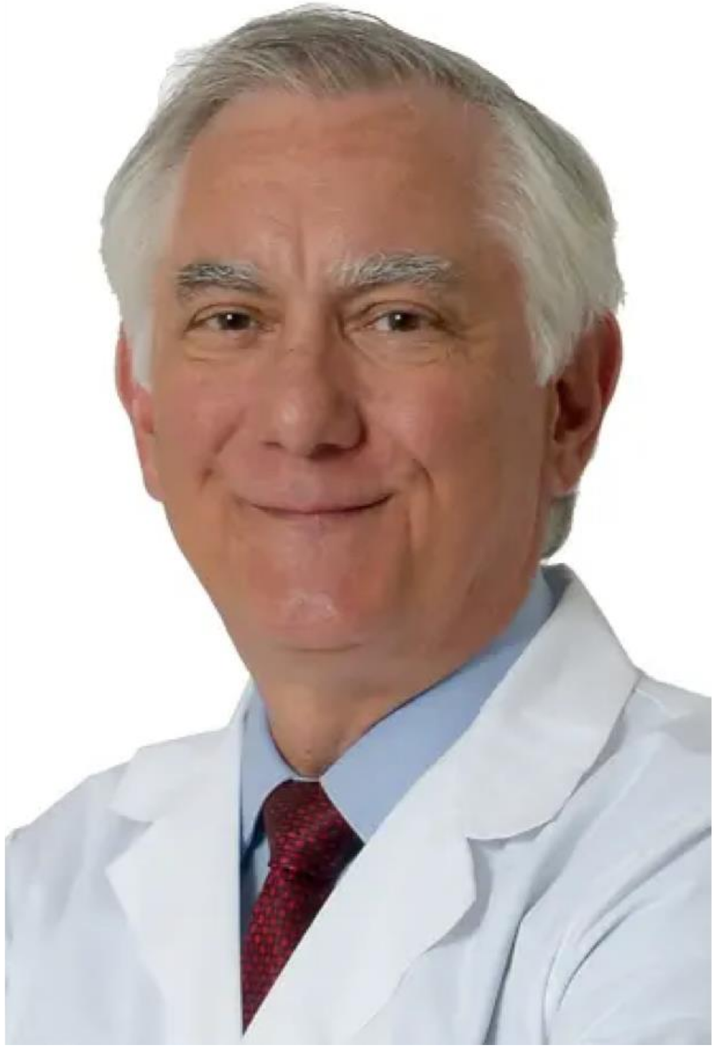
Functional Microdissection of Speech Cortex

University of California
San Francisco

Edward Chang, MD
Joan and Sanford I. Weill Chair
Jeanne Robertson Distinguished Professor
Neurological Surgery

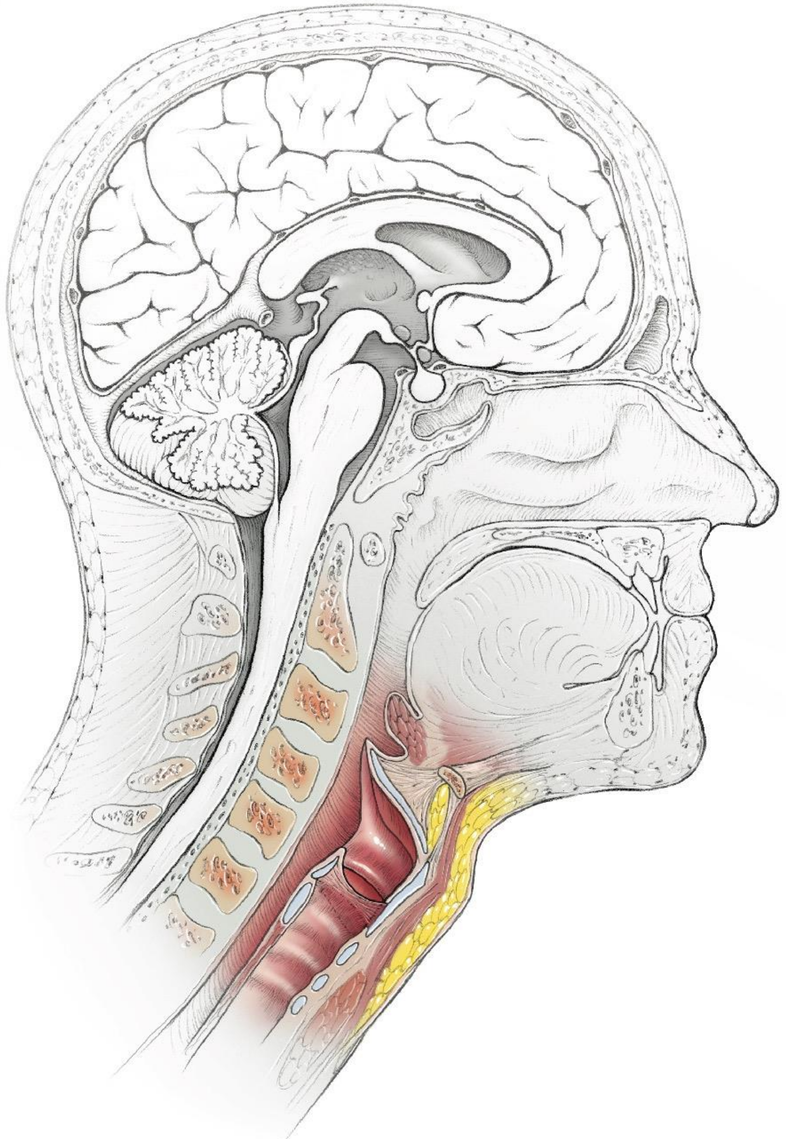
Nick Barbaro

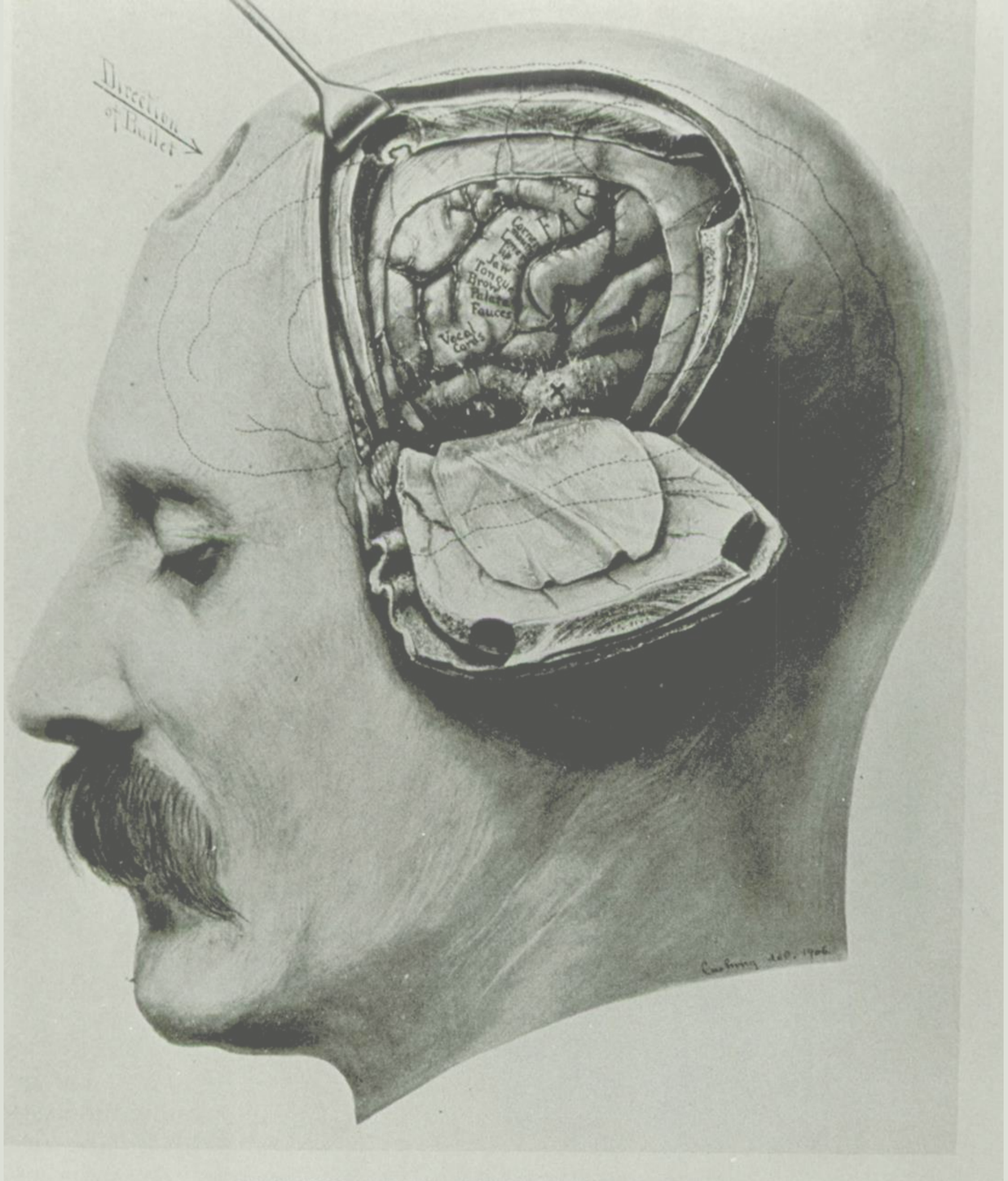


UCSF

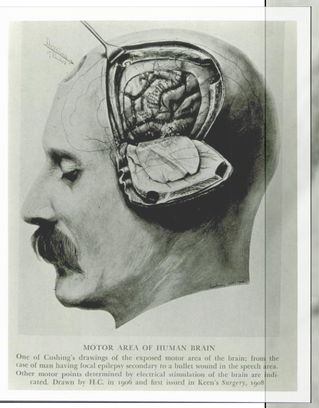
University of California
San Francisco

Speaking is a hallmark of our species





Harvey Cushing 1906

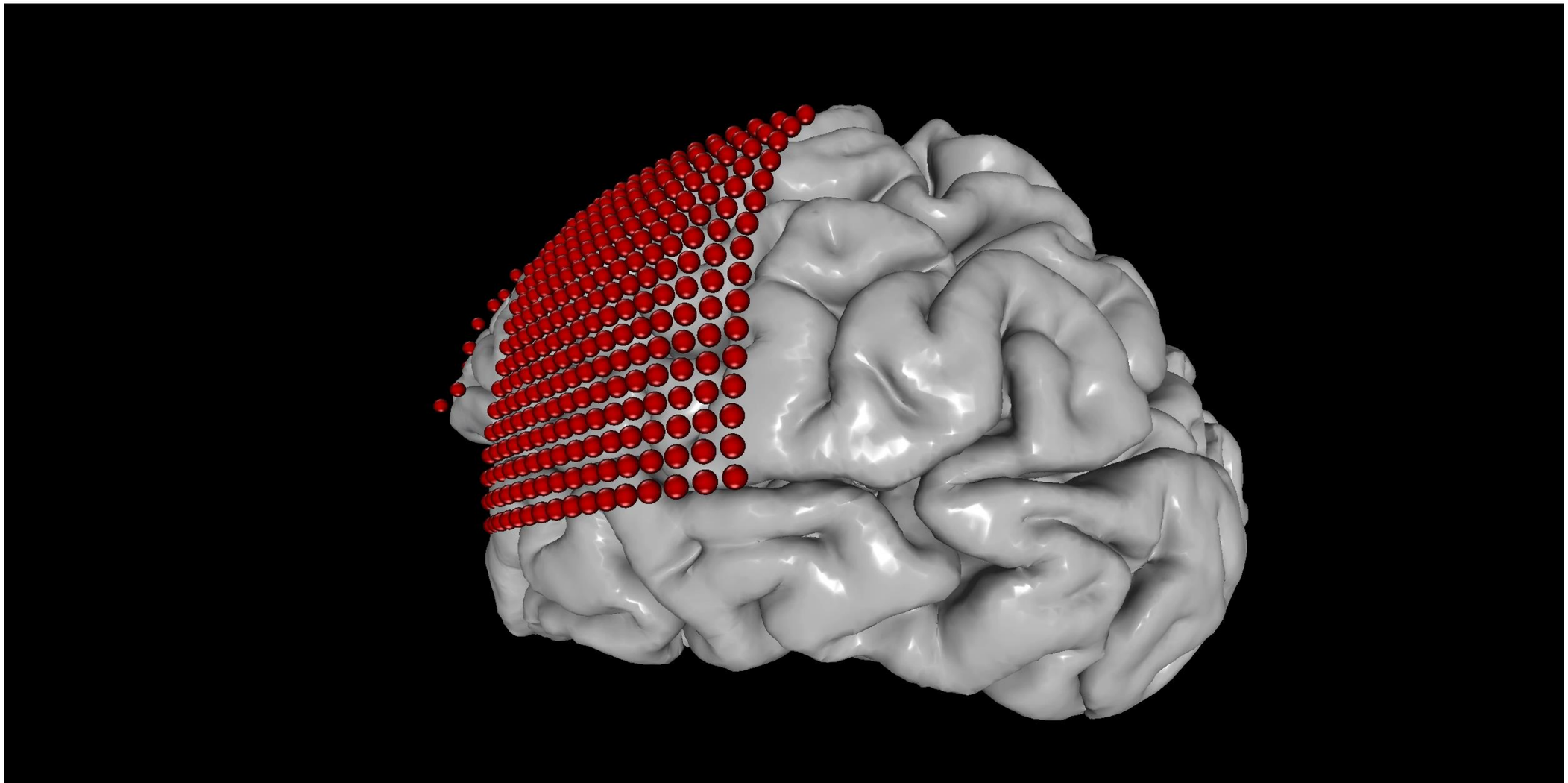


MOTOR AREA OF HUMAN BRAIN

One of Cushing's drawings of the exposed motor area of the brain; from the case of man having focal epilepsy secondary to a bullet wound in the speech area. Other motor points determined by electrical stimulation of the brain are indicated. Drawn by H.C. in 1906 and first issued in Keen's *Surgery*, 1908.

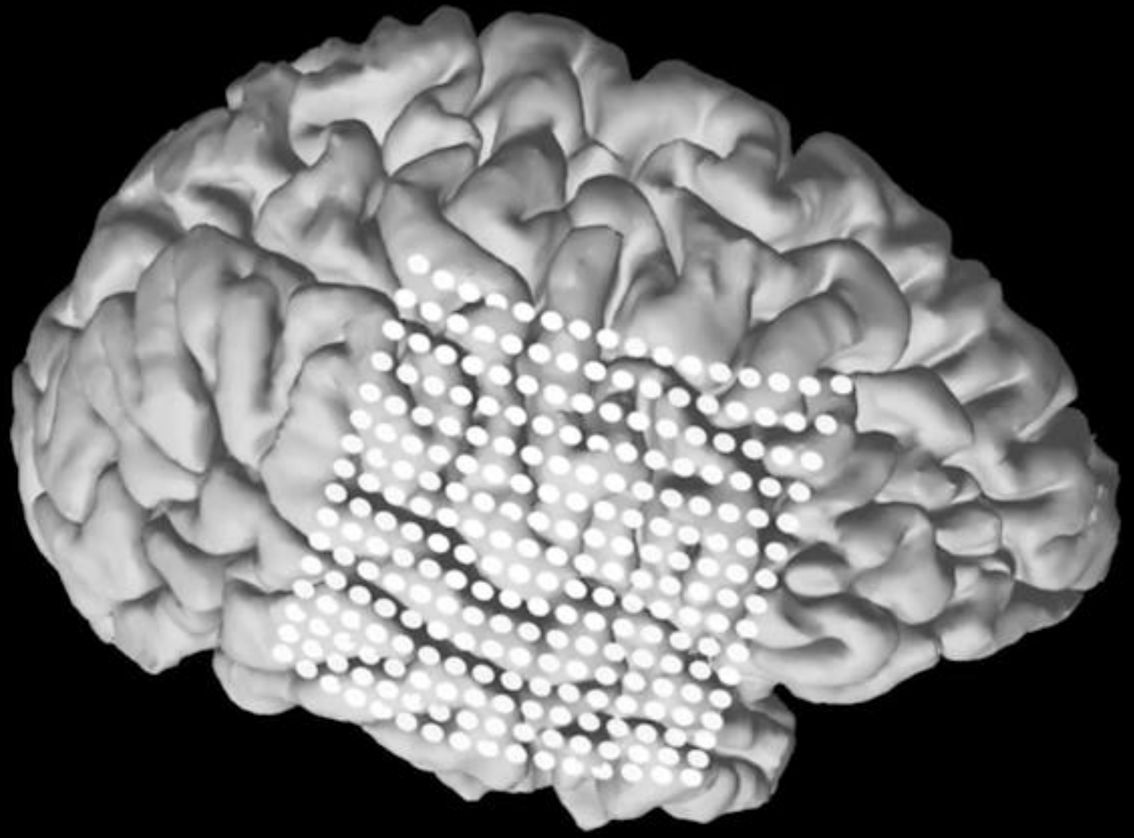
Electrocorticography (ECoG)

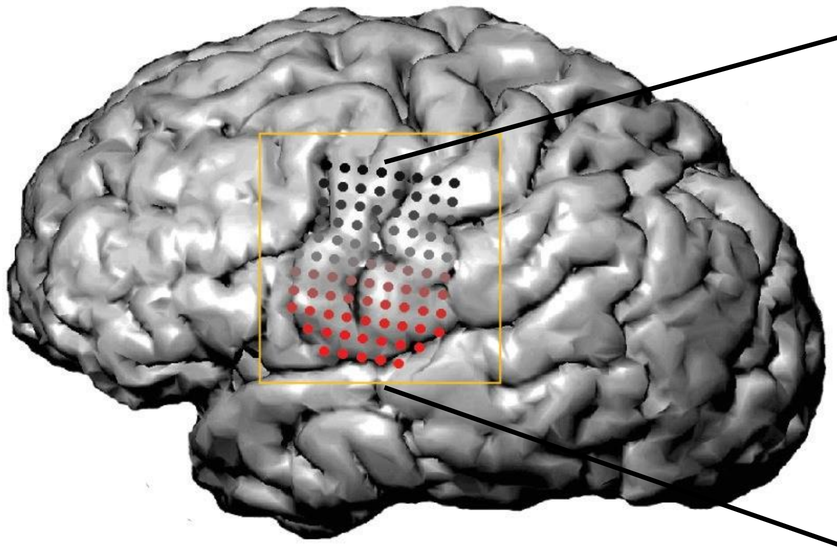
Implanted subdural electrode arrays for localization of epileptogenic foci, usually 7-10 days.

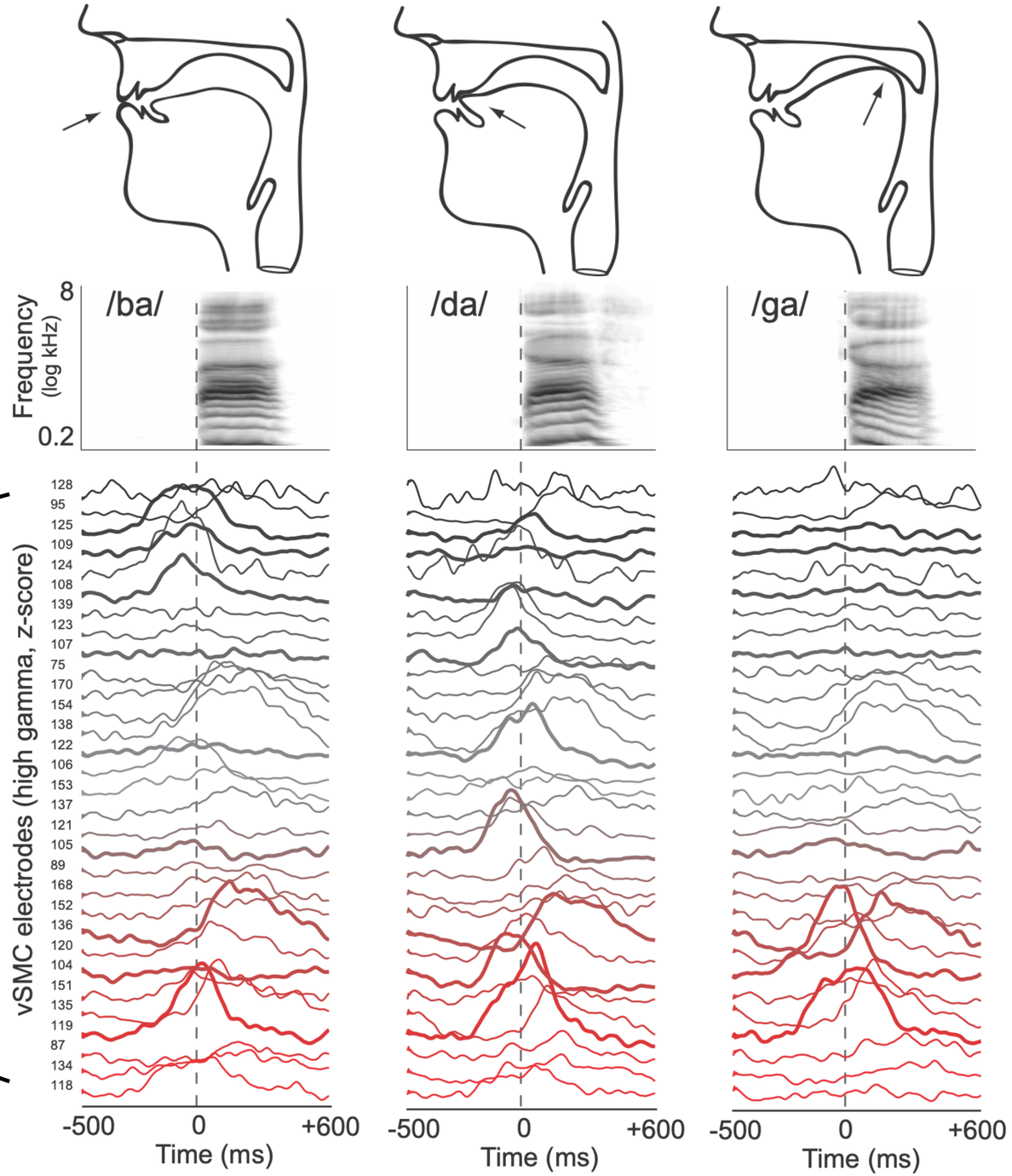



get well soon!
HOT
plastic bags & wrap · styrofoam · potato chip bags
candy wrappers · ceramic cups & dishes


ZOO
HALLS

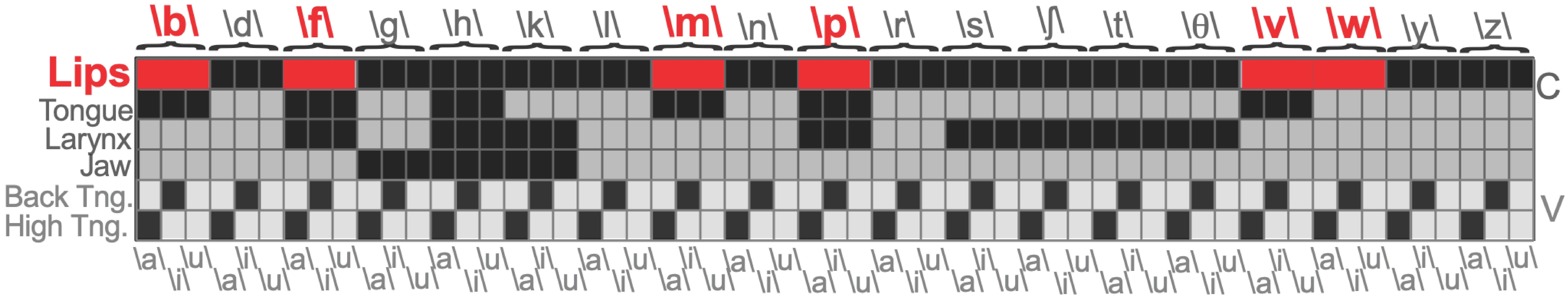


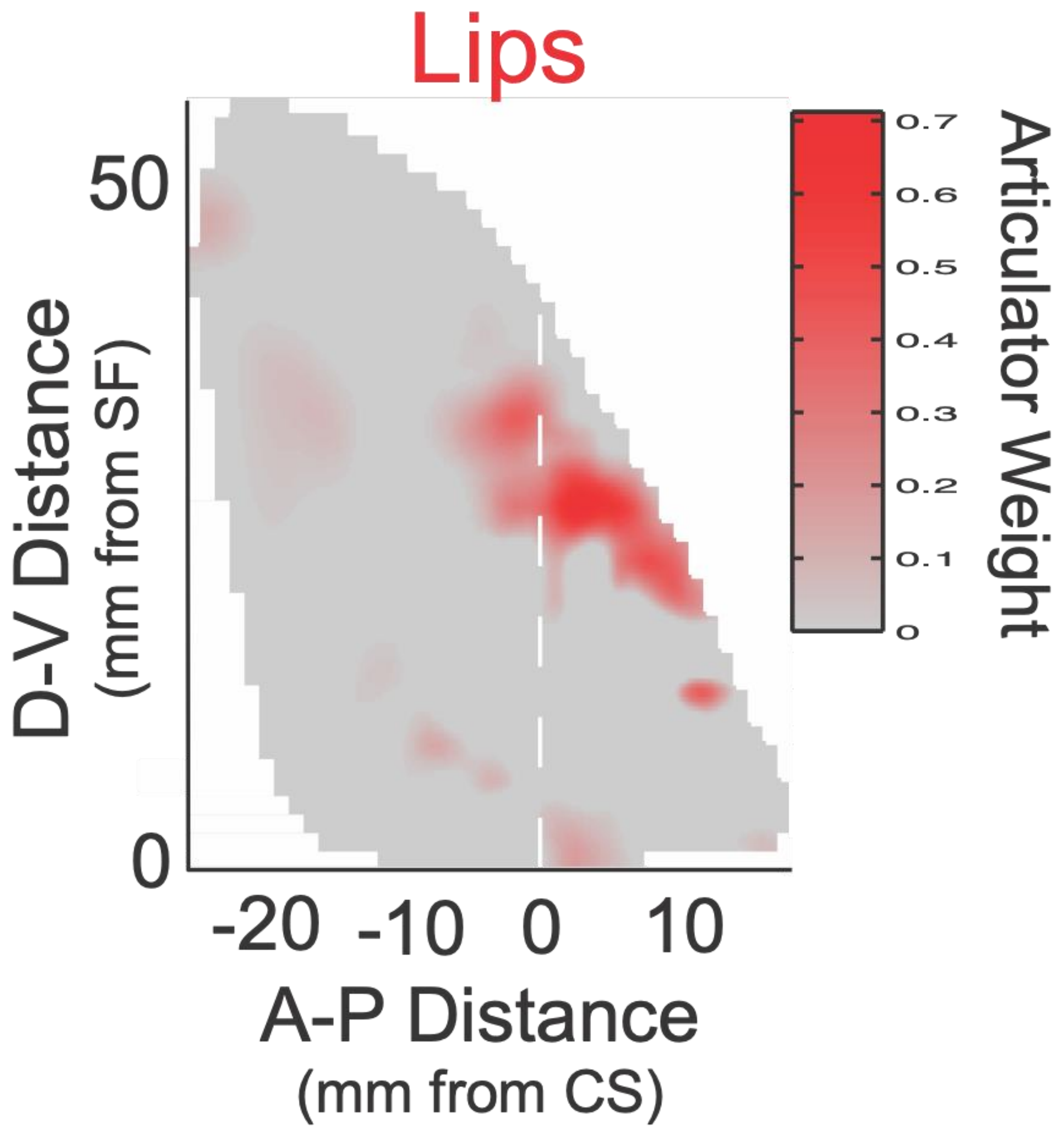




Bouchard, Mesgarani, Johnson, Chang *Nature* 2013

‘Labial’

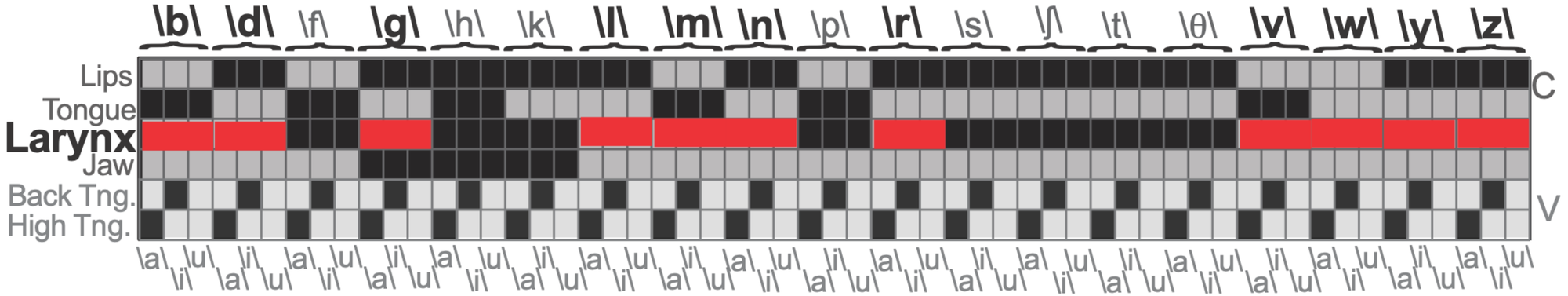


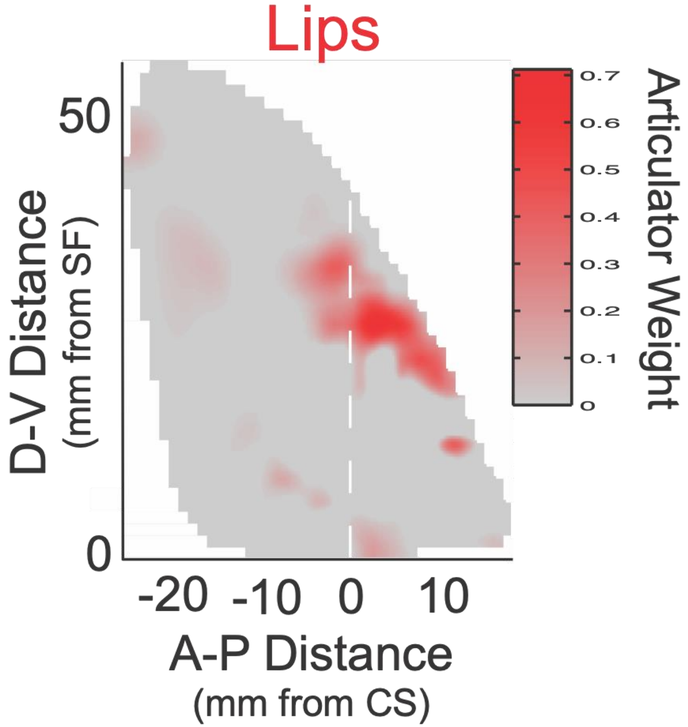


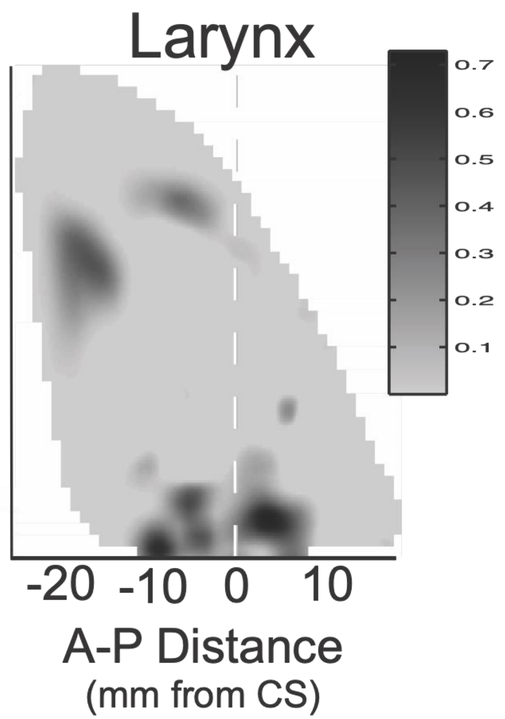
articulator vector matrix

Bouchard, Mesgarani, Johnson, Chang *Nature* 2013

‘Voiced’



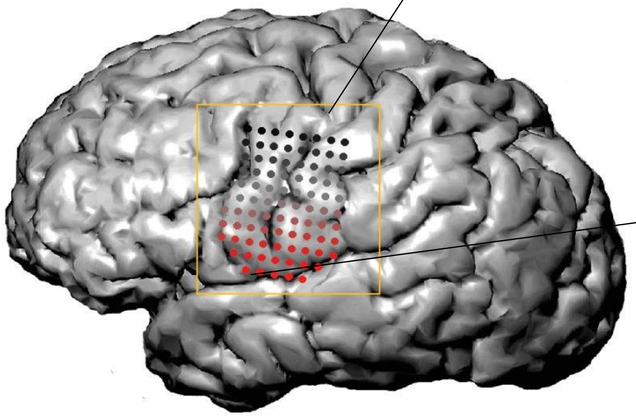


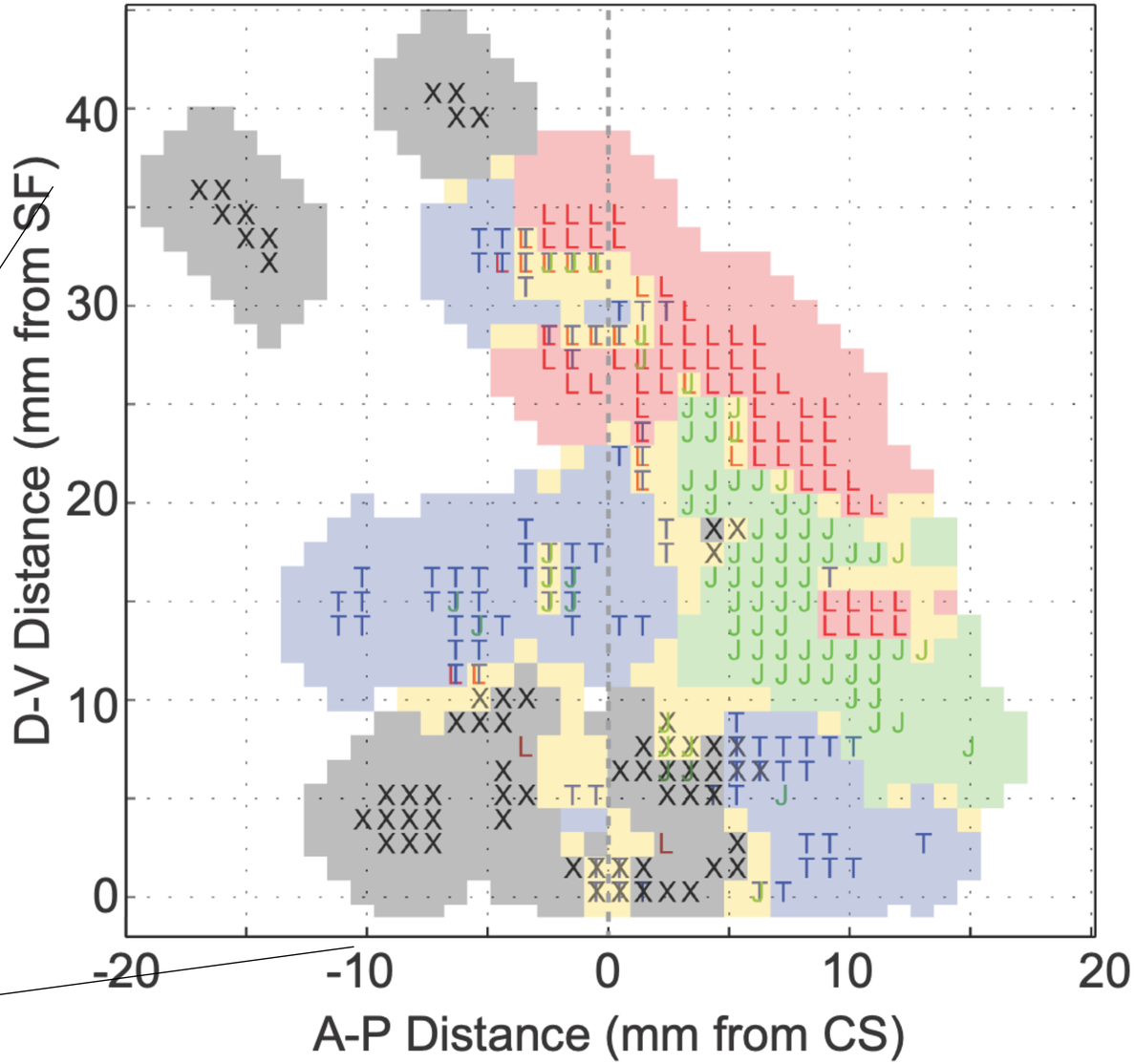


Bouchard, Mesgarani, Johnson, Chang *Nature* 2013

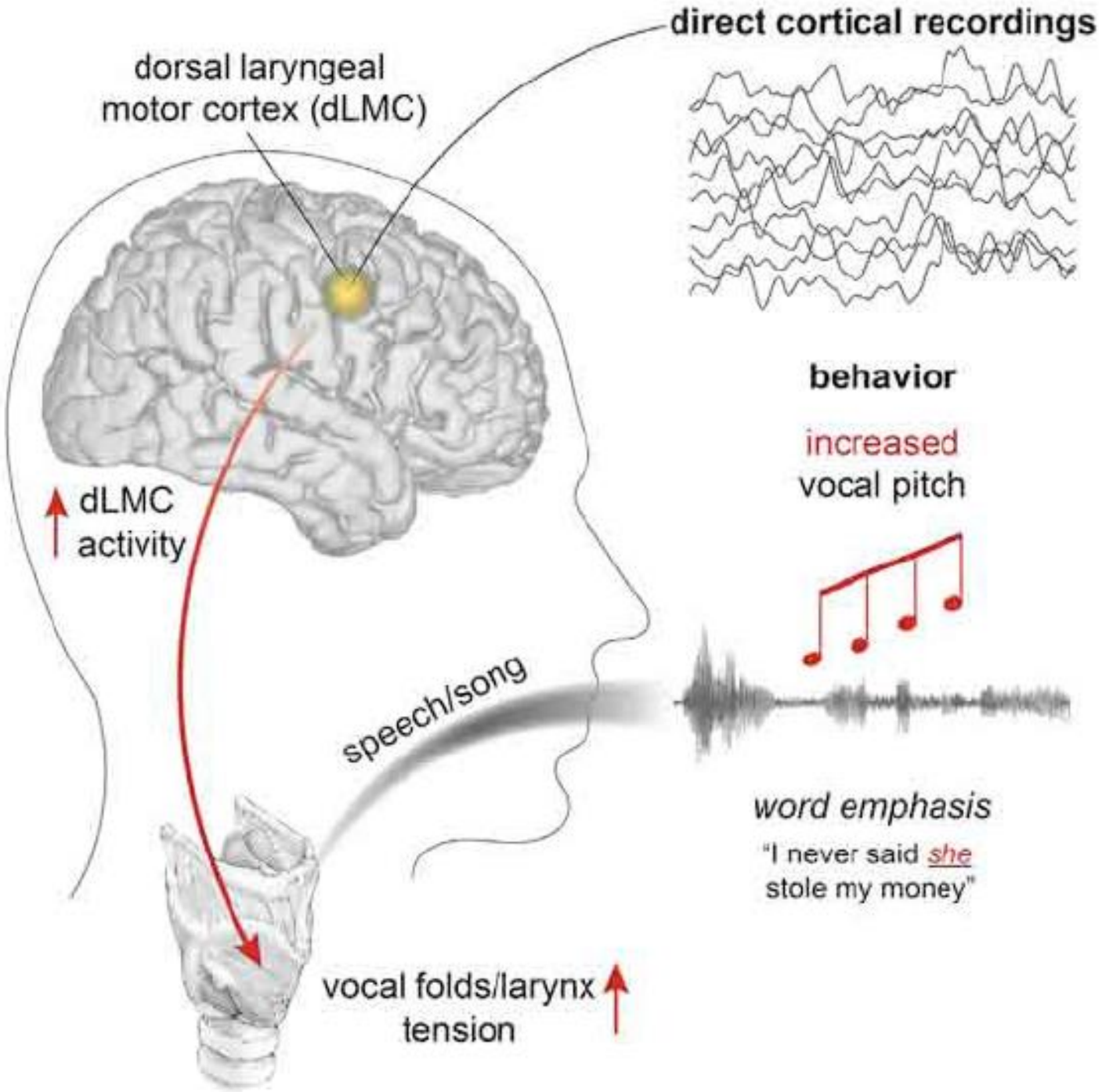
Functional organization: vocal tract

larynx (X)**
lips (L)
jaw (J)
tongue (T)
larynx (X)





Bouchard, Mesgarani, Johnson, Chang *Nature* 2013



Motor cortex control of laryngeal pitch

Dichter, et al., *Cell* 2018

Pitch Control to determine larynx encoding

I never said she stole my money

I never said she stole my money

I ***never*** said she stole my money

I never ***said*** she stole my money

I never said ***she*** stole my money

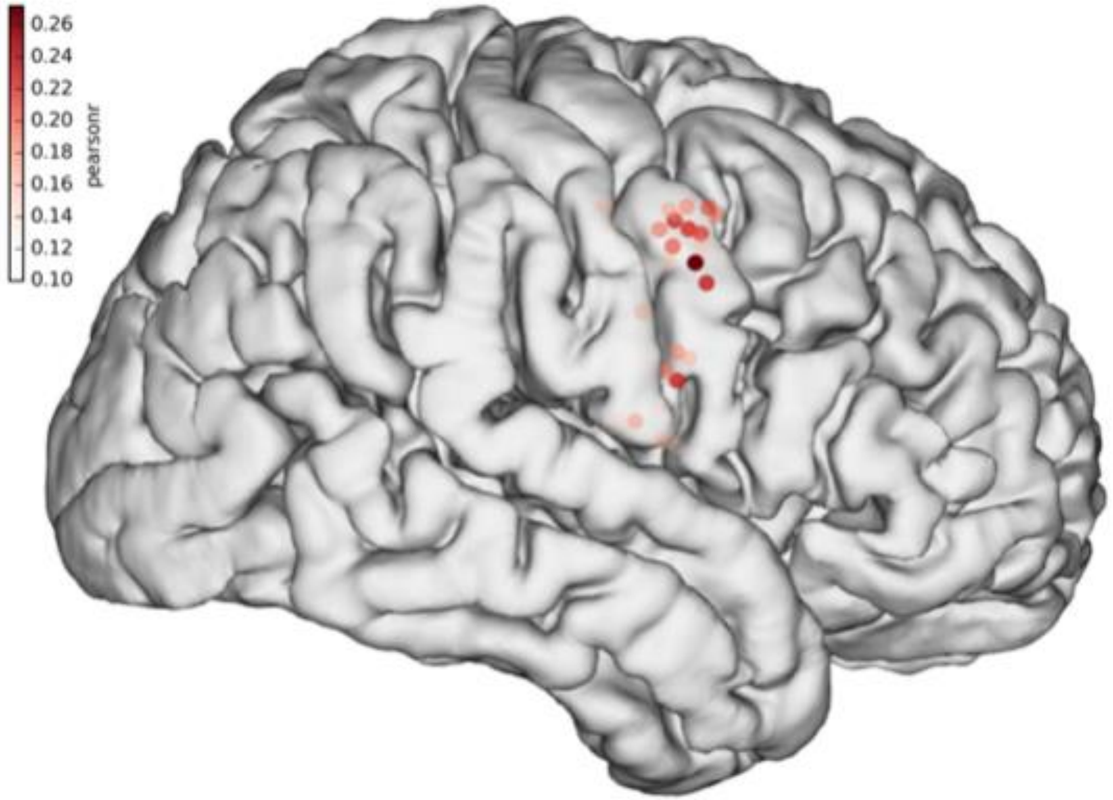
I never said she ***stole*** my money

I never said she stole ***my*** money

I never said she stole my ***money***

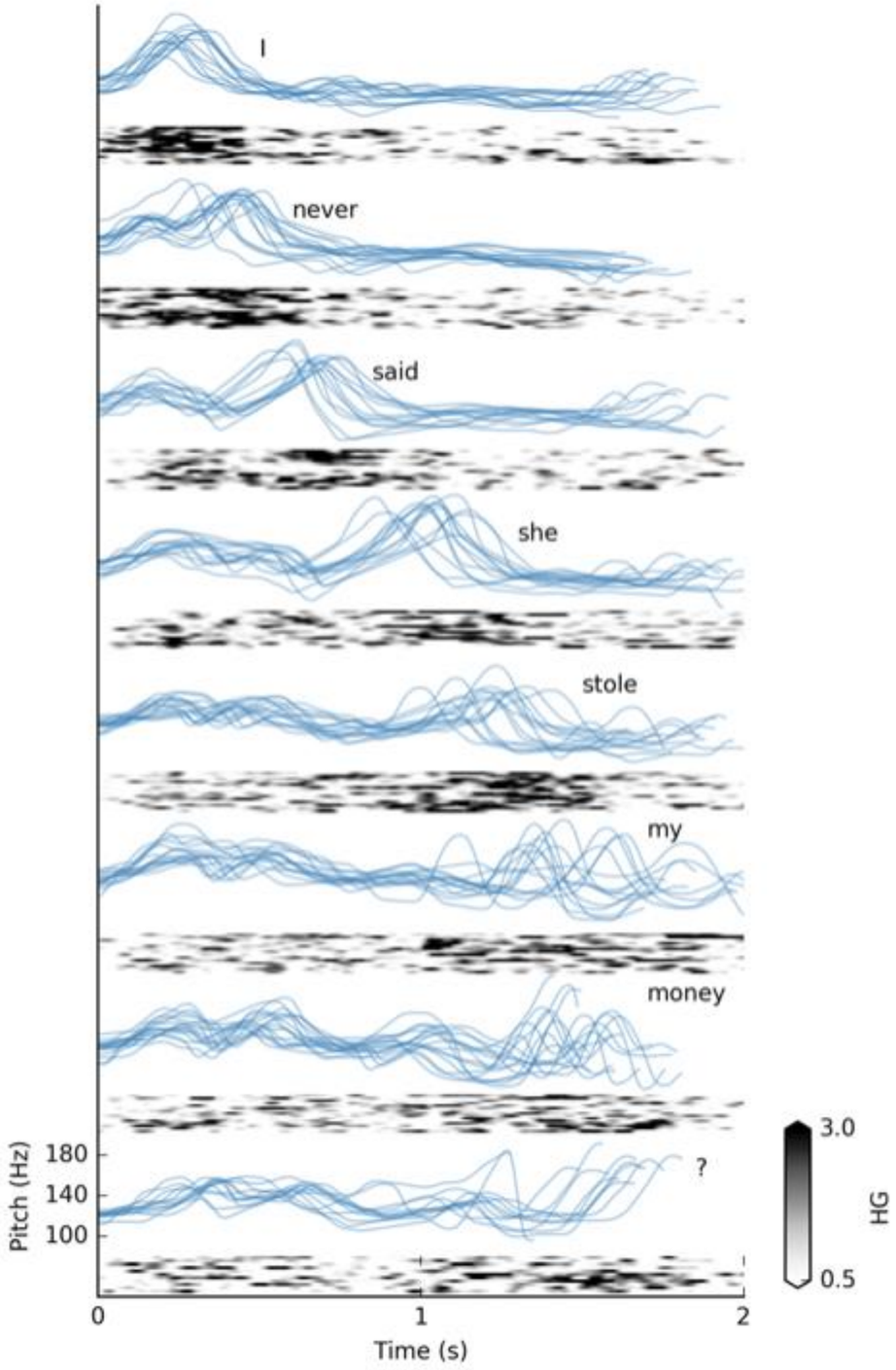
Dichter, et al., *Cell* 2018

Vocal pitch in dorsal larynx cortex



–also when singing melodies (‘do-re-mi’)

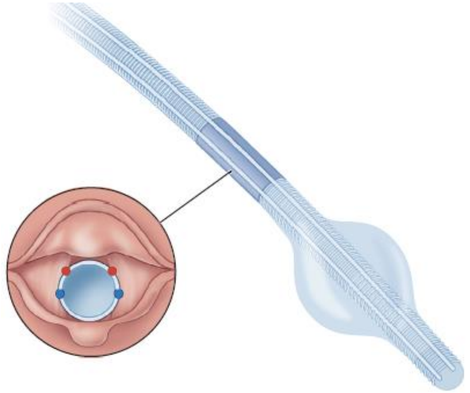
–playback shows auditory responses (delayed)



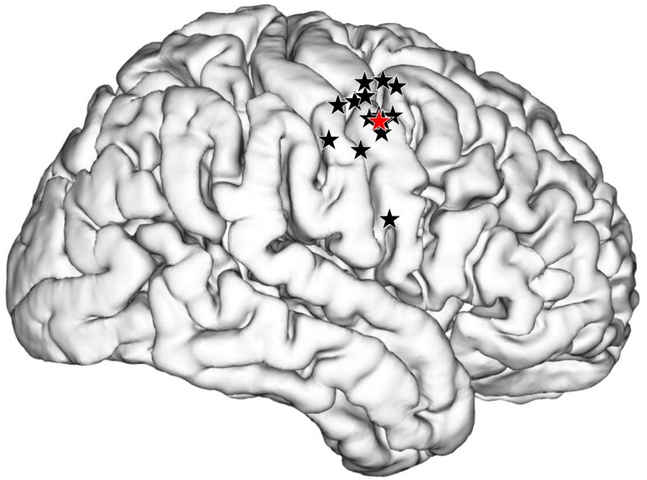
Dichter, et al., *Cell* 2018

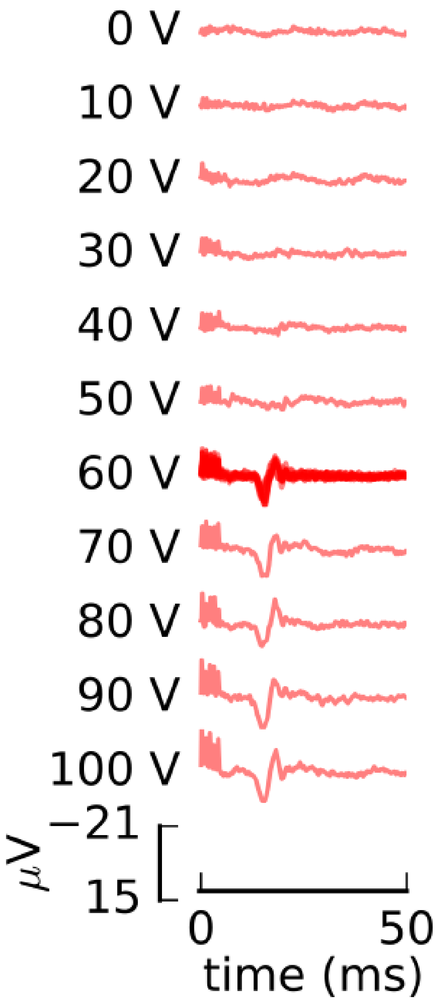
DLMC stimulation evokes larynx movement

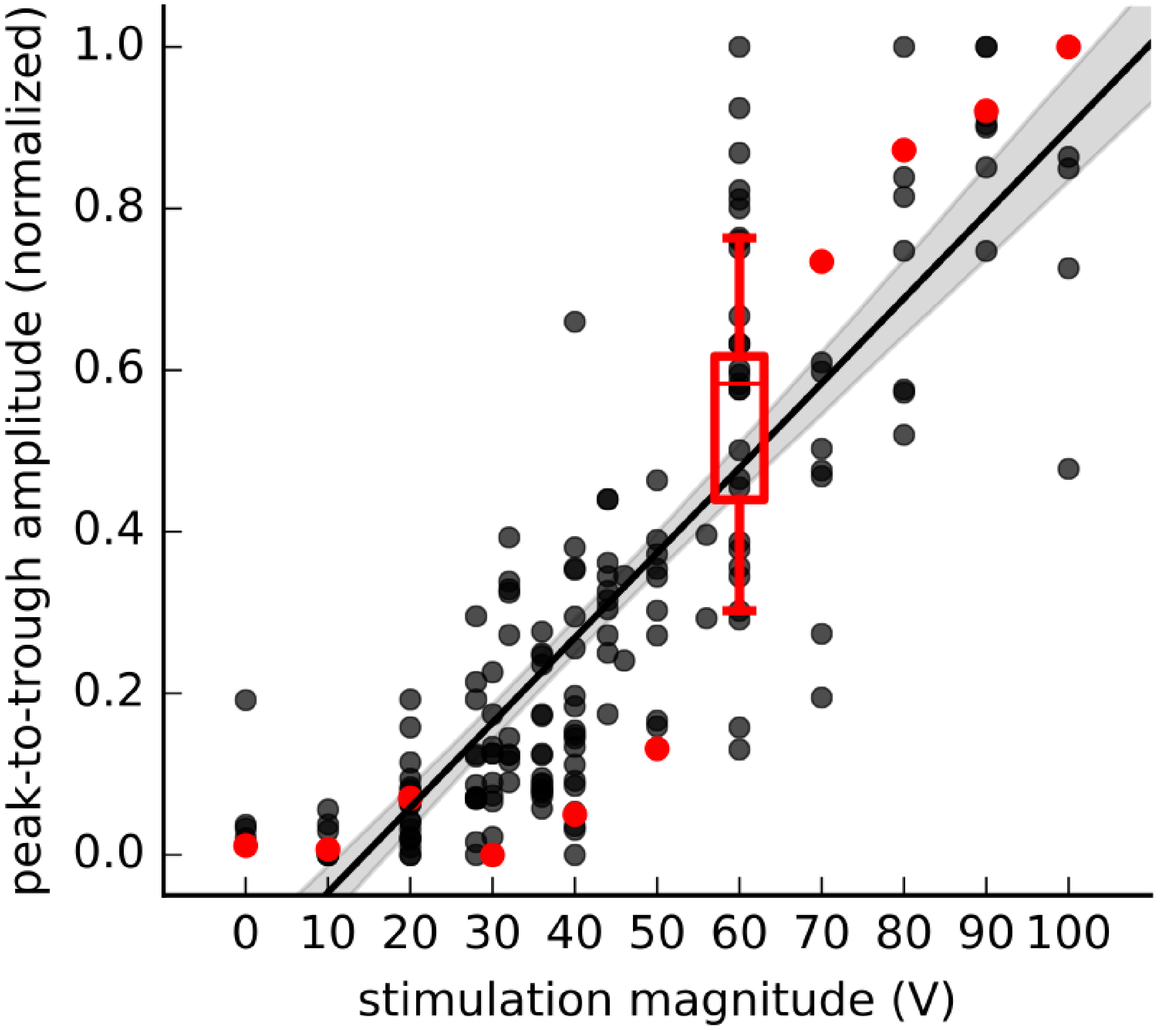
EMG



Electrical stimulation





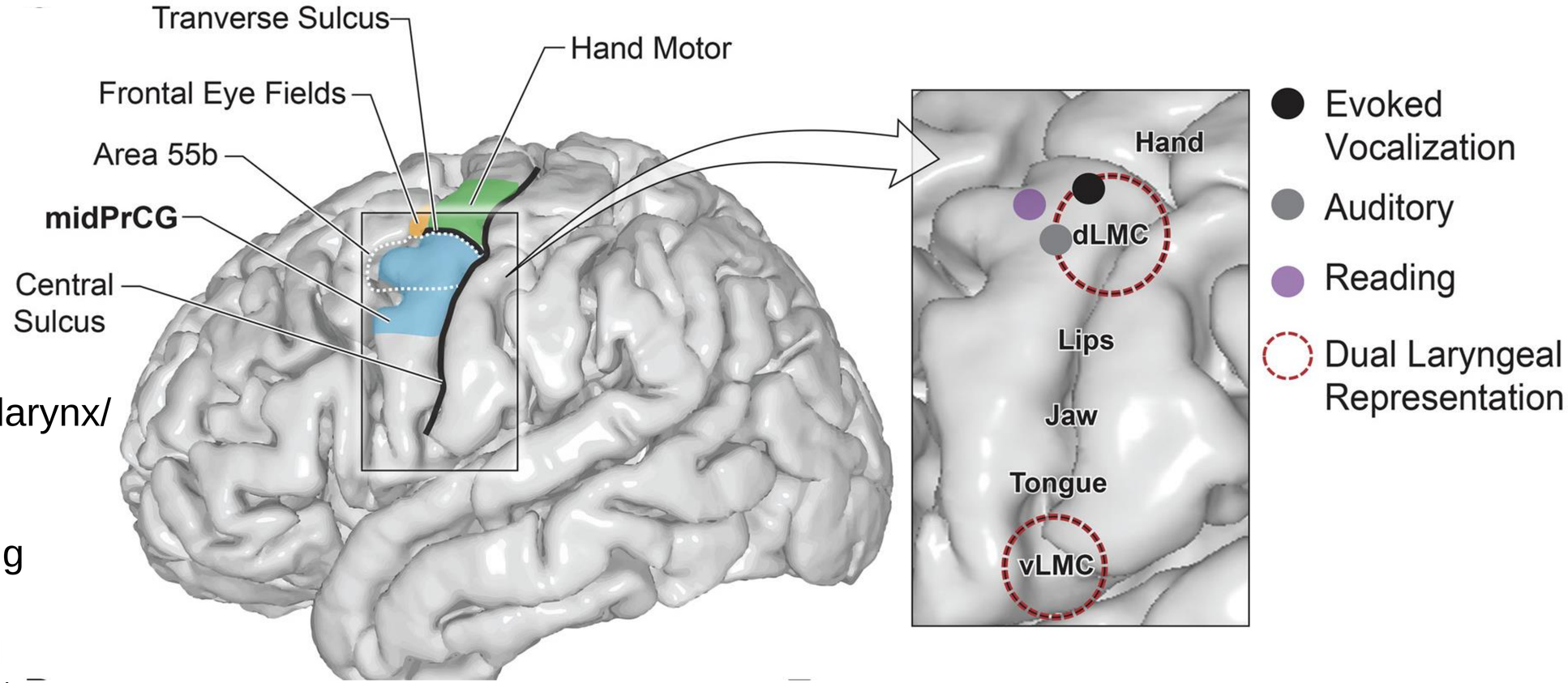


Dichter, et al., *Cell* 2018

Awake brain mapping


Dorsal larynx cortex stimulation evokes vocalization
with permission

The middle precentral gyrus (mPrCG) is an integrative cortical area for phonological processing

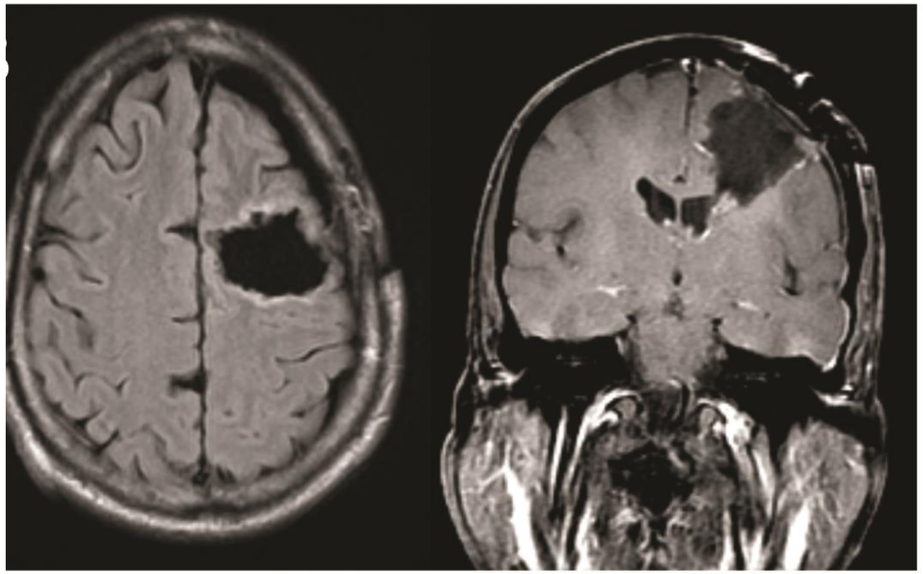


1. Direct motor control of larynx/
2. Vocalization (dLMC)
3. Auditory processing
4. Phonological processing
- motor sequences
- silent and overt reading
5. Coordination of articulators
- pure apraxia of speech

Silva, et al., *Journal of Neuroscience* 2022

MFG/MidPrCG injury causes apraxia of speech

Apraxia: disorder of articulatory coordination and planning in speech sound production that does not involve muscle weakness



Say: “Microscopic”

Chang, et al. *Neurosurgery* 2020

Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Neurobiology

The laryngeal motor cortex: its organization and connectivity

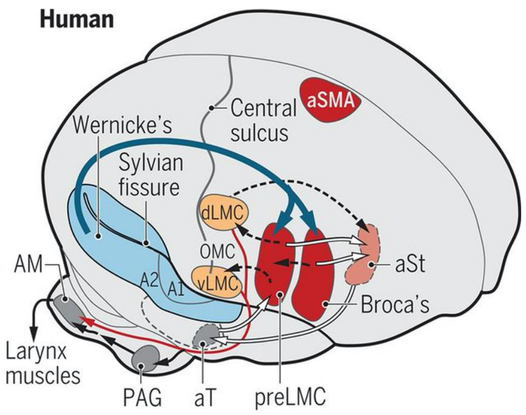
Kristina Simonyan[1,2]

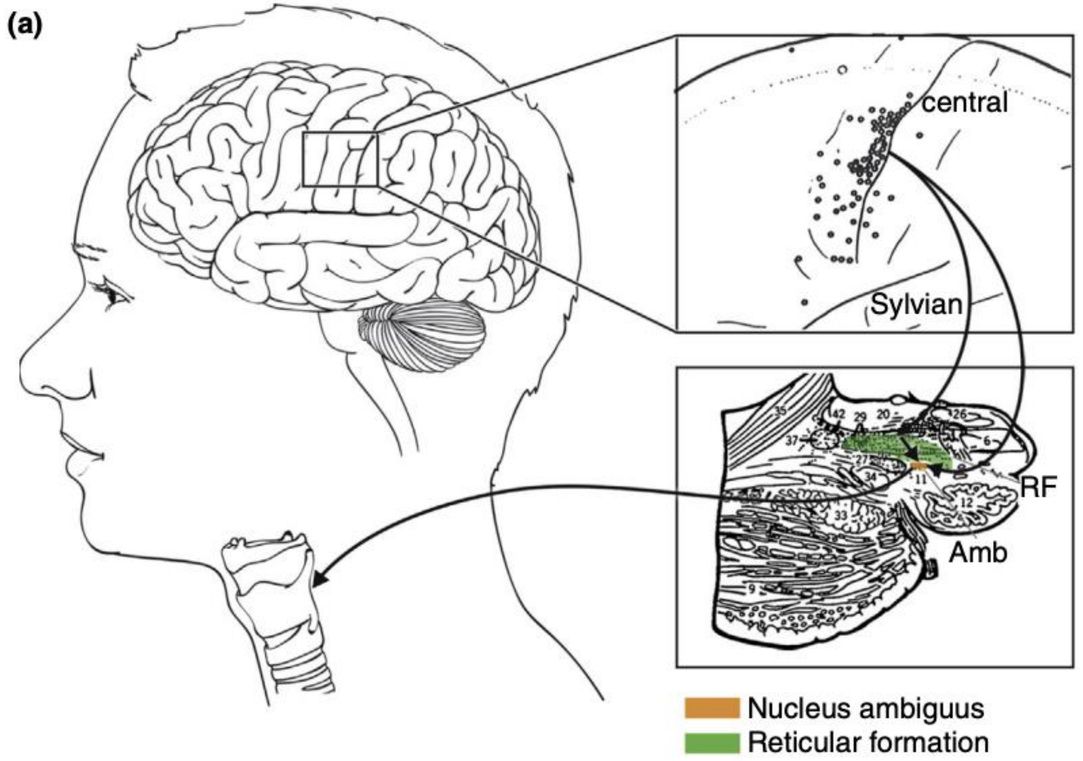
- Laryngeal motor cortex is indispensable for human but not monkey vocal motor control.
- A shift of laryngeal representation from the primary motor to premotor cortex may be a result of hominid evolution.

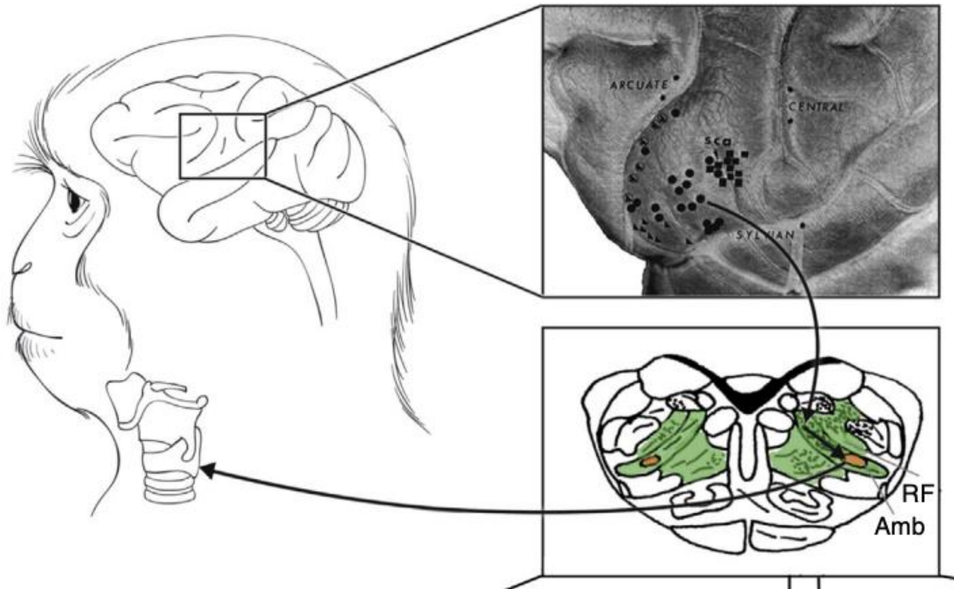
REVIEW

Evolution of vocal learning and spoken language

Erich D. Jarvis[1,2]

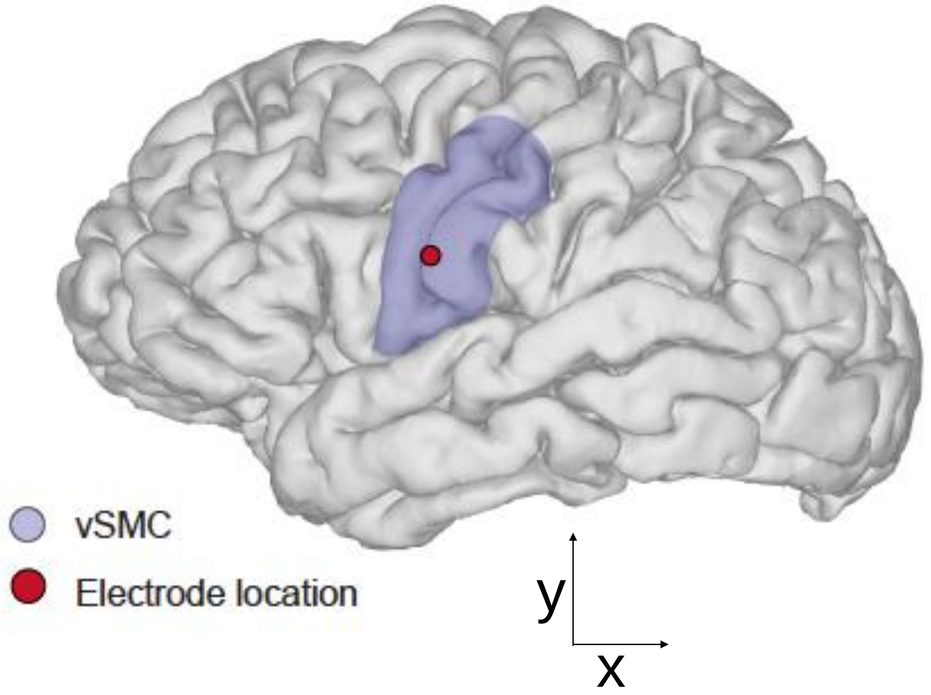


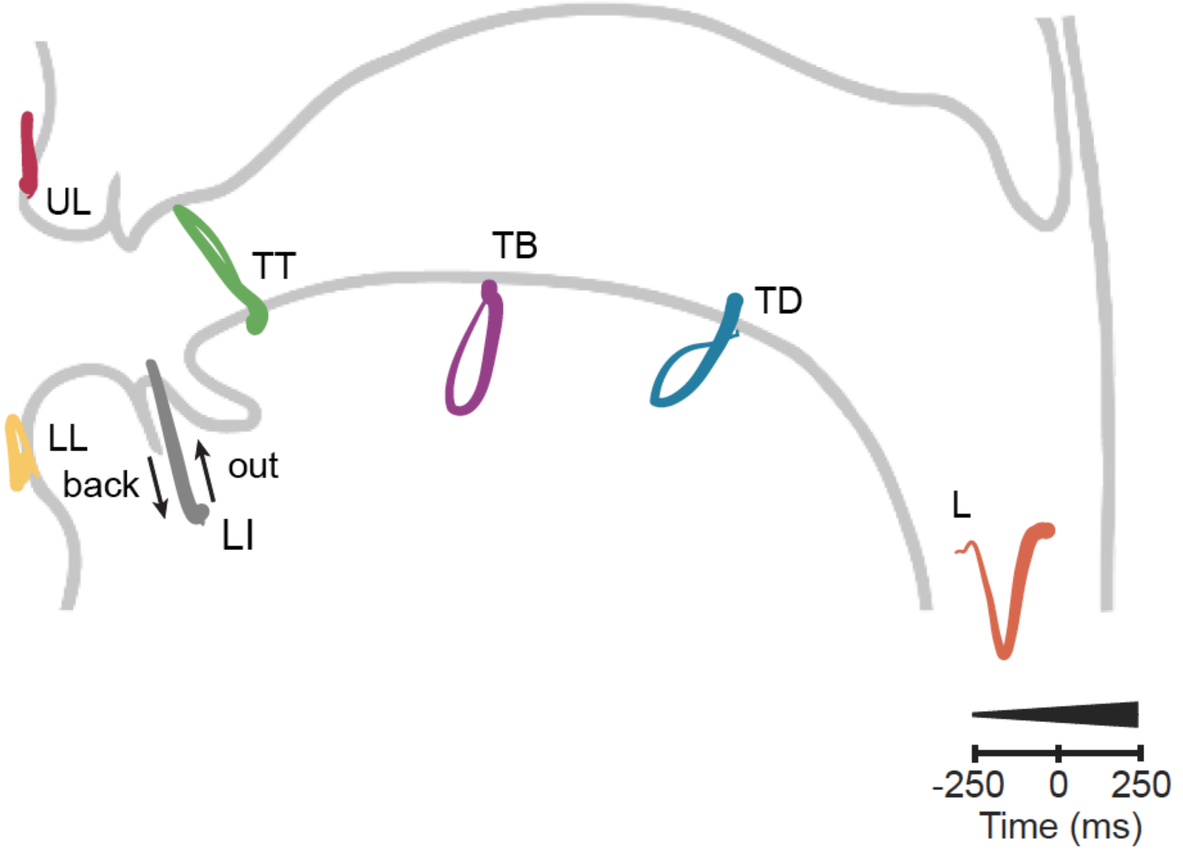




Articulatory movements

Trajectory Encoding at Single Electrode



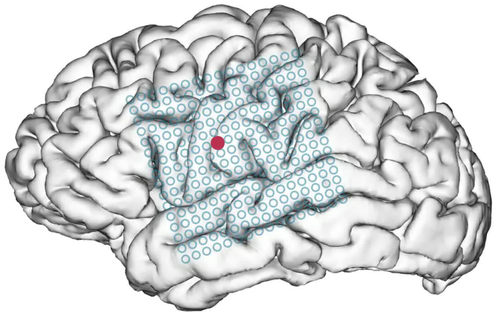


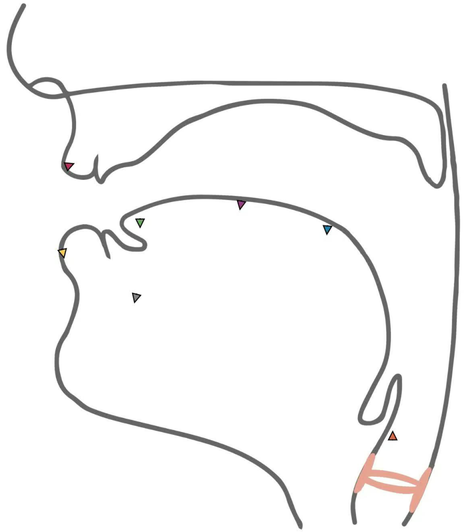
Speech primitives

- Coordinated, not single articulator
- ‘Out-and-back’ profile

Chartier*, Anumanchipalli*, et al. *Neuron* 2018

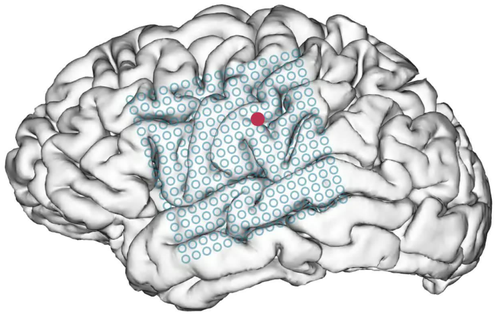
‘d’ : ‘dad’
(coronal trajectory)

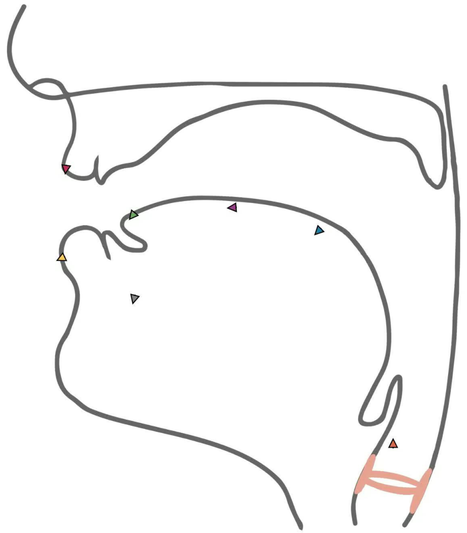




Chartier*, Anumanchipalli*, et al. *Neuron* 2018

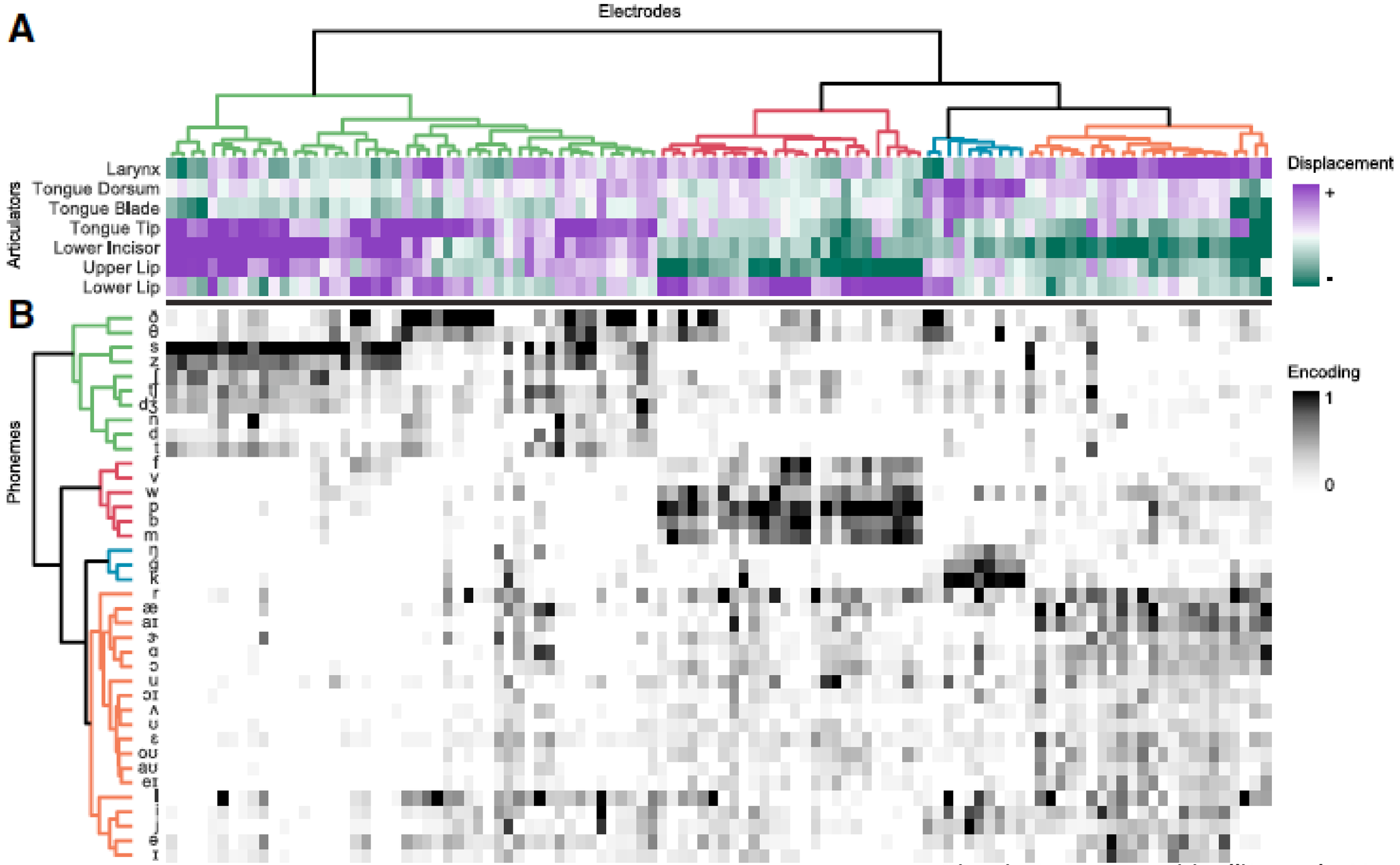
‘p’ : ‘pop’
(labial trajectory)





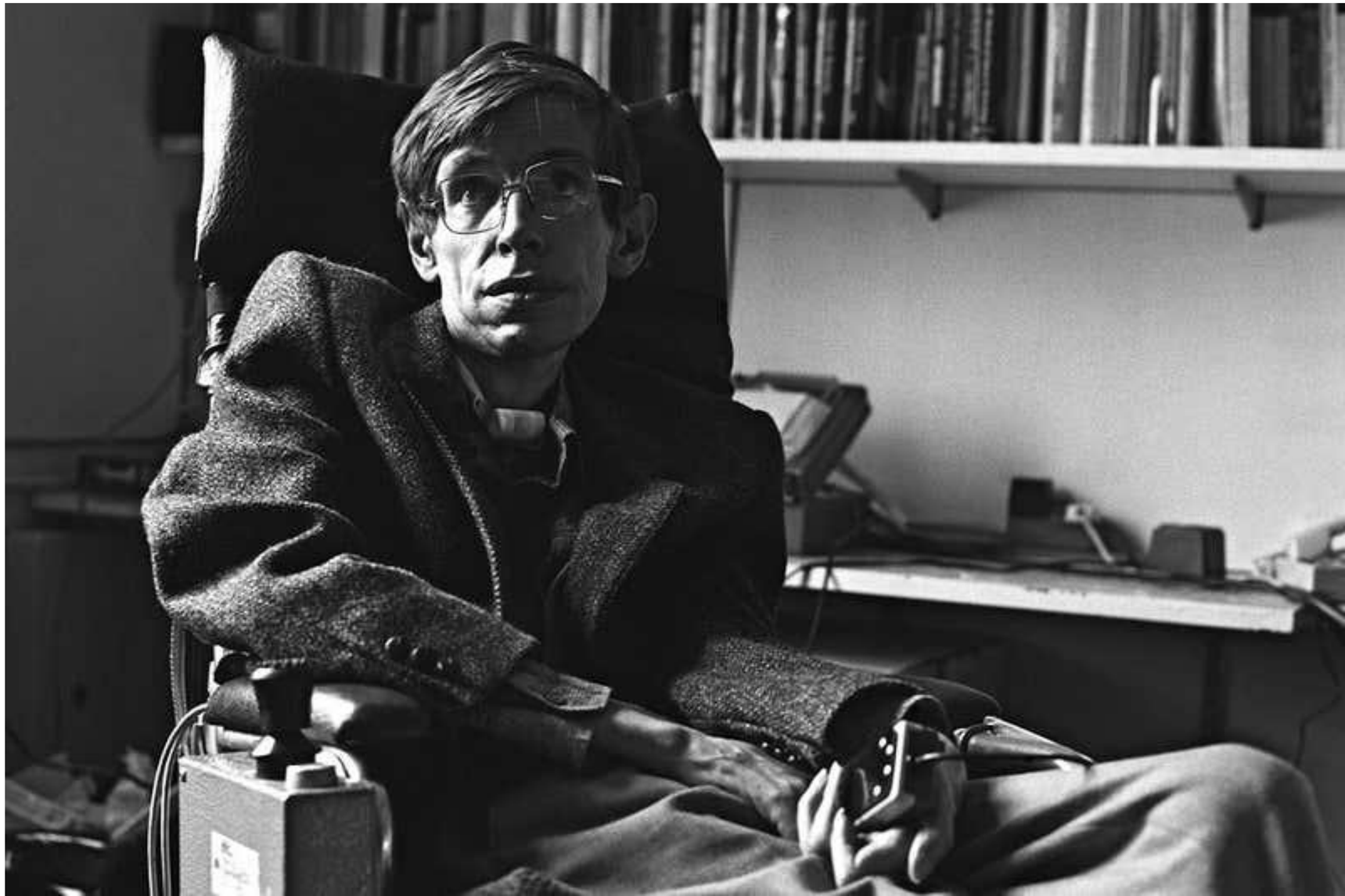
Chartier*, Anumanchipalli*, et al. *Neuron* 2018

Cortical encoding for all English sounds



Chartier*, Anumanchipalli*, et al. *Neuron* 2018

paralysis of communication



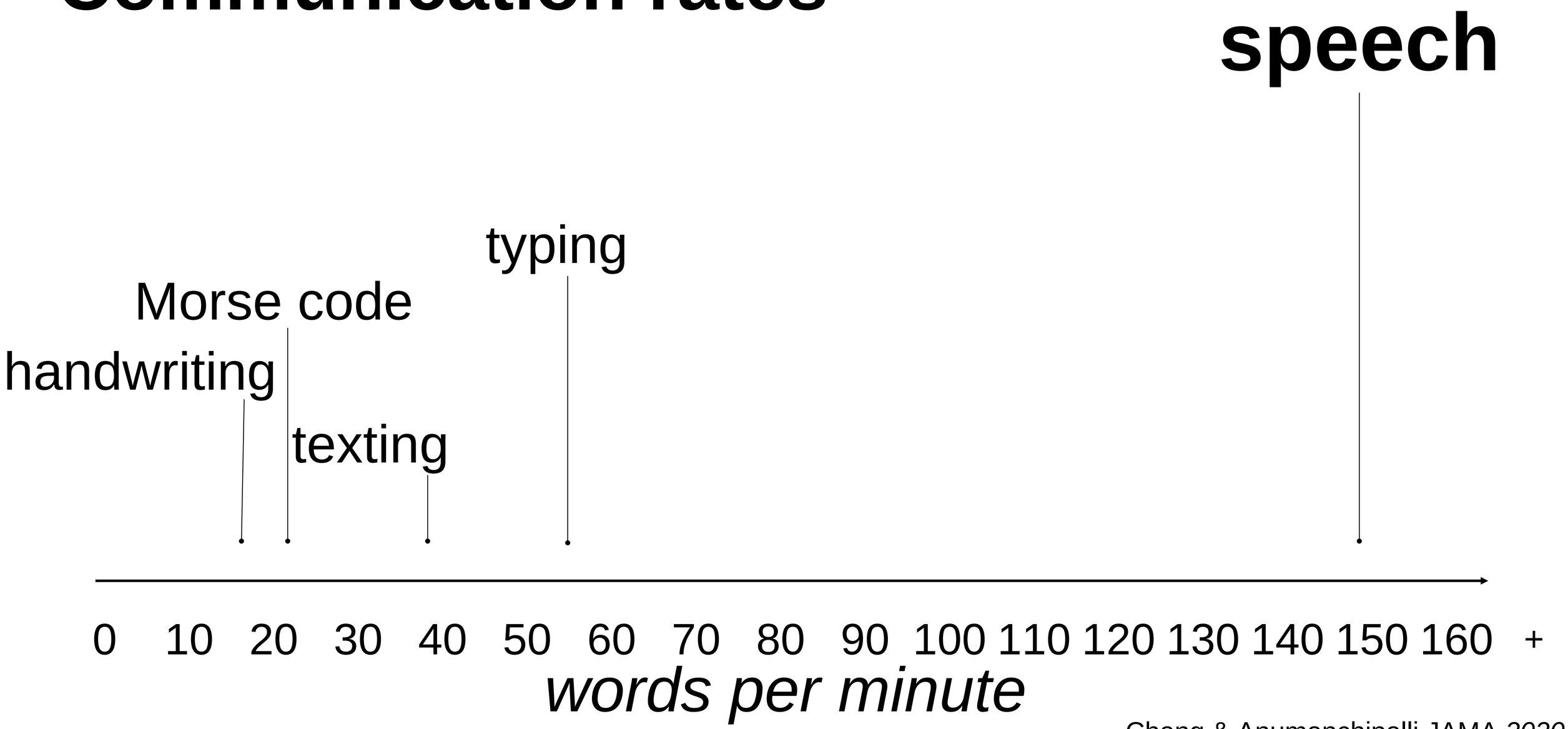
A Speech Synthesizer Direct to the Brain

Recordings from the brain's surface are giving scientists unprecedented views into how the brain controls speech.

by **Courtney Humphries** July 9, 2014

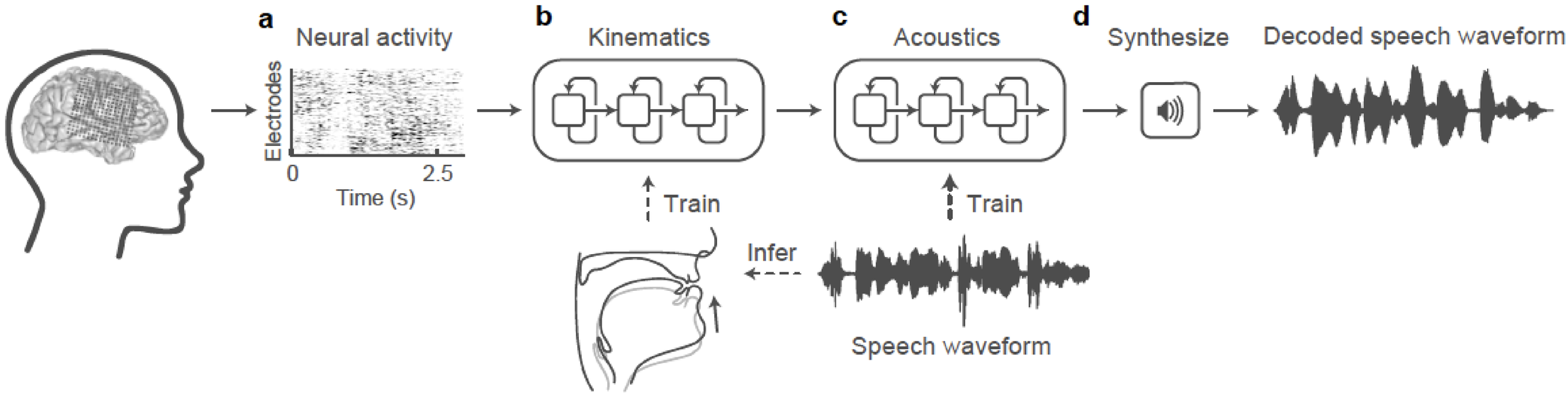
Could a person who is paralyzed and unable to speak, like physicist Stephen Hawking, use a brain implant to carry on a conversation?

Communication rates



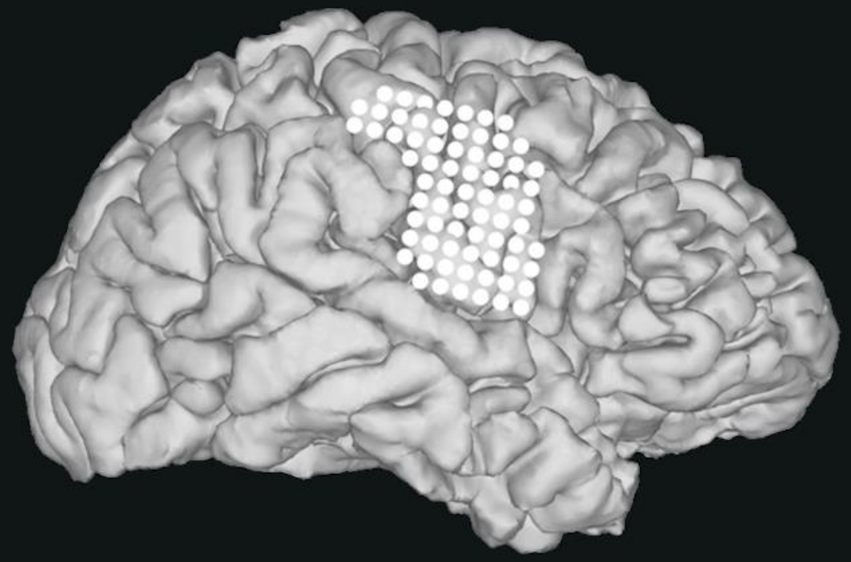
Chang & Anumanchipalli JAMA *2020*

A speech synthesizer direct to the brain

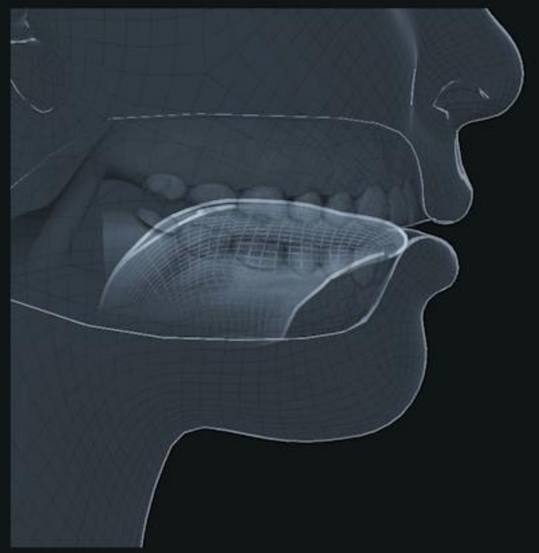


Anumanchipalli*, Chartier*, Chang *Nature 2019*

Speech synthesized from brain activity



Decode



Original

"The proof you are seeking is not available in books."

UCSF

Anumanchipalli*, Chartier*, Chang *Nature 2019*

BRAVO Trial (2019-)

BCI Restoration of Arm and VOice

Goal: pathway to clinical device (safe, robust, high performance)

Investigator: Chang (neurosurgery) and Ganguly (neurology)

Device: chronically implanted subdural grid (128e, 253e)+ percutaneous port

Coverage: lateral motor cortex (arm and speech)

Indication: severe paralysis impairing communication and limb movement

FDA IDE

The NEW ENGLAND JOURNAL of MEDICINE

ORIGINAL ARTICLE

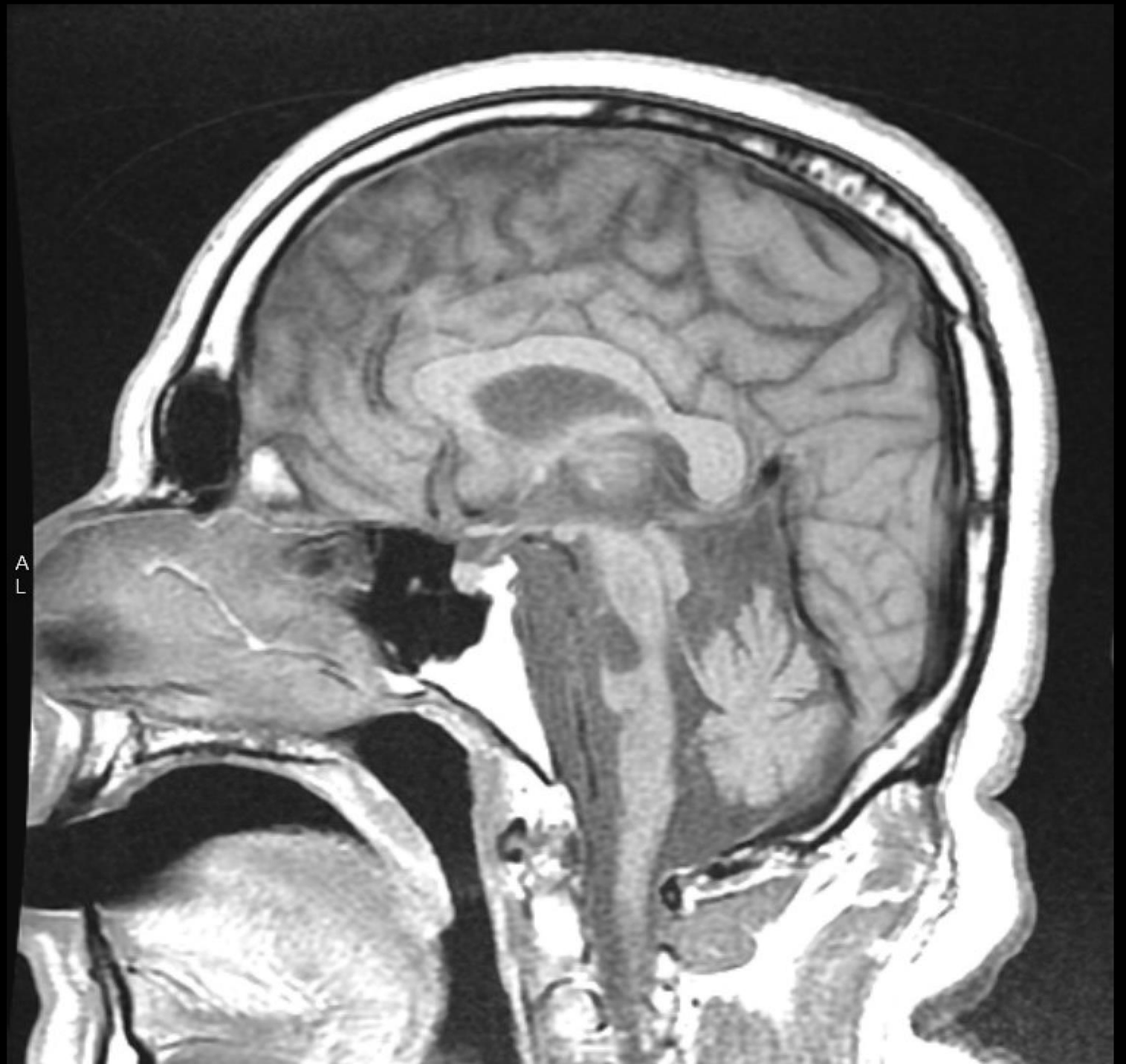
Neuroprosthesis for Decoding Speech in a Paralyzed Person with Anarthria

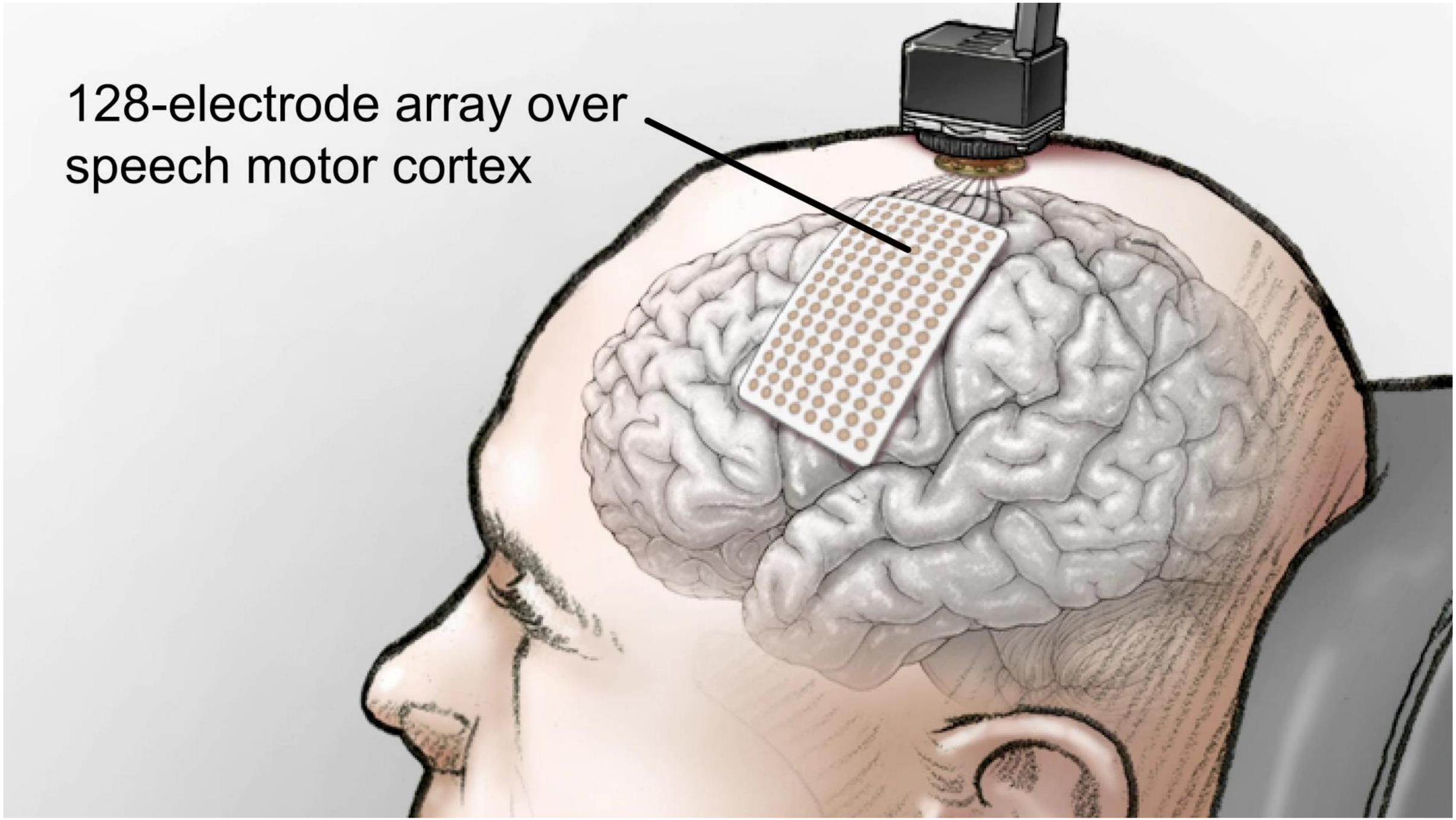
David A. Moses, Ph.D., Sean L. Metzger, M.S., Jessie R. Liu, B.S., Gopala K. Anumanchipalli, Ph.D., Joseph G. Makin, Ph.D., Pengfei F. Sun, Ph.D., Josh Chartier, Ph.D., Maximilian E. Dougherty, B.A., Patricia M. Liu, M.A., Gary M. Abrams, M.D., Adelyn Tu-Chan, D.O., Karunesh Ganguly, M.D., Ph.D., and Edward F. Chang, M.D.

2021

“Pancho”


takes
Speak
Editor
Chat off
sorry
no
You are very welcome
Okay
Please
Thank you
Hello Hello
Good morning
What?
Yes
Hey!
Hang on
Word Prediction
Space
Shift
Clear
you
it
my
do
get
go
need
and
but
for
the
to
on
in
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
p
qu
r
s
t
u
v
w
x
y
z
Delete Word
Func.
More Phrases
My Stories
Author
Back
My Phrases
Main Menu
start
DynaVox V MAX
DYNAVOX


A
L

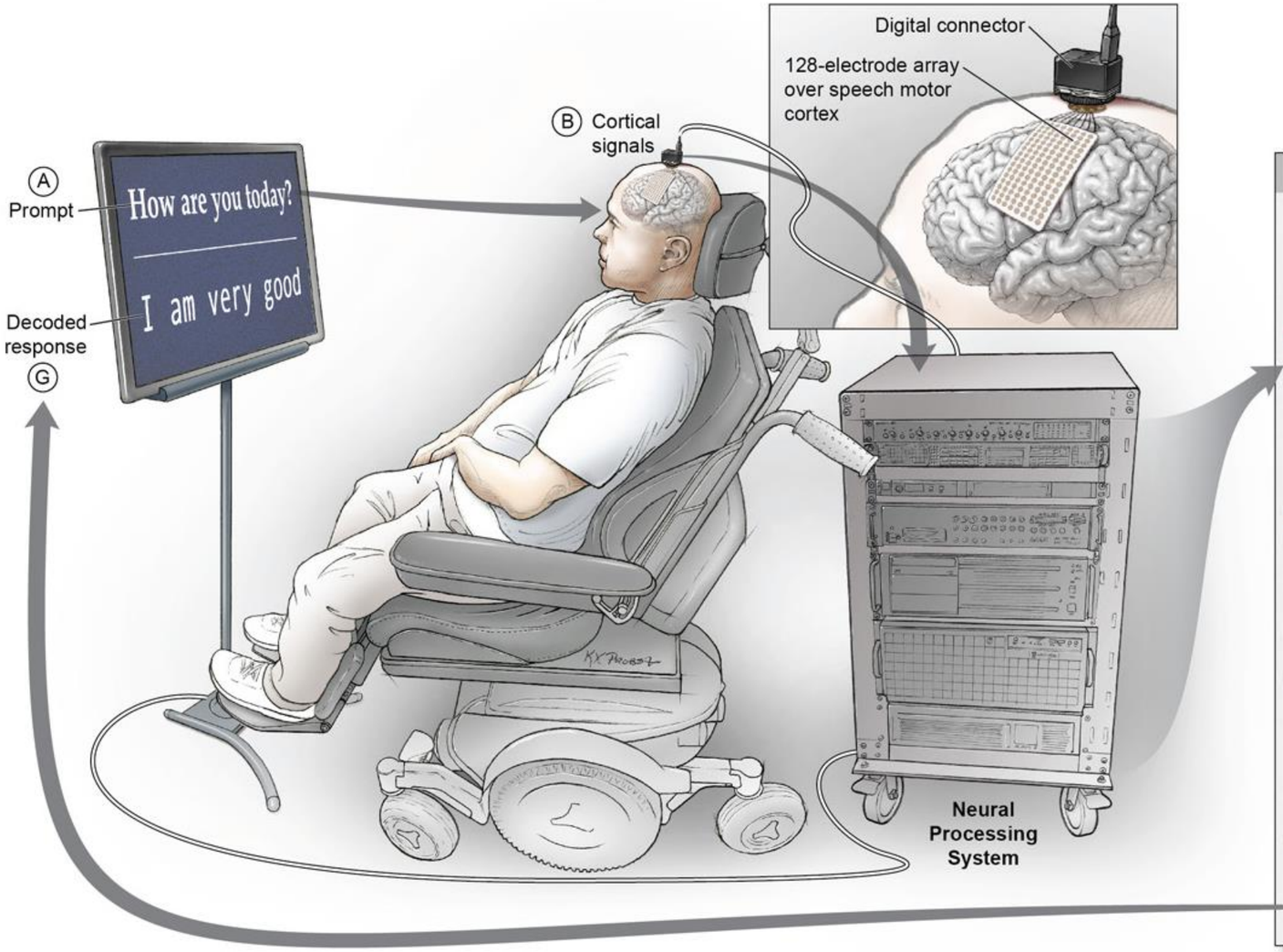


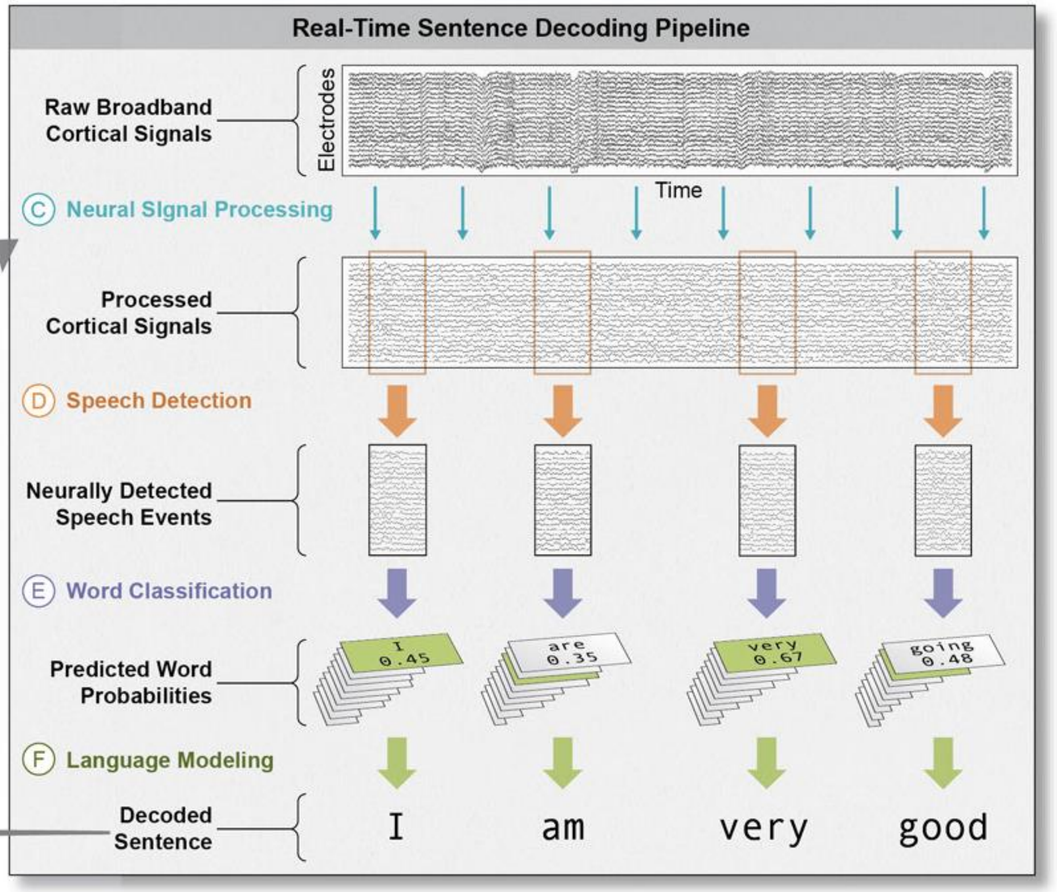
Moses, Metzger, Liu et al NEJM *2021*

The New York Times | https://www.nytimes.com/2021/07/14/health/speech-brain-implant-computer.html

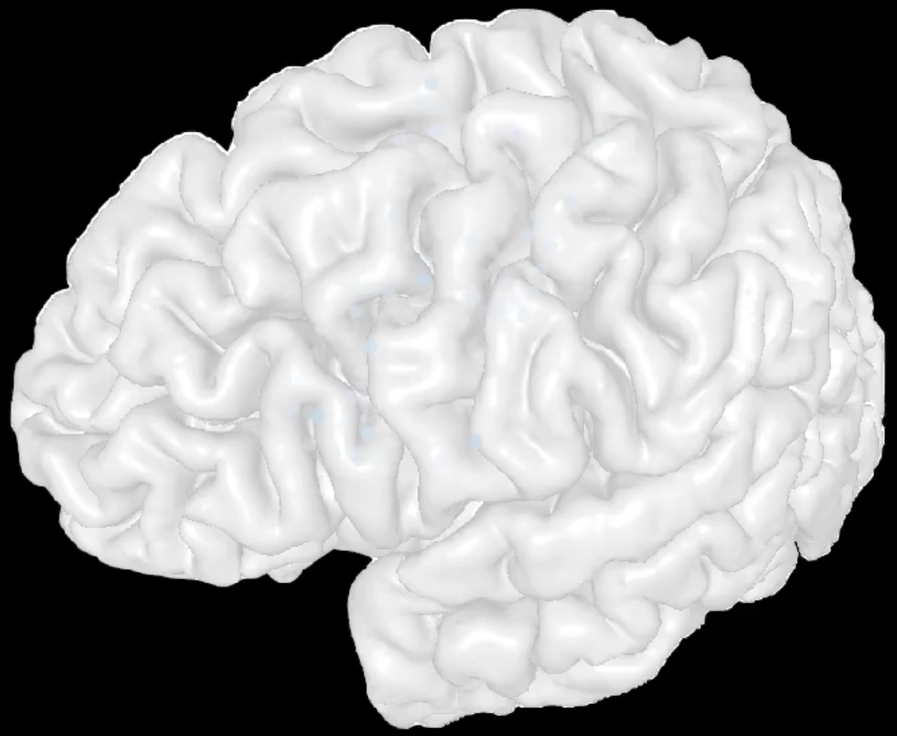
Tapping Into the Brain to Help a Paralyzed Man Speak

In a once unimagined accomplishment, electrodes implanted in the man's brain transmit signals to a computer that displays his words.

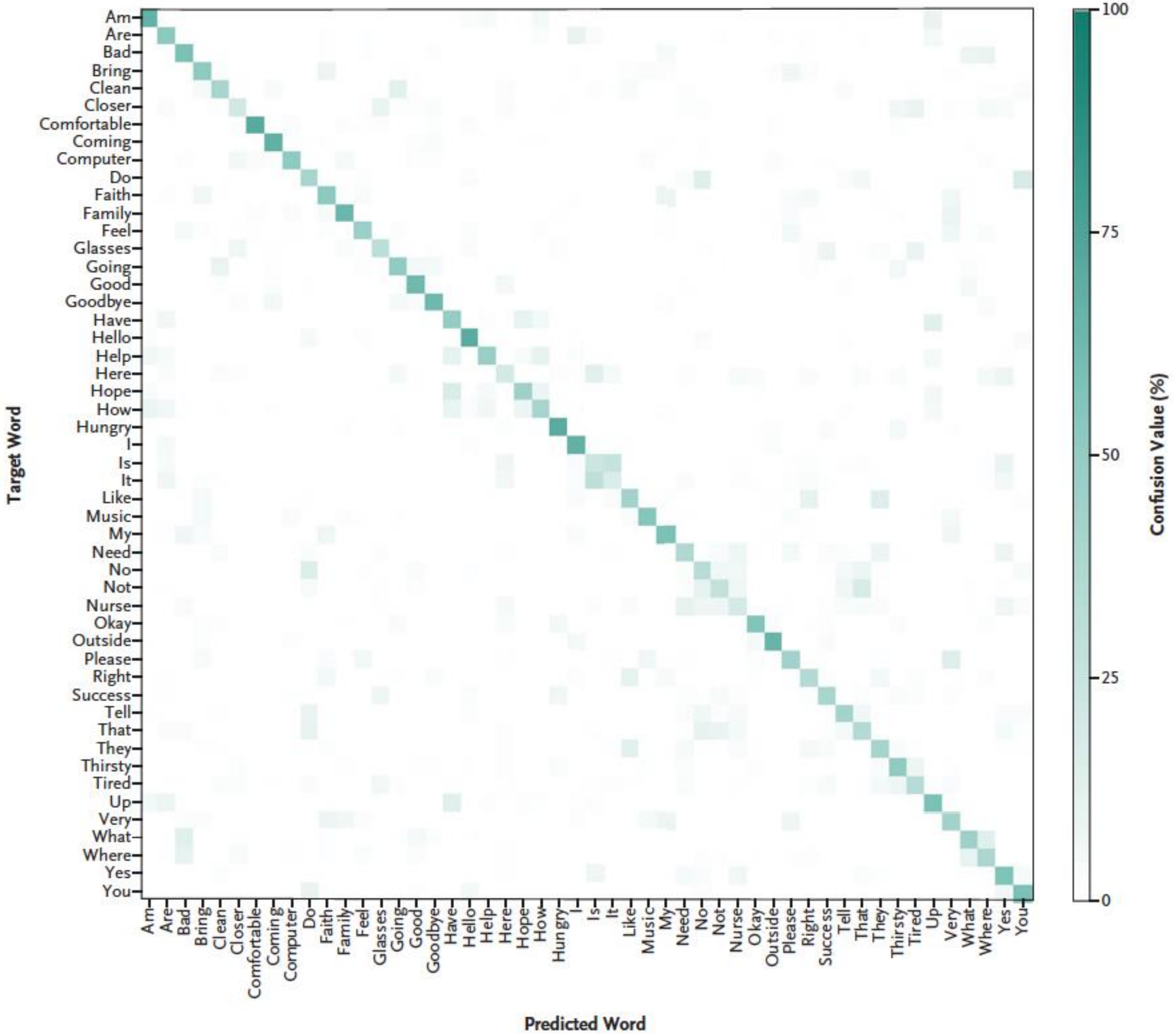


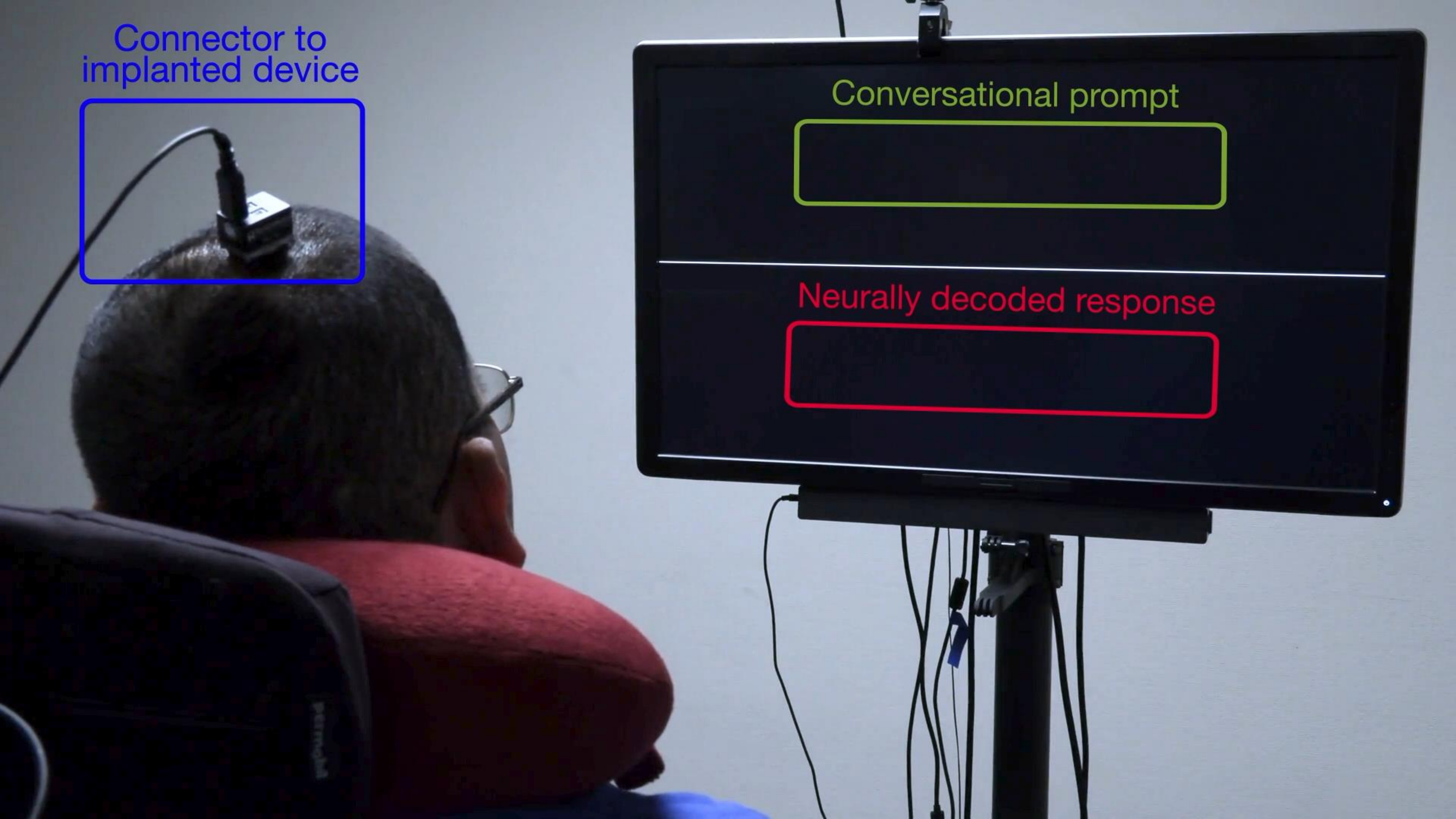


Moses, Metzger, Liu et al NEJM *2021*



The first 50 words…




Connector to implanted device
Conversational prompt
Neurally decoded response

“Ann”

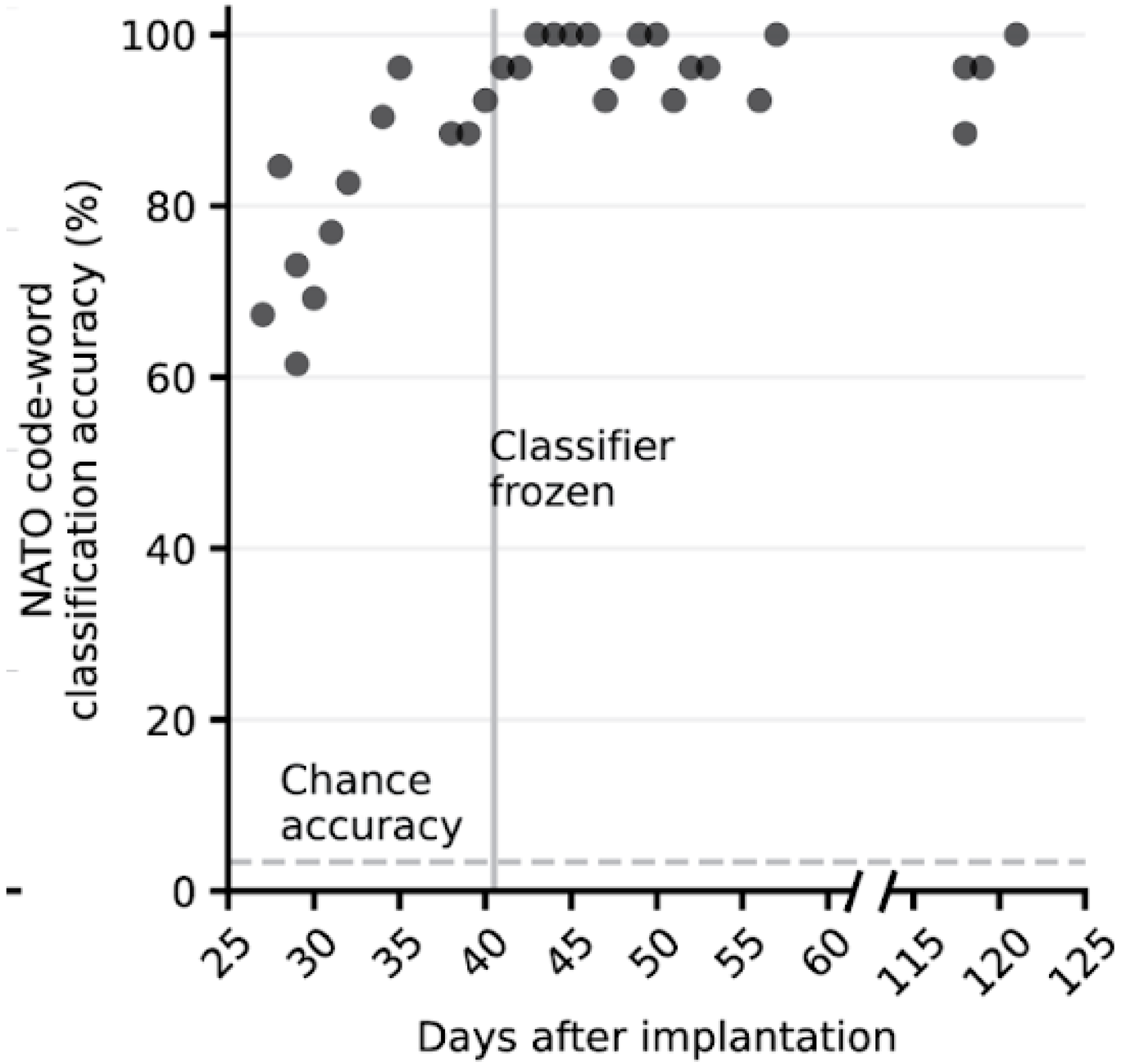
brainstem stroke

18 years ago

B3: Text decoding

NATO code word

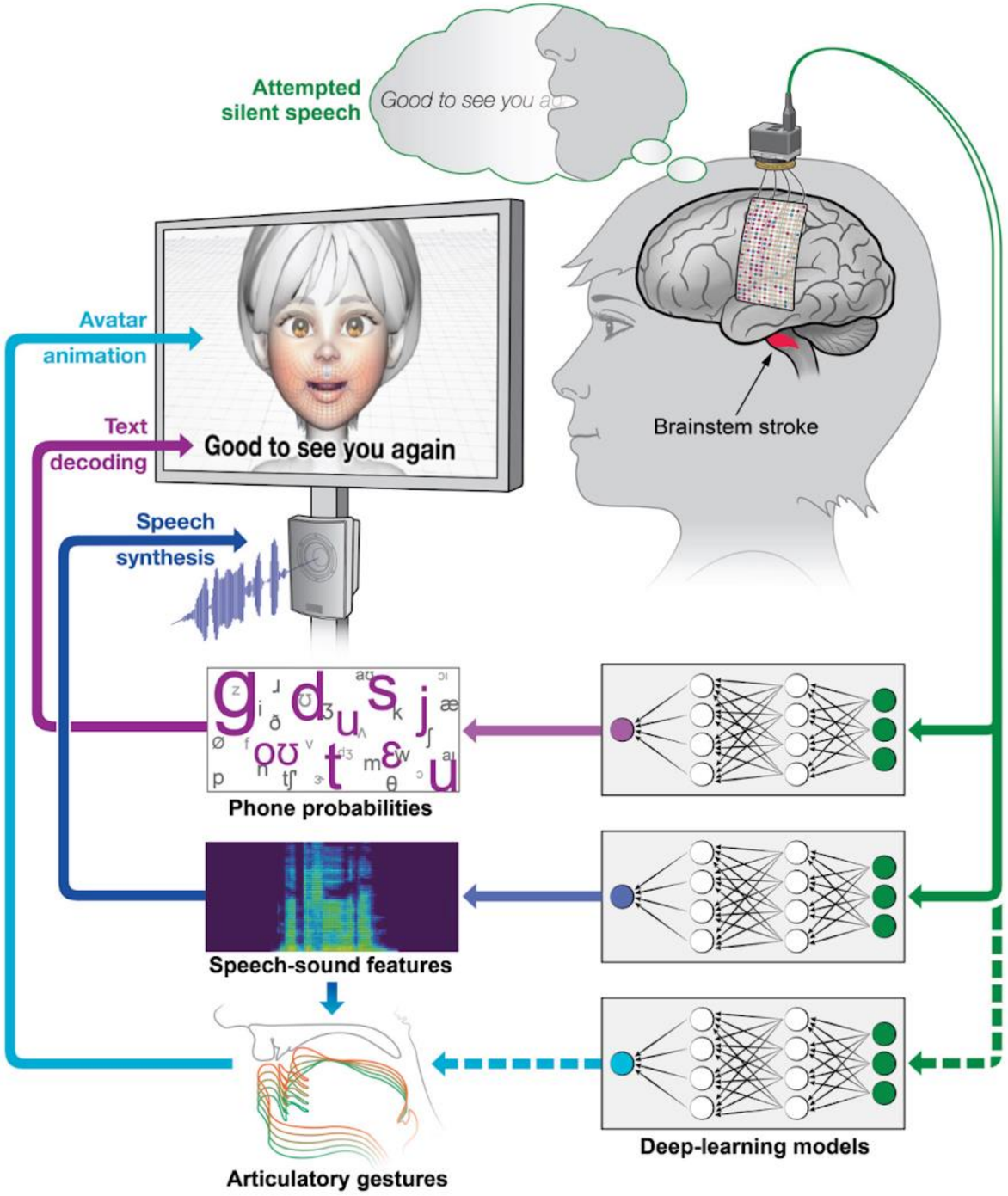
VERY STABLE OVER MONTHS

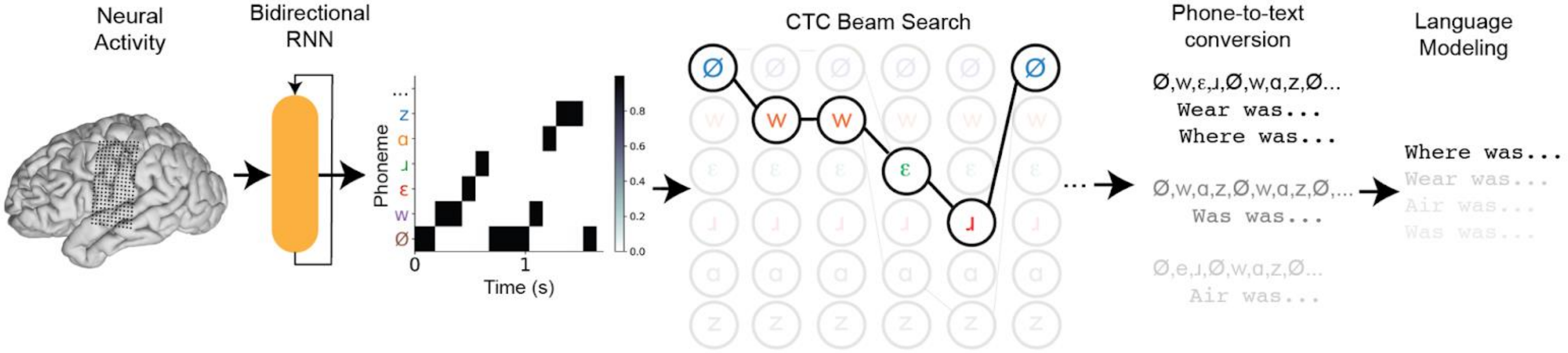


Multimodal speech neuroprosthesis

Goal is to <u>embody</u> speech restoration

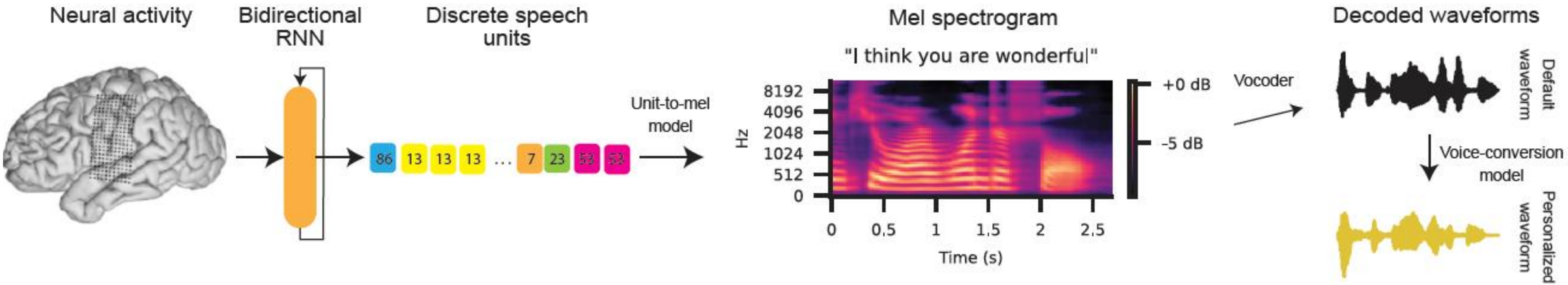
- **Enhance feedback-learning**
- **Restore personhood and identity**
- **More naturalistic speech output**
- **Facilitate virtual social interactions**



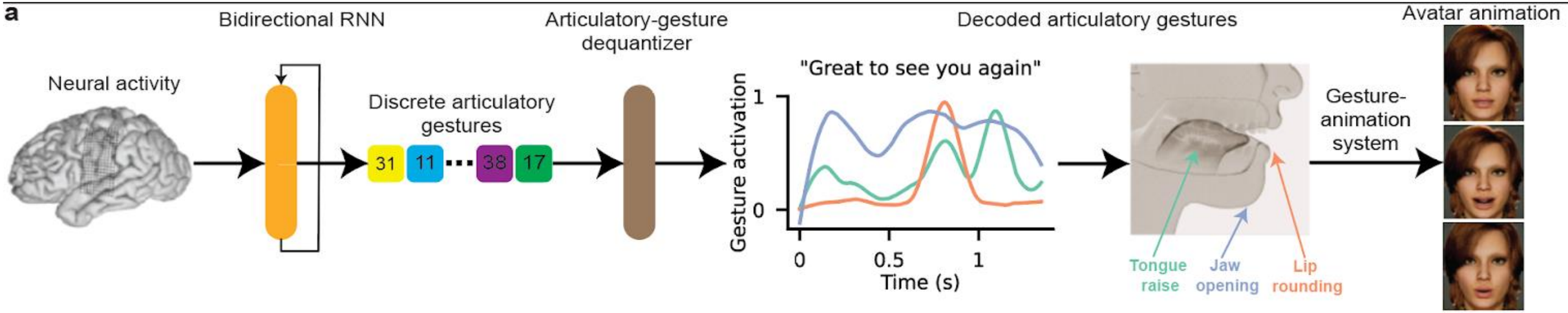

Neural Activity
Bidirectional RNN
Phoneme
...
z
ɑ
ɹ
ɛ
w
Ø
0
1
Time (s)
0.8
0.6
0.4
0.2
0.0
CTC Beam Search
Phone-to-text conversion
Ø,w,ɛ,ɹ,Ø,w,ɑ,z,Ø...
Wear was...
Where was...
Ø,w,ɑ,z,Ø,w,ɑ,z,Ø,...
Was was...
Ø,e,ɹ,Ø,w,ɑ,z,Ø...
Air was...
Language Modeling
Where was...
Wear was...
Air was...
Was was...

Text copy

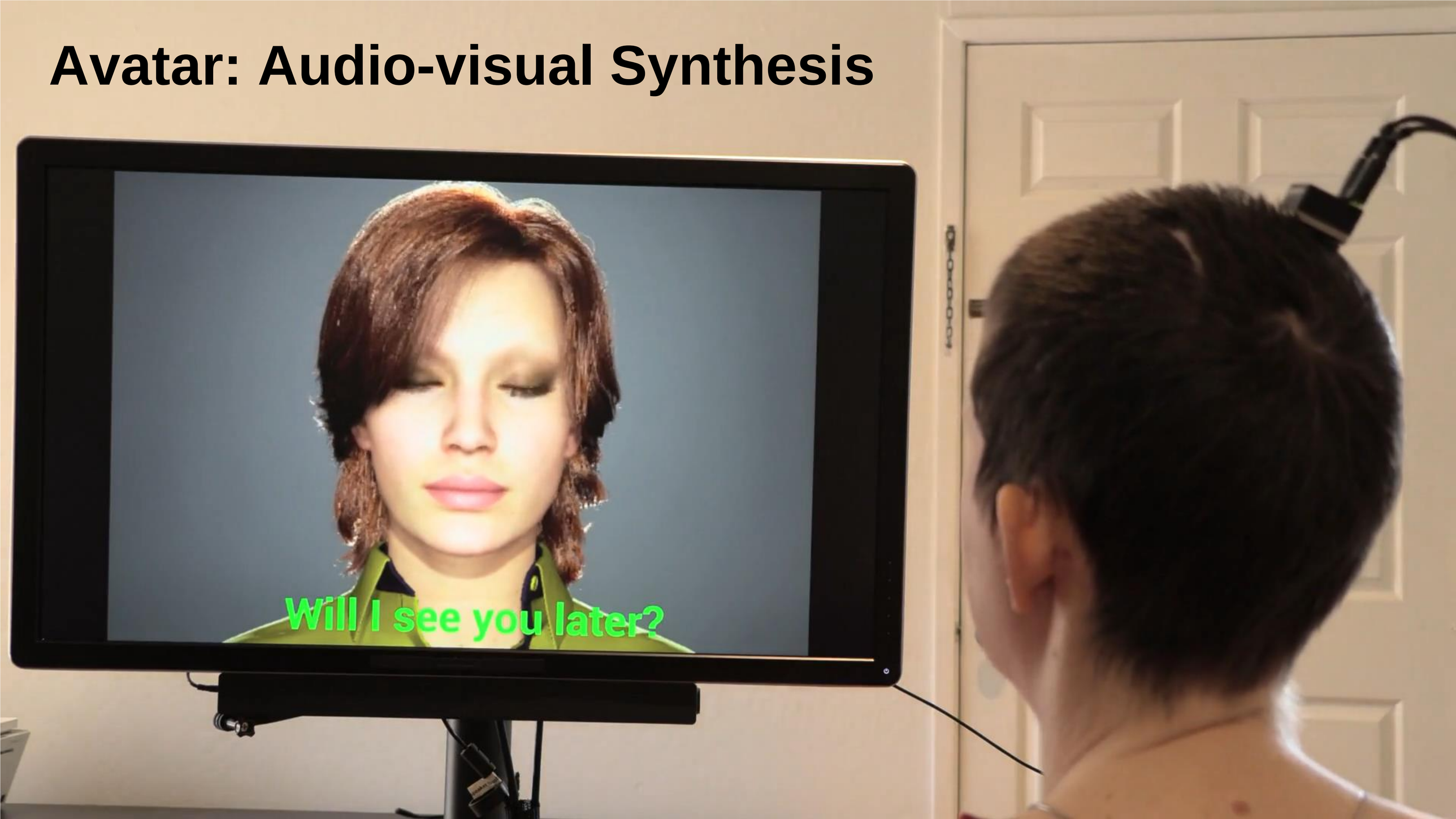
Speech synthesis



Facial avatar

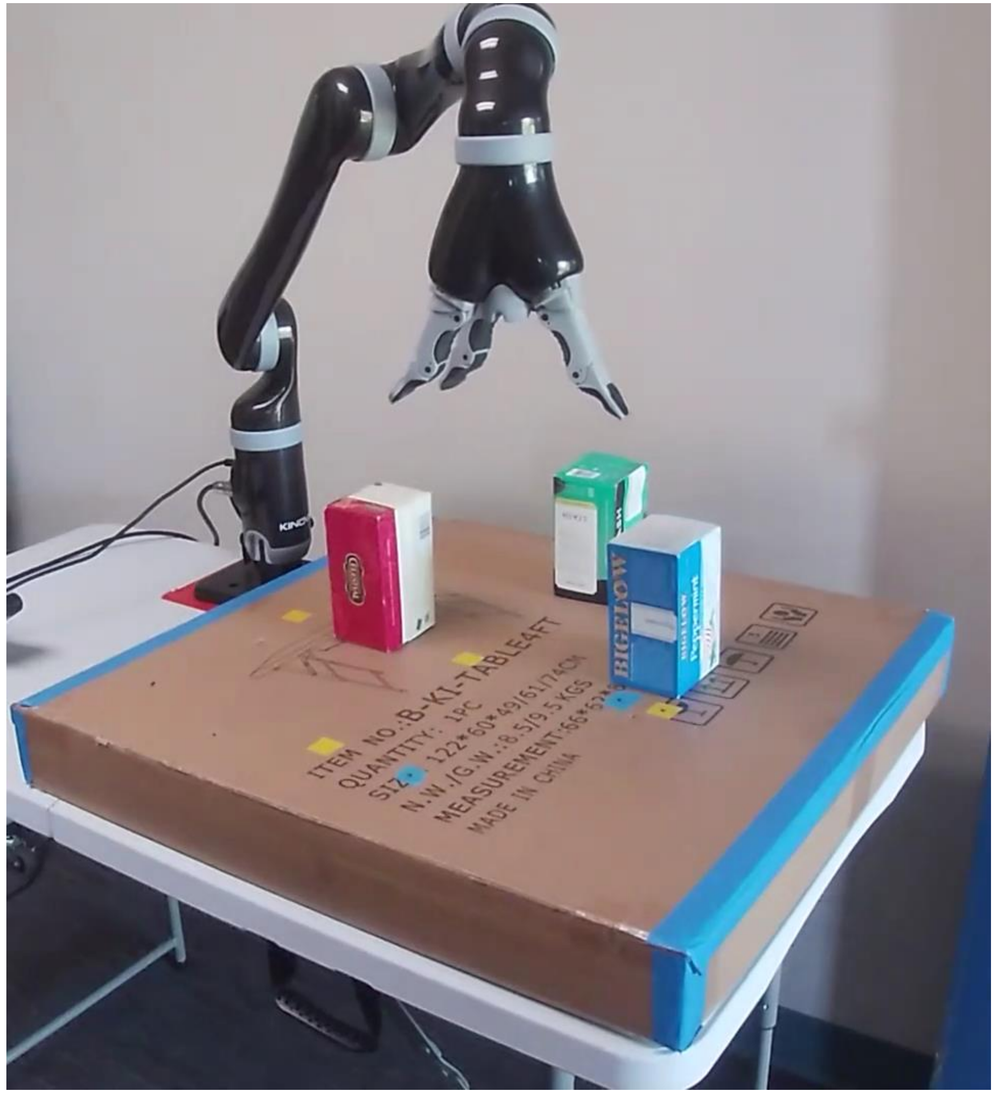


Avatar: Audio-visual Synthesis



Avatar- Expressions

Robotic arm



Ganguly lab collaboration
in progress

Speech neuroprosthesis

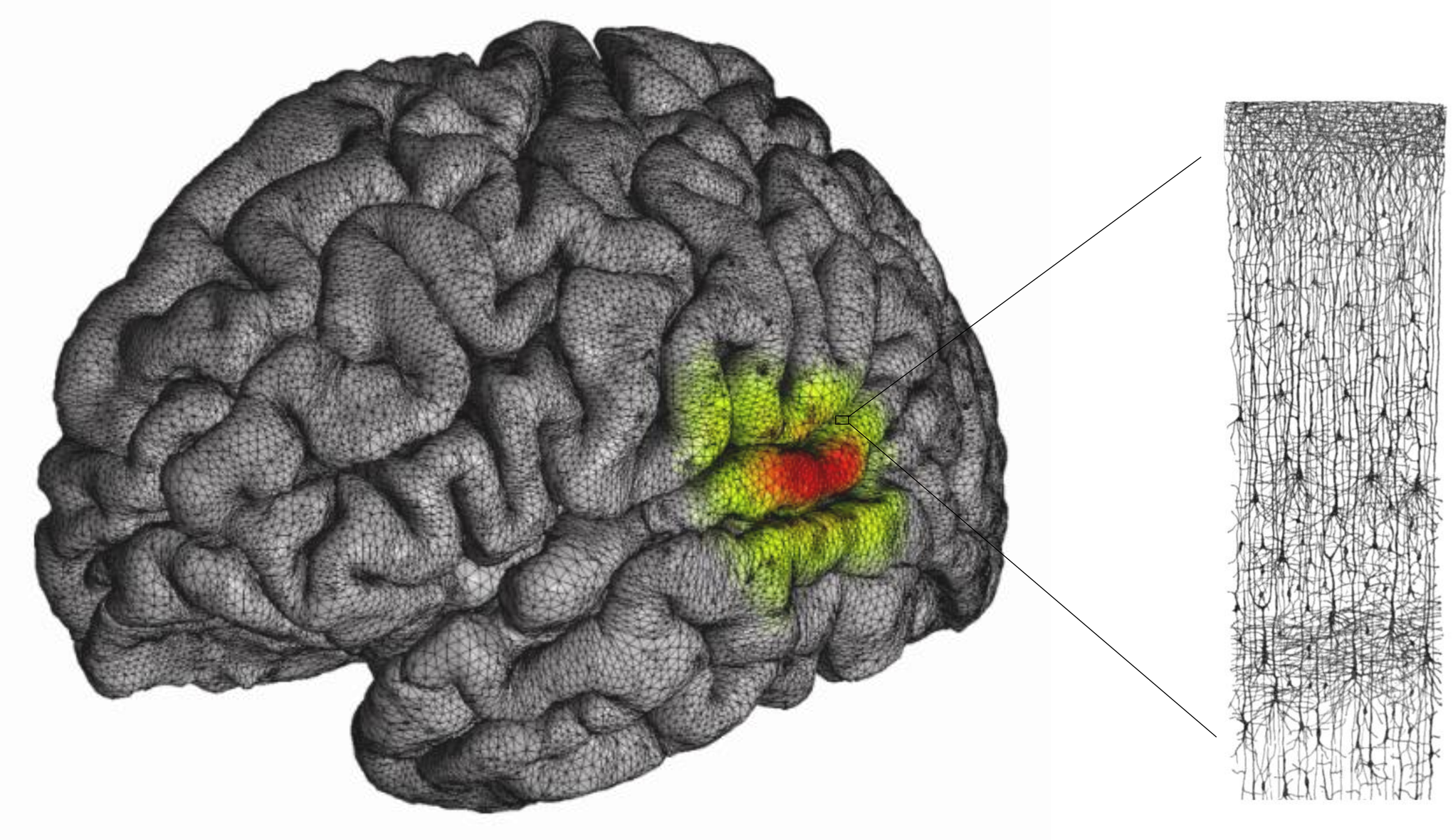
The science

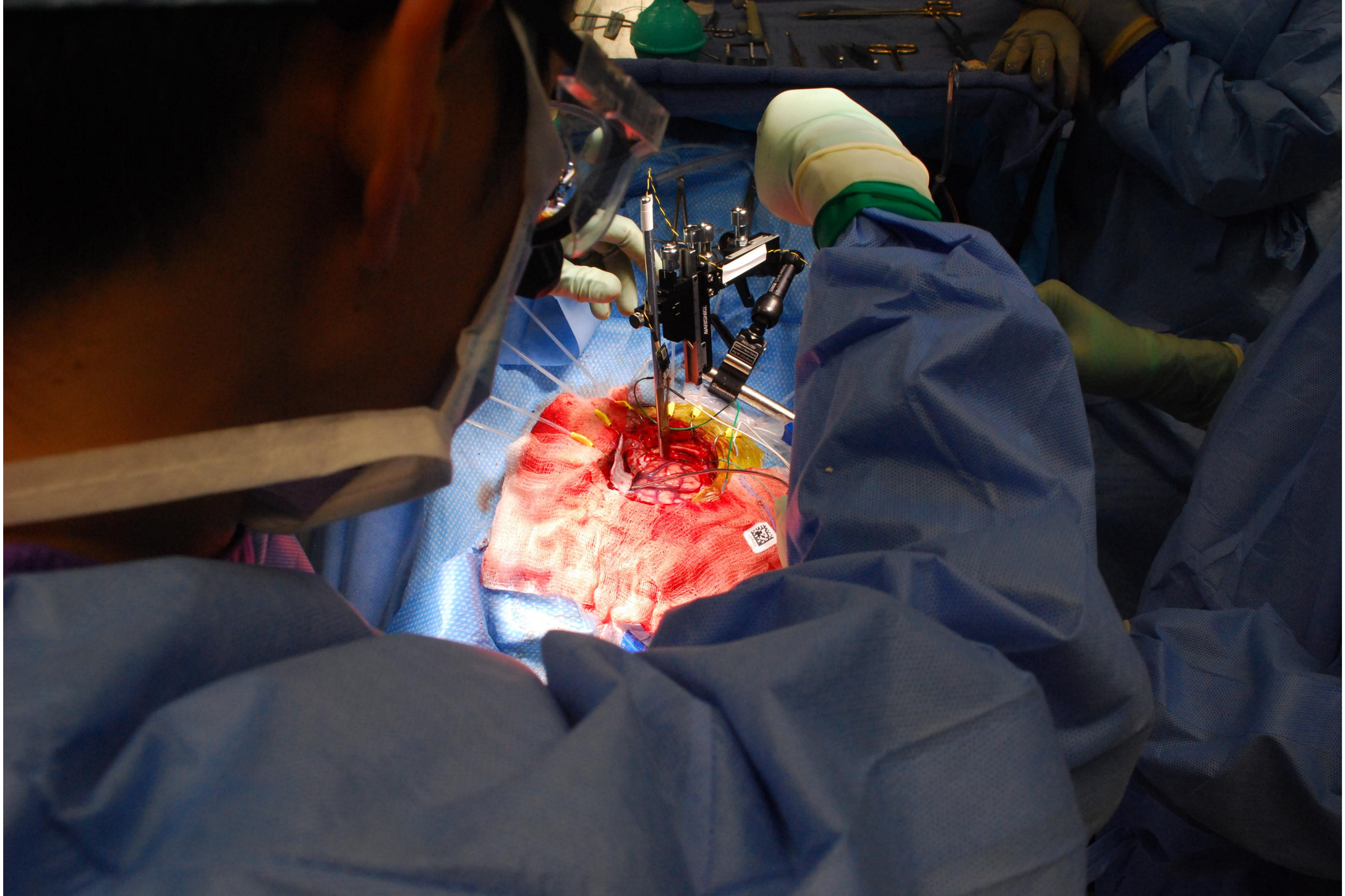
- The precentral gyrus encodes articulatory movements
- Dual laryngeal motor cortex
- Articulatory kinematic trajectories for all consonants and vowels

***The t**ranslation*

- High-performance text, synthesis, and facial avatar
- Embodied speech neuroprosthesis can enhance verbal and nonverbal communication
- Increased channel count and AI optimization increases performance

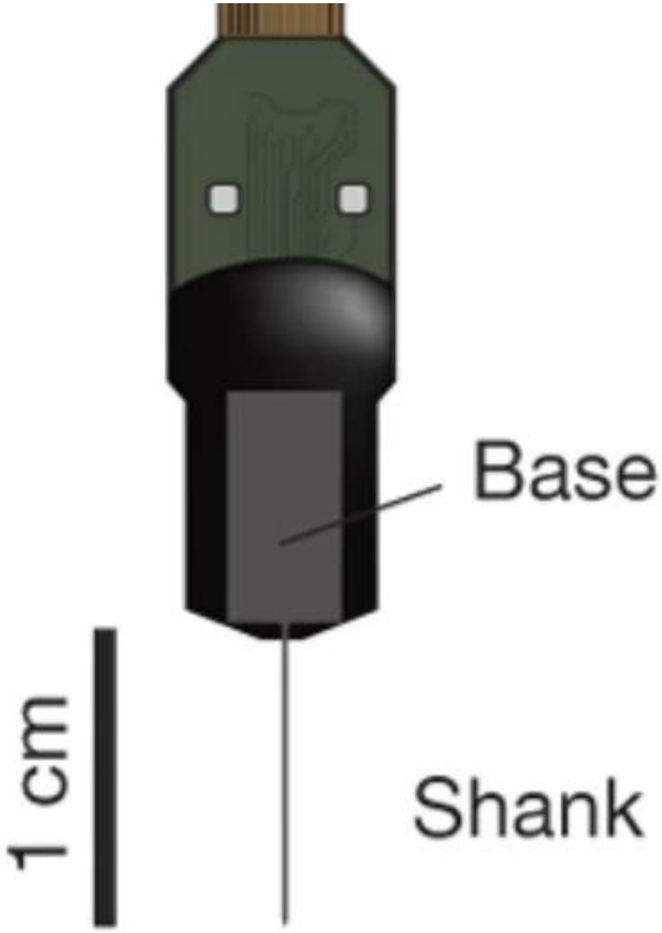
Towards cellular basis of language

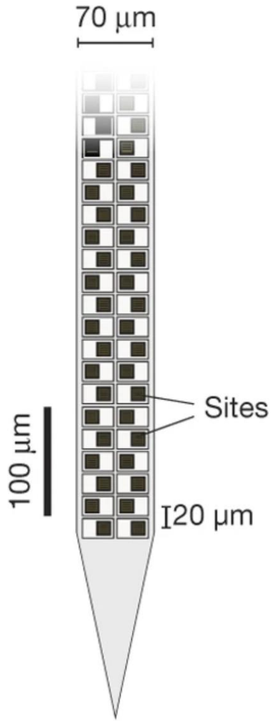




Neuropixels

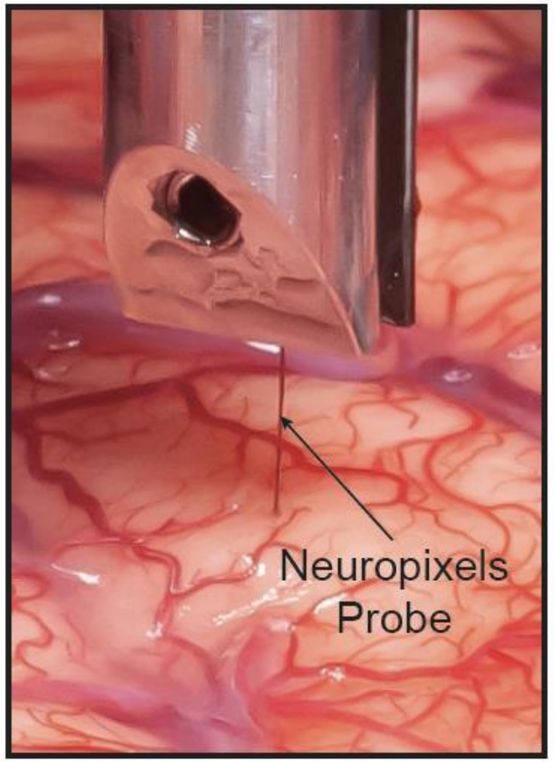
960 electrodes
(384 simultaneous recording)

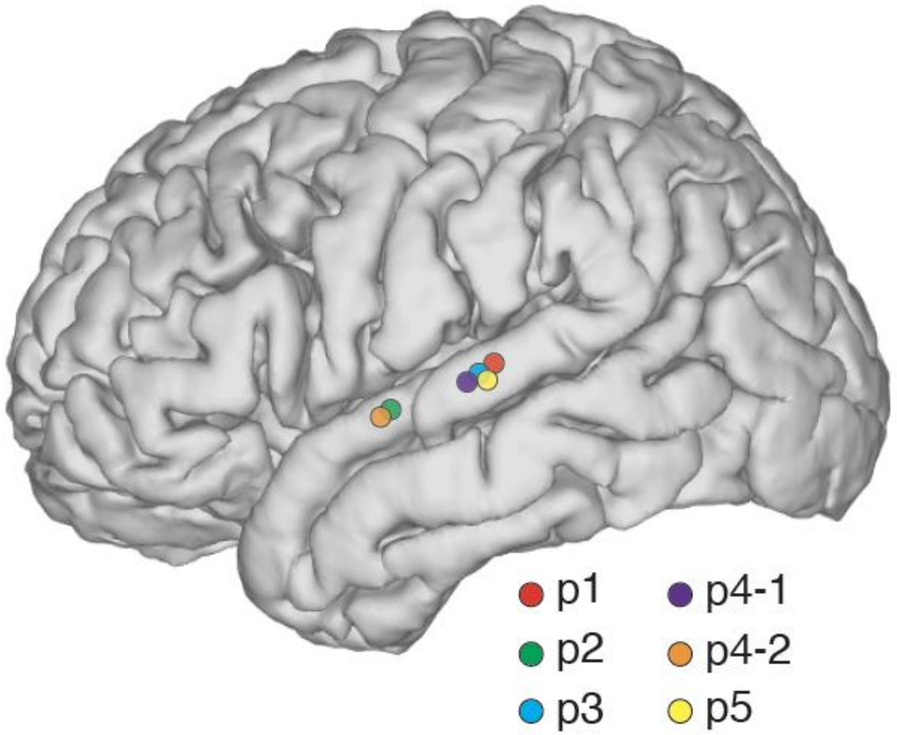


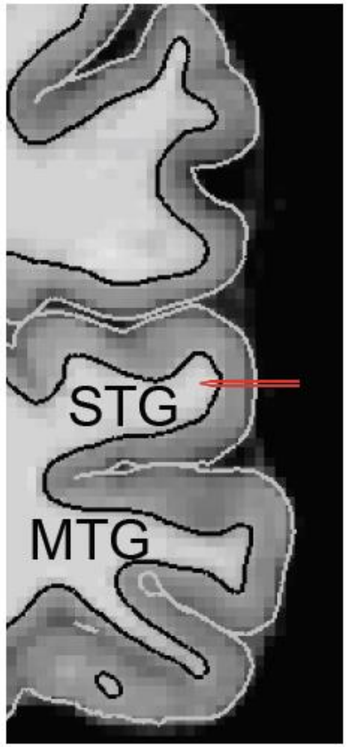


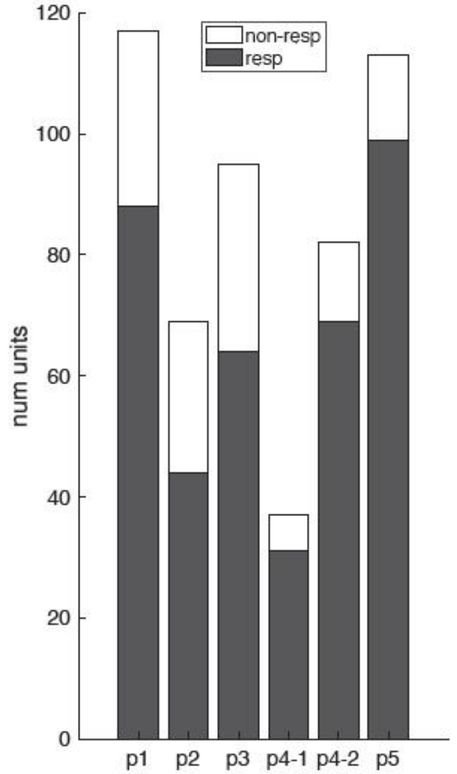
Recently translated into humans

Chung*, Sellers*, *et al*., 2022, *Neuron*
Paulk *et al*., 2022, *Nature Neuroscience*







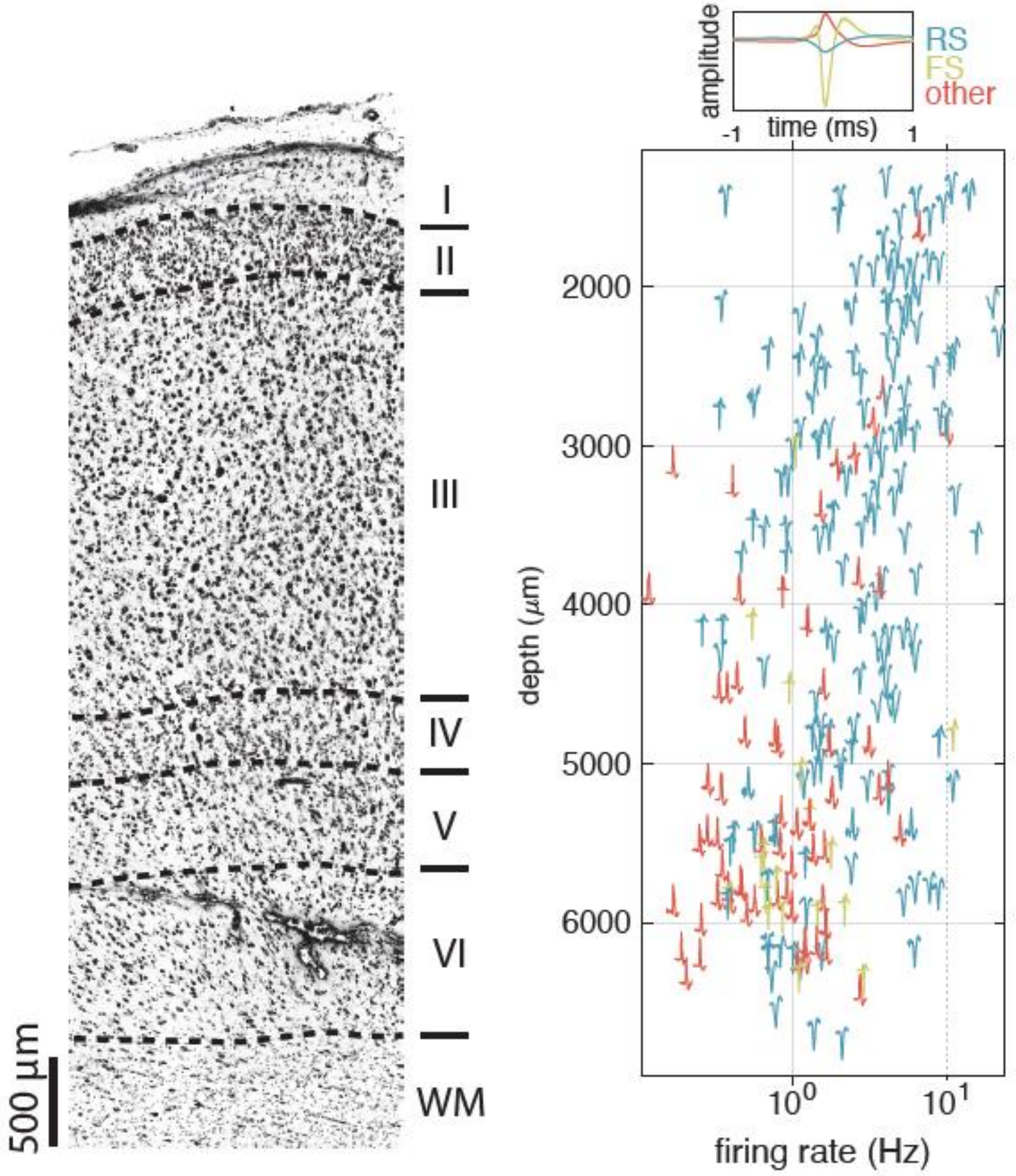


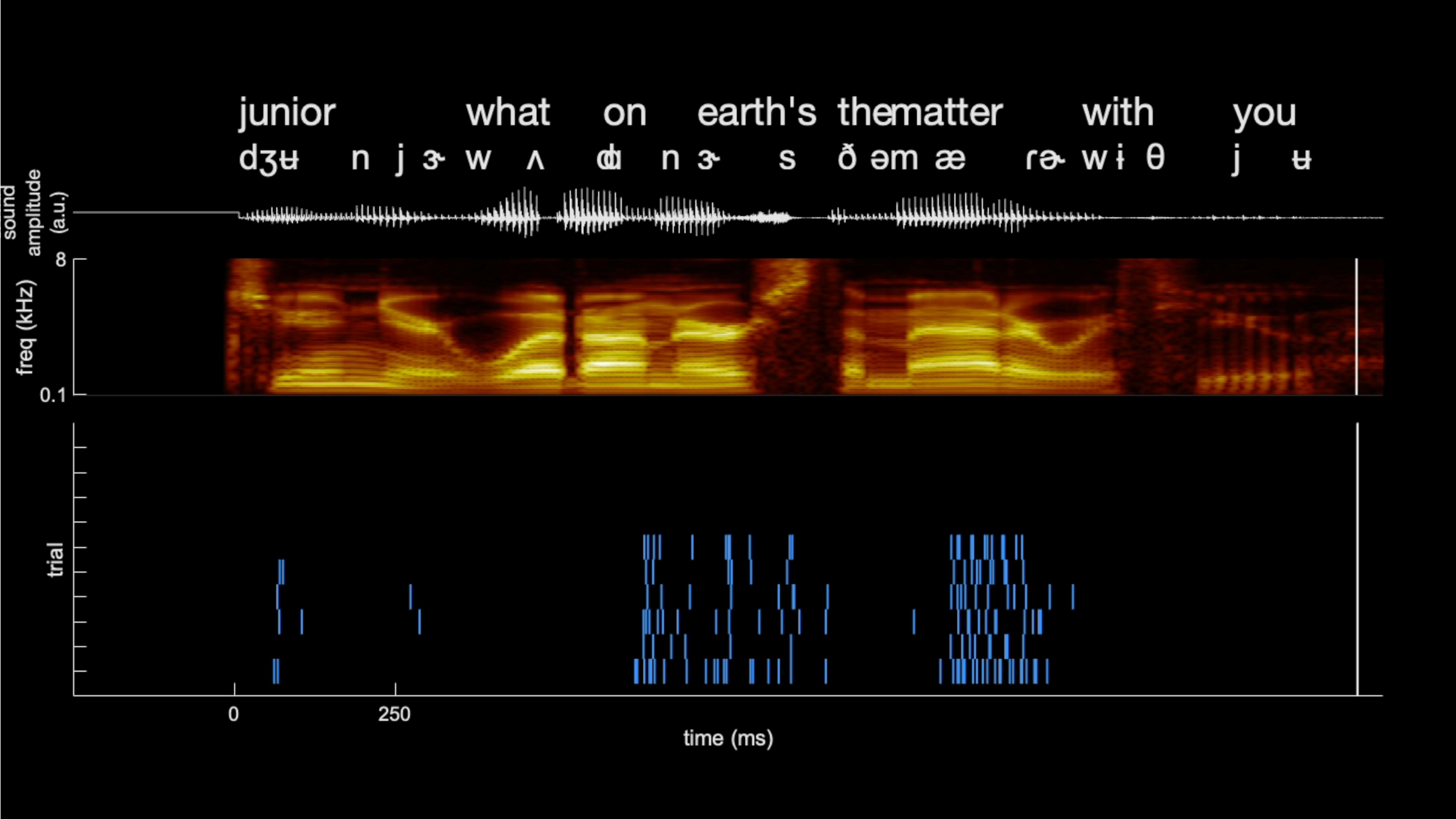
Recently translated into humans

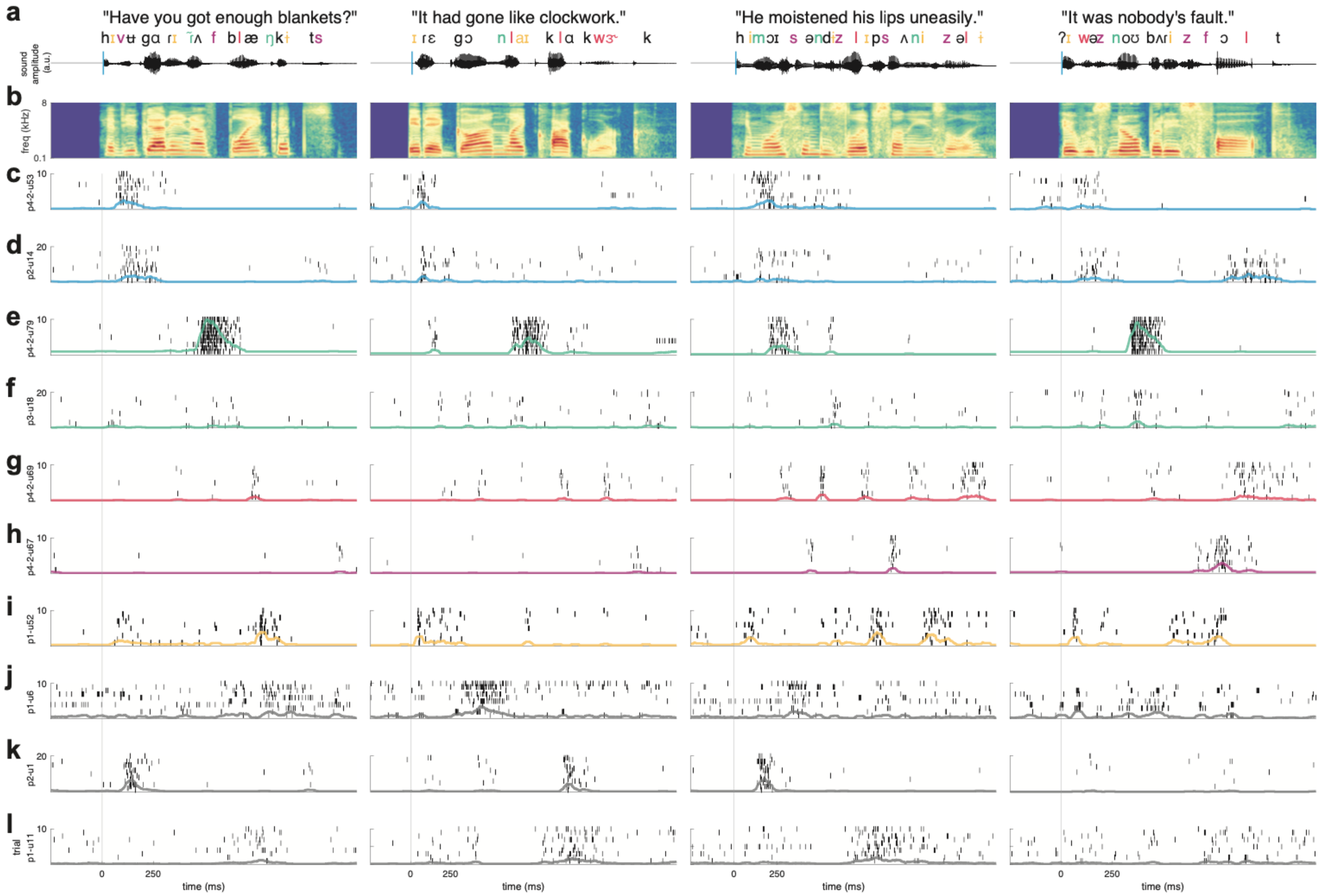
Chung*, Sellers*, *et al*., 2022, *Neuron*

Paulk *et al*., 2022, *Nature Neuroscience*

Multi laminar STG recordings

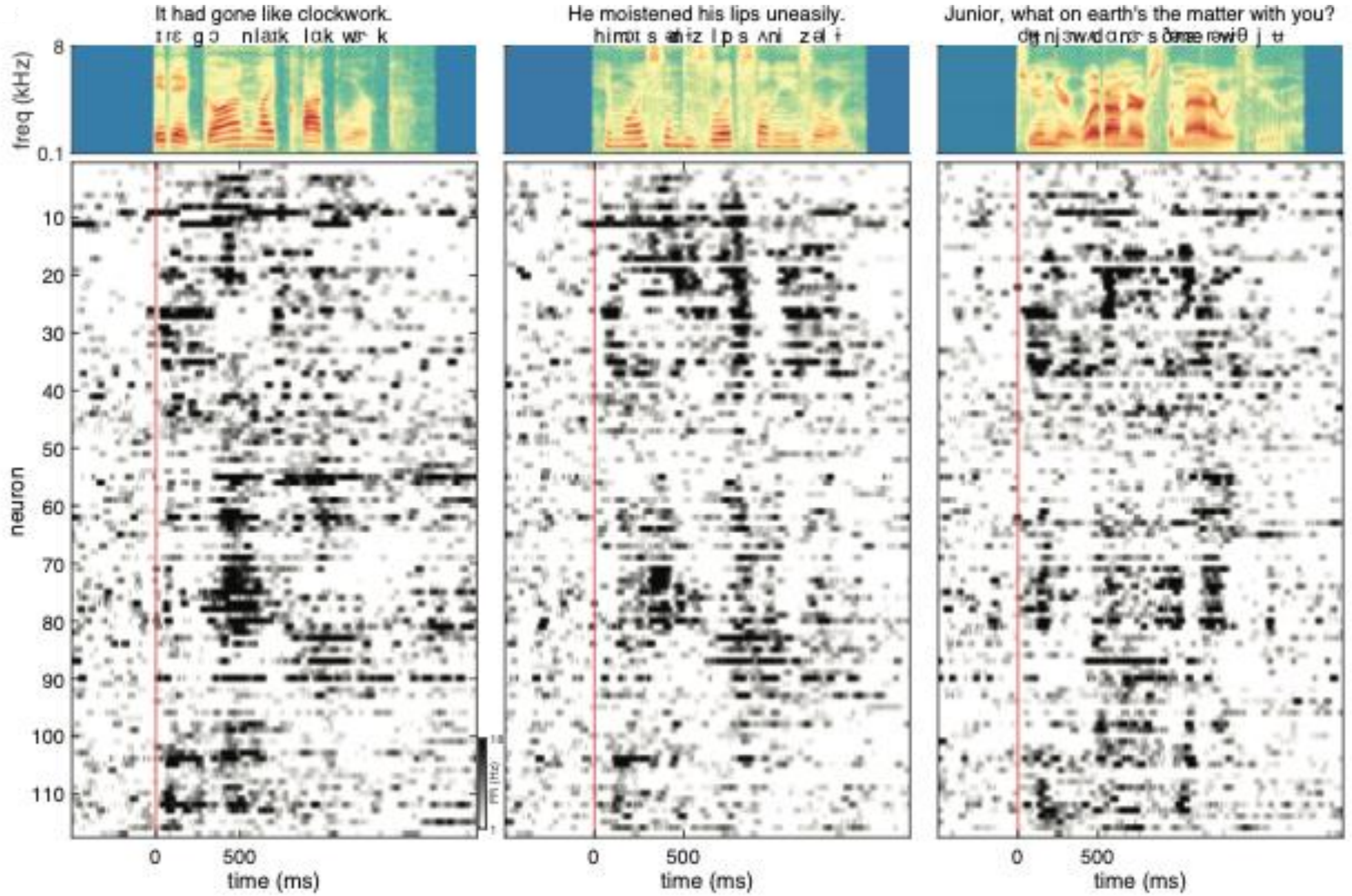



junior what on earth's thematter with you
dʒʉ n j ɝ w ʌ ɑ n ɝ s ð əm æ rə· w ɨ θ j ʉ
sound amplitude (a.u.)
8
freq (kHz)
0.1
trial
0
250
time (ms)


a
"Have you got enough blankets?"
hɪvʉ gɑ rɪ ɾʌ f blæ ŋkɨ ts
"It had gone like clockwork."
ɪ rɛ gɔ n laɪ k lɑ kwɝ k
"He moistened his lips uneasily."
h imɔɪ s əndɨz l ɪps ʌni z əl ɨ
"It was nobody's fault."
ʔɪ wəz noʊ bʌɾi z f ɔ l t
sound amplitude (a.u.)
b
freq (kHz)
8
0.1
c
p4-2-u53
d
p2-u14
e
p4-2-u79
f
p3-u18
g
p4-2-u69
h
p4-2-u67
i
p1-u52
j
p1-u6
k
p2-u1
l
trial
p1-u11
10
20
0
250
time (ms)

Neuronal responses across the cortical depth:

heterogeneity and local clustering



Chang Speech Lab

Ilina Bhaya-Grossman
Many Xu Duo
Laura Gwilliams
Sarah Harper
Patrick Hullett
Ankit Khambhati
Deb Levy
Matt Leonard
Kaylo Littlejohn
Jessie Liu
Sean Metzger
David Moses
Yitzak Norman
Terri Scott
Kristin Sellers
Alex Silva
Yizhen Zhang
Lingyun Zhao

Alumni

Gopala Anumanichipalli
Kristopher Bouchard
Maryam Bijanzadeh
Josh Chartier
Connie Cheung
David Conant
Ben Dichter
Erik Edwards
Neal Fox
Liberty Hamilton
Jon Kleen
Yuanning Li
Narayan Sankaran
Yulia Oganian
Emily Stephen
Nima Mesgarani
Leah Muller
Matthias Sjerps
Claire Tang

Collaborators

Barun Datta
Marleen Welkenhuysen
Mitchel Berger
Jinsong Wu/Junfeng Lu
Bharath Chandrasekan
Nina Dronkers
Karunesh Ganguly
Marilu Gorno-Tempini
Keith Johnson
John Houde
Robert Knight
Christoph Schreiner
Stephen Wilson

Funding

NIH BRAIN INITIATIVE U01
NIDCD
CZI
Simons
HHMI