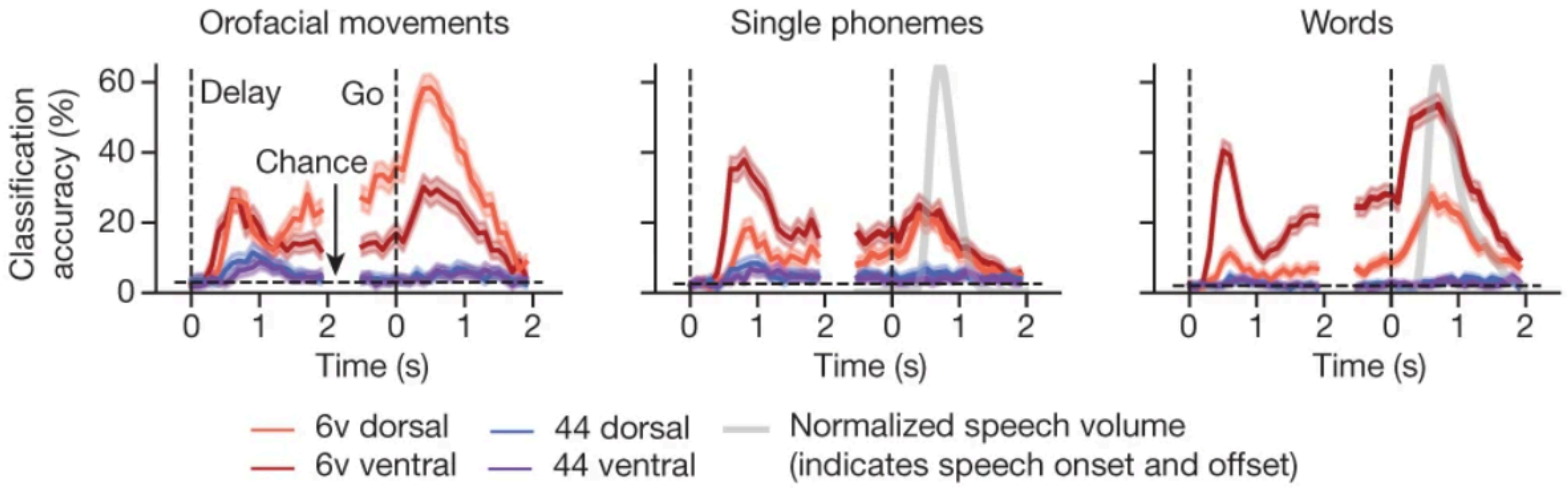




Willett, Kunz, Fan, et al. 2023

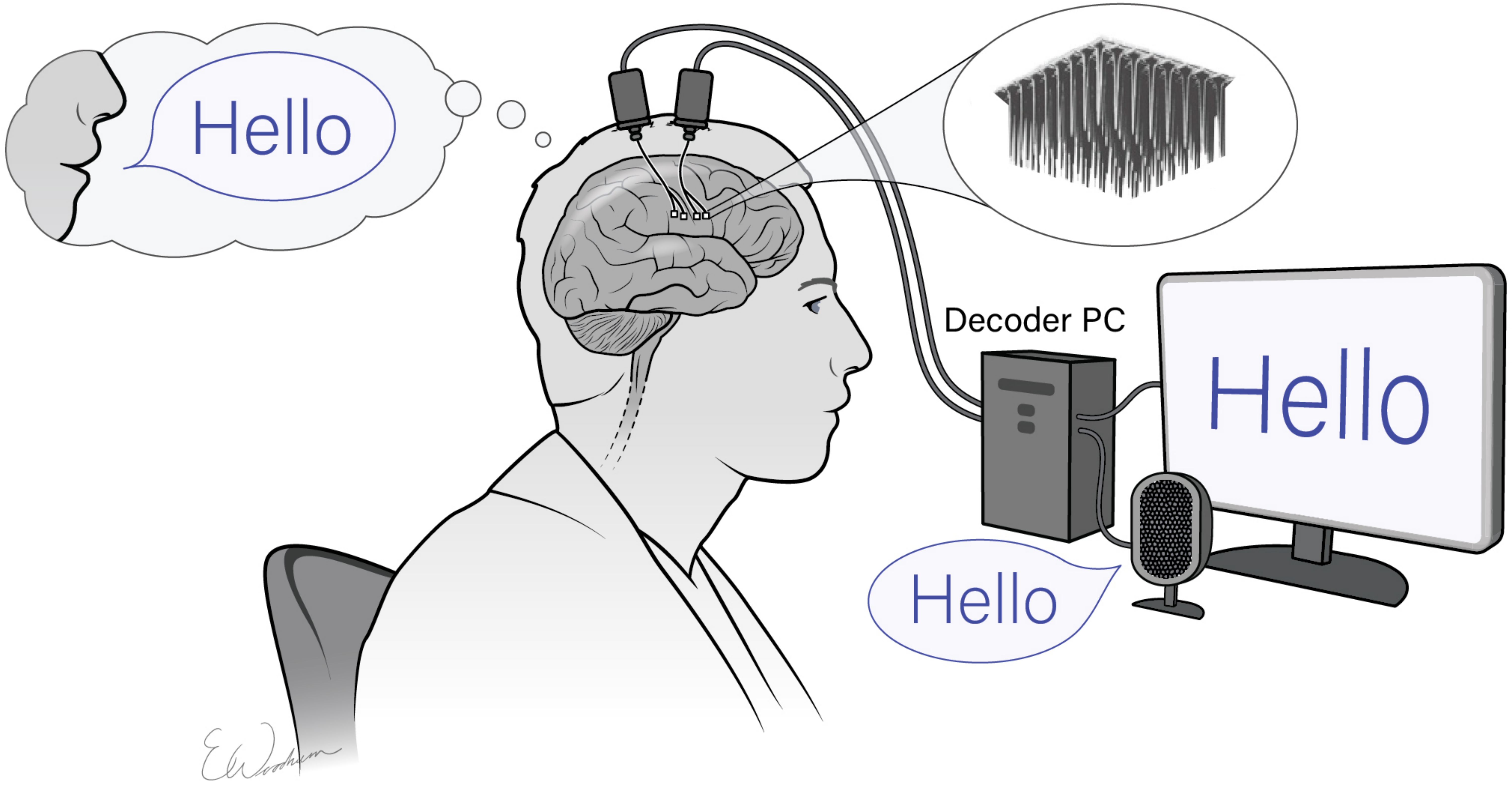
Neural representation of orofacial movements and speech





Willett, Kunz, Fan, et al. 2023

Real-time brain-to-text BCI



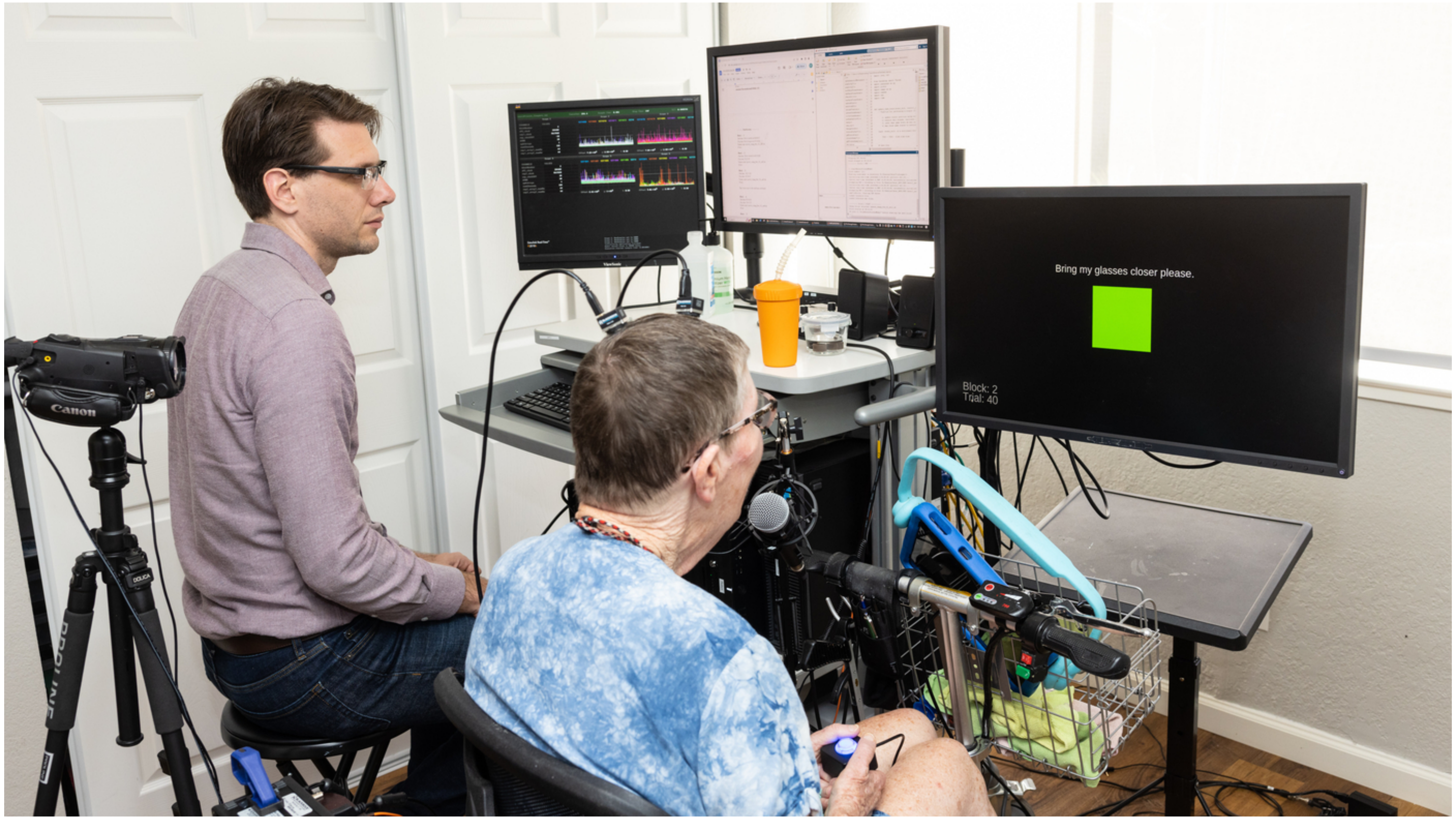
Willett, Kunz, Fan, et al. 2023

BrainGate2 Neural Interface System. CAUTION: Investigational Device. Limited by US Federal Law to Investigational Use

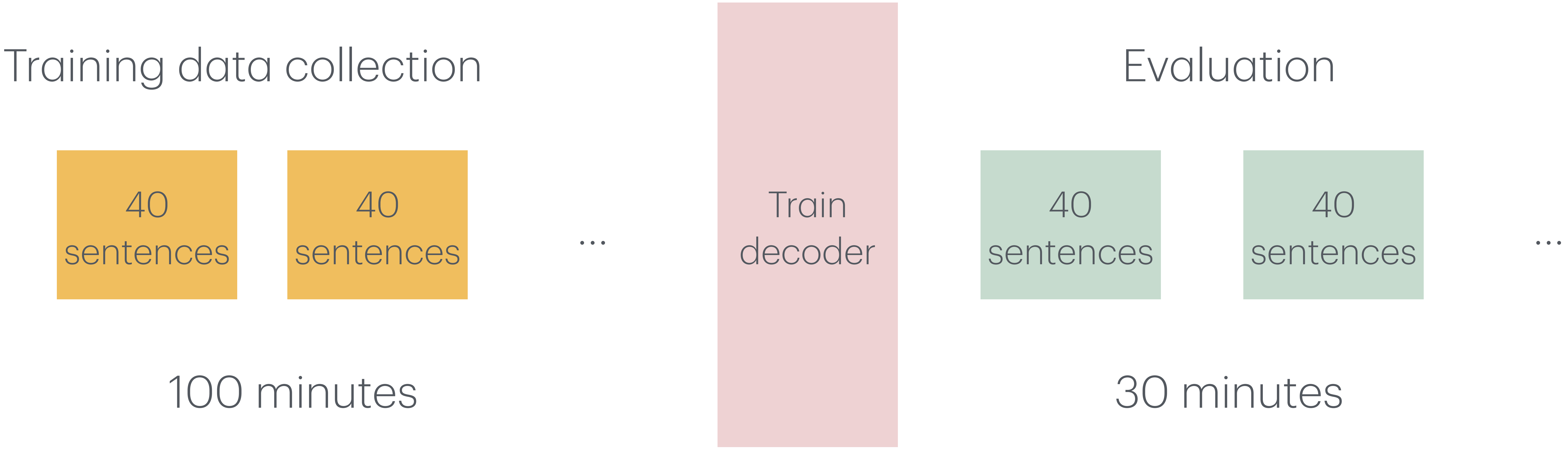

What are you proud of?
Block: 14
Trial: 15
PROLINE
BrainGate2 Neural Interface System. CAUTION: Investigational Device. Limited by US Federal Law to Investigational Use


I do not have much to compare it to.
Block: 17
Trial: 29
BrainGate2 Neural Interface System. CAUTION: Investigational Device. Limited by US Federal Law to Investigational Use

Data collection



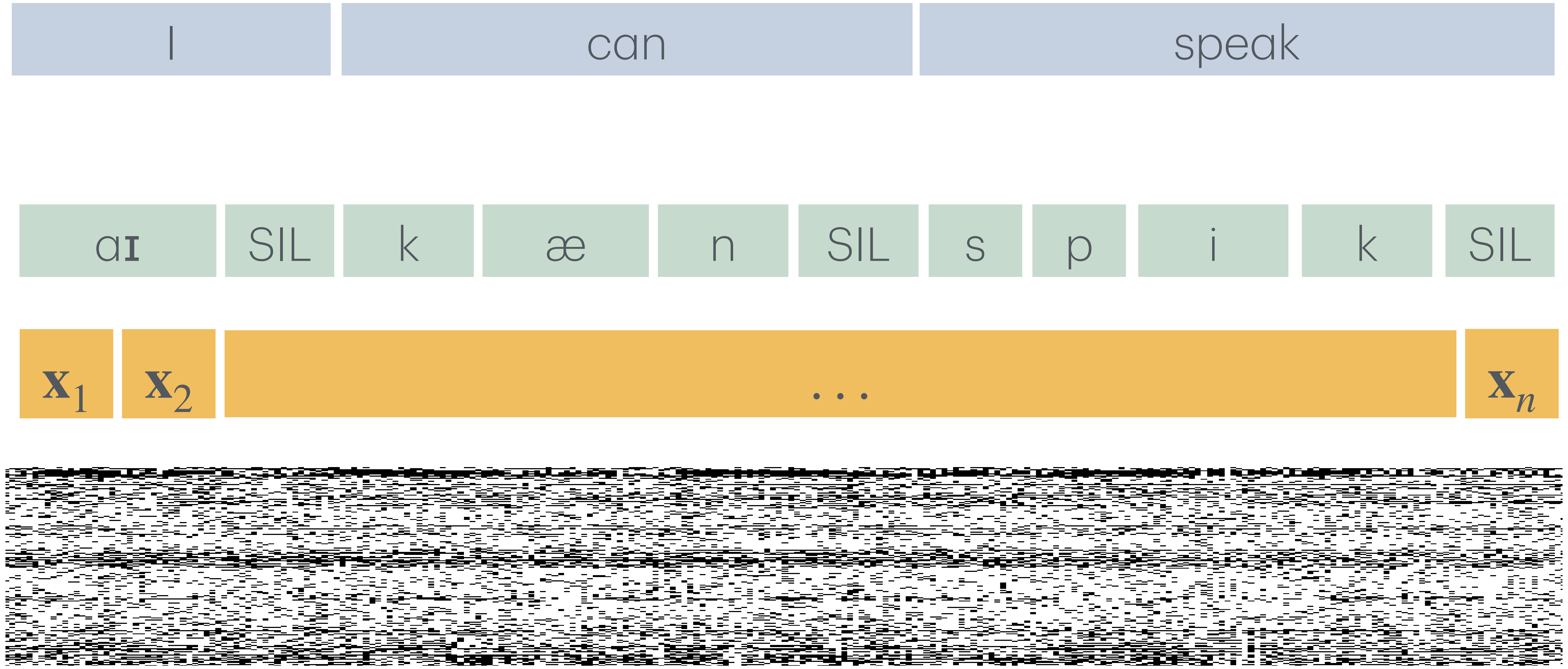
Data collection



Training and evaluation sentences are randomly selected from the Switchboard corpus of telephone conversation (~1,0000 sentences)

Problem definition

- Neural feature inputs: $\{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_n\} \quad \mathbf{x}_i \in \mathbb{R}^{d \times 1}$
- Words outputs: $\{\mathbf{y}_1, \mathbf{y}_2, \ldots, \mathbf{y}_m\} \quad \mathbf{y}_i \in \mathbb{R}^{V \times 1}$



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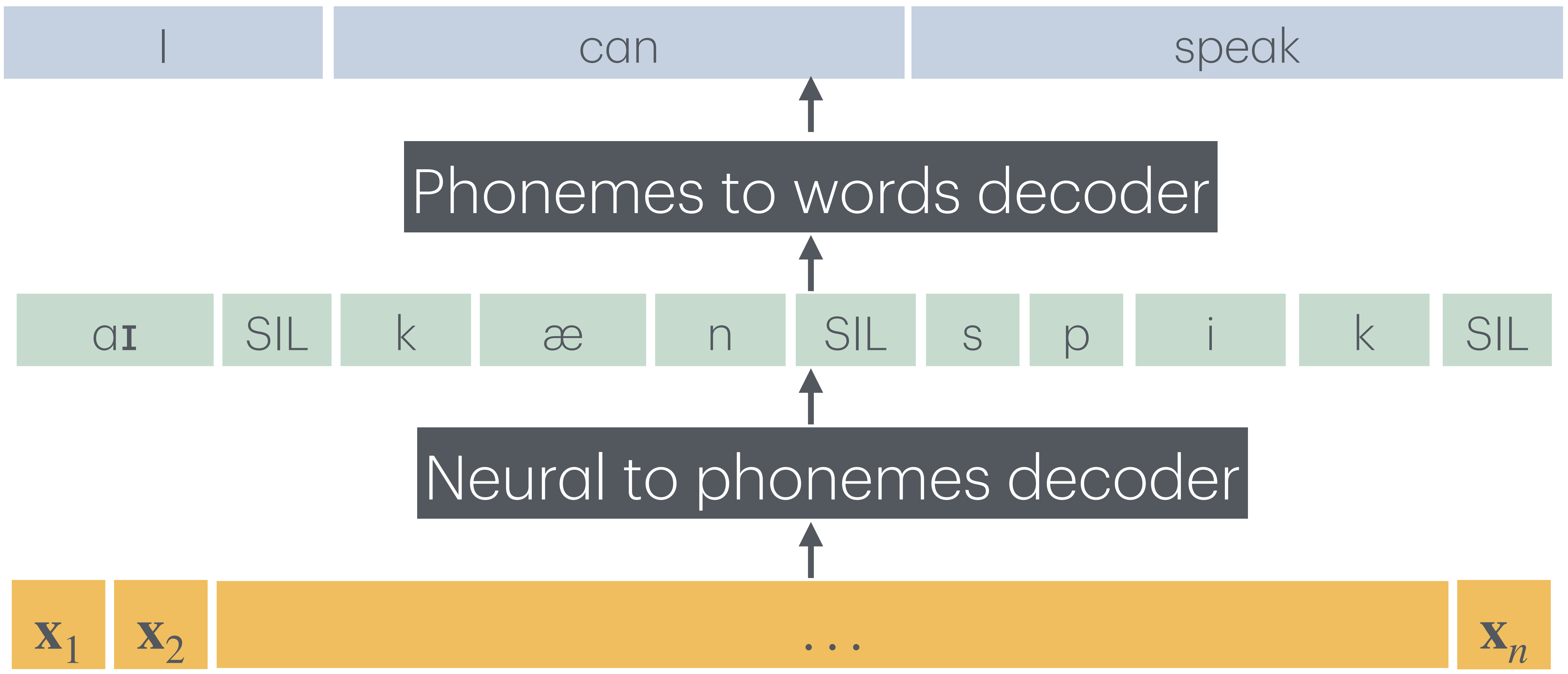
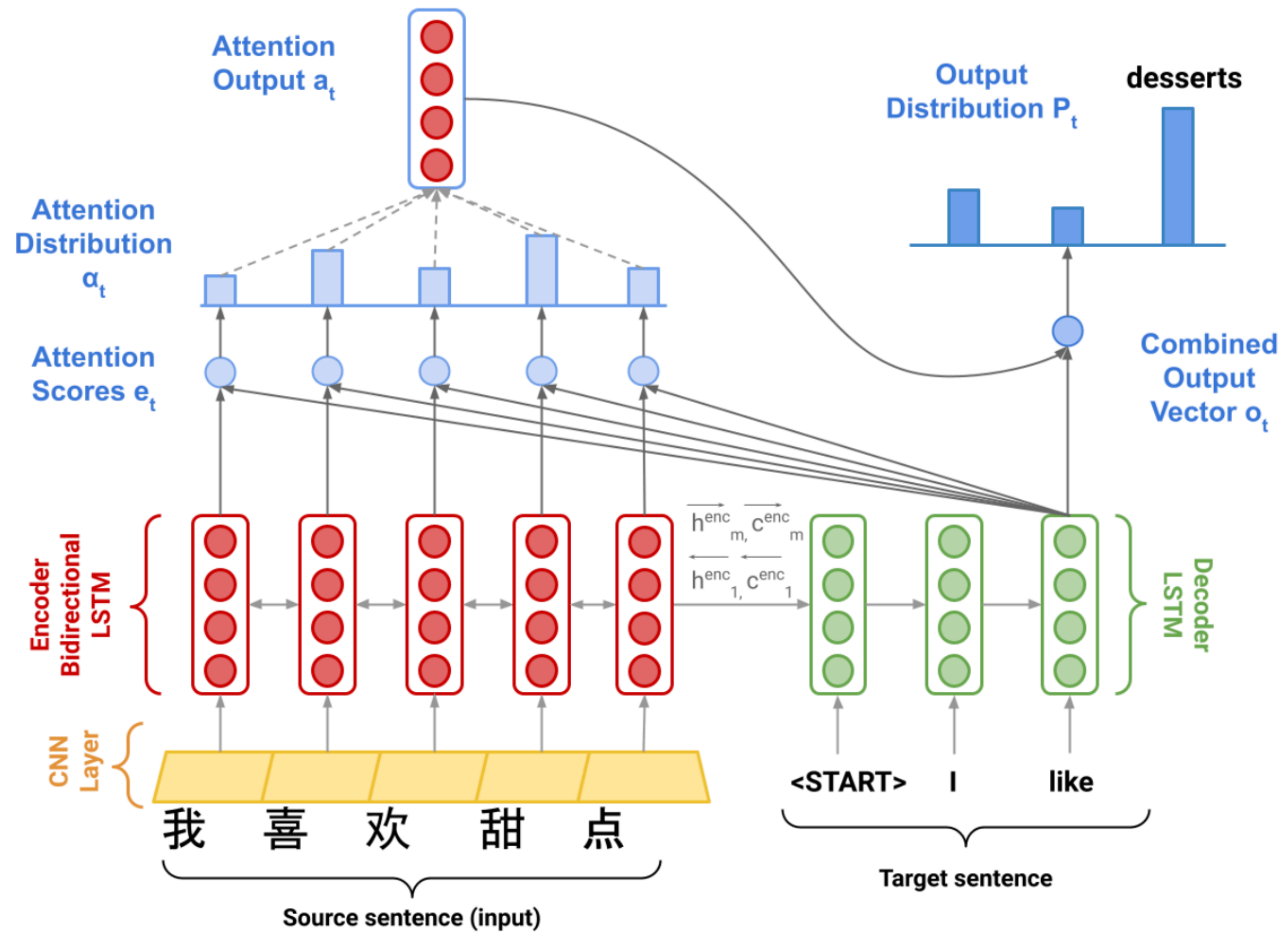
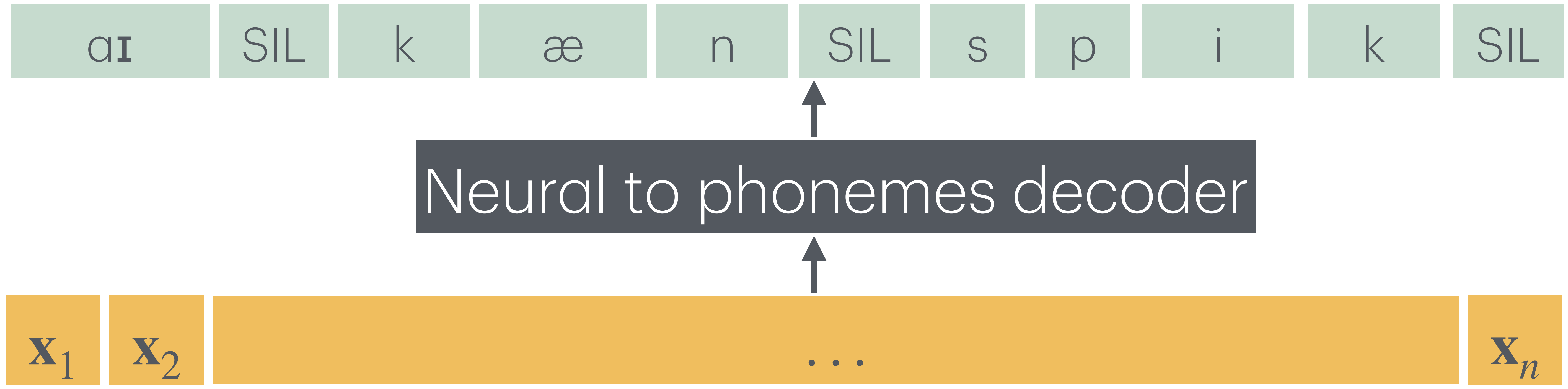


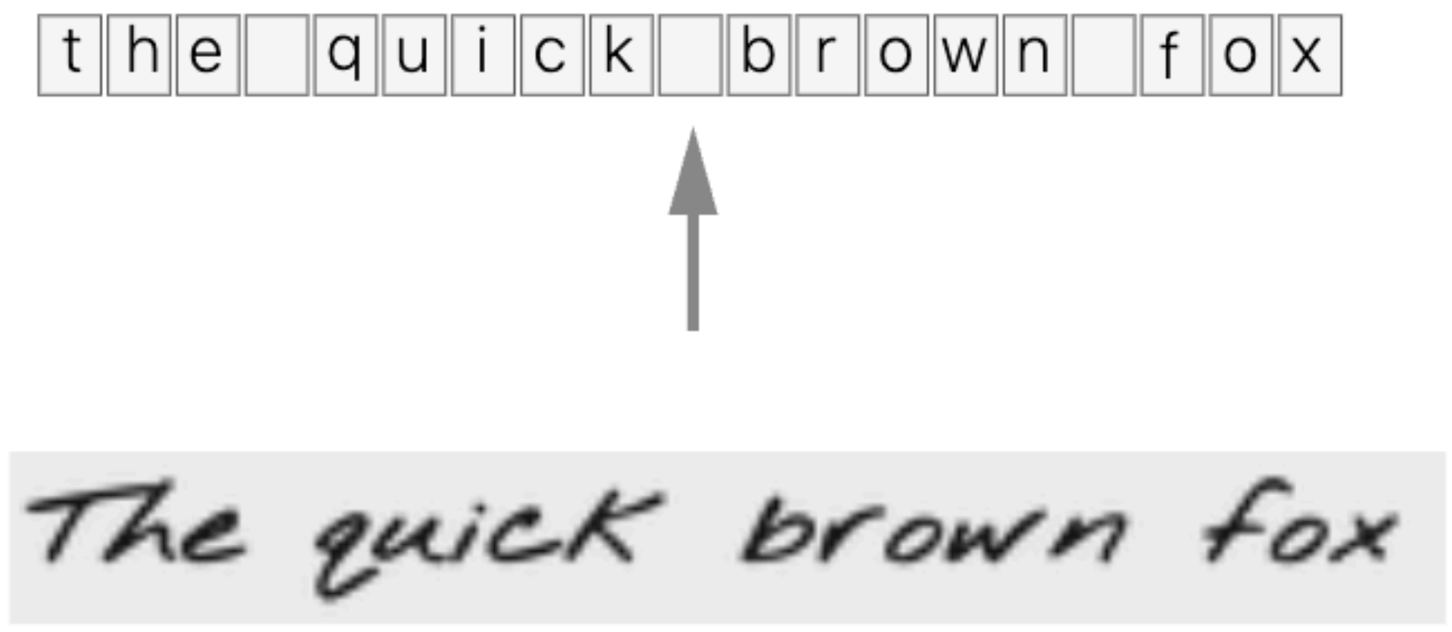
Neural to phonemes decoder

- A Seq2Seq problem
  - Encoder-decoder models allow arbitrary alignment between inputs and outputs.
  - Neural to phonemes decoding only needs monotonic alignment.

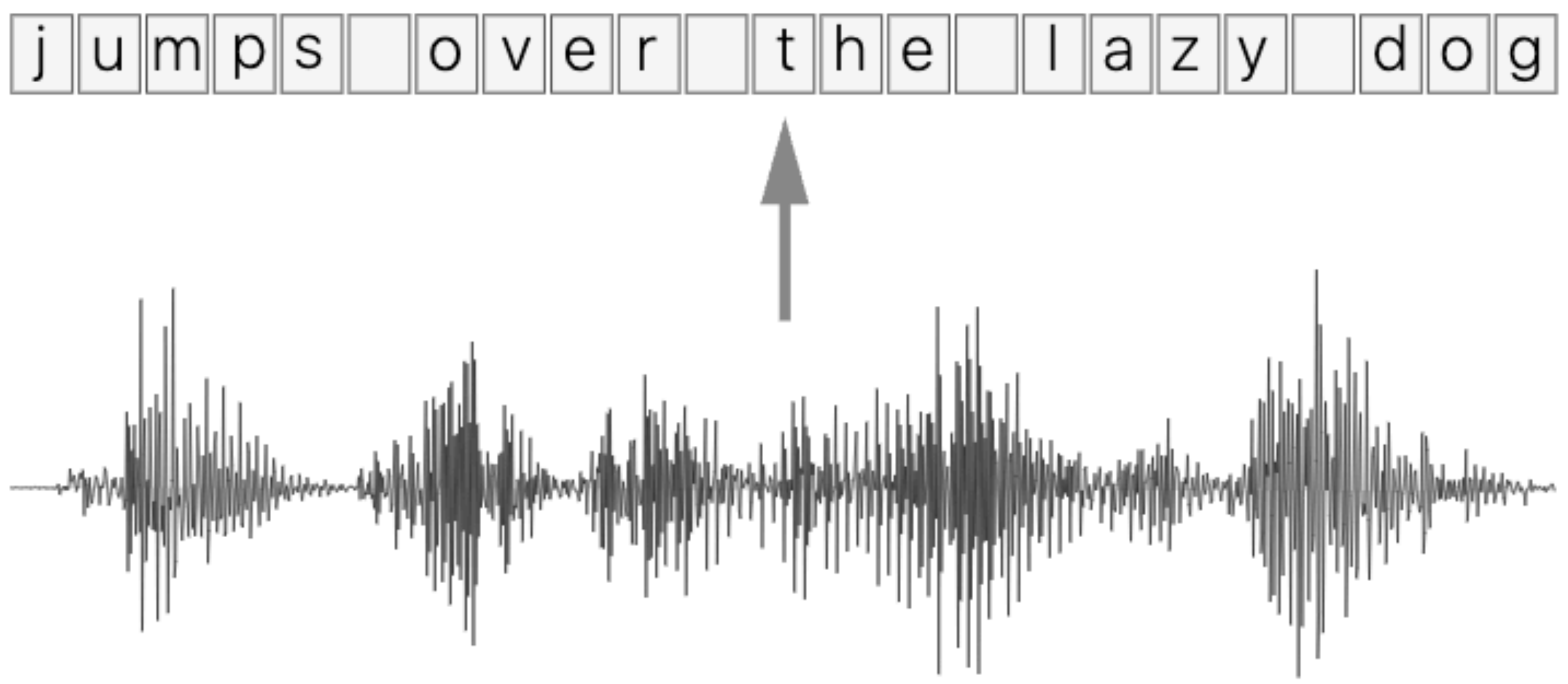




Sequence modeling with Connectionist Temporal Classification (CTC)



Handwriting recognition: The input can be (x, y) coordinates of a pen stroke or pixels in an image.



Speech recognition: The input can be a spectrogram or some other frequency based feature extractor.

A. Hannun 2017

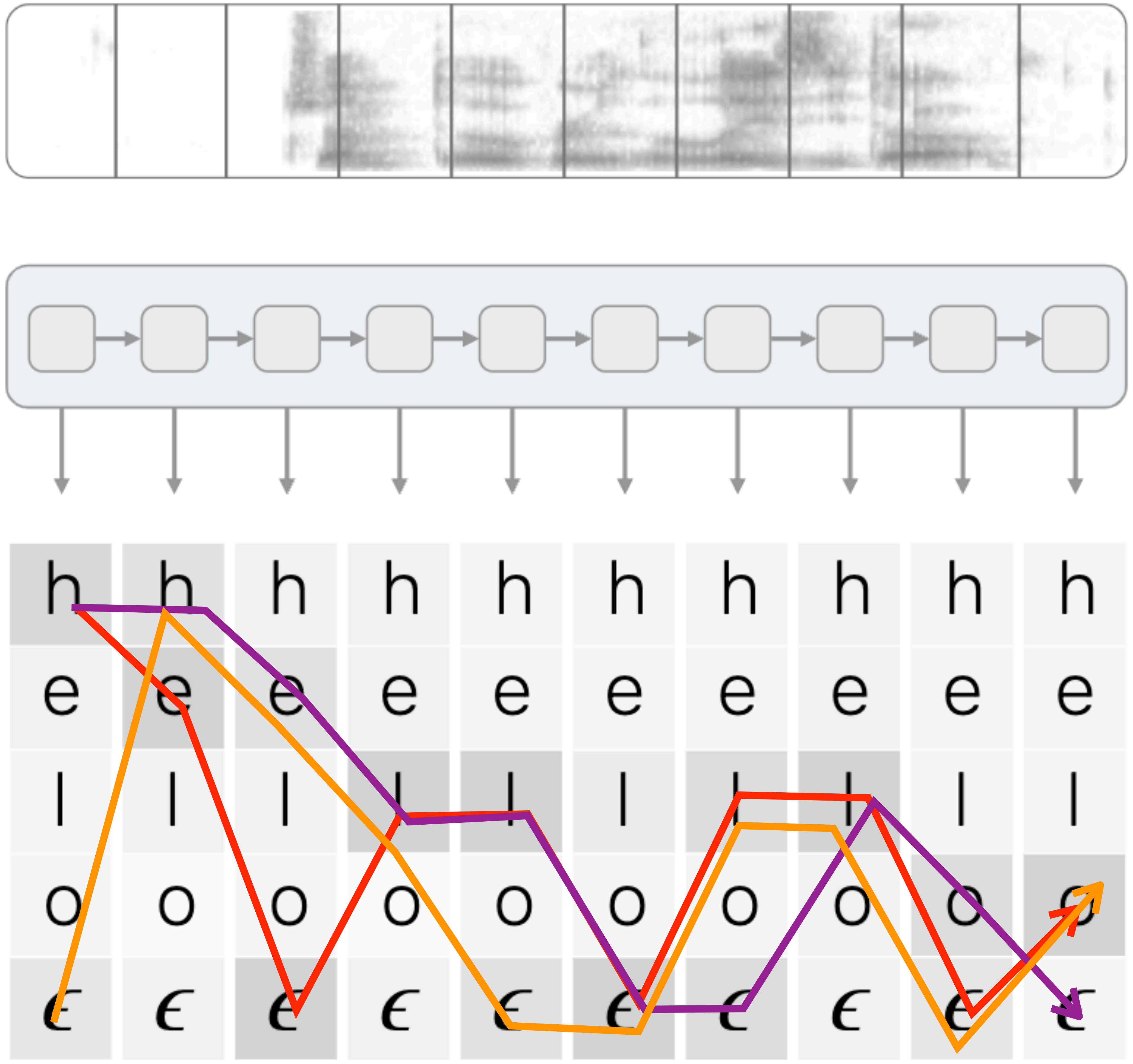
Sequence modeling with CTC

Inputs

CTC outputs post-processing

A. Hannun 2017

CTC training



ε h e l ε ε l l ε o

h e ε l l ε l l ε o

h h e l l ε ε l o o

...

h e l l o

$$p(Y \mid X) \quad = \quad \sum_{A \in \mathcal{A}_{X,Y}} \quad \prod_{t=1}^{T} p_t(a_t \mid X)$$

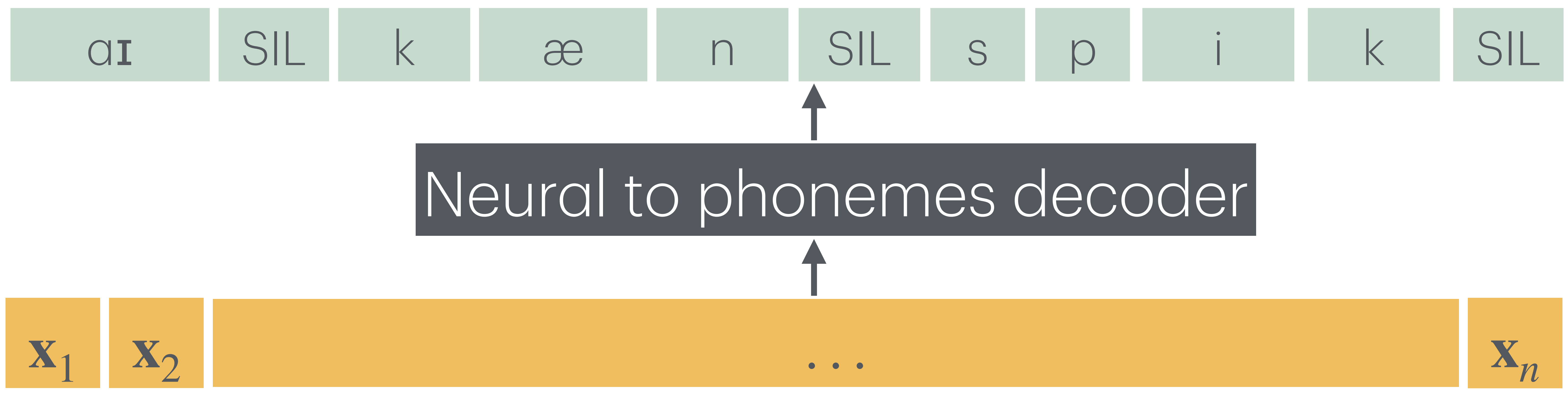
The CTC conditional **probability**

marginalizes over the set of valid alignments

computing the **probability** for a single alignment step-by-step.

A. Hannun 2017

What neural network to use?

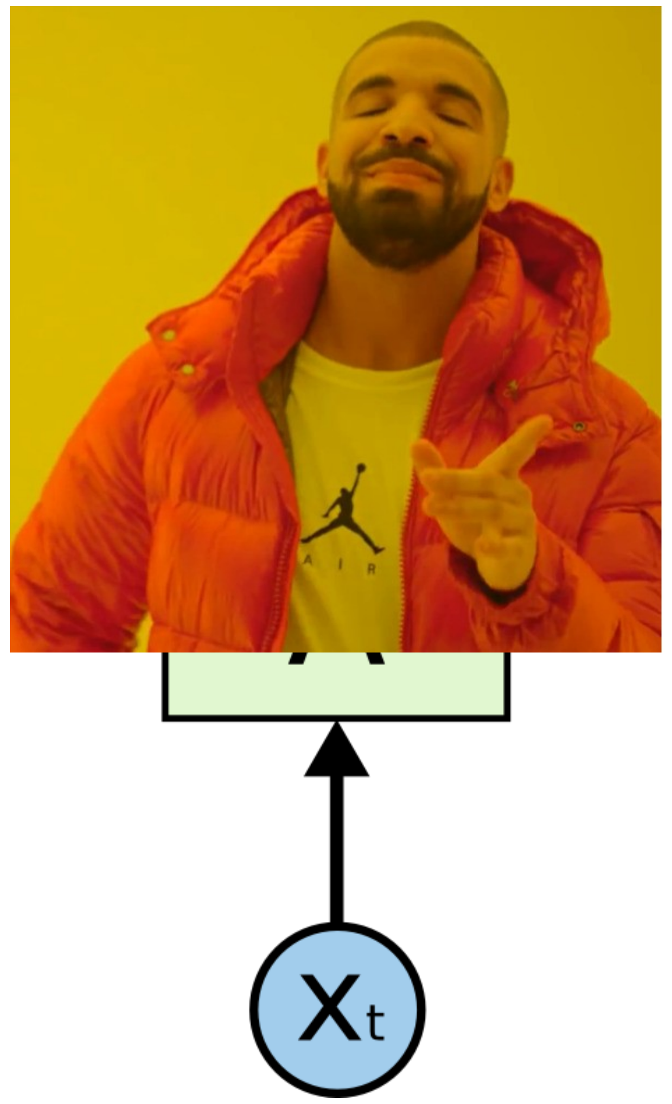


What neural network to use?

Transformer

- ✋ Large datasets
- ✋ Long-range dependency

RNN

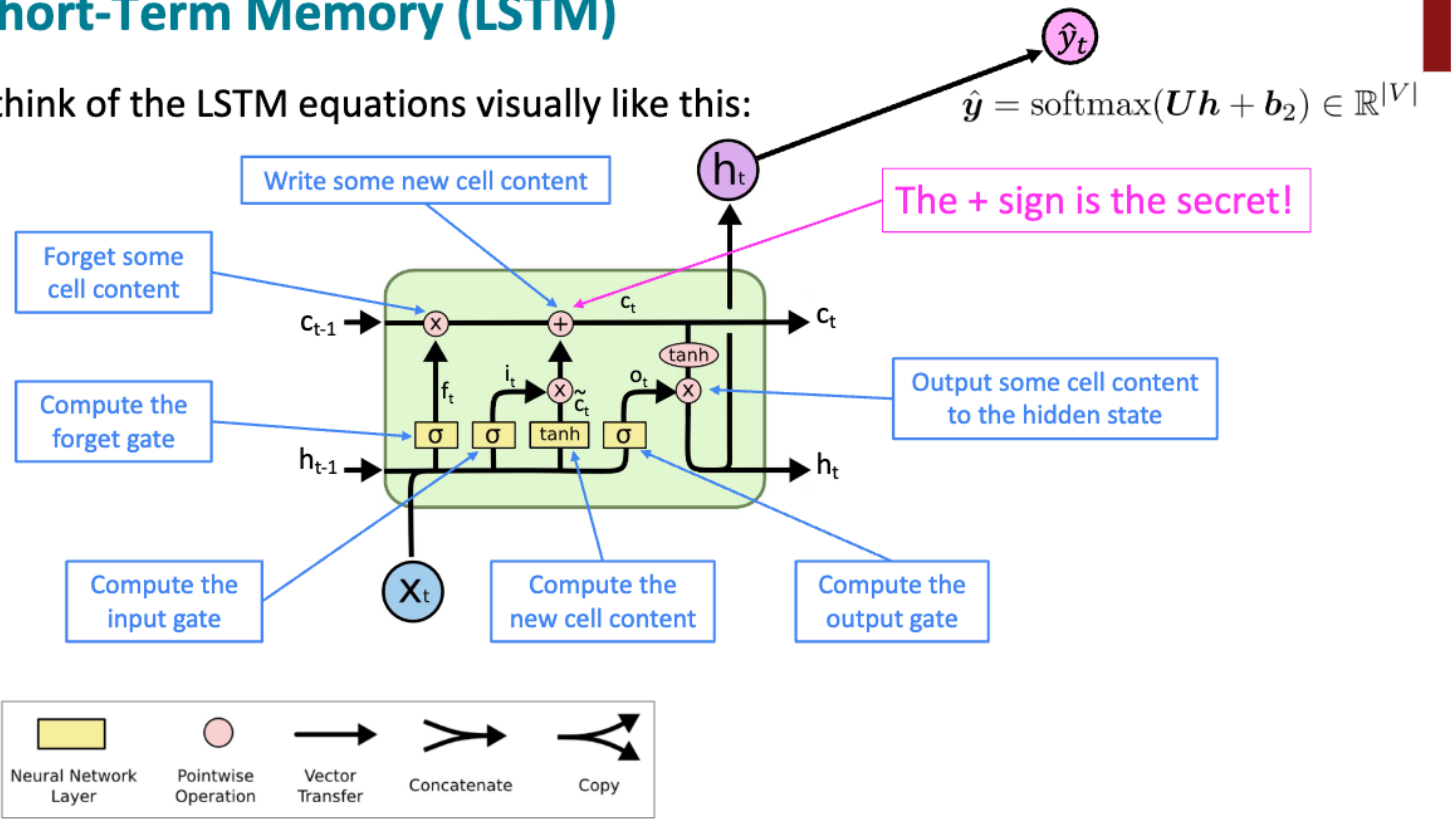


- 👉 Small datasets
- 👉 Short-range dependency
- 👉 Efficient real-time processing

LSTM

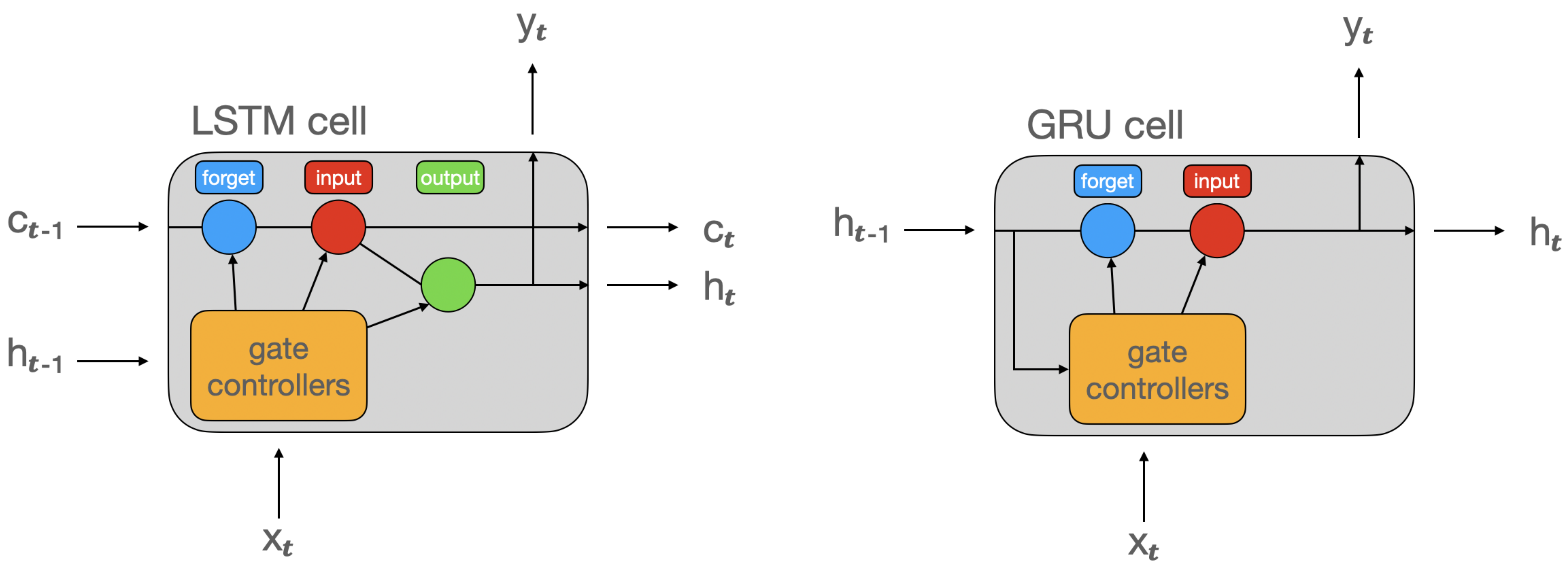
Long Short-Term Memory (LSTM)

You can think of the LSTM equations visually like this:



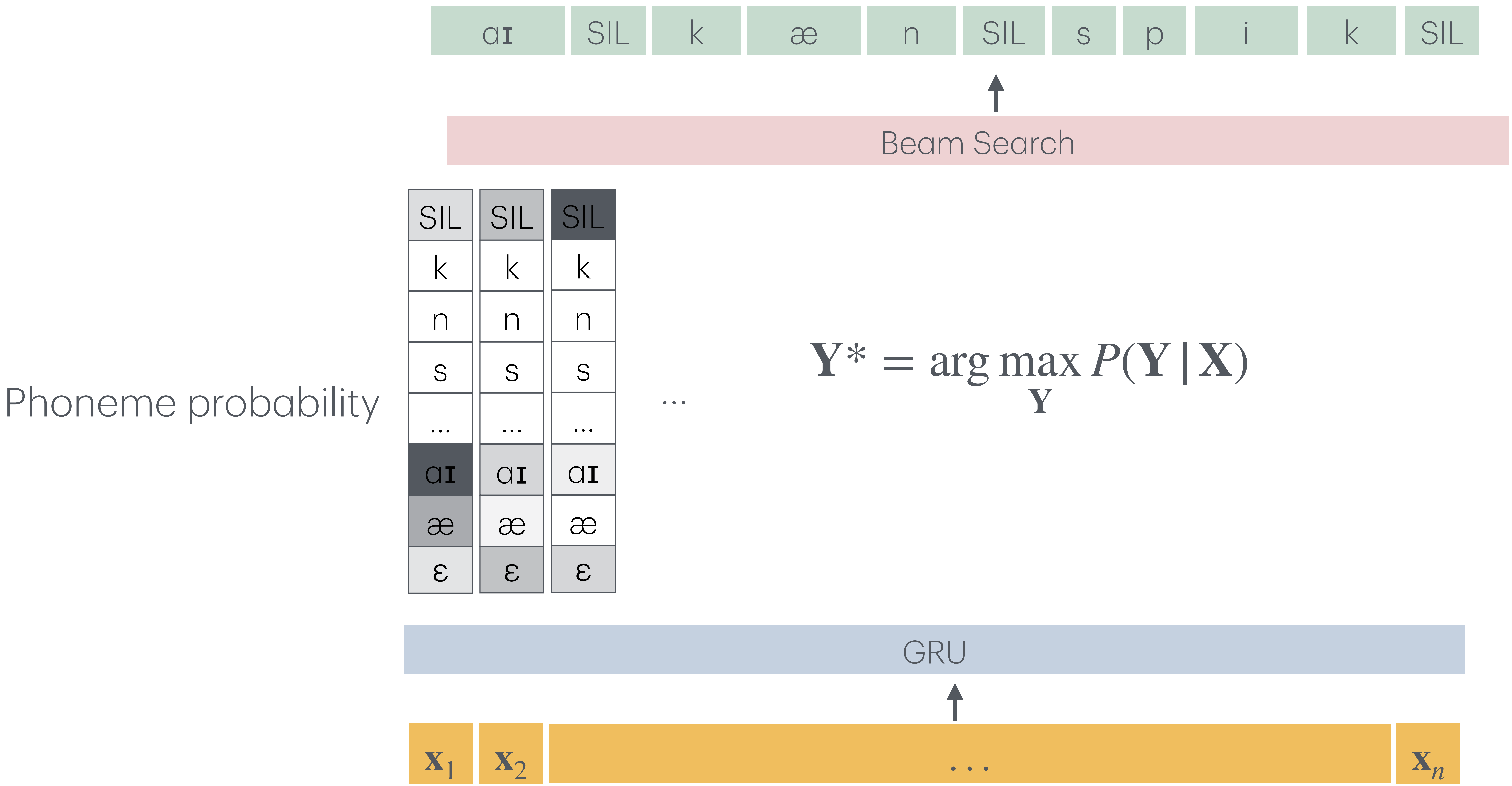
Source: http://colah.github.io/posts/2015-08-Understanding-LSTMs/

Gated Recurrent Units (GRU)



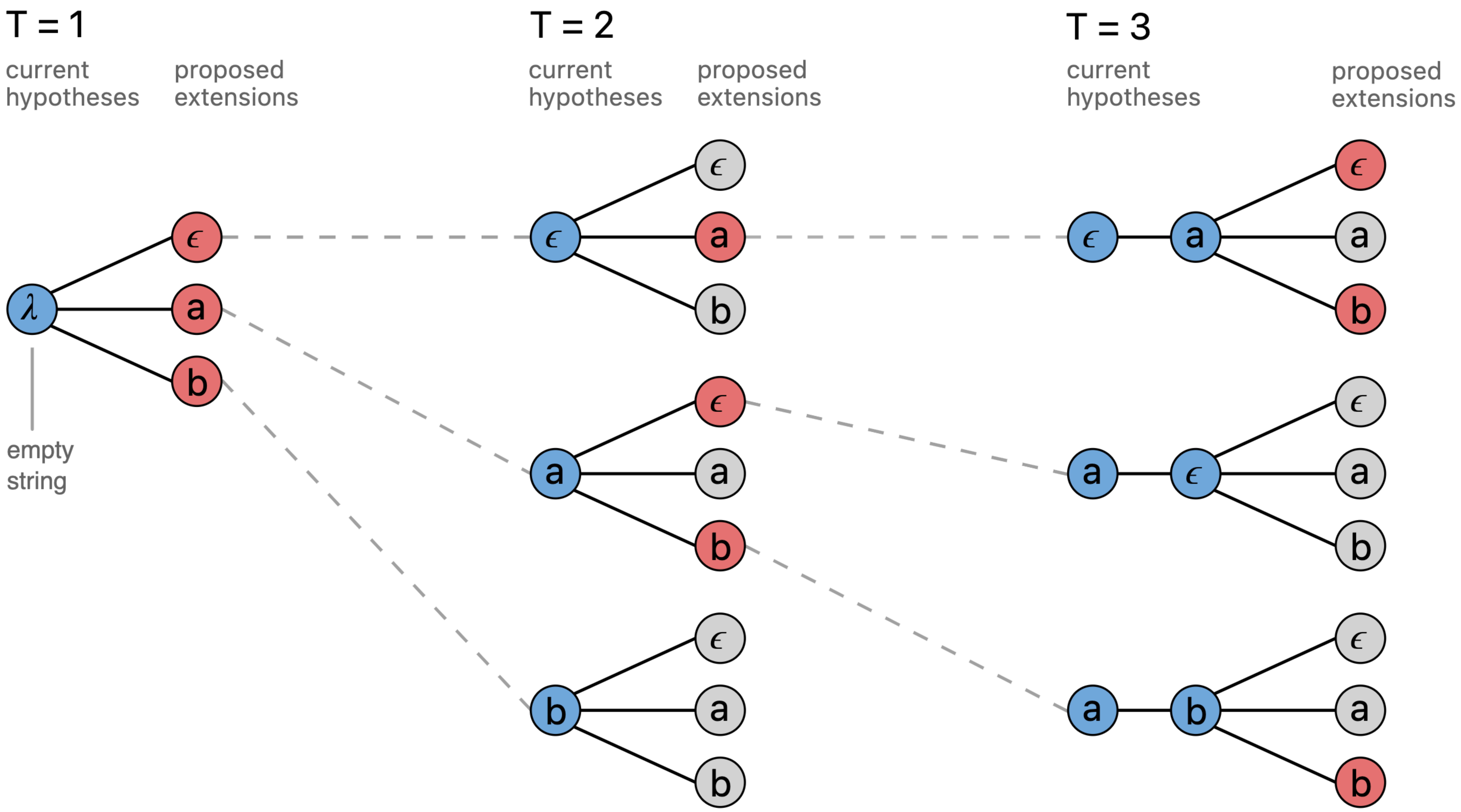
Source

CTC inference



$$\mathbf{Y}^* = \arg\max_{\mathbf{Y}} P(\mathbf{Y} \mid \mathbf{X})$$

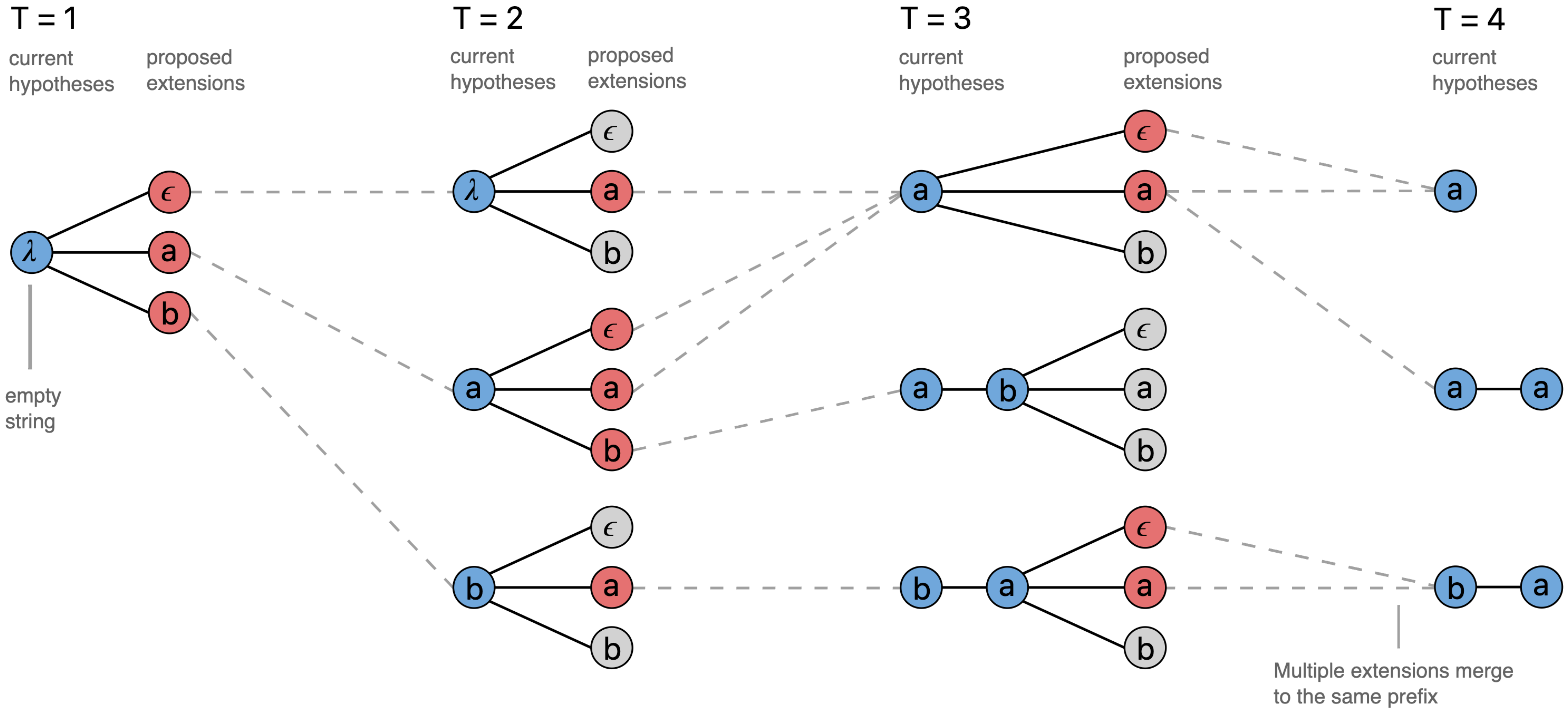
CTC beam search



A standard beam search algorithm with an alphabet of $\{\epsilon, a, b\}$ and a beam size of three.

A. Hannun 2017

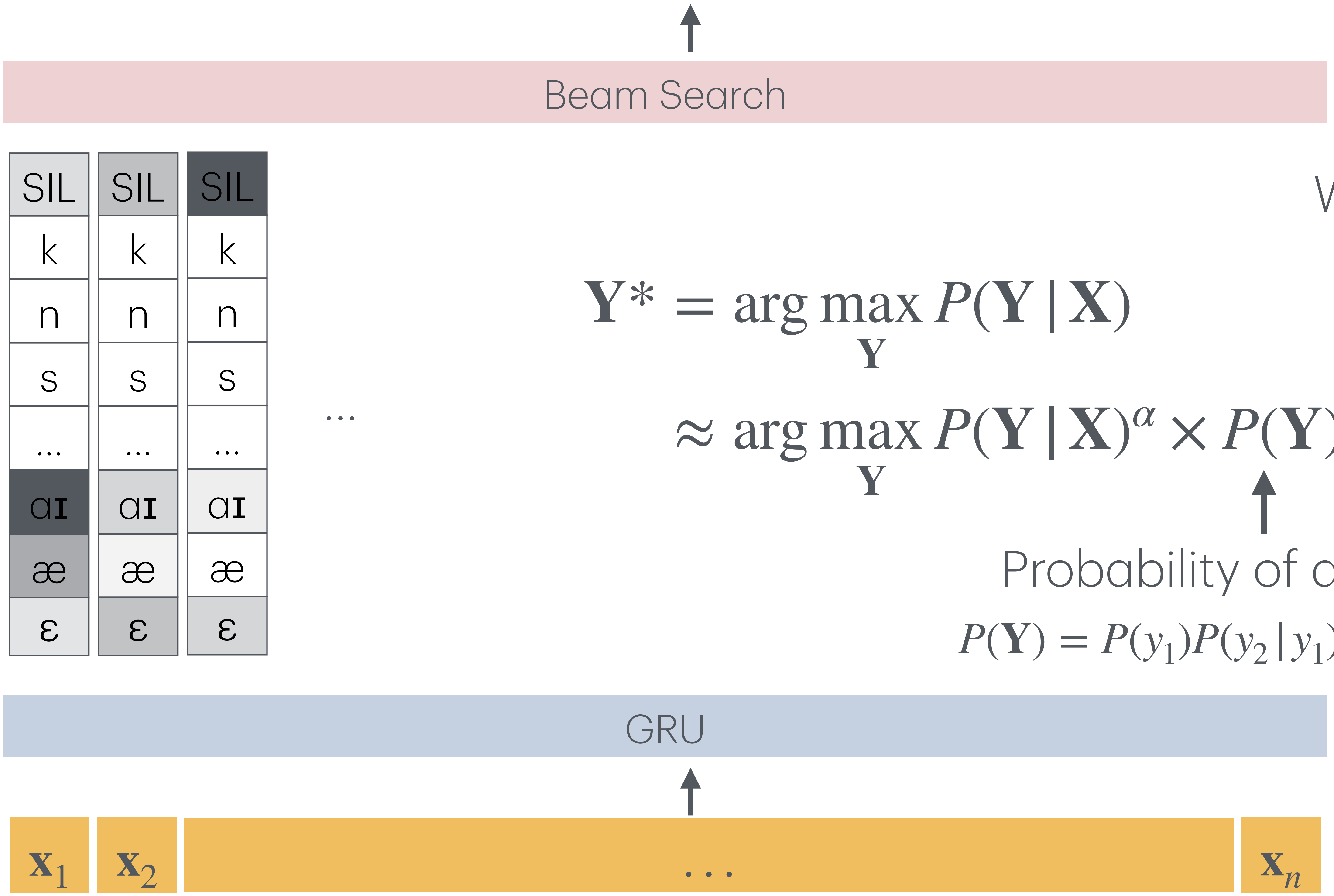
CTC beam search



The CTC beam search algorithm with an output alphabet $\{\epsilon, a, b\}$ and a beam size of three.

A. Hannun 2017

CTC inference with language models



Phoneme probability

$$\mathbf{Y}^* = \arg\max_{\mathbf{Y}} P(\mathbf{Y} \mid \mathbf{X})$$

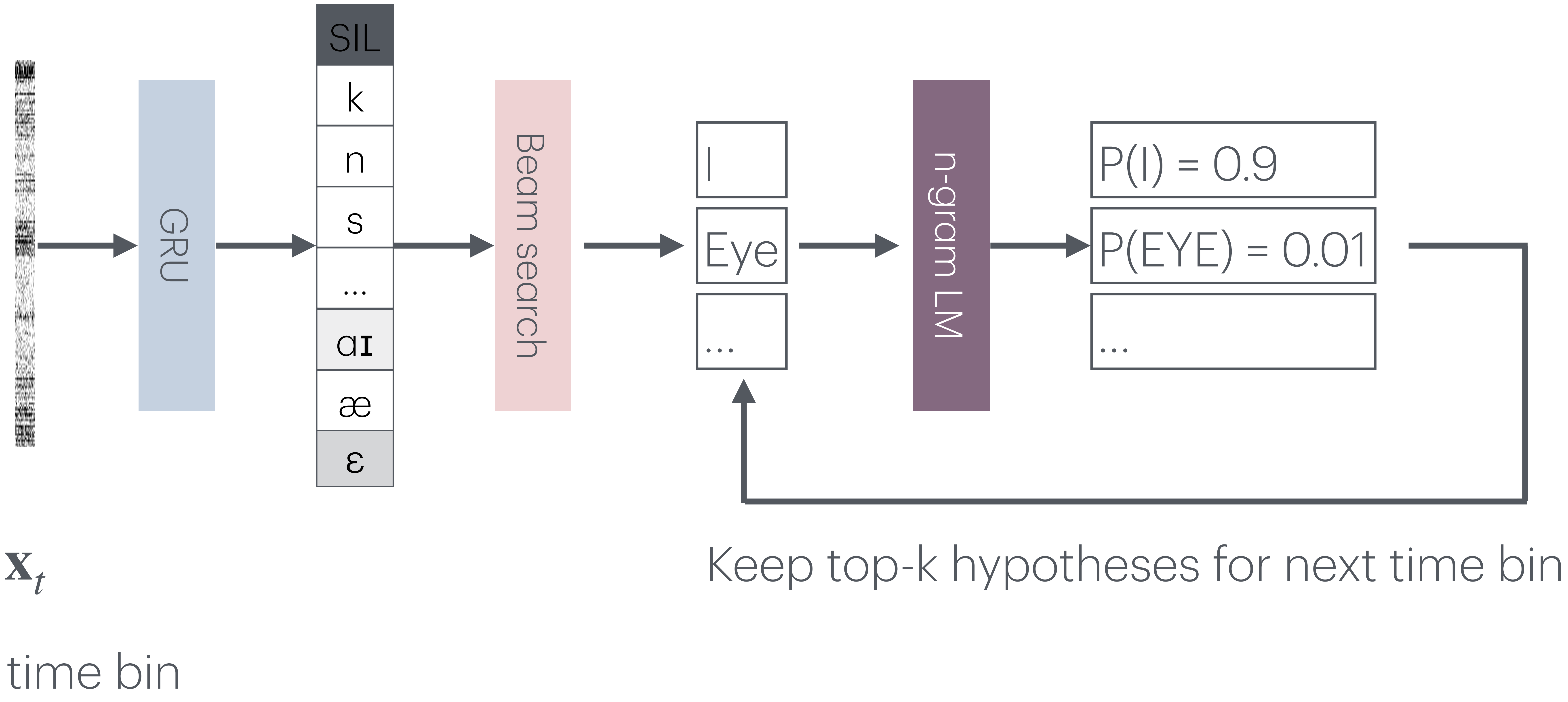
$$\approx \arg\max_{\mathbf{Y}} P(\mathbf{Y} \mid \mathbf{X})^{\alpha} \times P(\mathbf{Y}) \times L(\mathbf{Y})^{\gamma}$$

Word insertion bonus

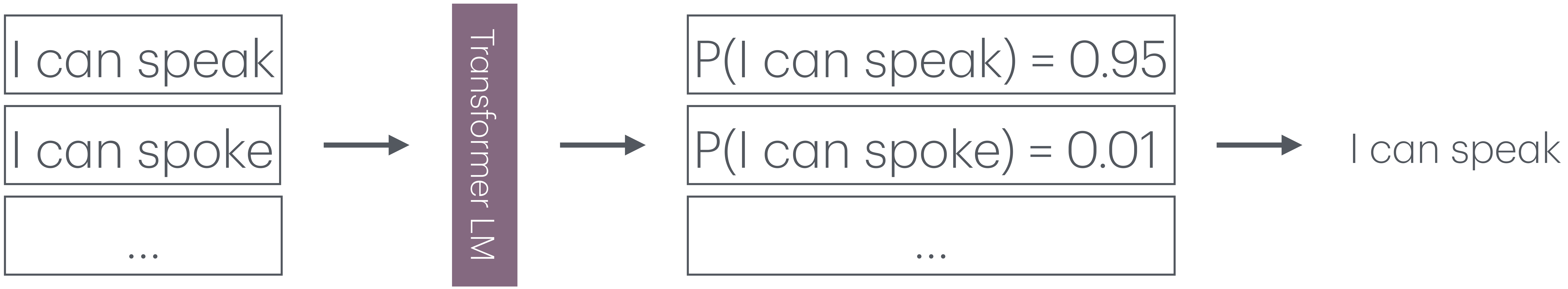
Probability of a sentence

$$P(\mathbf{Y}) = P(y_1)P(y_2 \mid y_1)P(y_3 \mid y_2, y_1)\ldots$$

Integrating language models in real-time decoding

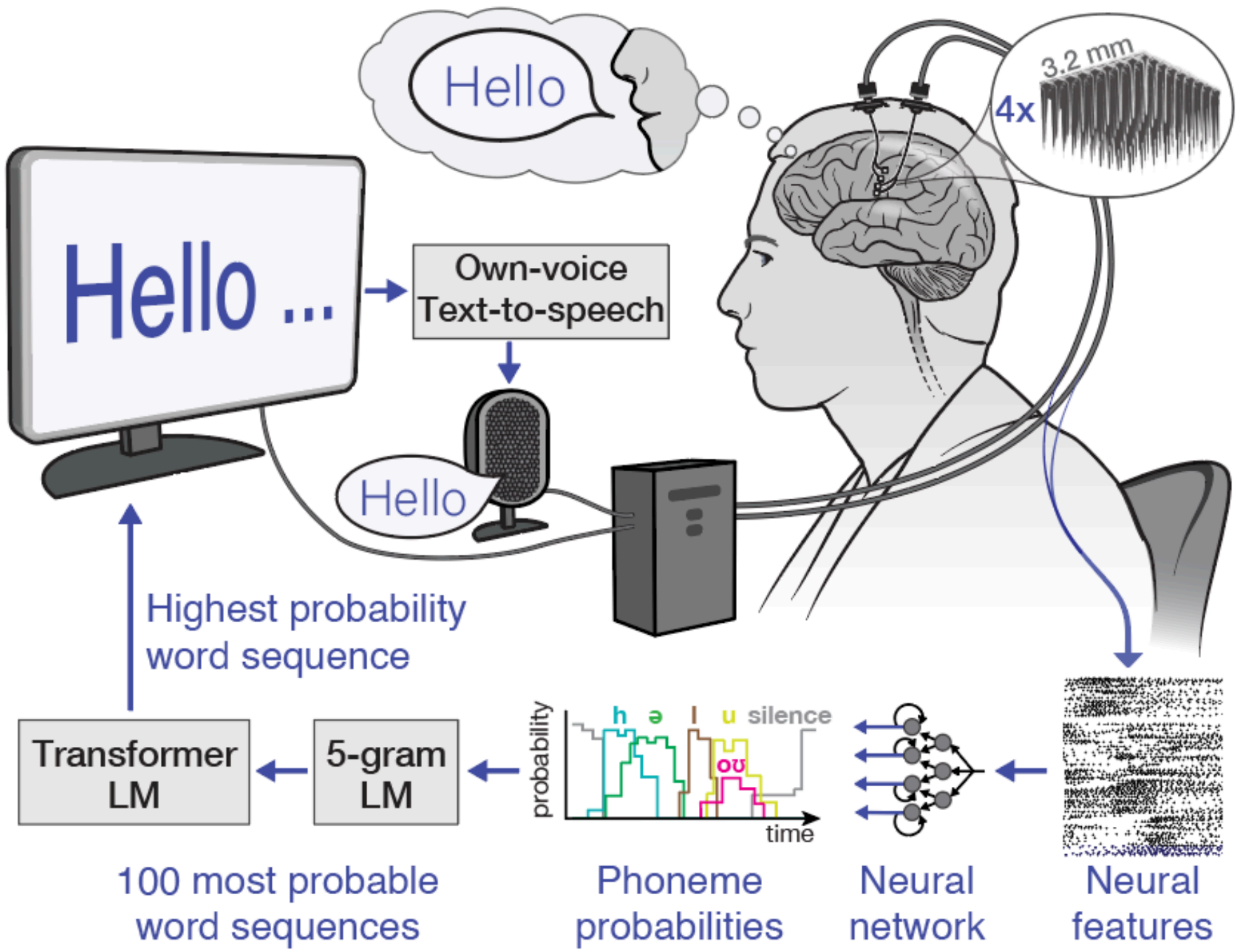


Transformer LM for 2nd pass rescoring



n-best hypotheses

Putting everything together



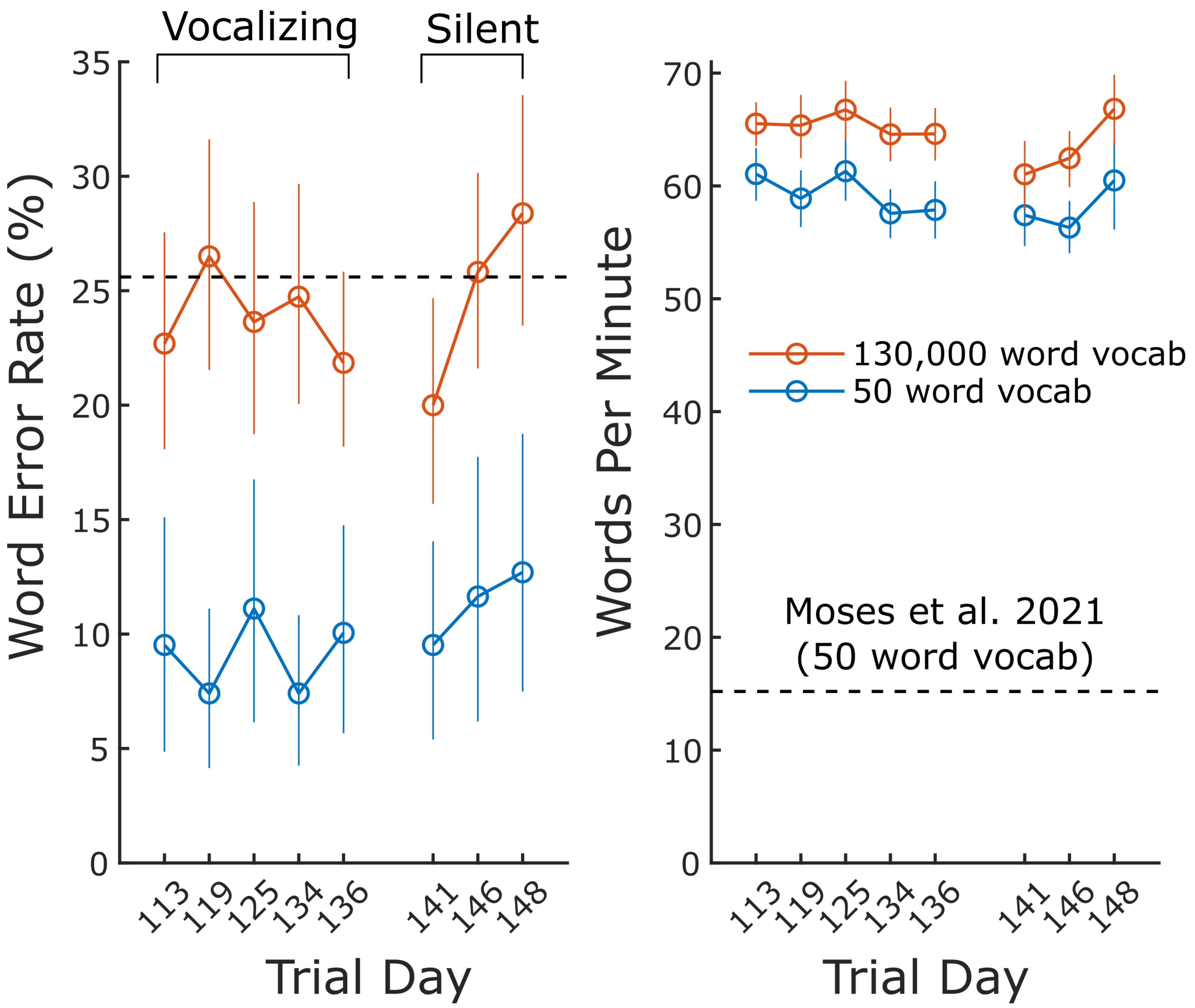
N. Card et al. 2023

Evaluation

Word error rate: normalized edit distance between predicted words and ground truth words.

$$WER(\mathbf{Y}, \hat{\mathbf{Y}}) = \frac{distance(\mathbf{Y}, \hat{\mathbf{Y}})}{length(\mathbf{Y})}$$

Brain-to-Text Benchmark '24



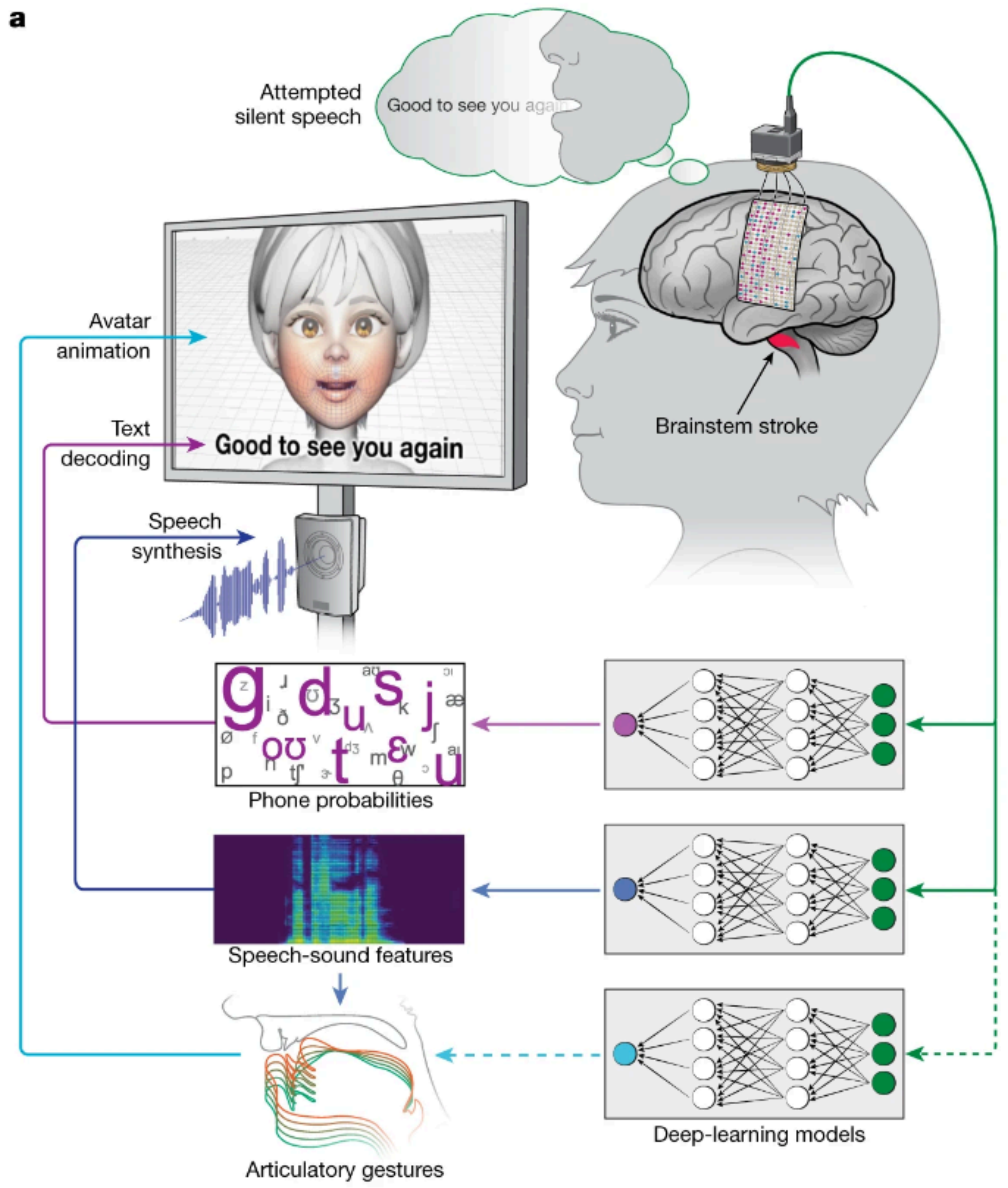
What T12 said

“So many years of not being able to communicate and then suddenly the people in the room got what I said. I don’t remember what I exactly said after the prescribed script finished, but it had to be along the lines of ‘Holy shit, it worked, I’m so happy, and you guys did it.’”

Stanford magazine

Future of Speech BCIs

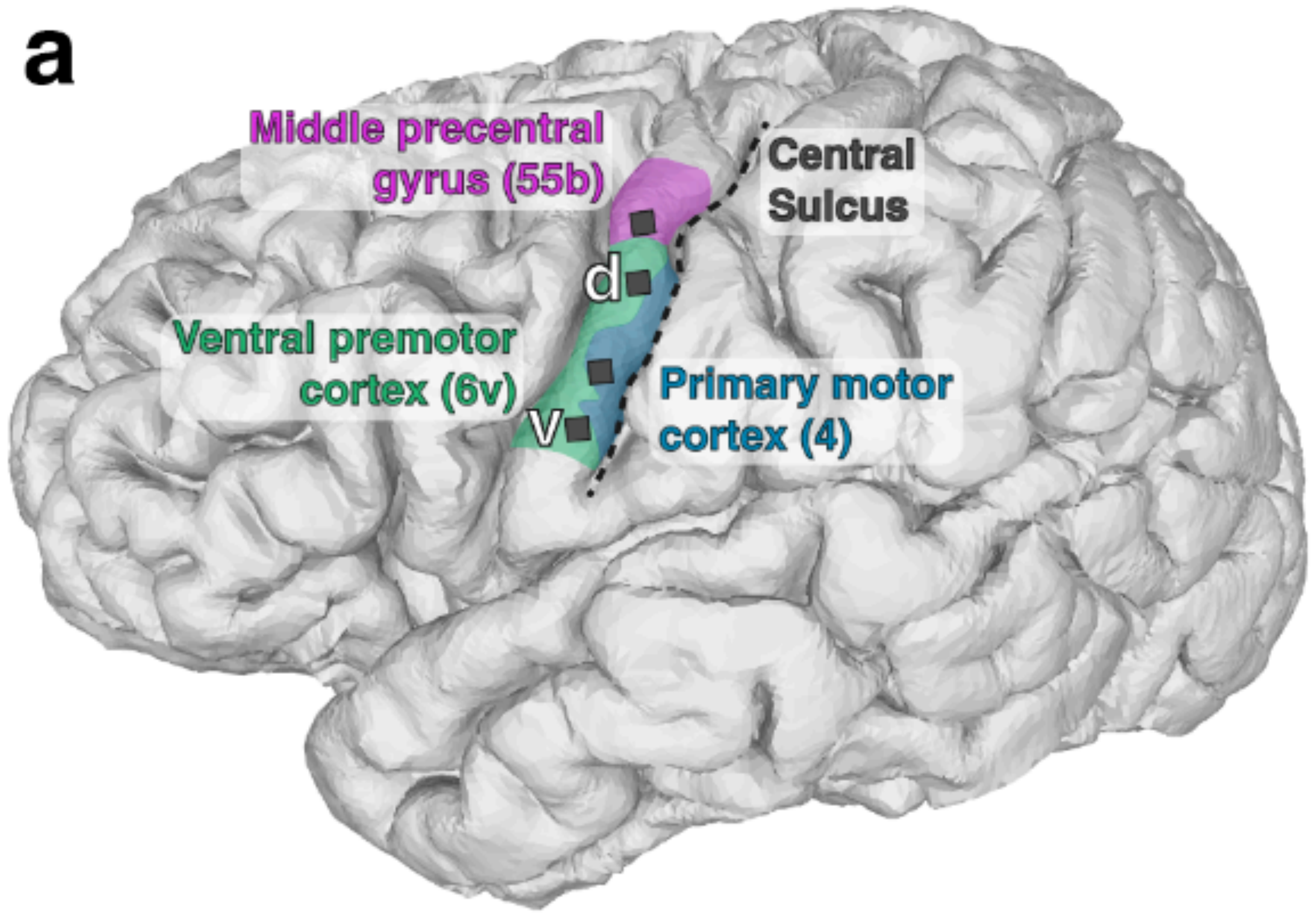
Multimodal Speech BCI

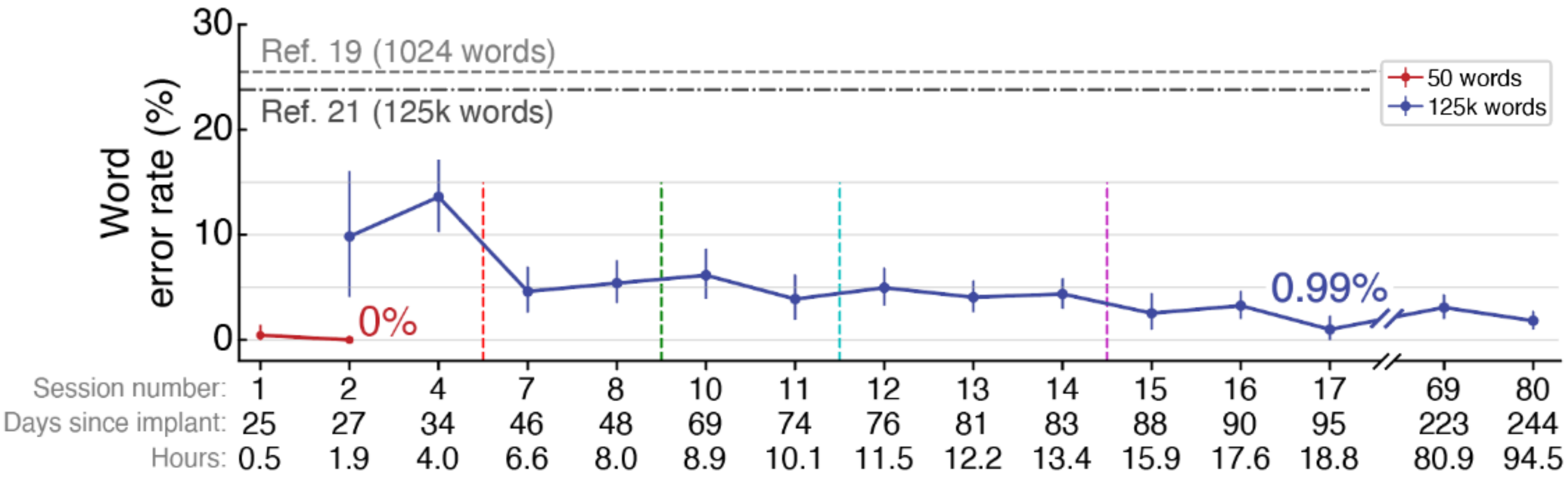


Metzger et al. 2023


D:\bravo3_chang
D:\bravo3_chang\20230411-113726\20230411-113726
File description
Remote Recording Control
Setup
Disable File Splitting
Stop
Spike Count
0
Packet Count
88459334
File Size (MB)
1883.0
Section
1
Available (MB)
7177665
Current Time
12:49:06

An accurate speech BCI for personal use

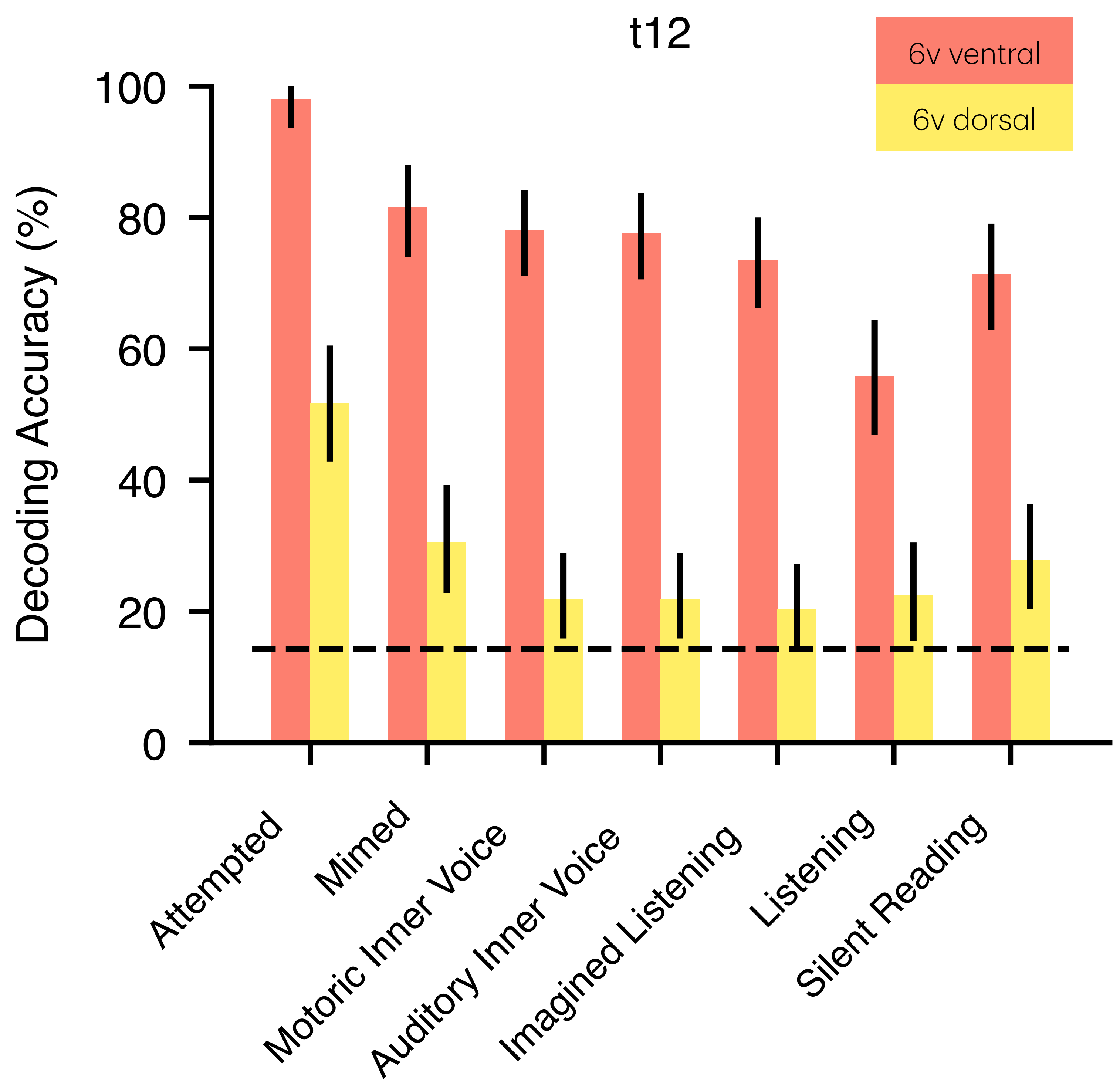




Card et al. 2024


100% CORRECT
MOSTLY CORRECT
INCORRECT
DONE
Activate spelling mode

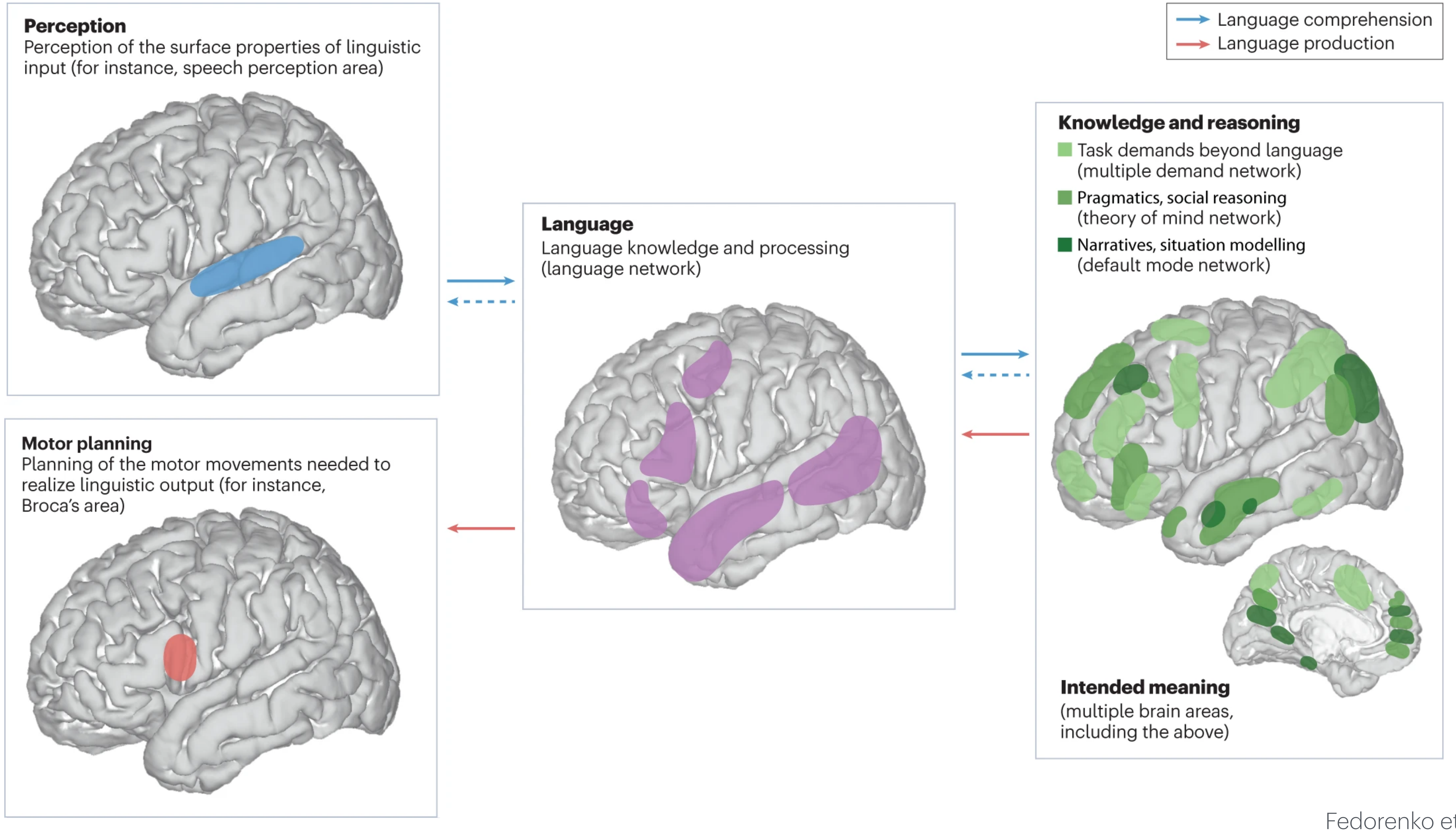
Restoring effortless and natural communication by decoding inner speech



Cope & Kalantzis / Transpositional Grammar • meaningpatterns.net/inner-speech

Erin, unpublished

Language processing in the brain



Fedorenko et al. 2024

BCIs raise new neuroethics considerations

- Should BCIs be allowed to read inner thoughts and memories?
  - Read out inner speech that would not naturally be enacted?
  - Read out memories that may otherwise be lost to Alzheimer's disease?
  - Read out subconscious fears to assist desensitization psychotherapy?

BCIs raise new neuroethics considerations

- Should BCIs be allowed to enhance cognitive function beyond natural levels?
  - Move a robotic arm faster and more accurately than a native arm?
  - Purchase a memory to skip a grade of mathematics in high school?
- We are currently grappling with the same questions:
  - Steroids, stimulants, elective plastic surgery …

BCIs raise new neuroethics considerations

Although some of these ideas and questions may appear farfetched at present, as brain function and dysfunction continues to be revealed, BCI systems could build on these discoveries and create even more daunting ethical quandaries. But equally important is the immediate need to help people suffering from profound neurological disease and injury through restorative BMIs. In order to achieve the right balance it is imperative that we as physicians, scientists and engineers proceed in close conversation and partnership with ethicists, government oversight agencies, and patient advocacy groups.

Summary

- Recent advancements in AI and NLP, combined with years of neuroscience and neuroengineering research, show potential for restoring natural communication to people with speech impairments.
- We will soon have systems to assist people with communication disorders and paralysis.
- And understand better how the brain processes language!
- This brings hope to people like Howard and T12!


NEW HOPE FOR ALS PATIENTS
TODAY

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hhmi
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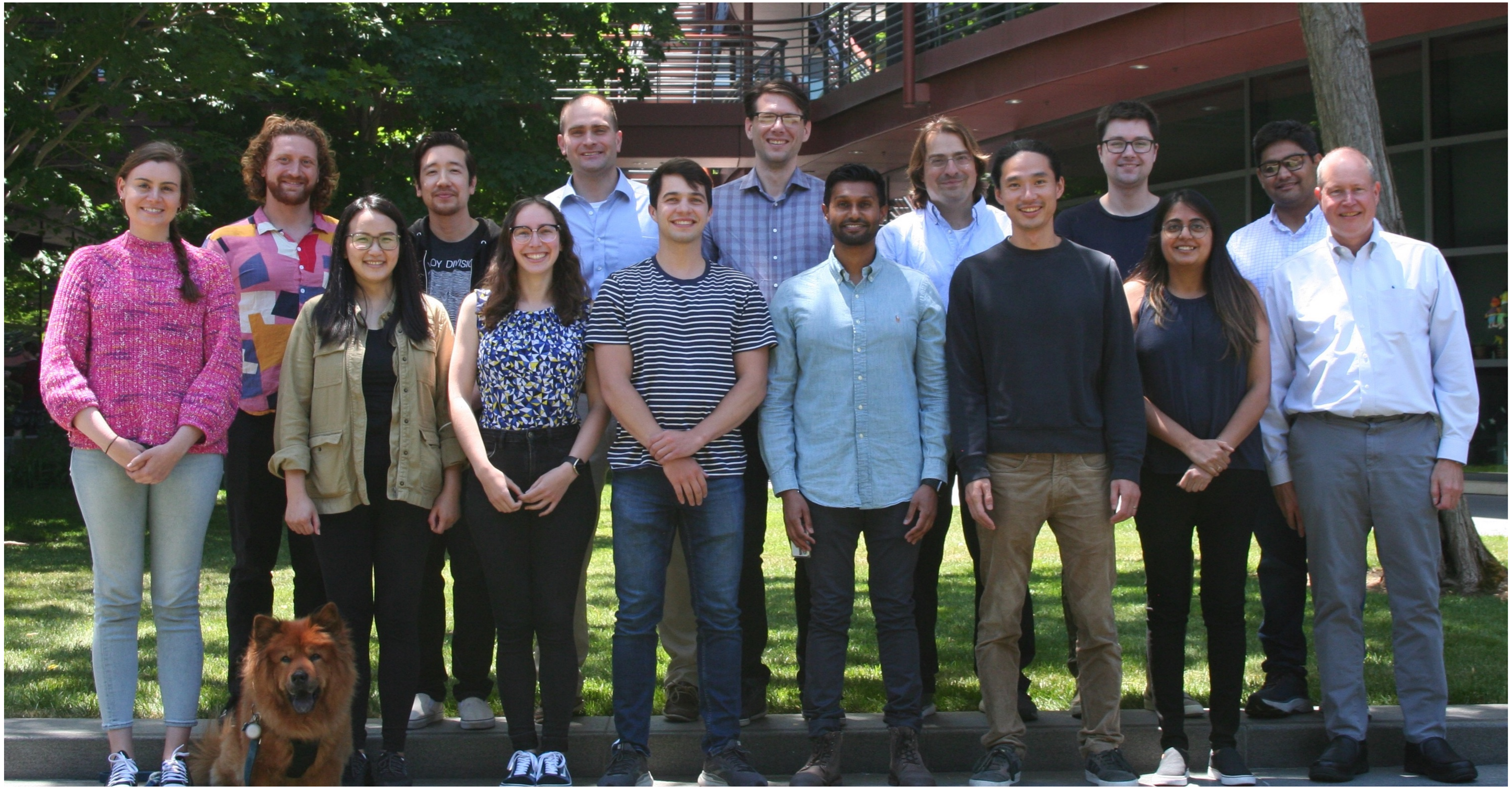
Medical Institute

Participants
T5, T6 and T12



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