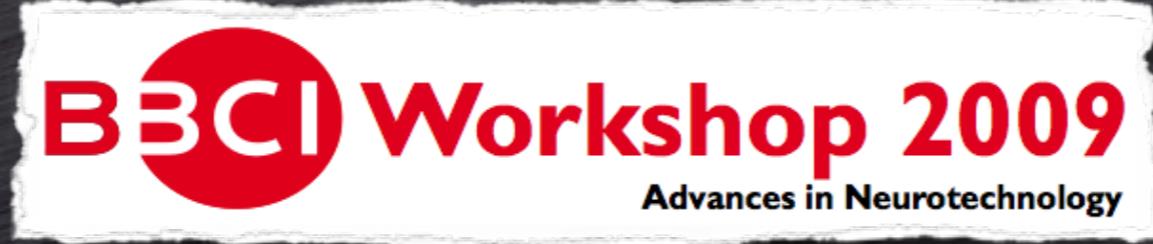


Theory and Application of Electrocorticographic (ECoG) Signals in Humans



Berlin, Germany

July 8, 2009

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Associate Professor of Neurology, Albany Medical College, Albany, New York

Associate Professor of Biomedical Sciences, State University of New York, Albany, New York

Adj. Assistant Professor of Neurosurgery, Washington University in St. Louis, St. Louis, Missouri

Adj. Associate Professor of Biomedical Engineering, Rensselaer Polytechnic Institute, Troy, New York

Electrocorticographic Signals (ECoG) in Humans

Relationship

BCI Control

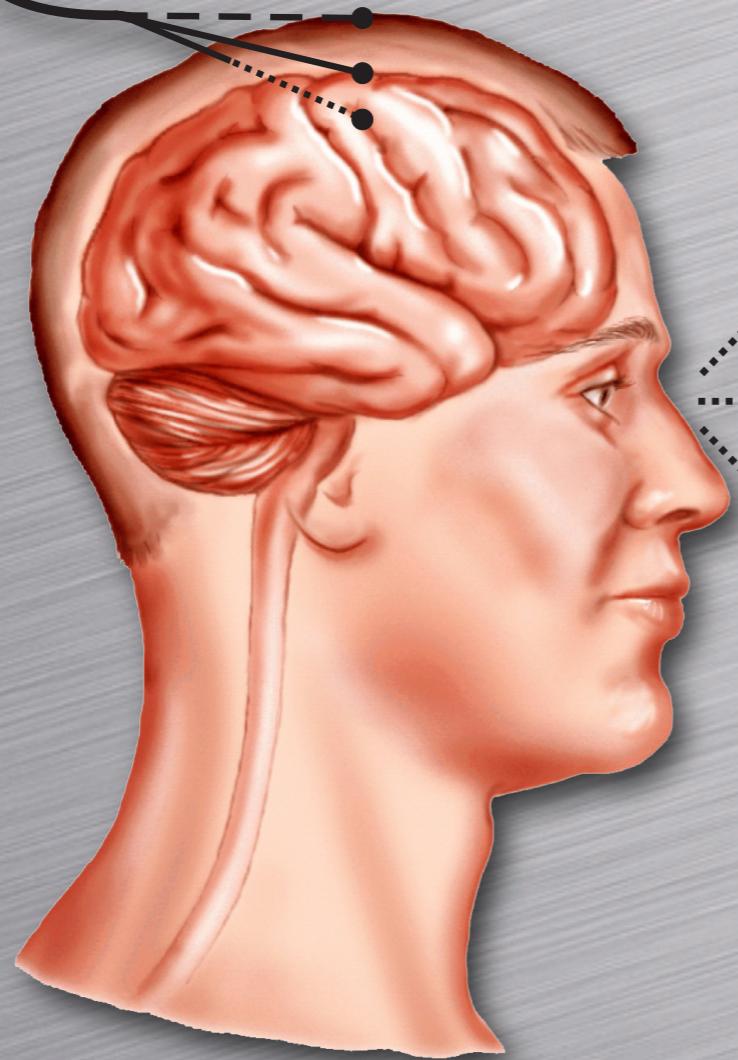
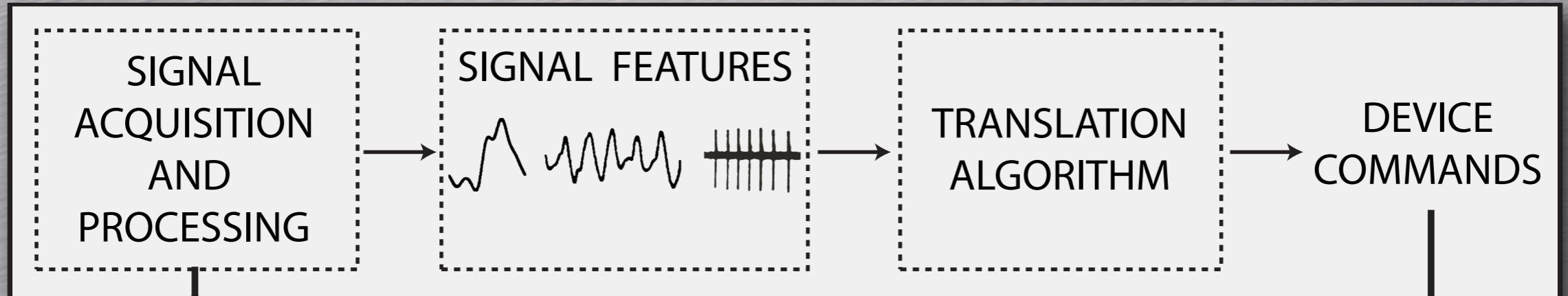
Characteristics

Diagnosis

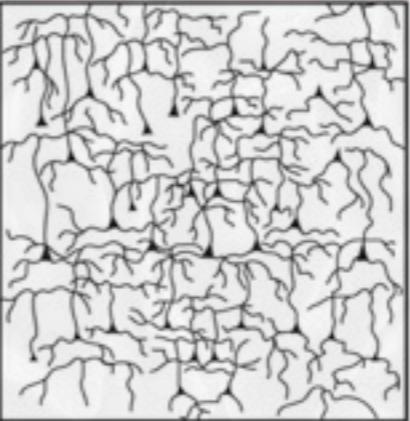
ECoG

Open Questions

Future Directions

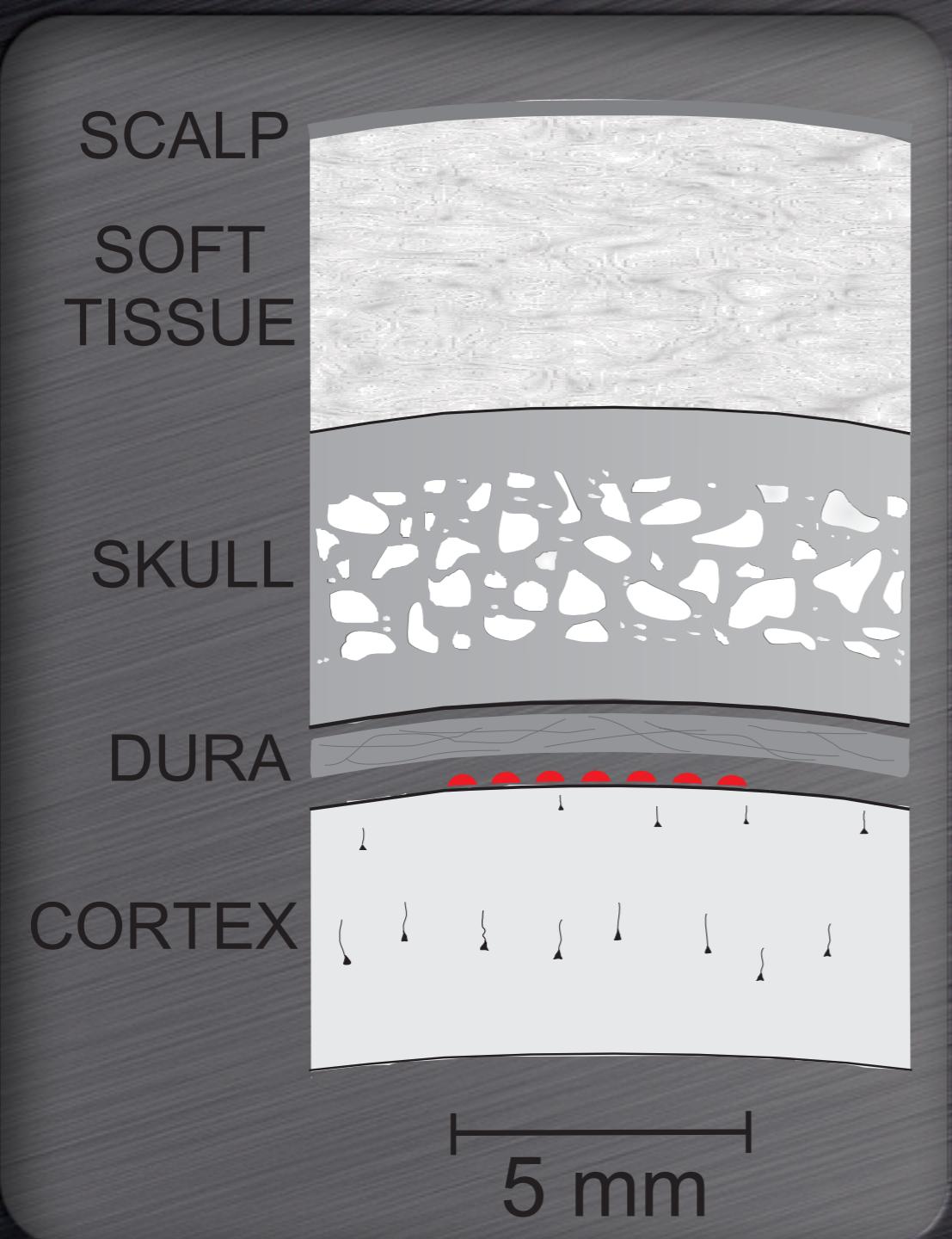


Different BCI Signal Modalities

| | Regional Domain | Signals | Invasiveness |
|-----------------|-----------------|---|--------------|
| EEG | 3-5cm | | Non-invasive |
| ECoG | .5-1cm |  | Invasive |
| Field Potential | 1mm | | |
| Single Unit | 200 microns |  | |

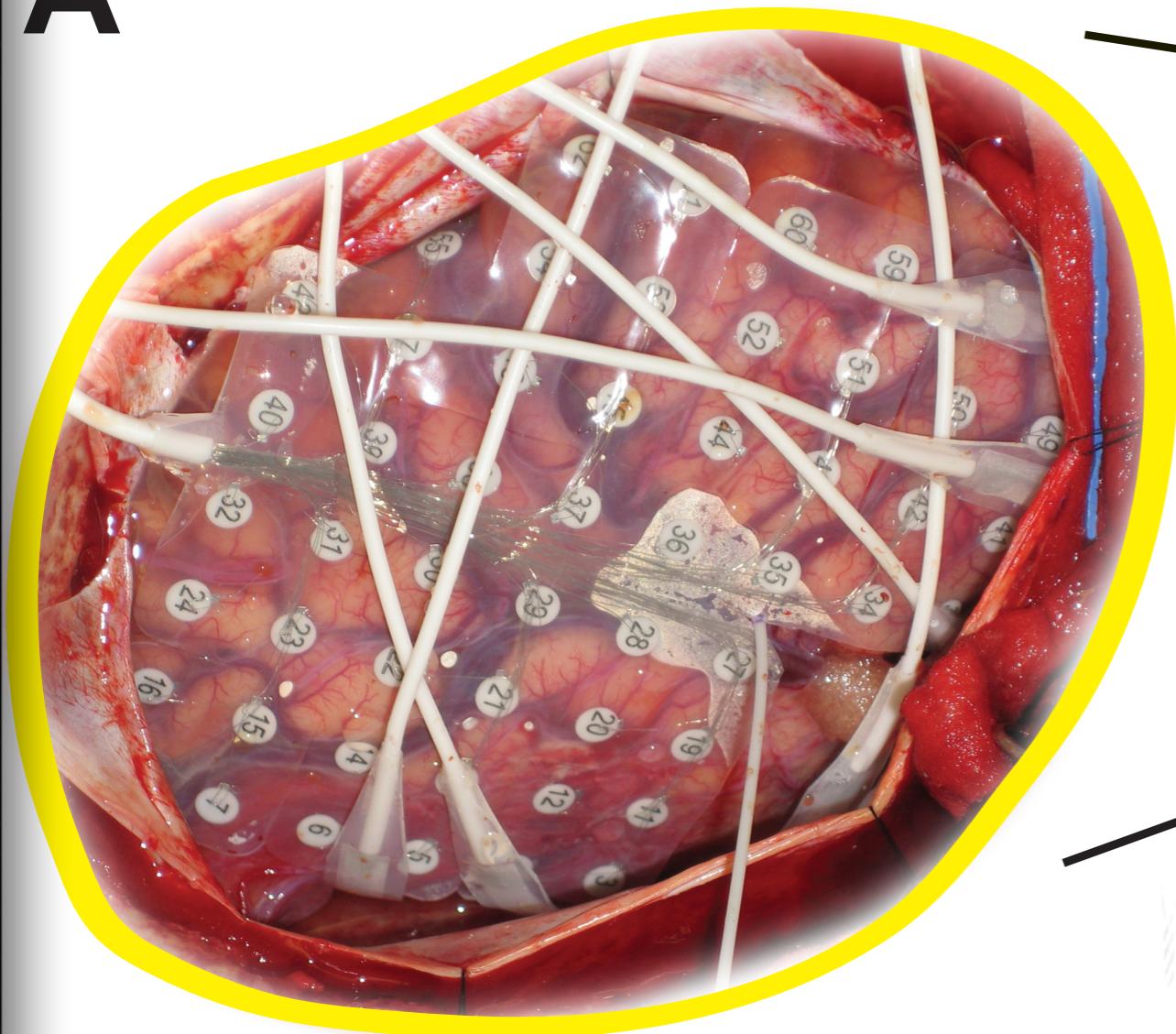
Leuthardt, Schalk et al., *Neurosurgery*, 2006

Electrocorticography (ECoG)

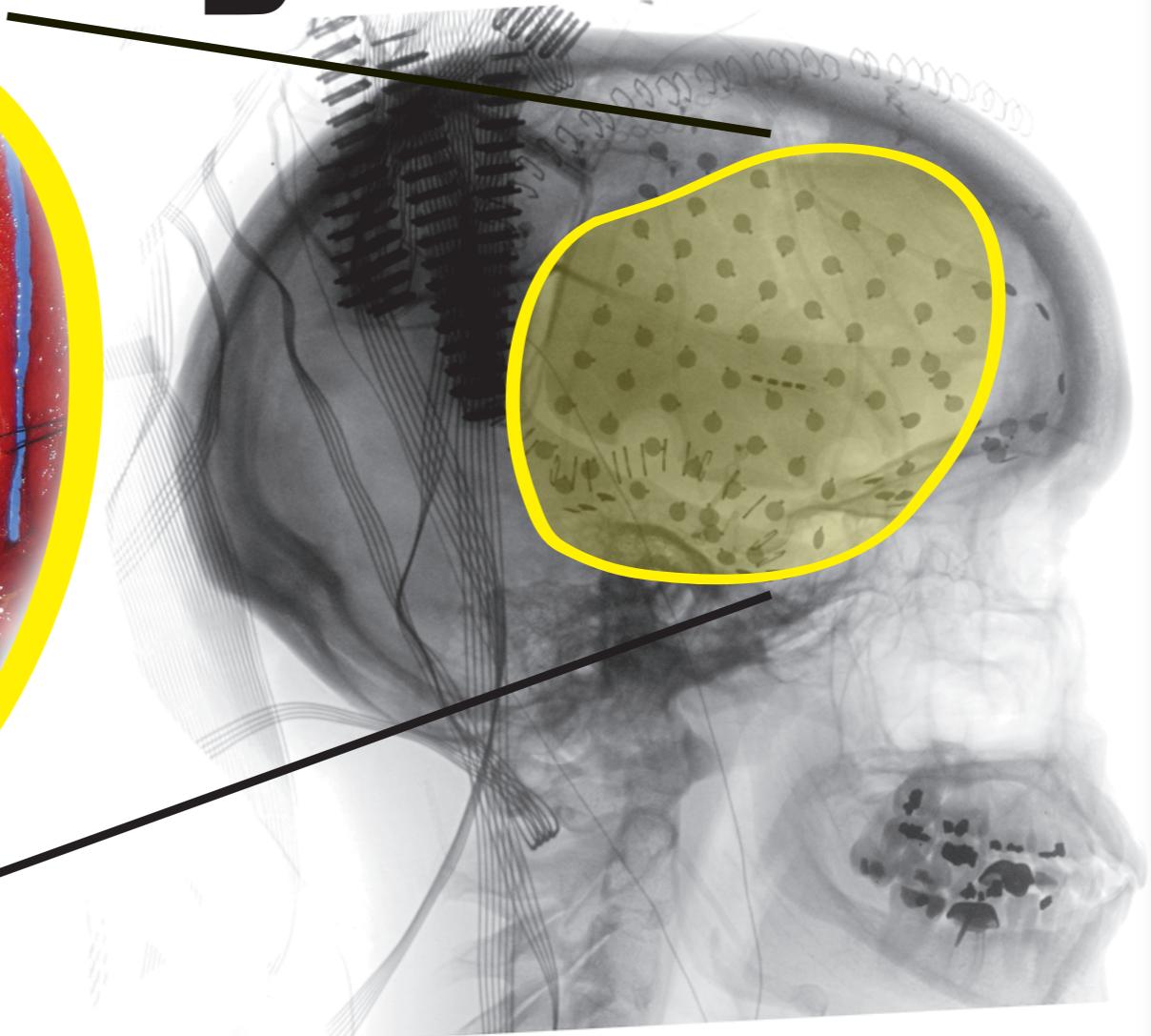


Electrocorticographic Signals (ECoG) in Humans

A



B



Brunner, Ritaccio, Schalk et al., *Epilepsy and Behavior*, 2009

We find in baboons that such chronically implanted electrodes (of diameter $\frac{1}{2}$ – 1 mm) record activity in the spike frequency range (1000-10000 Hz) that accompanies and just precedes specific voluntary movements of the contralateral arm or leg. ... The ratio of signal to noise can be greatly improved by selecting lower frequencies ... [between] 80 and 250 Hz.

Brindley and Craggs, *J. Physiol. (Lond.)*, 1972

We are interested in the possibility of using signals from the motor cortex for driving an artificial motor pathway, a powered limb or a powered splint in paraplegic, hemiplegic or tetraplegic patients. For this purpose it is safest to place the recording electrodes inside the skull but outside the dura mater.

Brindley and Craggs, *J. Physiol. (Lond.)*, 1972

Movement control requires recordings from neurons.

J.K. Chapin, *Current Opinion in Neurology*, 2000

It is impossible ... to obtain a direct readout of movement intent [without action potentials].

J.P. Donoghue, *Nature Neuroscience*, 2002



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J.K. Chapin, *Current Opinion in Neurology*, 2000



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More Recently ...

More Recently ...

Pesaran et al., *Nature Neuroscience*, 2002

“Local field potential activity discriminated between directions with approximately the same accuracy as the spike rate.”

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“Hand movement target and velocity can be inferred from multiple local field potentials (LFPs) in single trials approximately as efficiently as from multiple single-unit activity (SUA) recorded from the same electrodes.”

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Pesaran et al., *Nature Neuroscience*, 2002

“Local field potential activity discriminated between directions with approximately the same accuracy as the spike rate.”

Mehring et al., *Nature Neuroscience*, 2003

“Hand movement target and velocity can be inferred from multiple local field potentials (LFPs) in single trials approximately as efficiently as from multiple single-unit activity (SUA) recorded from the same electrodes.”

Schalk et al., *J Neural Eng*, 2007

“The fidelity of the decoding [of hand position], reported in the present study [using ECoG in humans], is within the range of those achieved using implanted microelectrodes in monkeys.”

More Recently ...

Pesaran et al., *Nature Neuroscience*, 2002

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Waldert et al., *J Neurosci*, 2008

“[Hand] movement directions could be inferred on a single-trial basis from MEG activity. ... Based on simultaneous MEG and EEG recordings, we show that the inference of movement direction works equally well for both recording techniques.”

More Recently ...

Pesaran et al., *Nature Neuroscience*, 2002

"Local field potential activity discriminated between directions with approximately the same accuracy as the spike rate."

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Waldert et al., *J Neurosci*, 2008

"[Hand] movement directions could be inferred on a single-trial basis from MEG activity. ... Based on simultaneous MEG and EEG recordings, we show that the inference of movement direction works equally well for both recording techniques."

Leuthardt, Schalk et al., *J Neural Eng*, 2004; Mehring et al., *J Physiol Paris*, 2004; Rickert et al., *J Neurosci*, 2005; Sanchez et al., *J Neurosci Meth*, 2008; Pistohl et al., *J Neurosci Meth*, 2008

Electrocorticographic Signals (ECoG) in Humans

Characteristics

- mu/beta rhythms
- gamma activity
- local motor potential

ECoG

Relationship

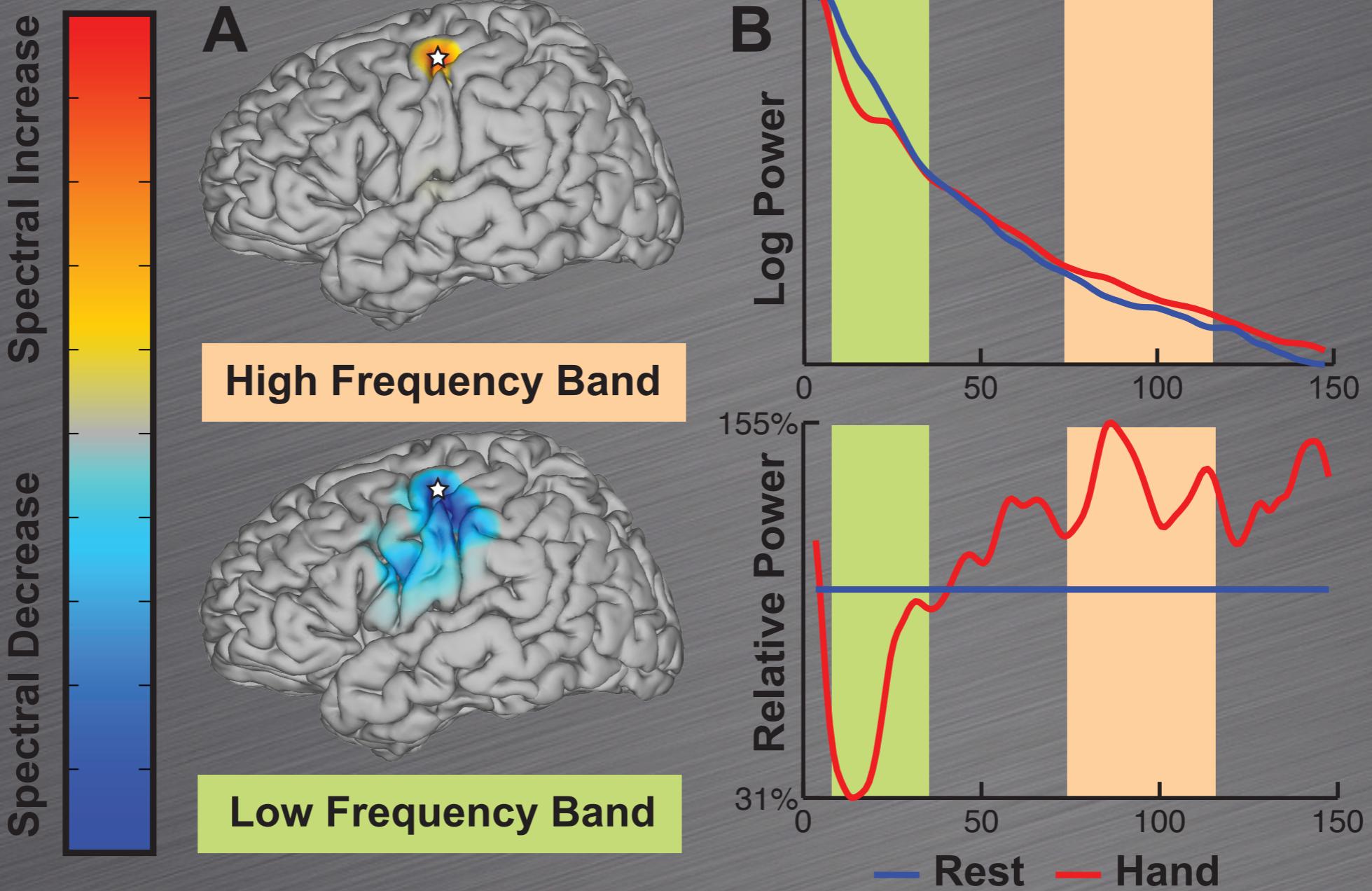
BCI Control

Diagnosis

Open Questions

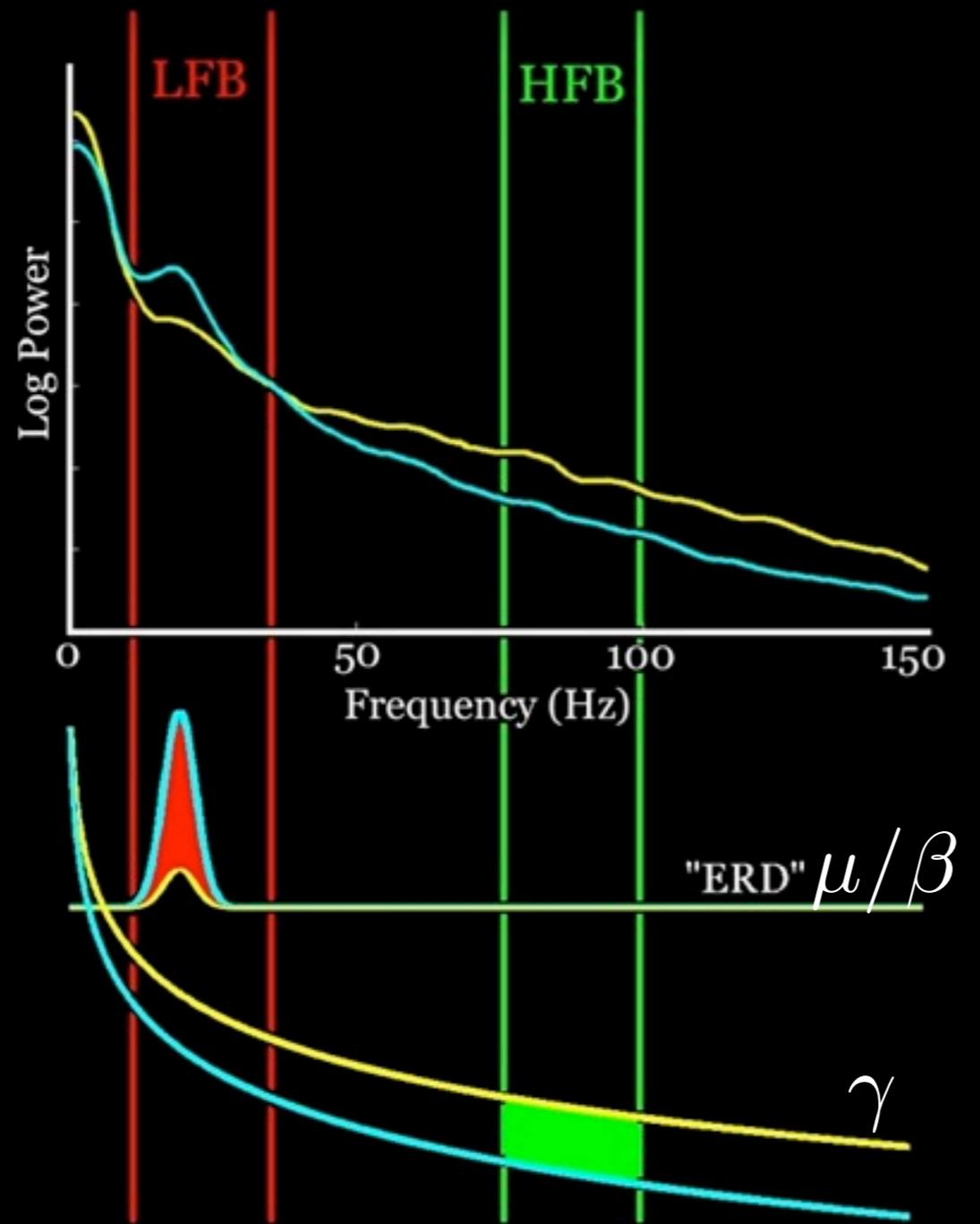
Future Directions

Mu/Beta and Gamma



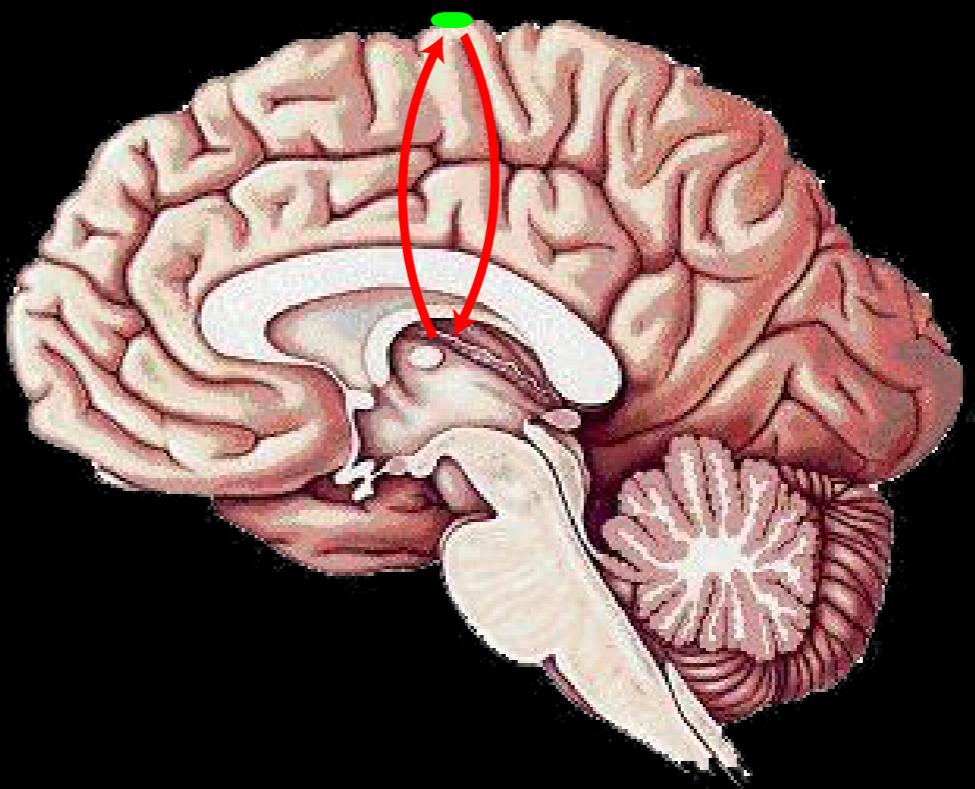
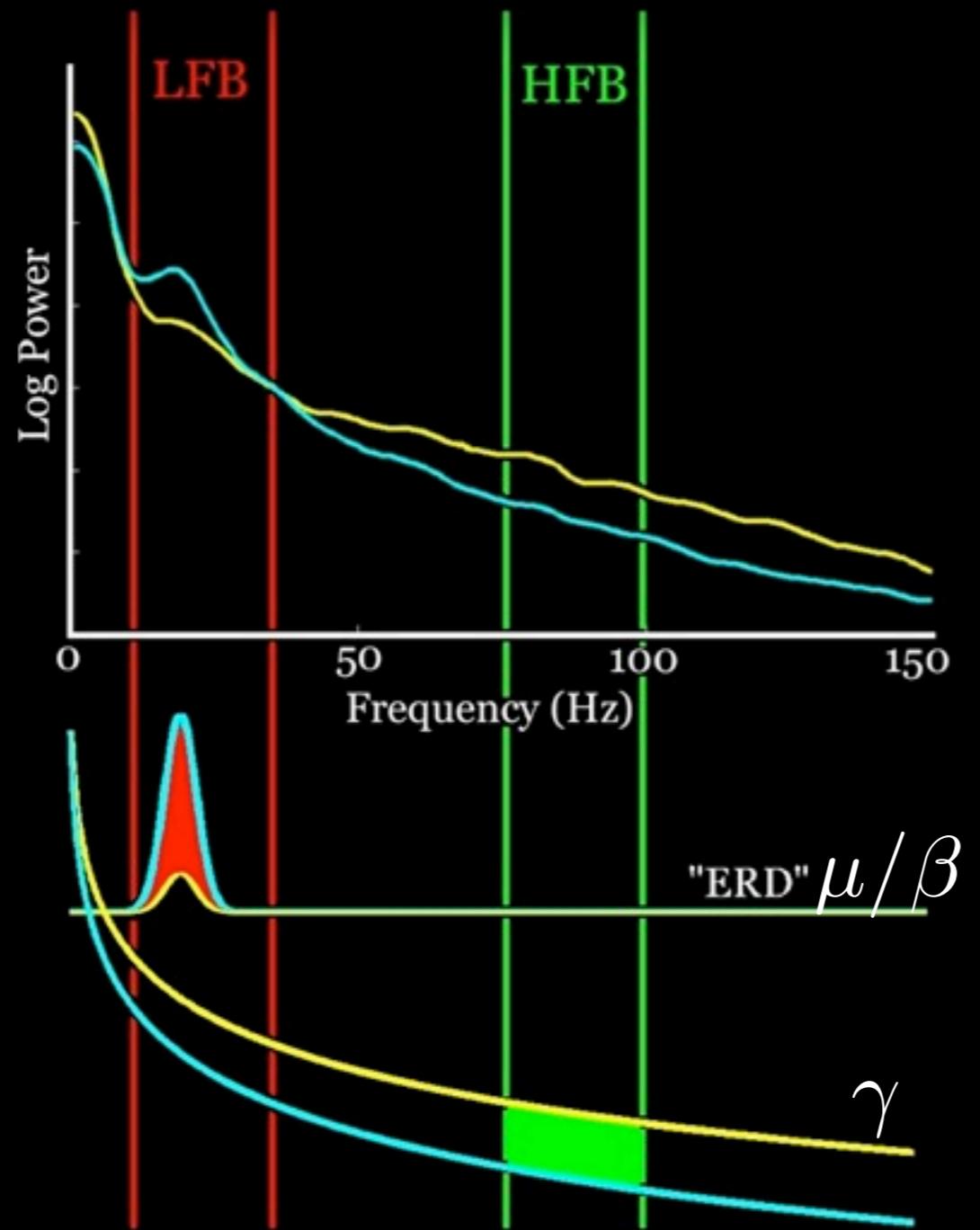
e.g., Crone et al., 1998, 2000, 2001; Graimann et al., 2002; Fetz, Ojemann et al., 1999, 2001; Sinai et al., 2005;
Miller, Schalk et al., 2007; Leuthardt, Schalk, et al., 2007; Brunner, Schalk et al., 2009

Mu/Beta and Gamma



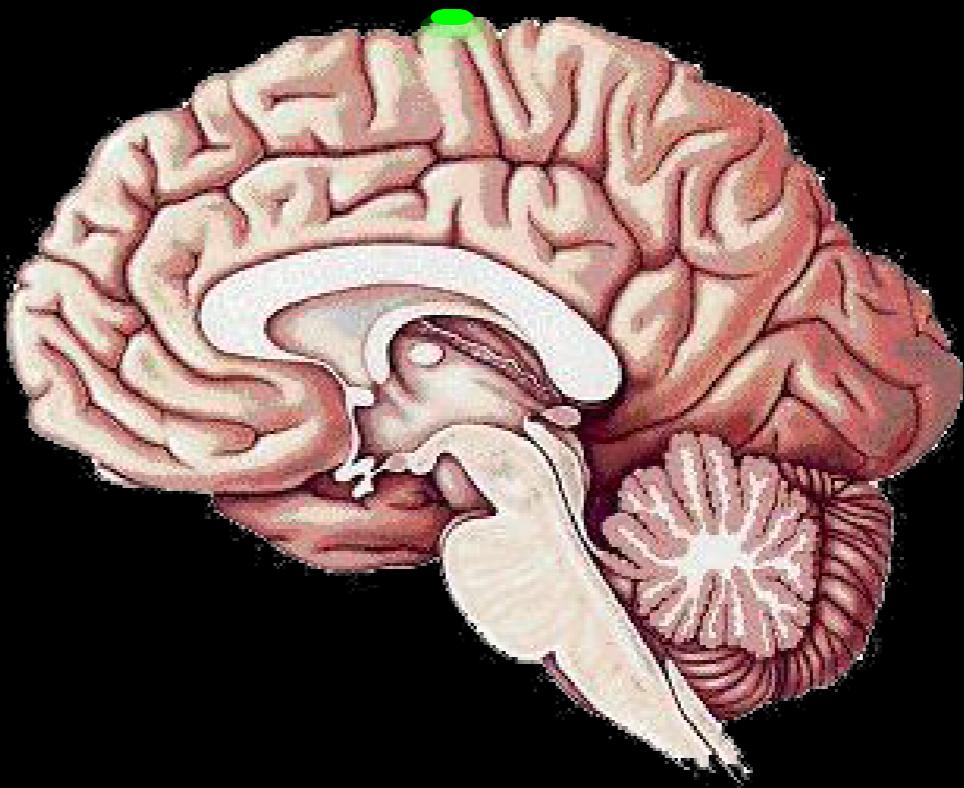
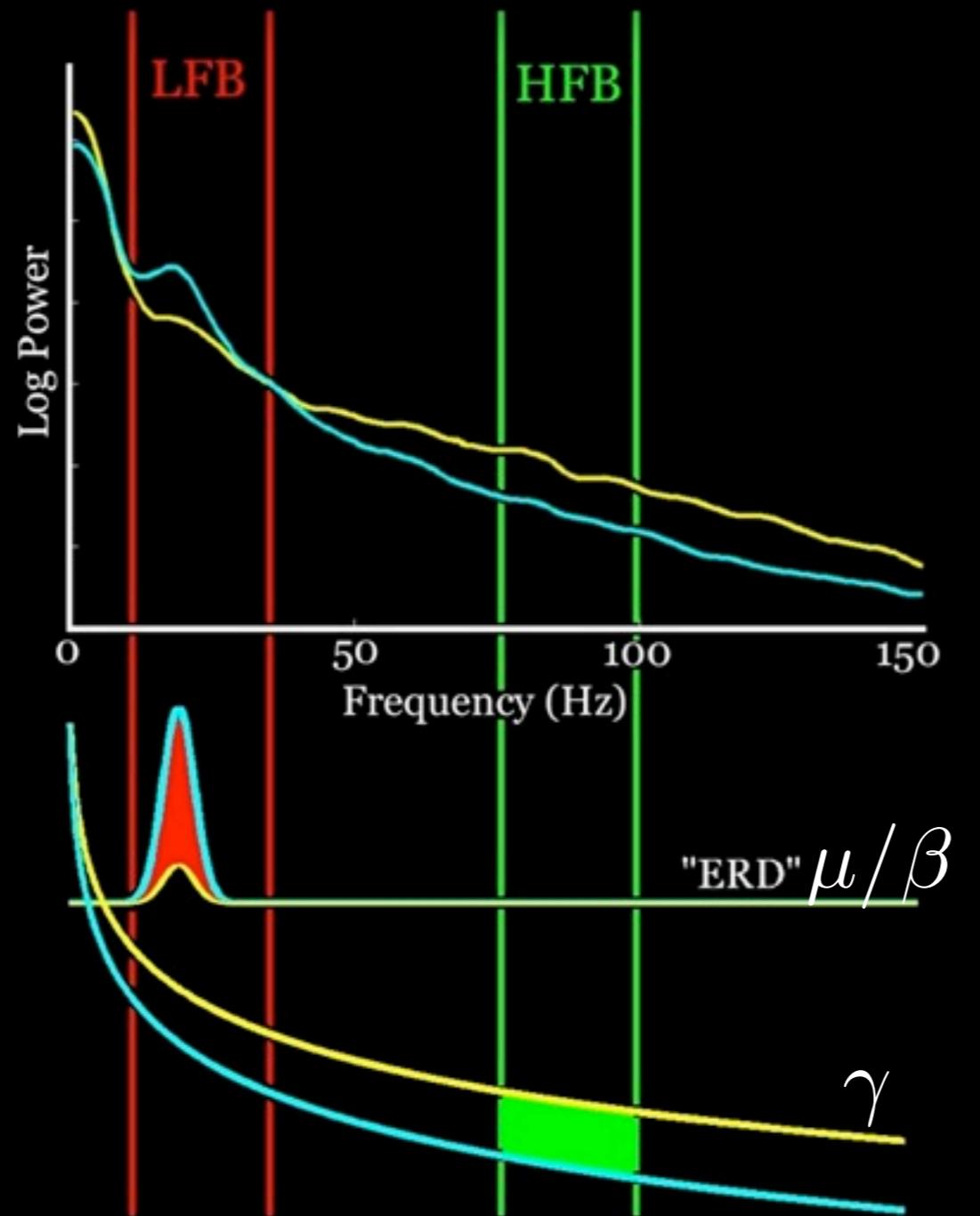
Miller, Schalk et al., in preparation

Mu/Beta and Gamma



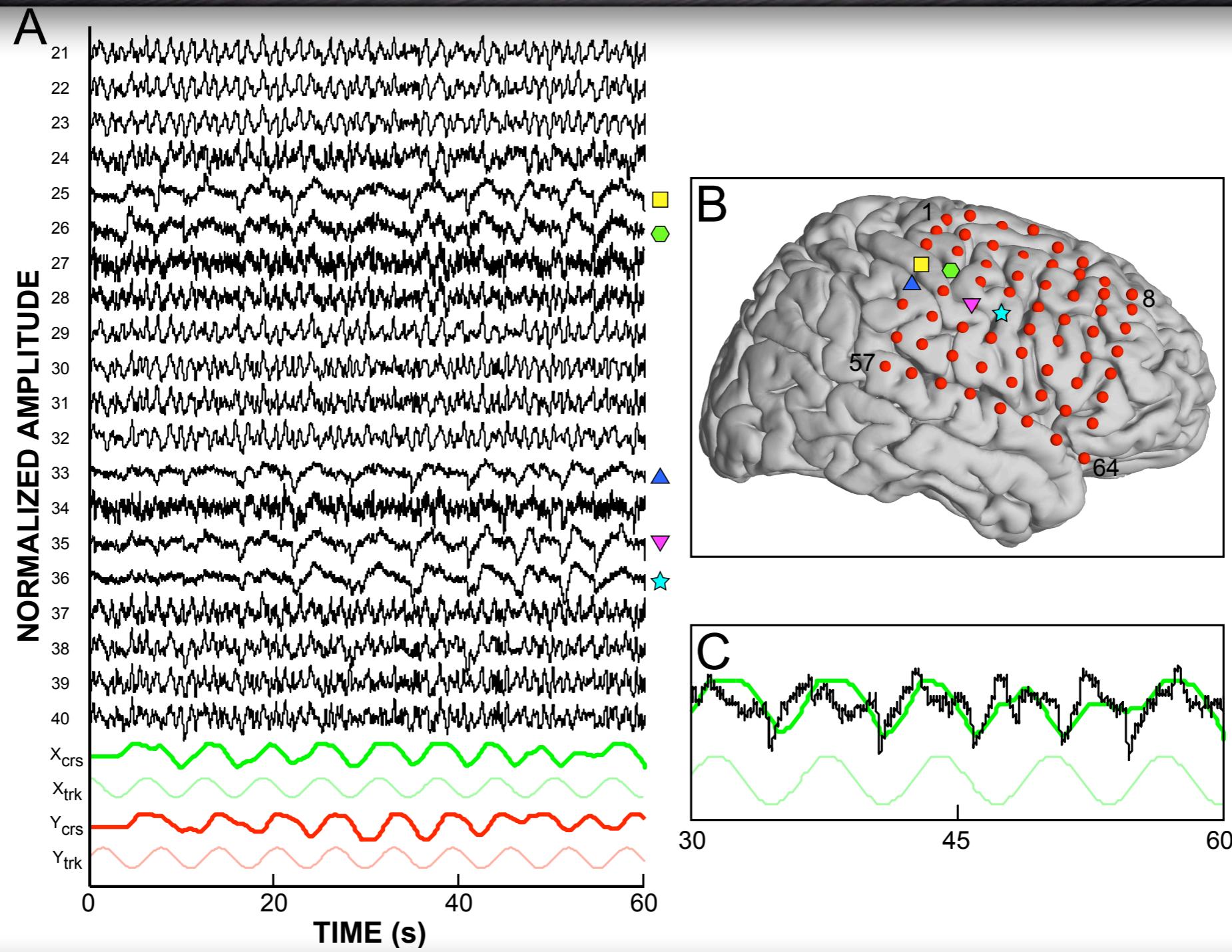
Miller, Schalk et al., in preparation

Mu/Beta and Gamma



Miller, Schalk et al., in preparation

The Local Motor Potential (LMP)



Schalk et al., *J Neural Eng*, 2007

Electrocorticographic Signals (ECoG) in Humans

Relationship

BCI Control

Characteristics

Diagnosis

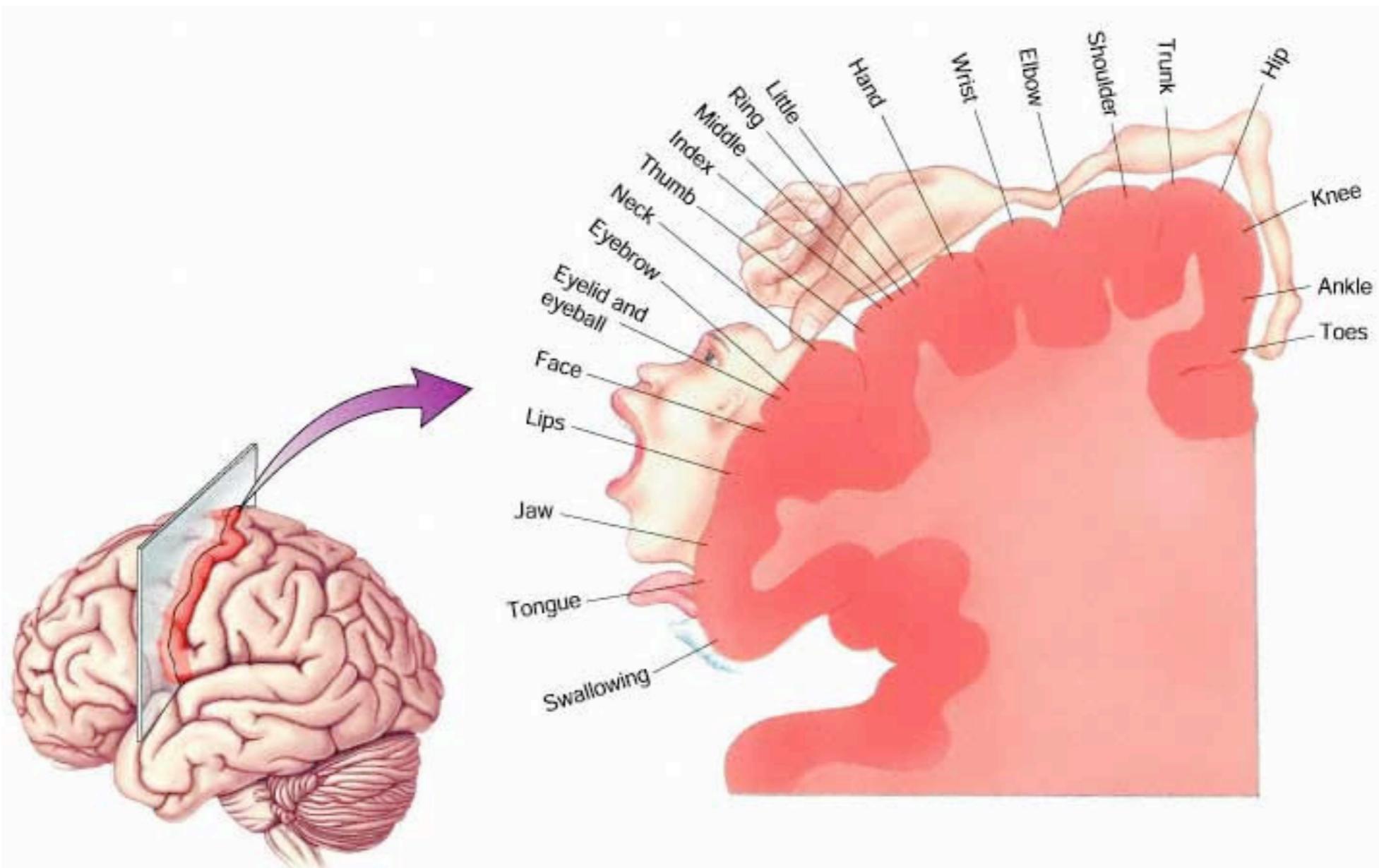
ECoG

Open Questions

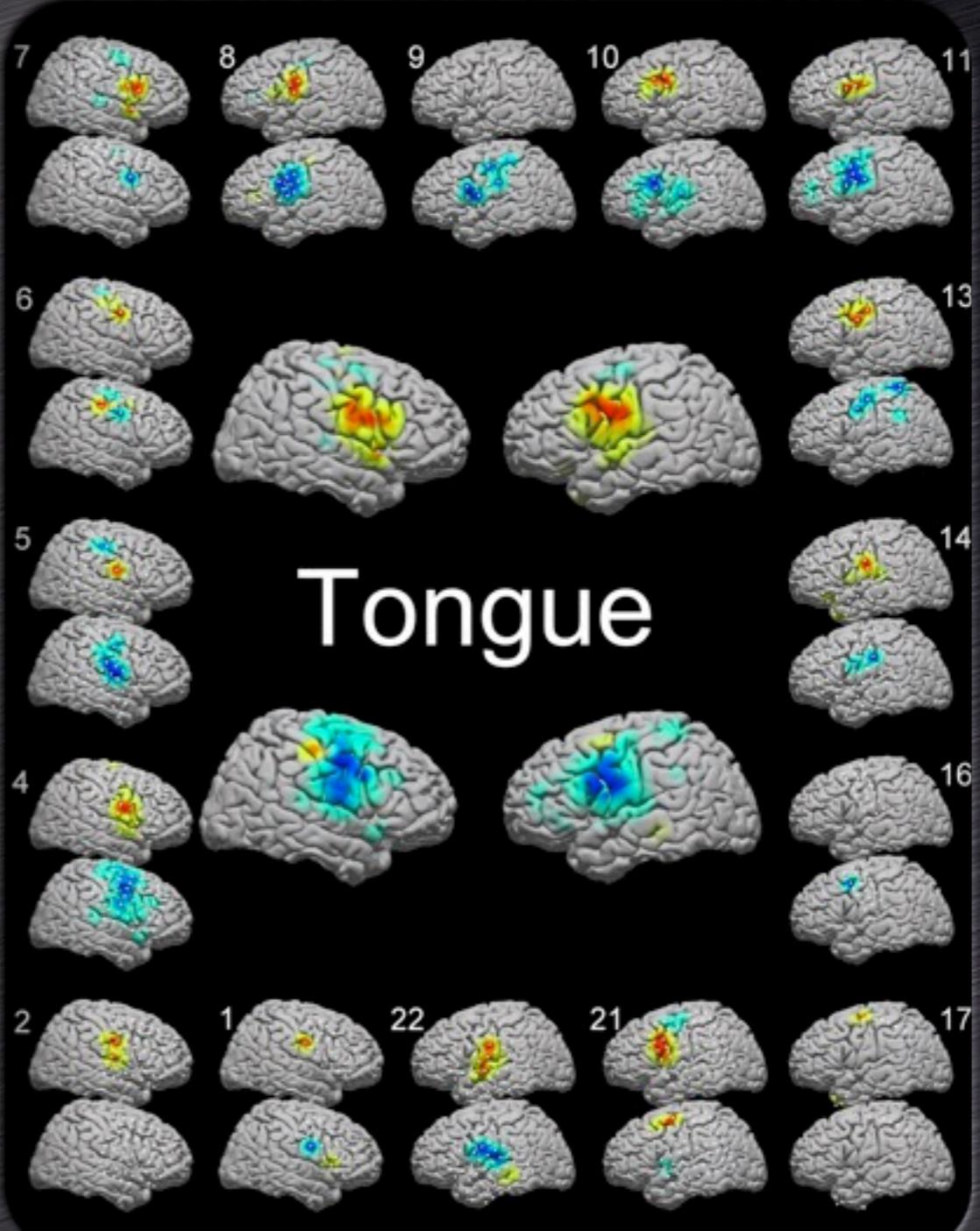
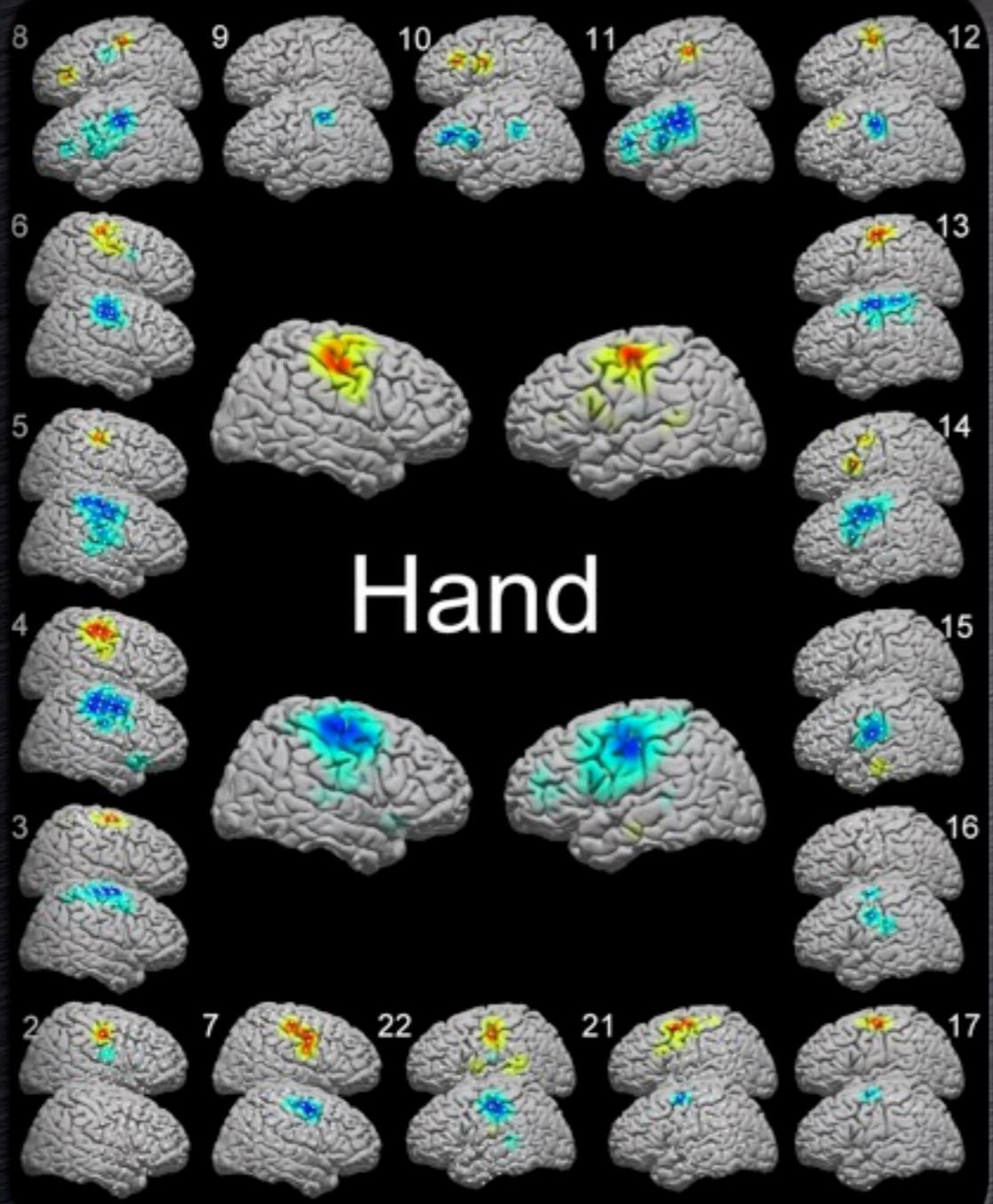
- general movements
- other types of sensors
- specific movements

Future Directions

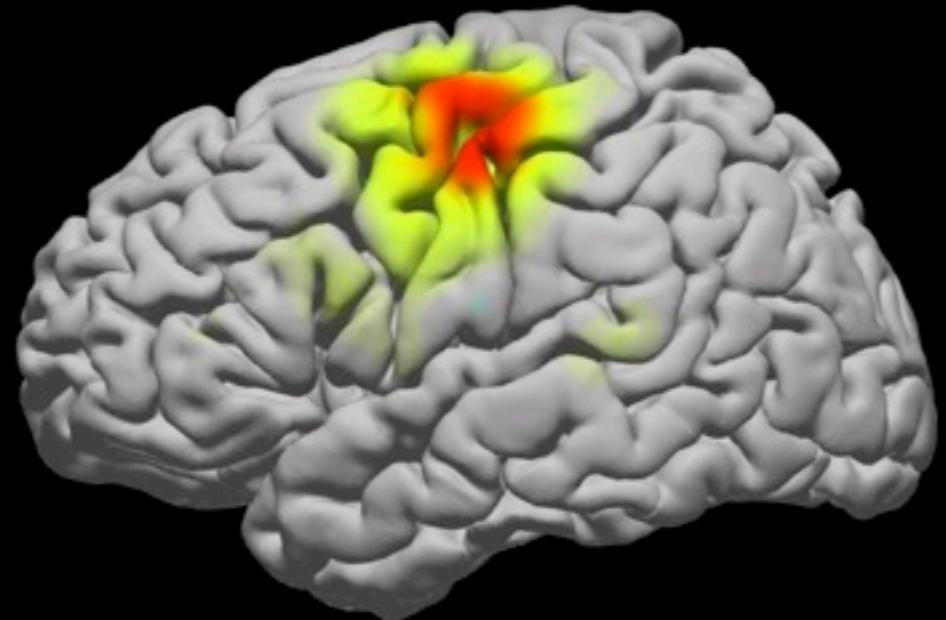
Relationship with General Movement Parameters: Motor Homunculus



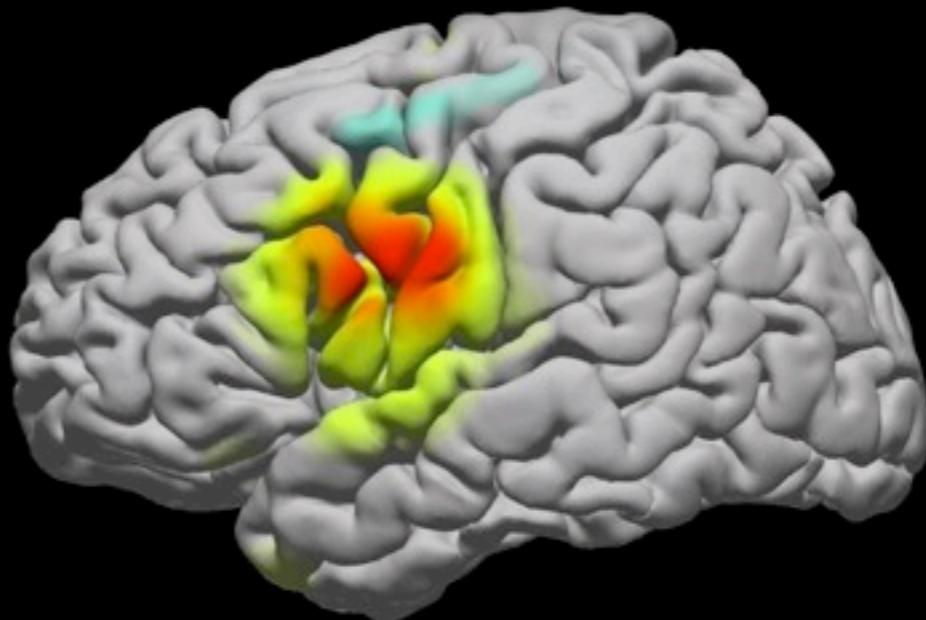
Relationship of ECoG with Hand/Tongue Movements



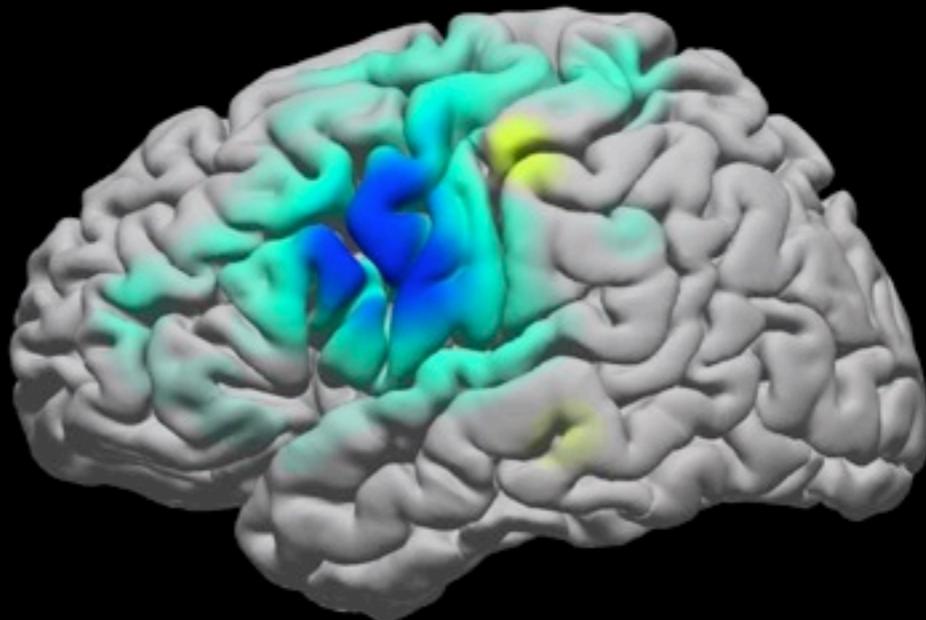
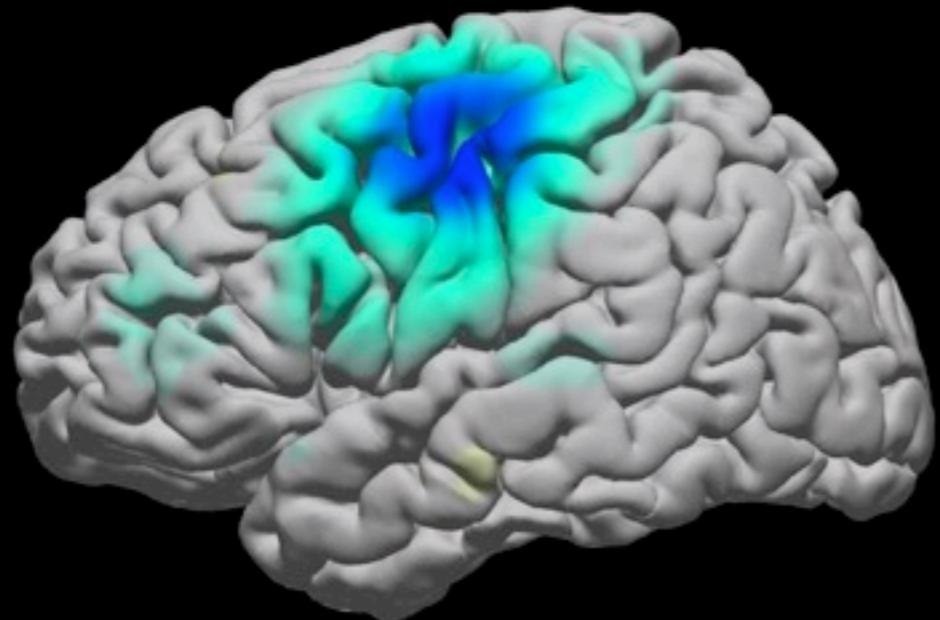
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Hand Movement

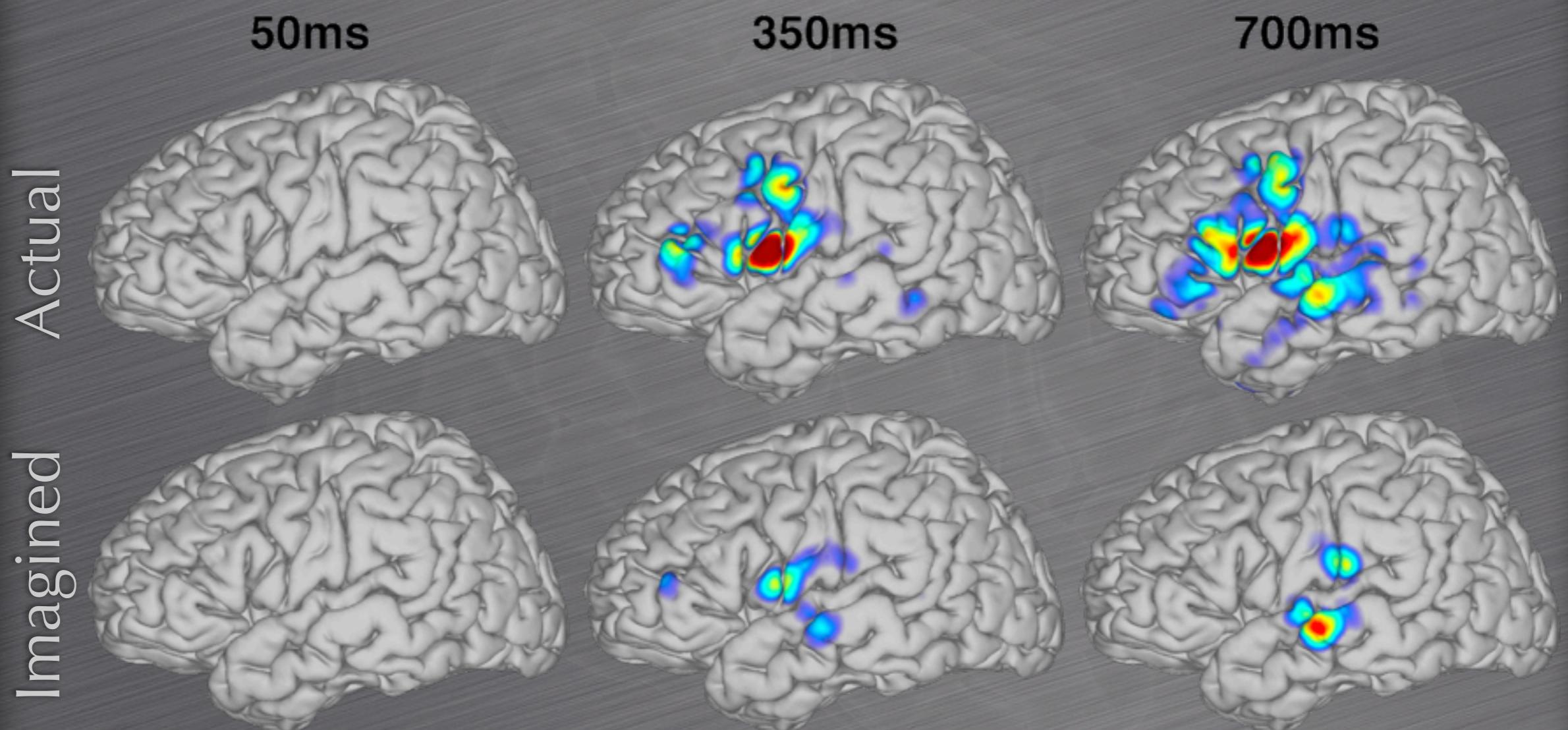


Tongue Movement



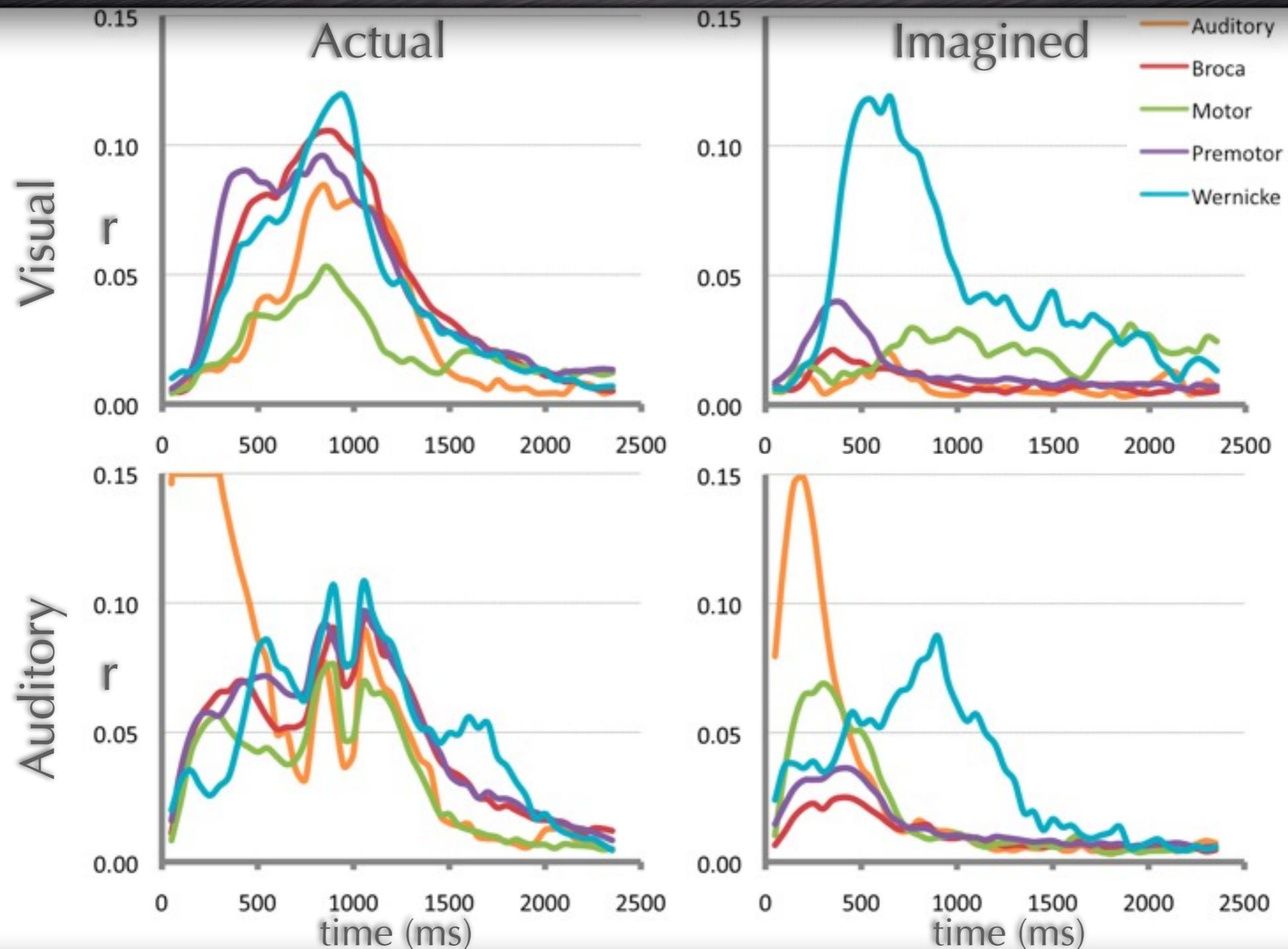
Miller, Schalk et al., *J Neurosci*, 2007

Relationship of Gamma With Speech Function



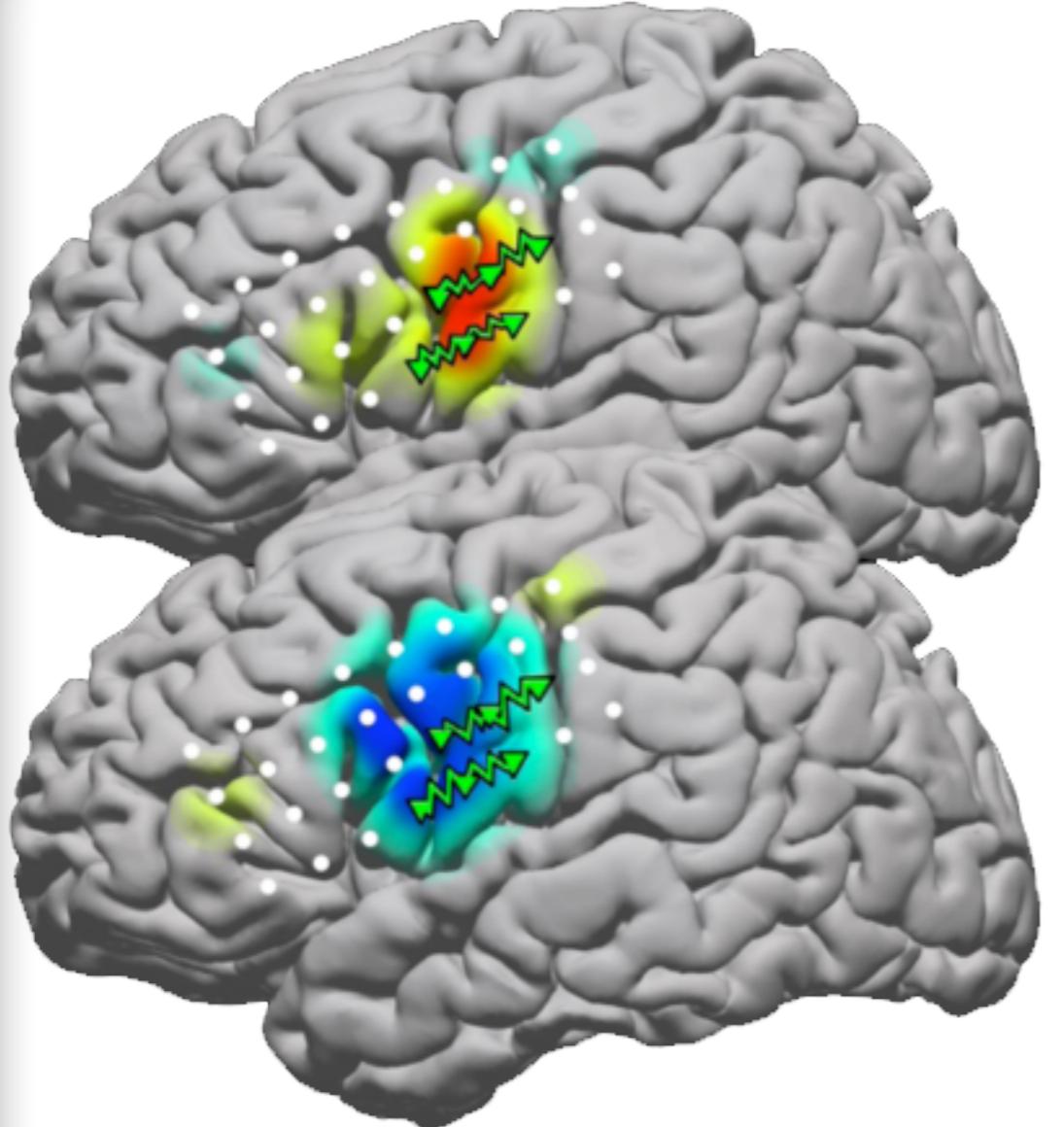
Kim, Schalk, *J Neurosci*, in submission; Pei, Schalk, in preparation

Relationship of Gamma With Speech Function

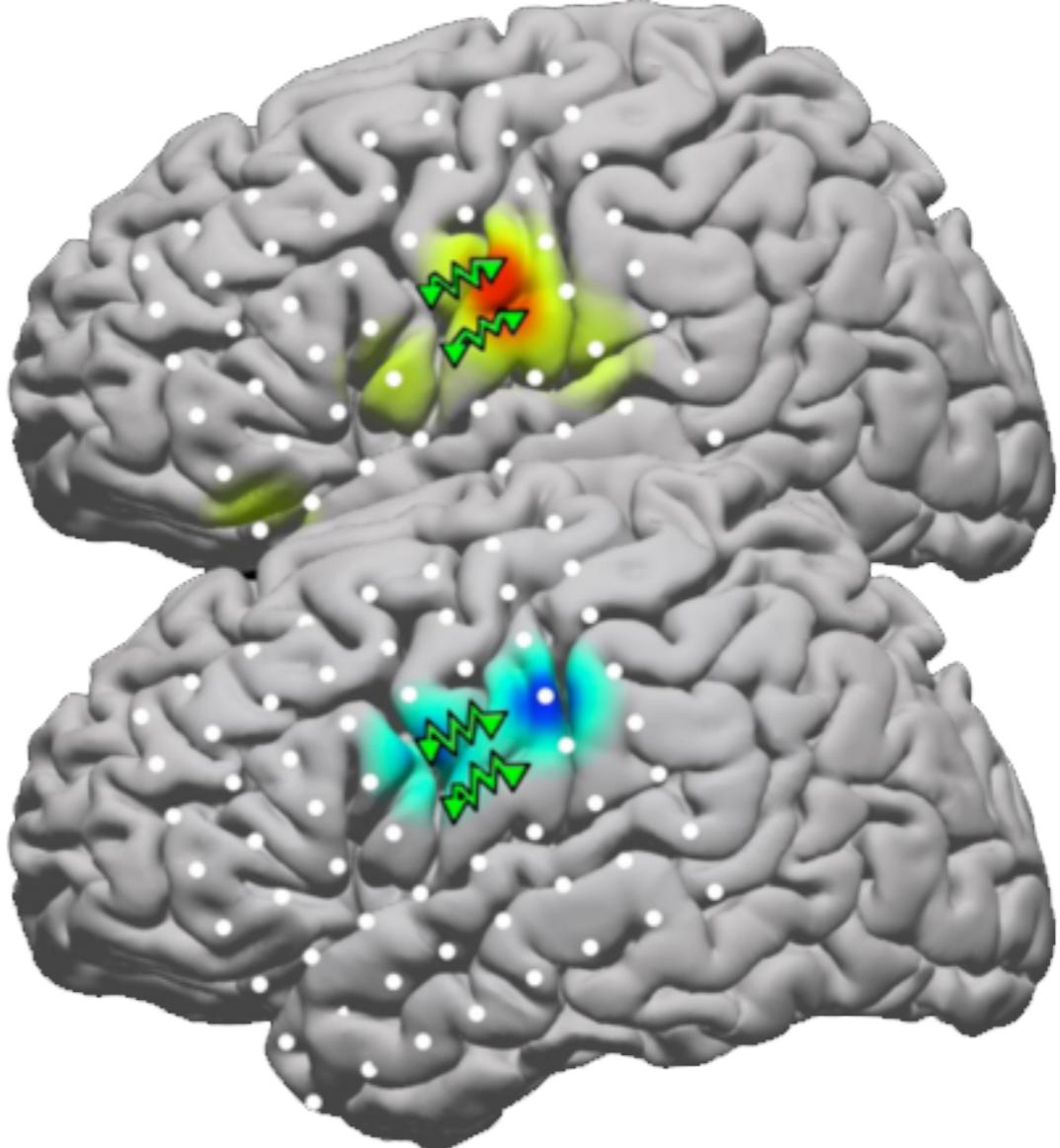


Leuthardt, Schalk et al., in preparation

Relationship of Gamma With Electrical Stimulation

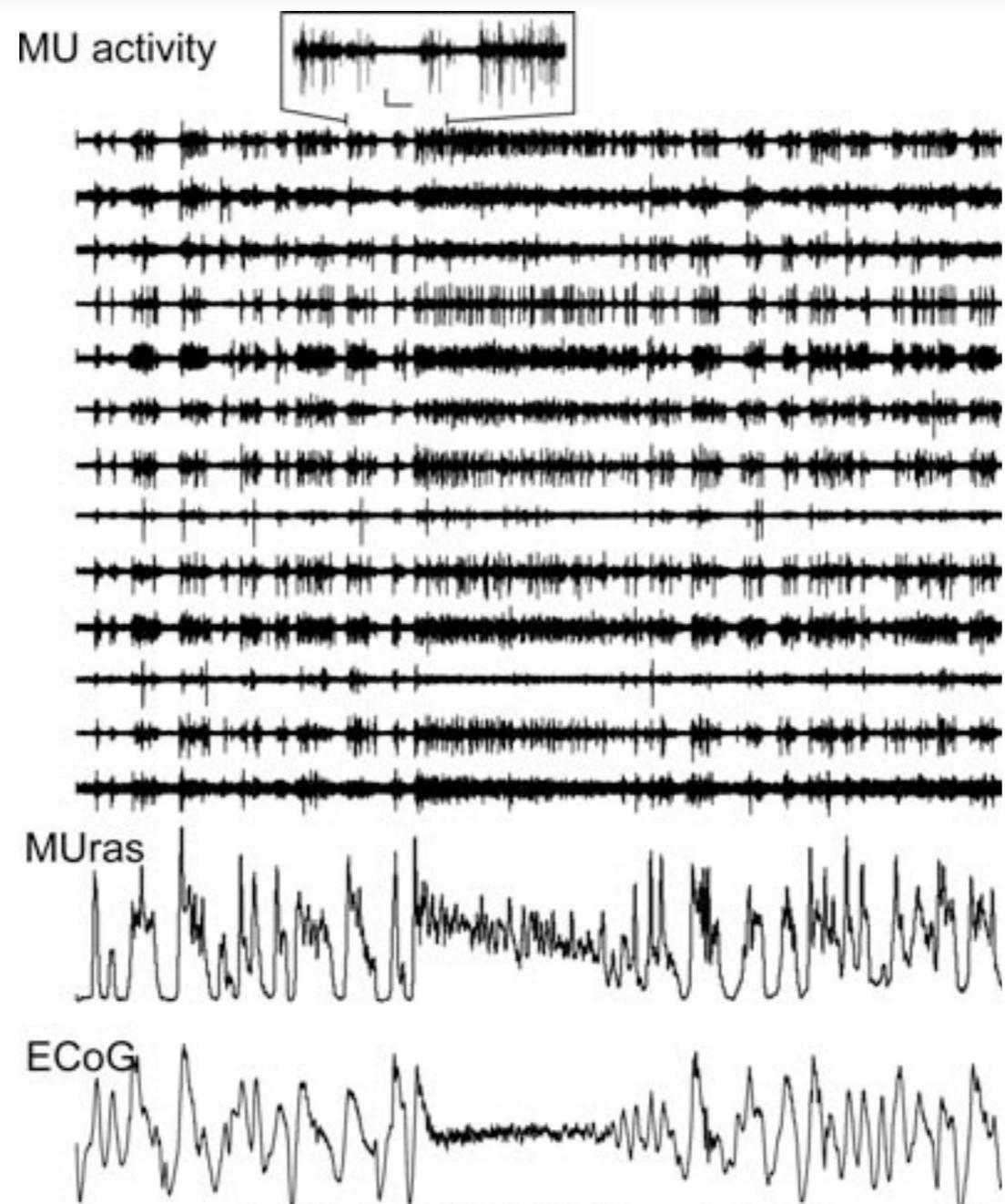


Tongue



Crone et al., *Brain*, 1998; Sinai et al., *Brain*, 2005; Miller, Schalk et al., *J Neurosci*, 2007;
Leuthardt, Schalk et al., *Neurosurgery*, 2007; Towle et al., *Brain*, 2008; Brunner, Schalk et al., *Epilepsy and Behav*, 2009

Relationship of ECoG with Multi-Unit Activity (in rats)



Kasanetz et al., *J Physiol*, 2006

Relationship of Gamma with fMRI

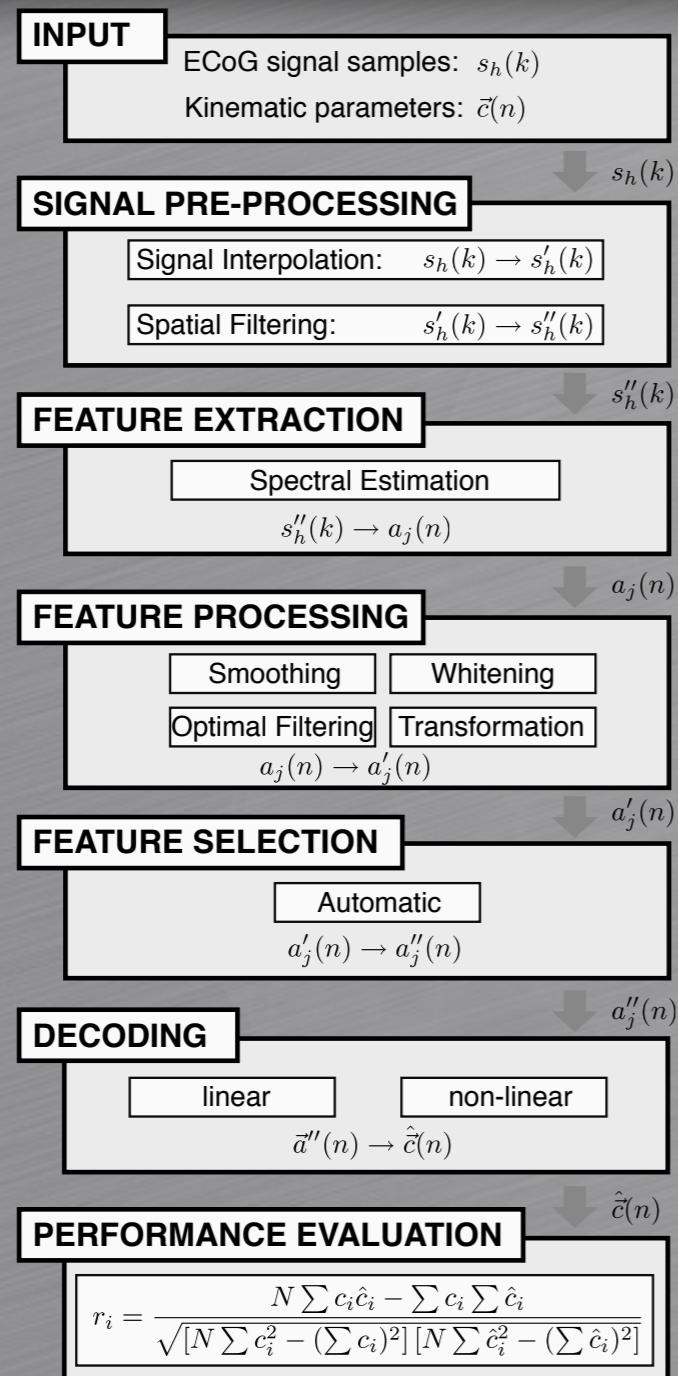
Fluctuations in hemodynamic response were only loosely related to action potential frequency but tightly correlated to the power of LFP oscillations in the gamma range.

Niessing et al., *Science*, 2005

Gamma band modulations co-localize with BOLD variations

Lachaux et al., *Hum Brain Mapp*, 2007

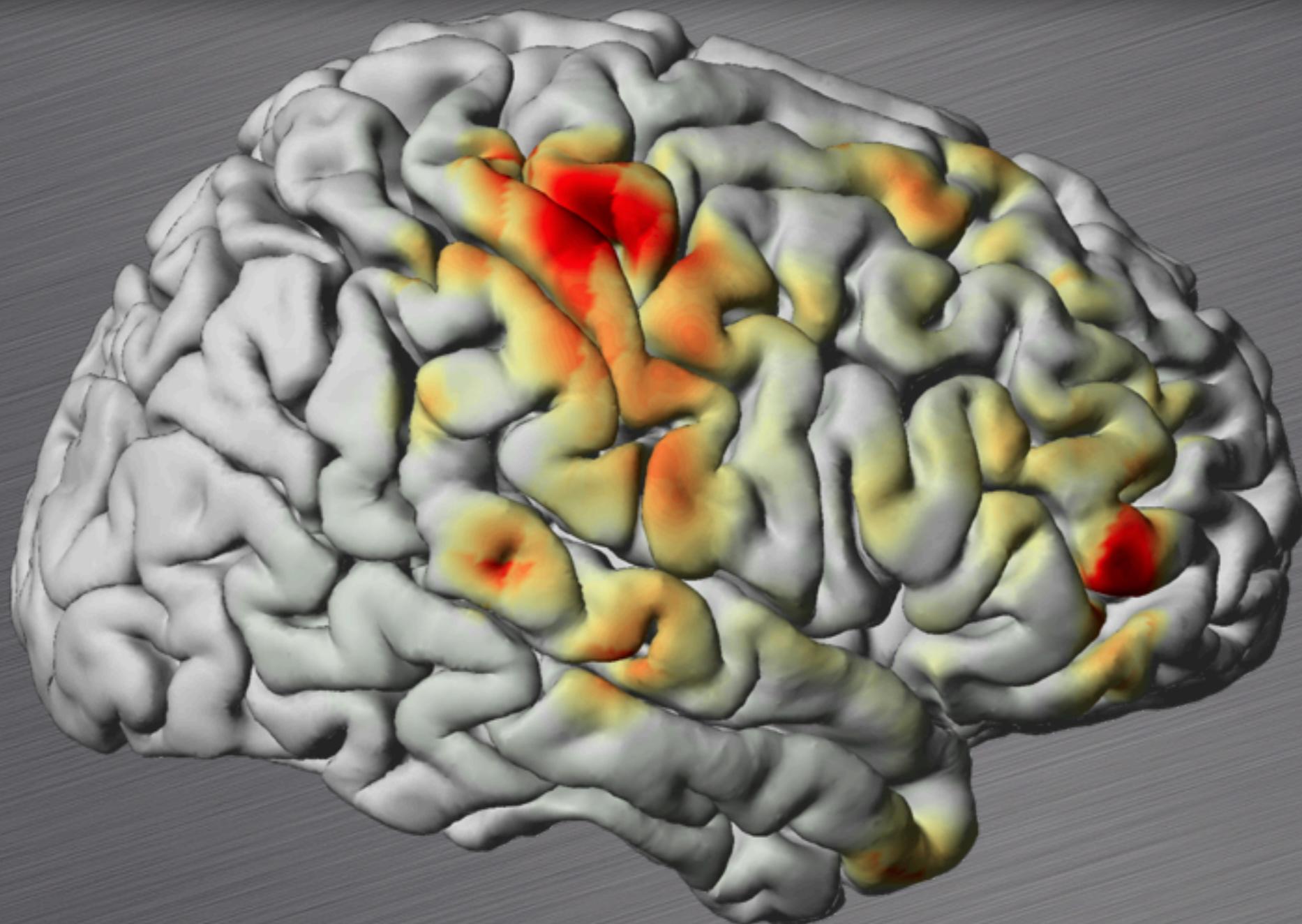
Relationship of ECoG with Details of Movements: Decoding of Function



Decoding Direction of Hand Movements

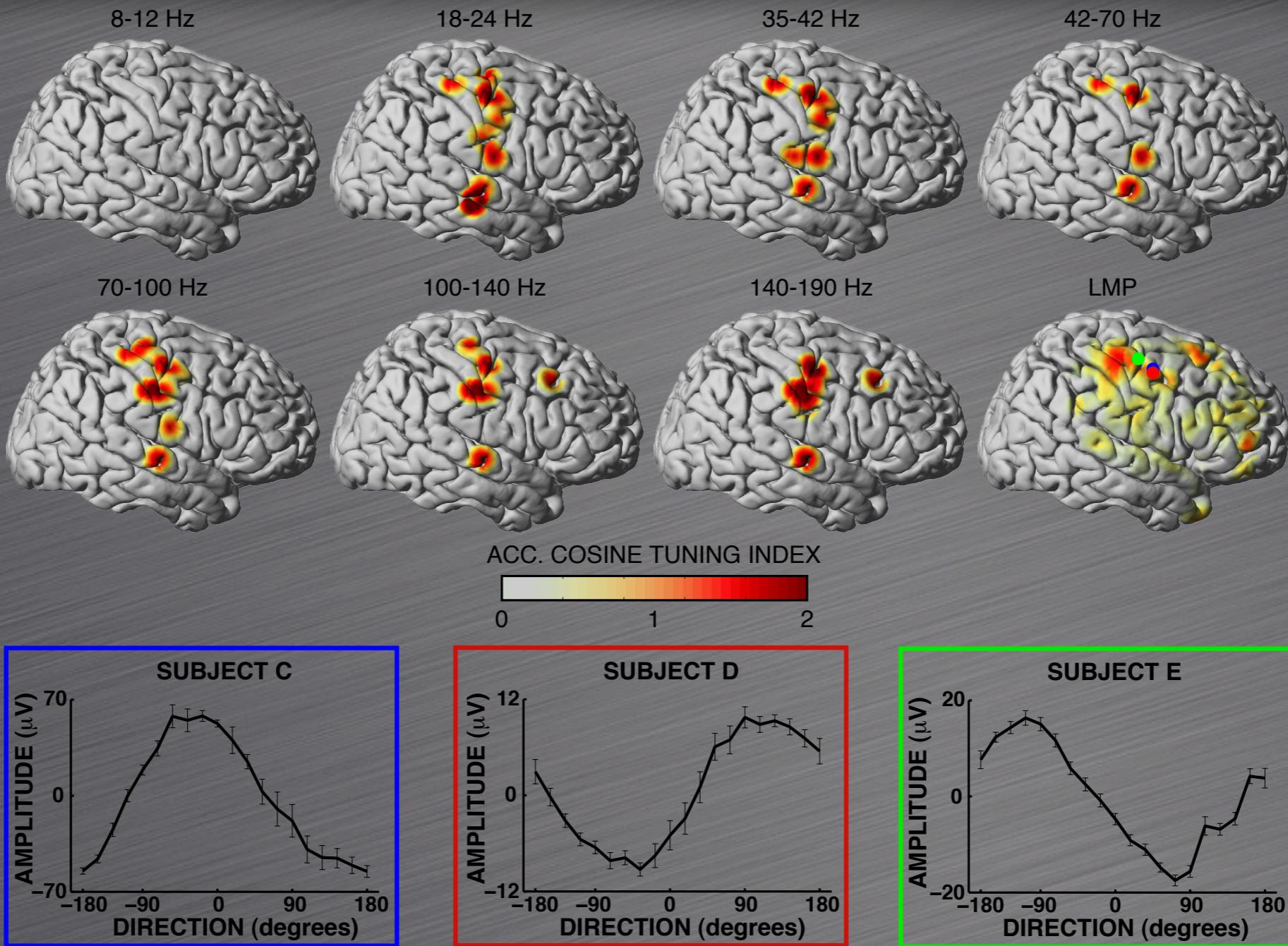


Tuning to Direction of Hand Movements



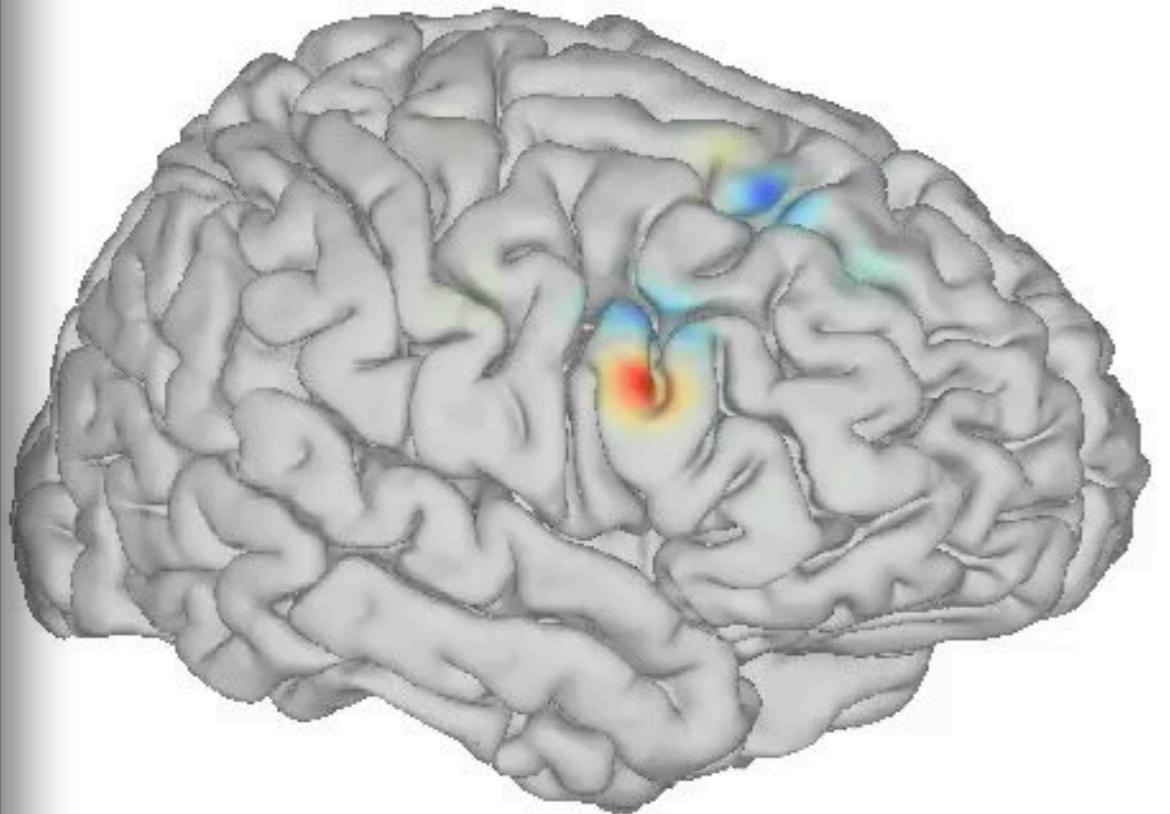
Schalk et al., *J Neural Eng*, 2007

Tuning to Direction of Hand Movements

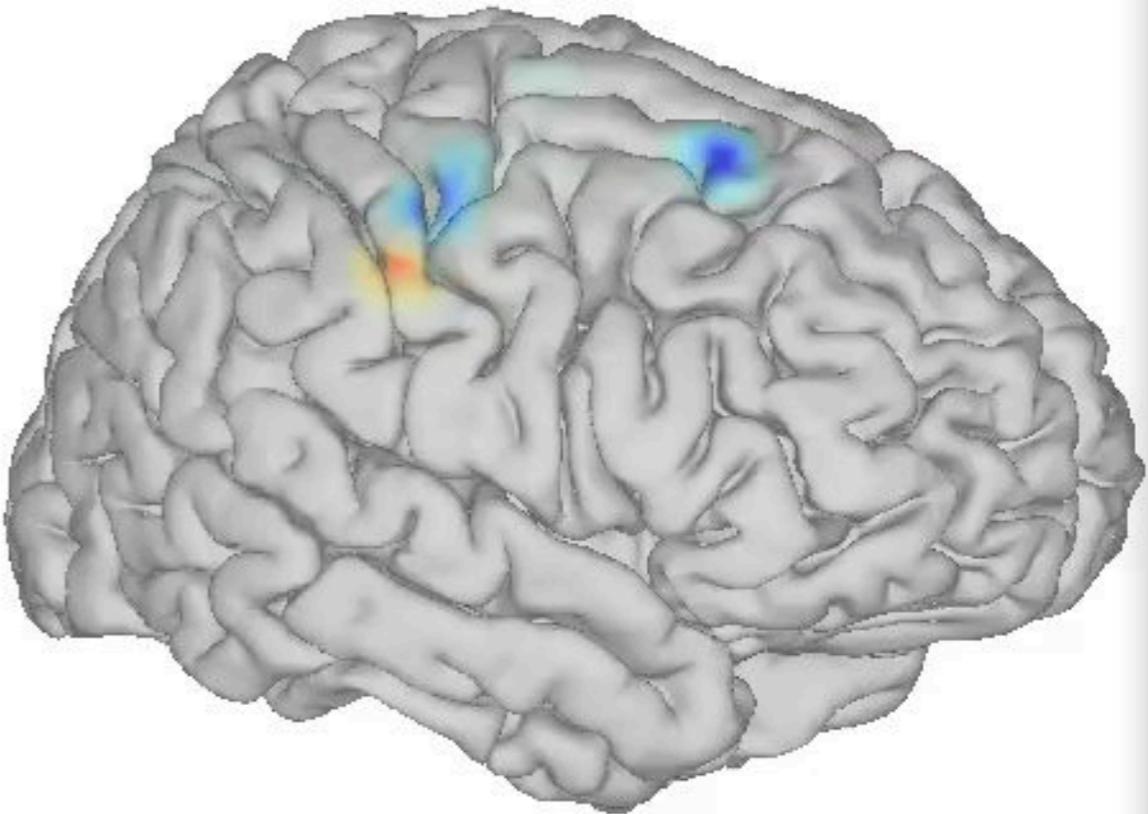


Schalk et al., *J Neural Eng*, 2007

Spatio-Temporal Gamma Activity Related to Hand Movements



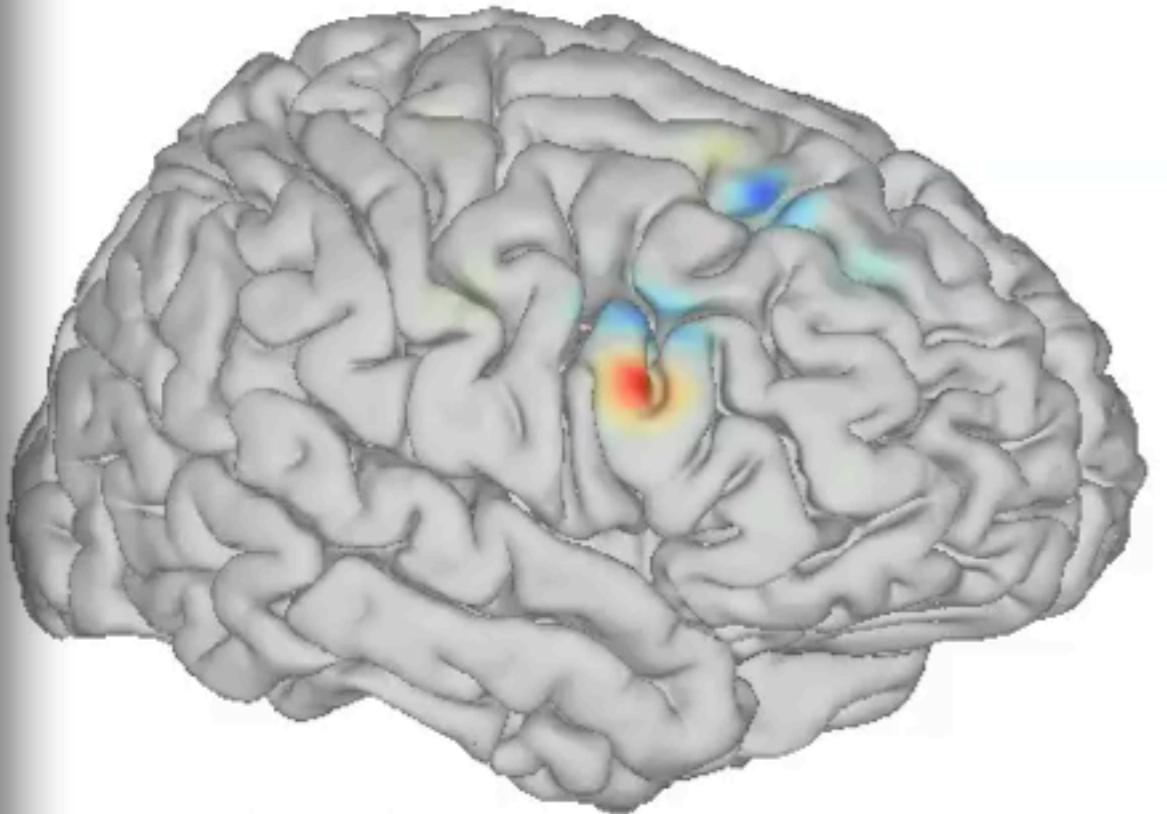
Subject C
Horizontal Cursor Position Weights



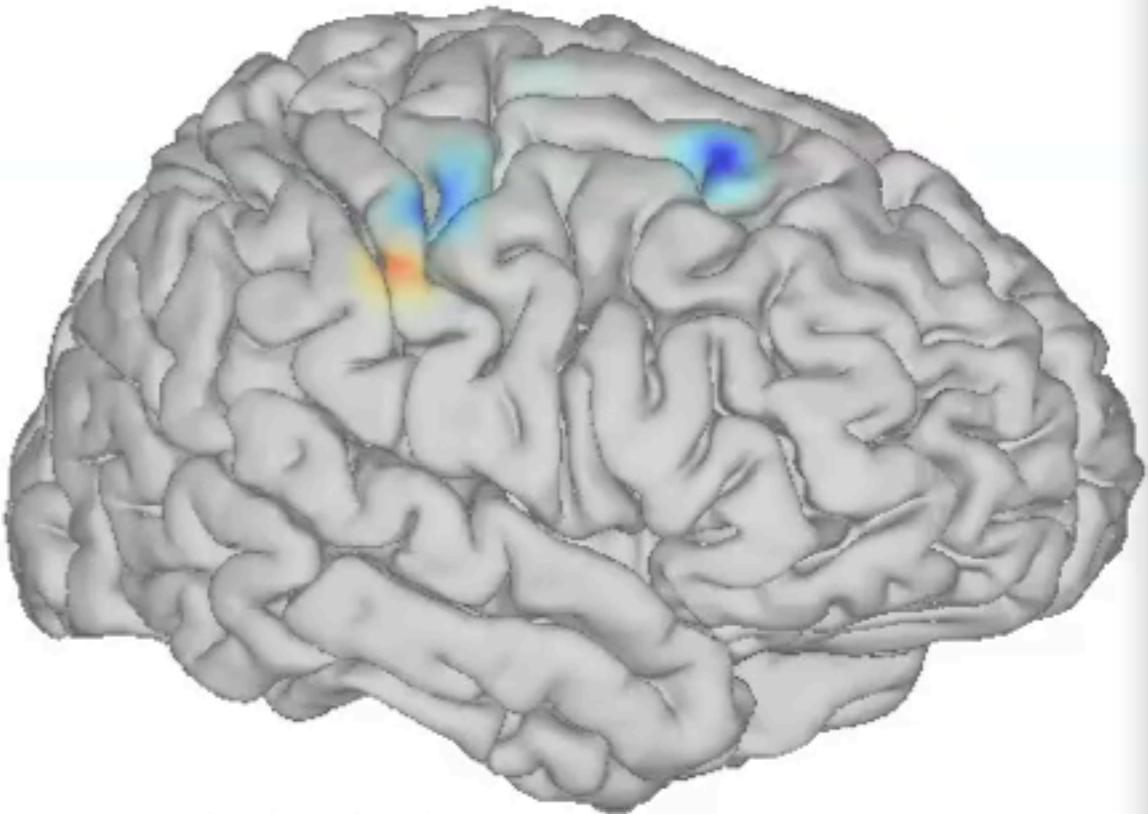
Subject C
Vertical Cursor Position Weights

Schalk et al., *J Neural Eng*, 2007

Spatio-Temporal Gamma Activity Related to Hand Movements



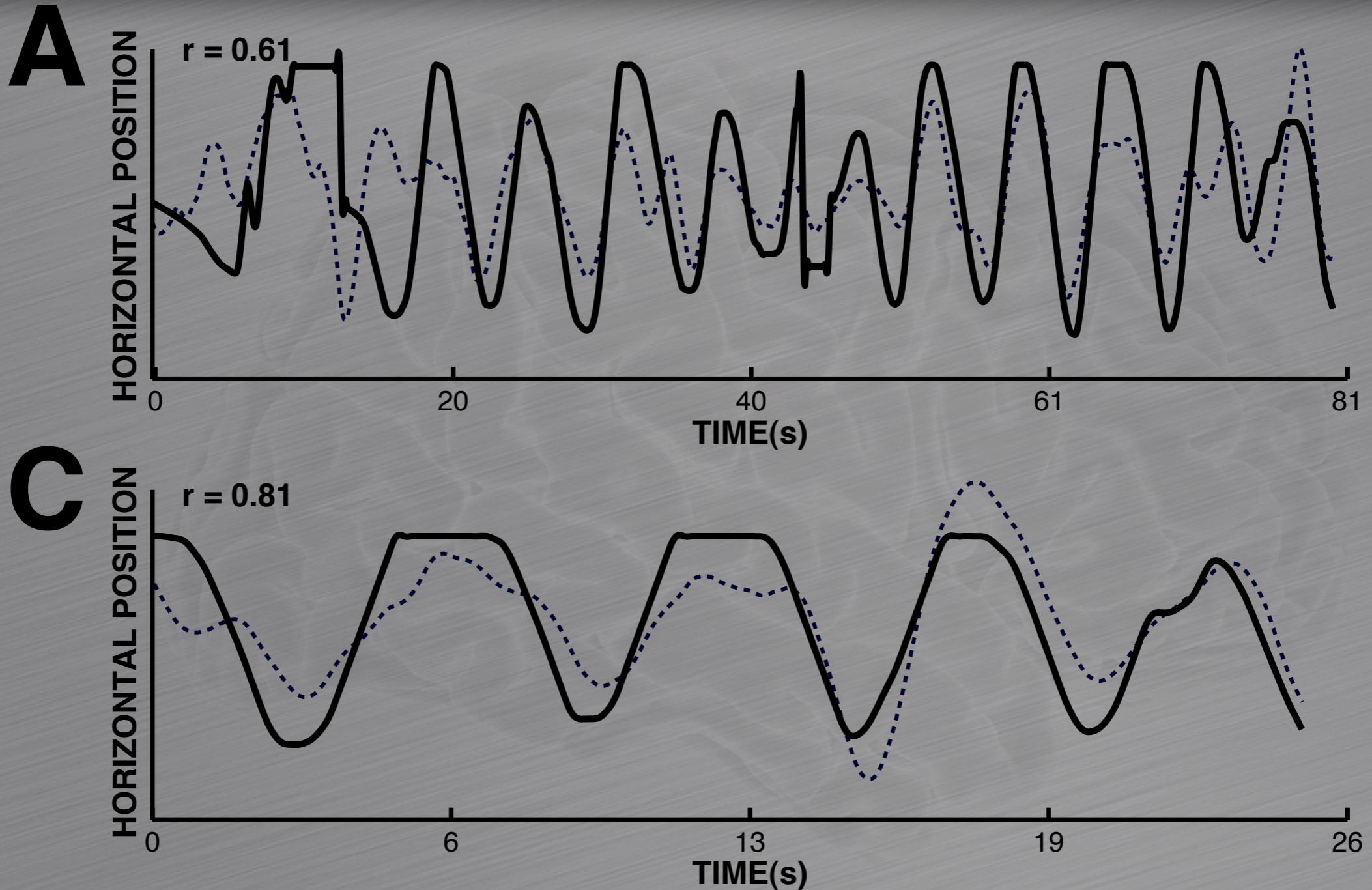
Subject C
Horizontal Cursor Position Weights



Subject C
Vertical Cursor Position Weights

Schalk et al., *J Neural Eng*, 2007

Decoding Hand Position



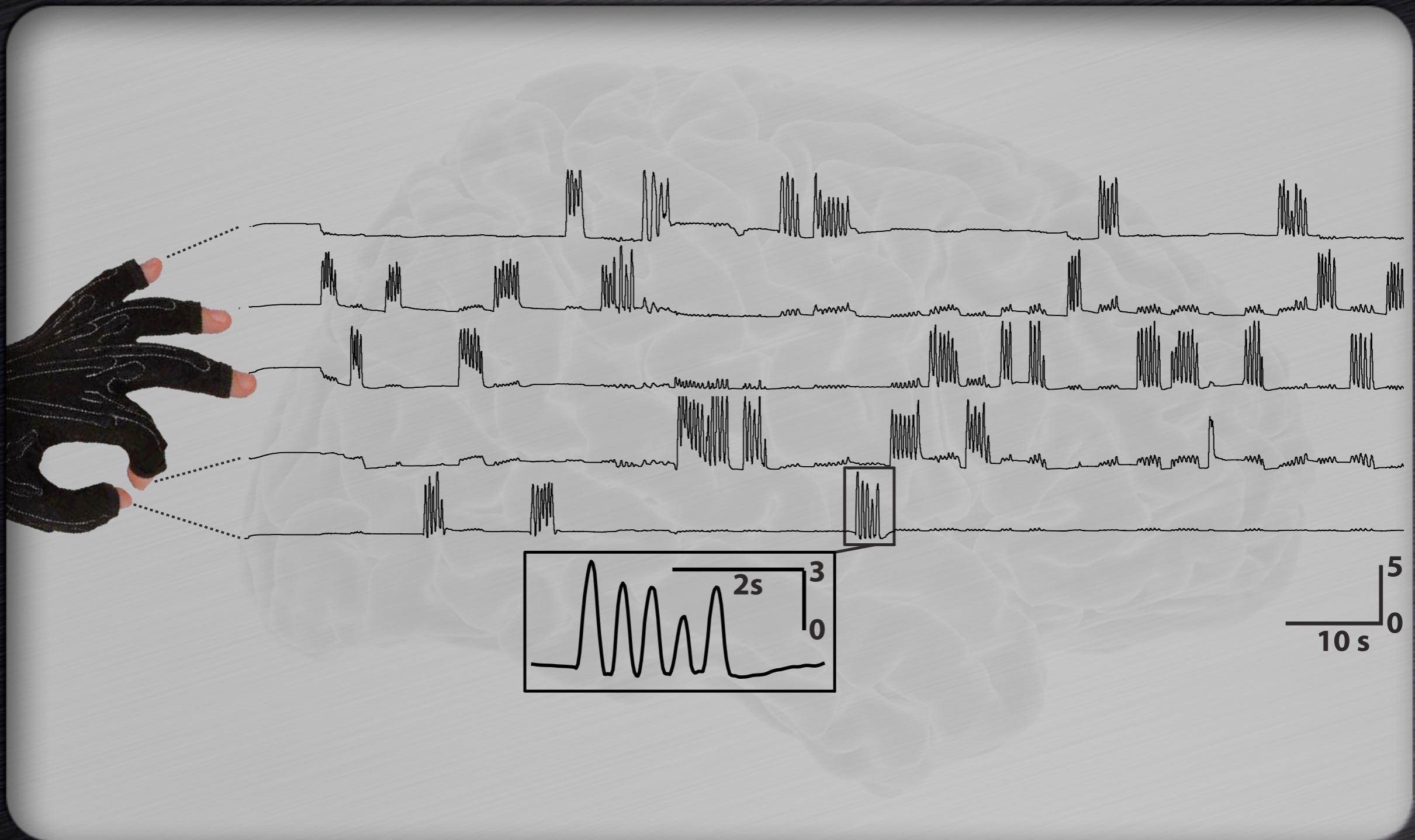
Schalk et al., *J Neural Eng*, 2007

Pistohl et al., *J Neurosci Meth*, 2008

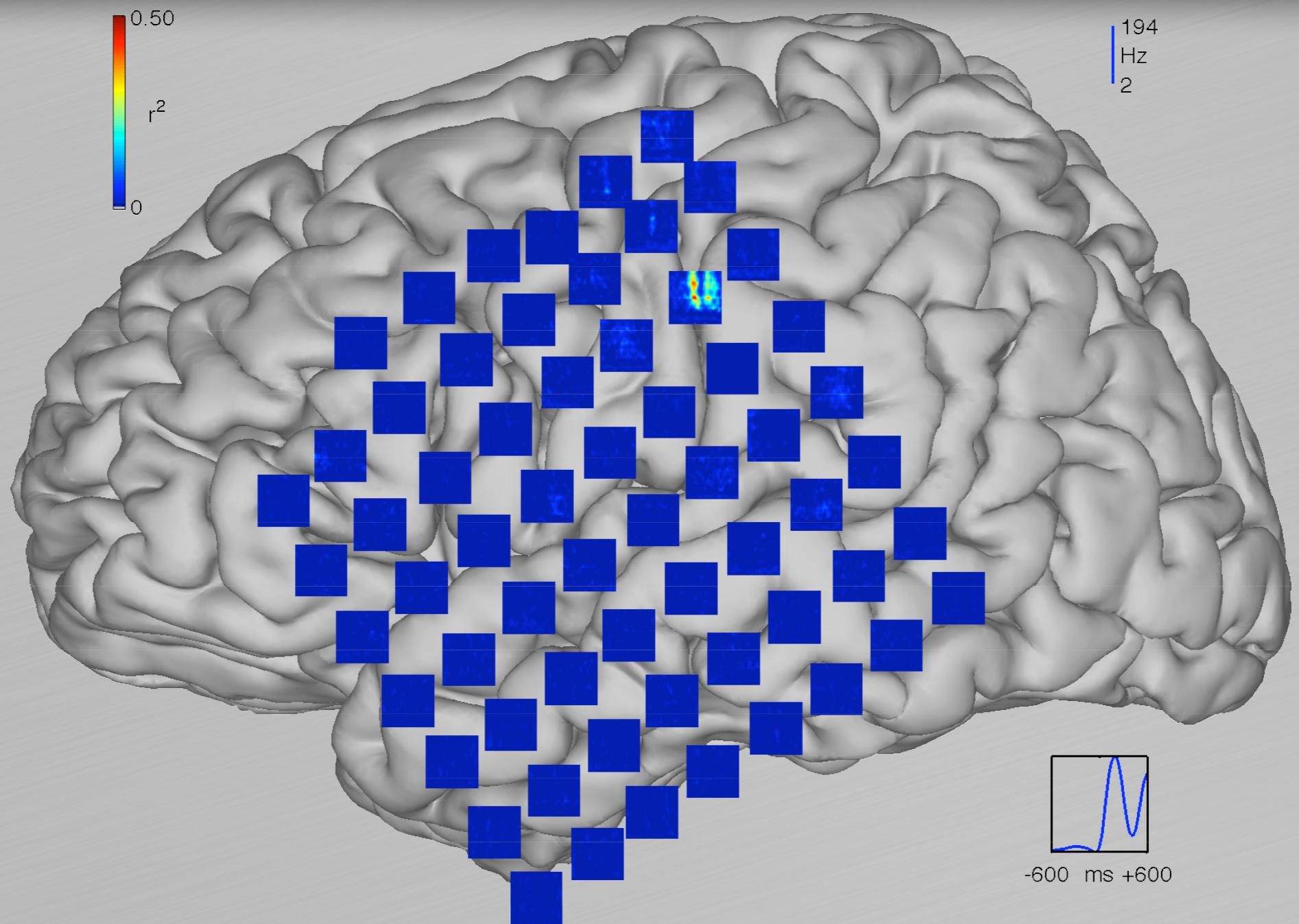
Decoding Hand Movements

| Study and Source | Position r | Velocity r |
|--|--------------|--------------|
| Schwartz and Moran, 1999, p. 2713 | – | 0.77 |
| Carmena et al., 2003, Fig. 1F & 3C | 0.33-0.63 | 0.27-0.73 |
| Paninski et al., 2004, Table 1 | 0.47 | – |
| Lebedev et al., 2005, Table 2 | – | 0.56 |
| Averbeck et al., 2005, est. from Fig. 8A,B | – | 0.74 |
| Schalk et al., 2007 | 0.52 | 0.50 |

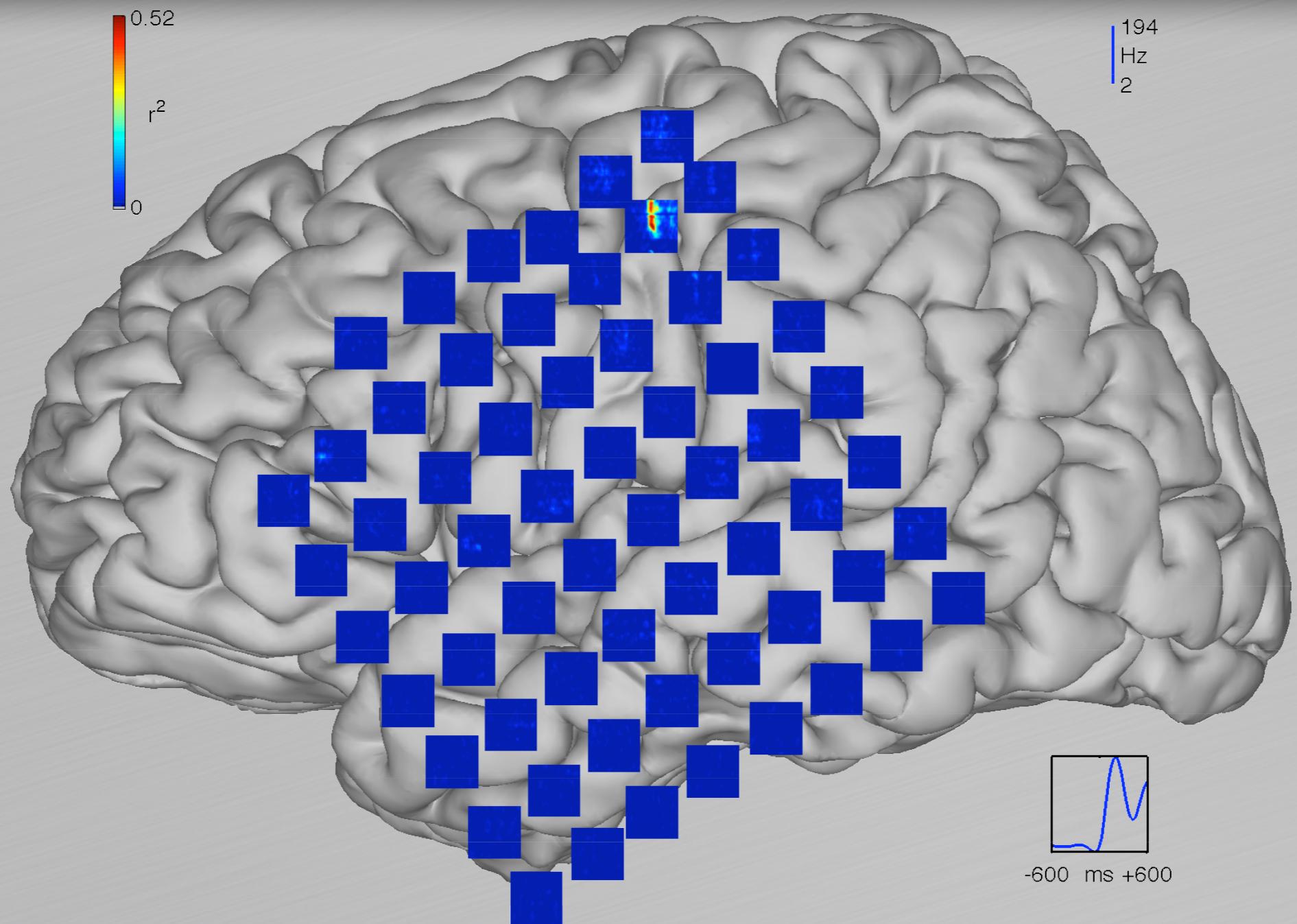
Decoding Finger Flexion



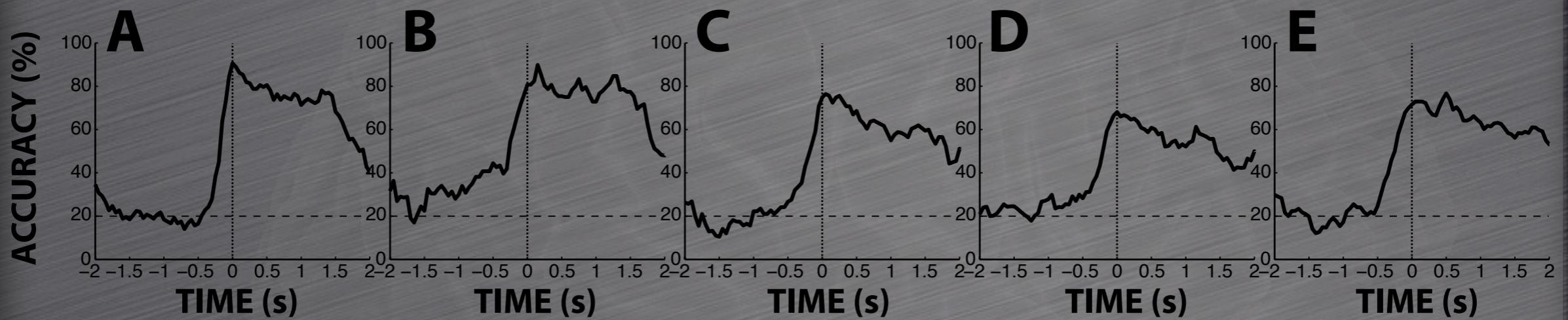
Response to Thumb Movement



Response to Index Finger Movement

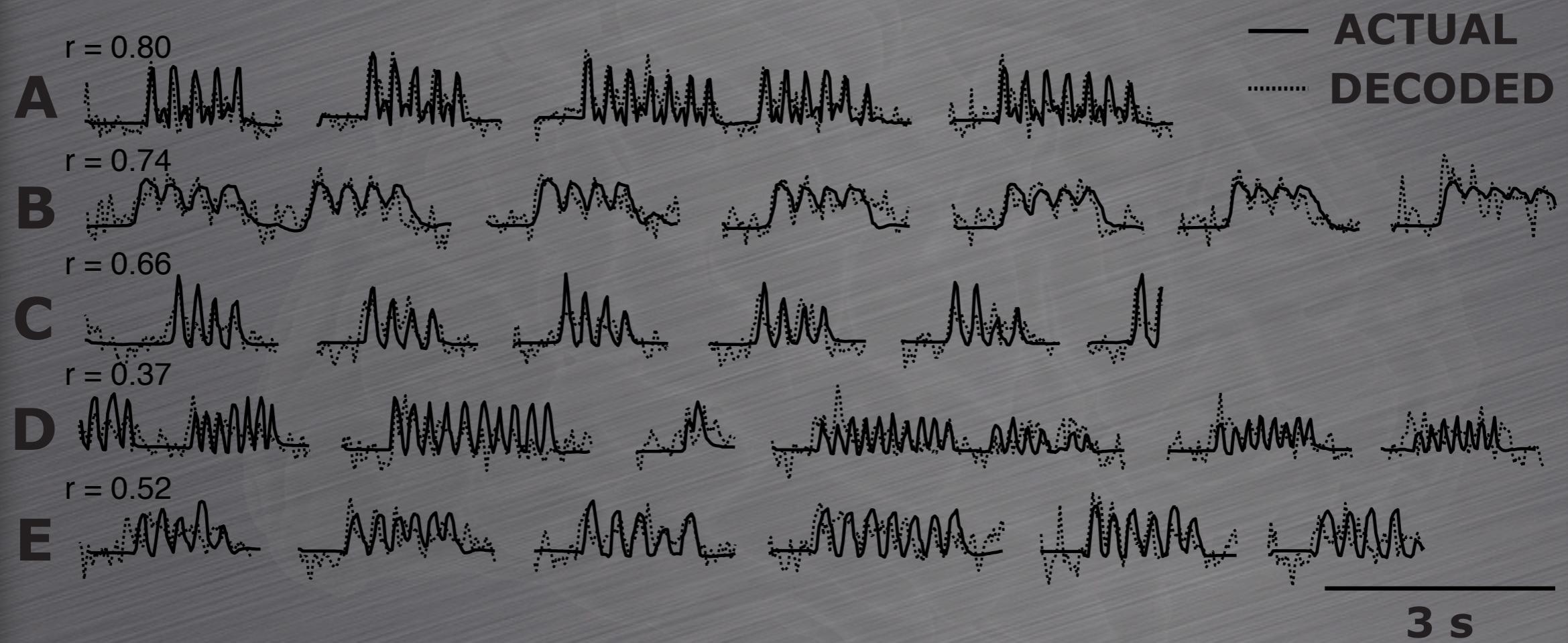


Classification of Individual Fingers in 5 Subjects



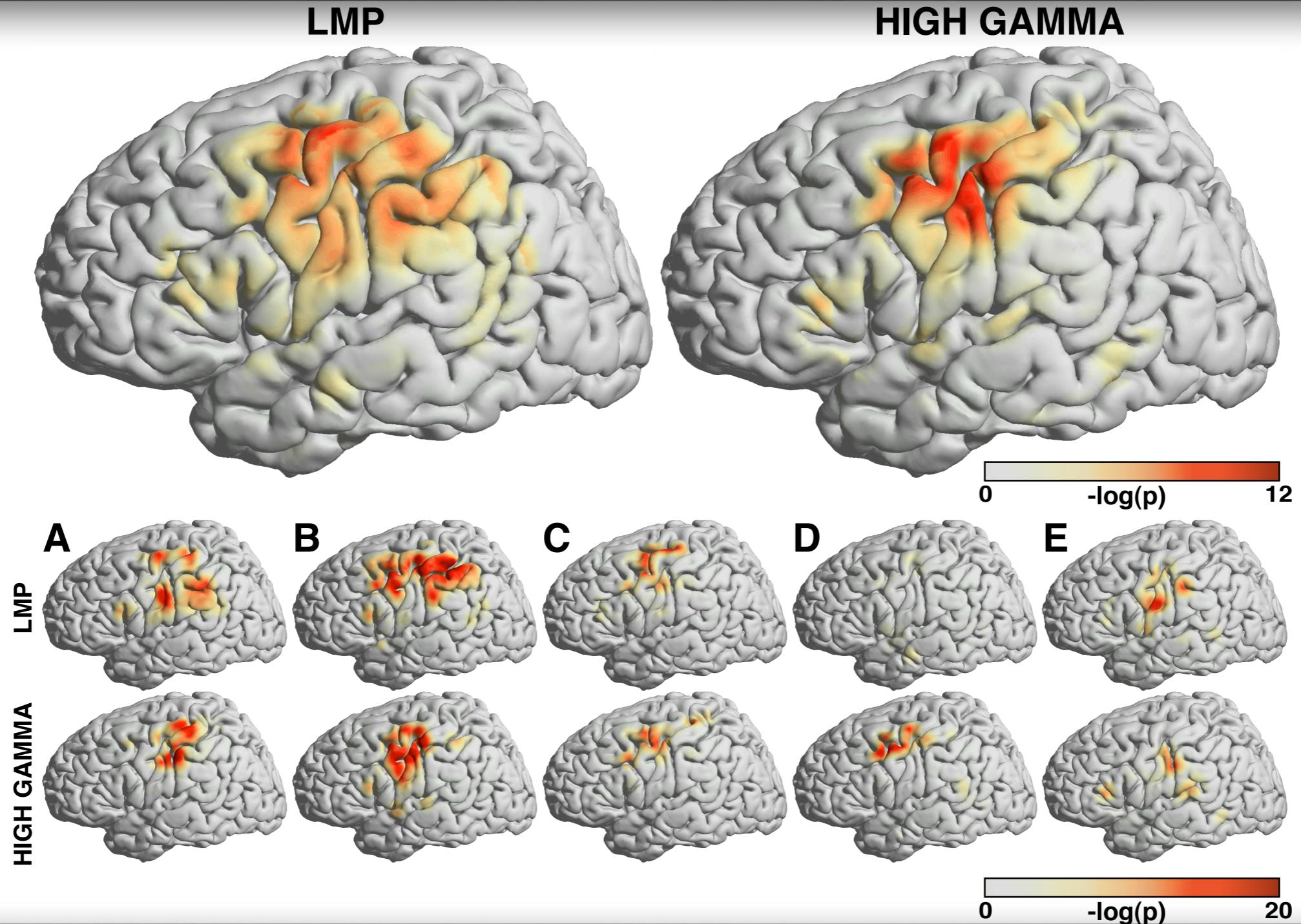
Kubanek, Schalk et al., *J Neural Eng*, in revision

Decoding Thumb Flexion



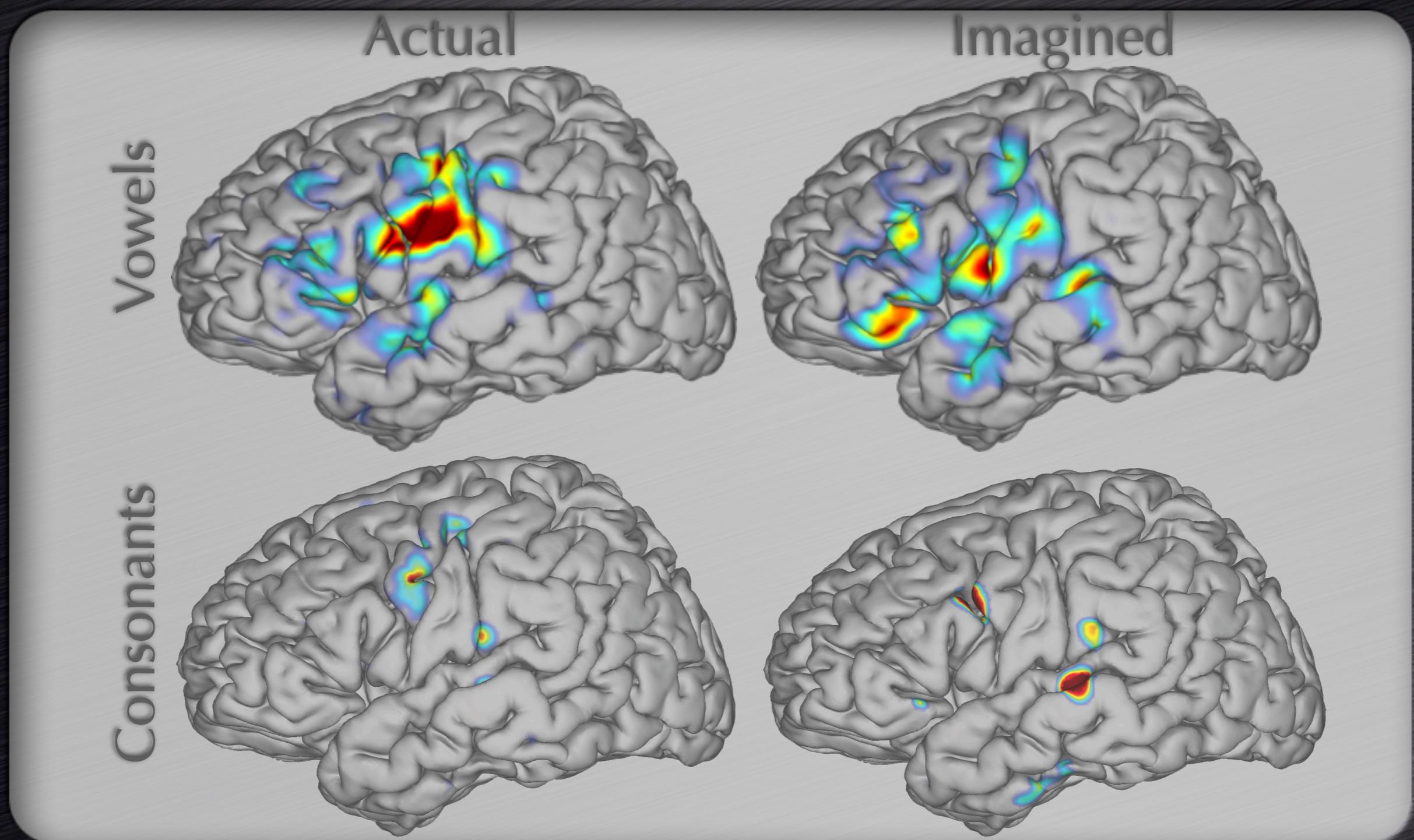
Kubanek, Schalk et al., *J Neural Eng*, in revision

Decoding Thumb Flexion



Kubanek, Schalk et al., *J Neural Eng*, in revision

Decoding Vowels and Consonants



Pei, Schalk et al., in preparation

Electrocorticographic Signals (ECoG) in Humans

BCI Control

Relationship

Diagnosis

Characteristics

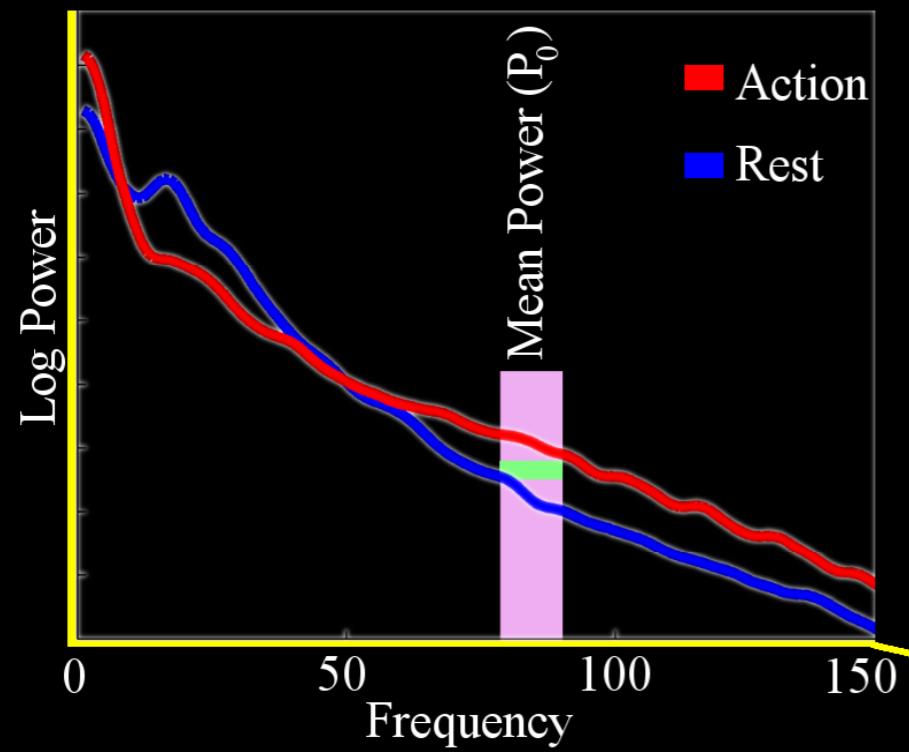
Open Questions

ECoG

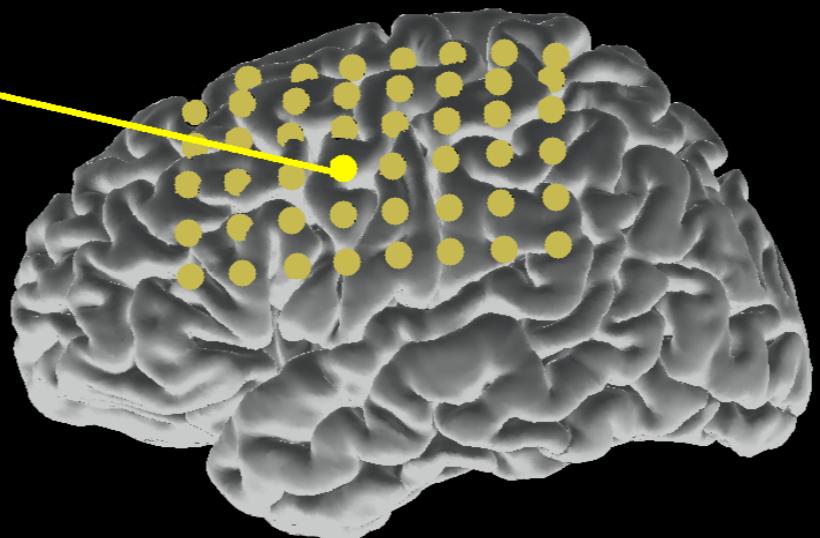
Future Directions



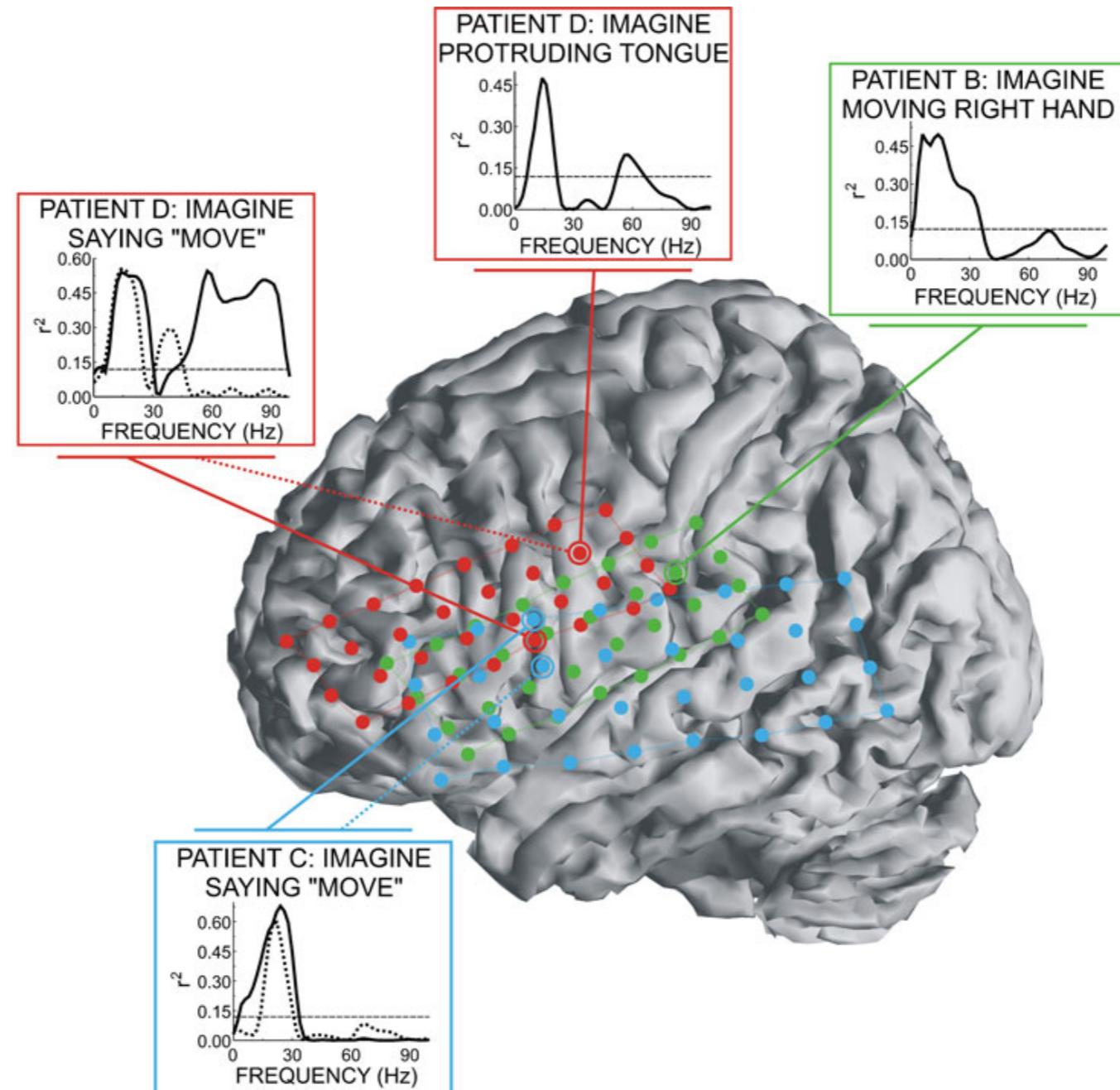
Associating Brain Activity with Cursor Movement



$$\dot{y}(t) = g(P(t) - P_0)$$

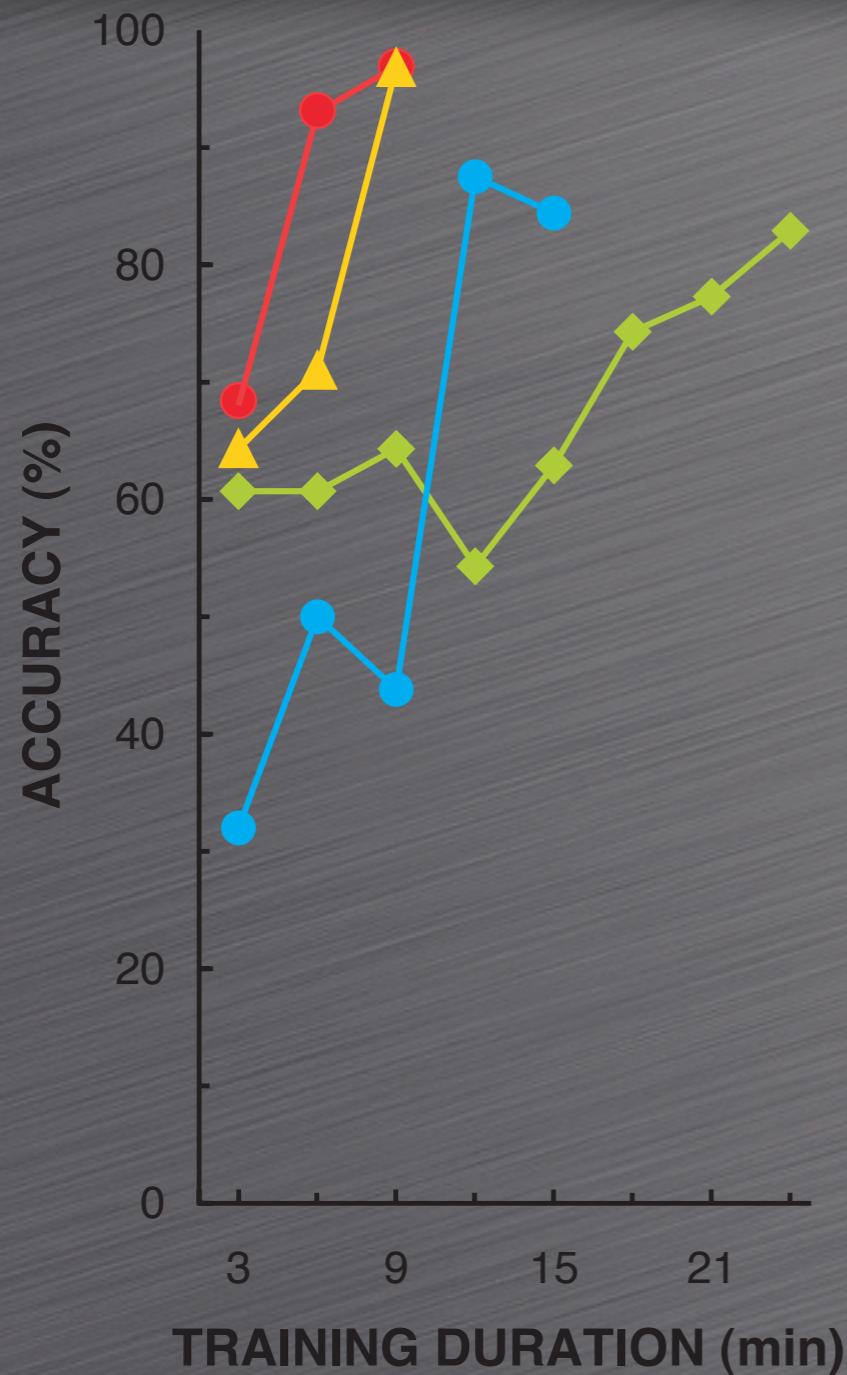


One-Dimensional BCI Control



Leuthardt, Schalk et al., *J Neural Eng*, 2004

One-Dimensional BCI Control



Leuthardt, Schalk et al., *J Neural Eng*, 2004
Leuthardt, Schalk et al, *IEEE T Biomed Eng*, 2006
Wilson, Schalk et al., *IEEE T Biomed Eng*, 2006
Felton et al., *J Neurosurg*, 2007
US Patent #7,120,486
International patent pending

Movie courtesy of Eric Leuthardt, WashU



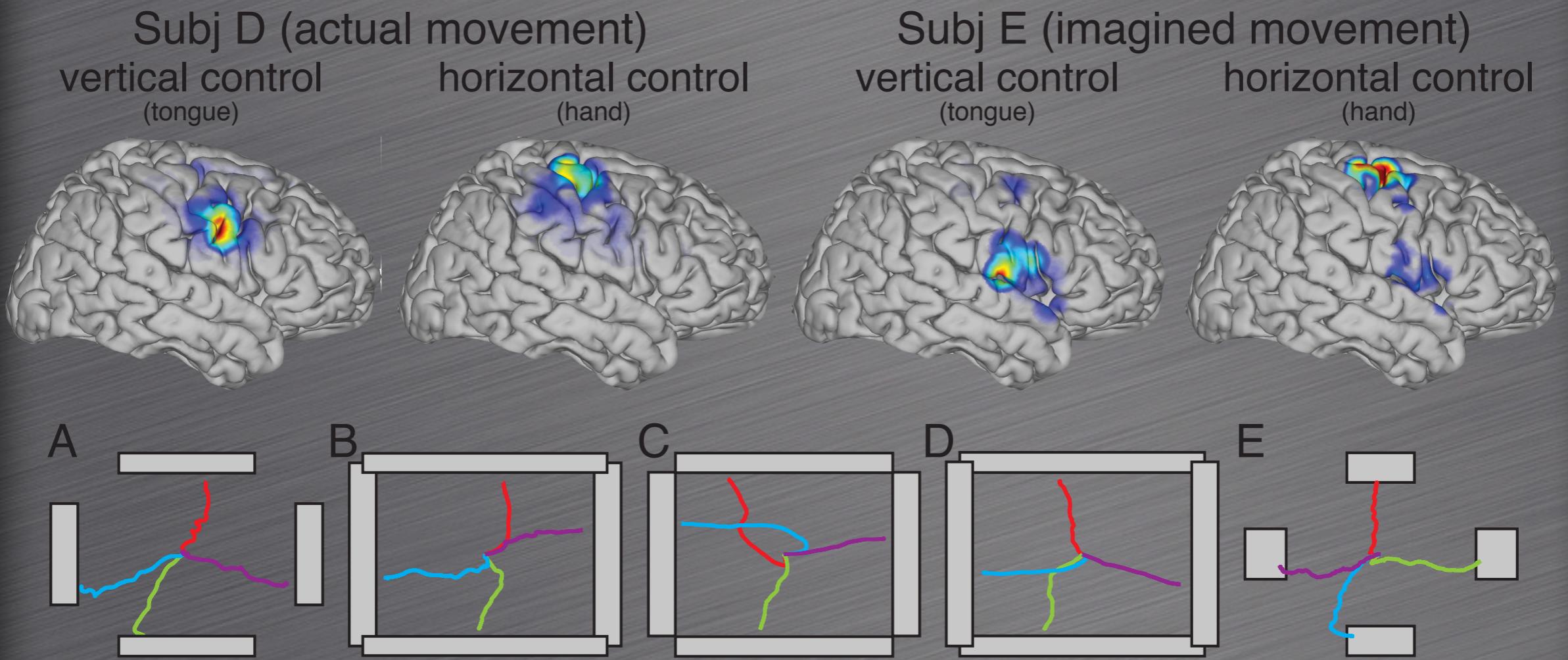
powered by
BCI2000

Brain Control with Imagined Movements



powered by
BCI2000

Two-Dimensional BCI Control



Schalk et al., *J Neural Eng*, 2008

Triggering Action with the Brain: Clint Eastwood, 1982

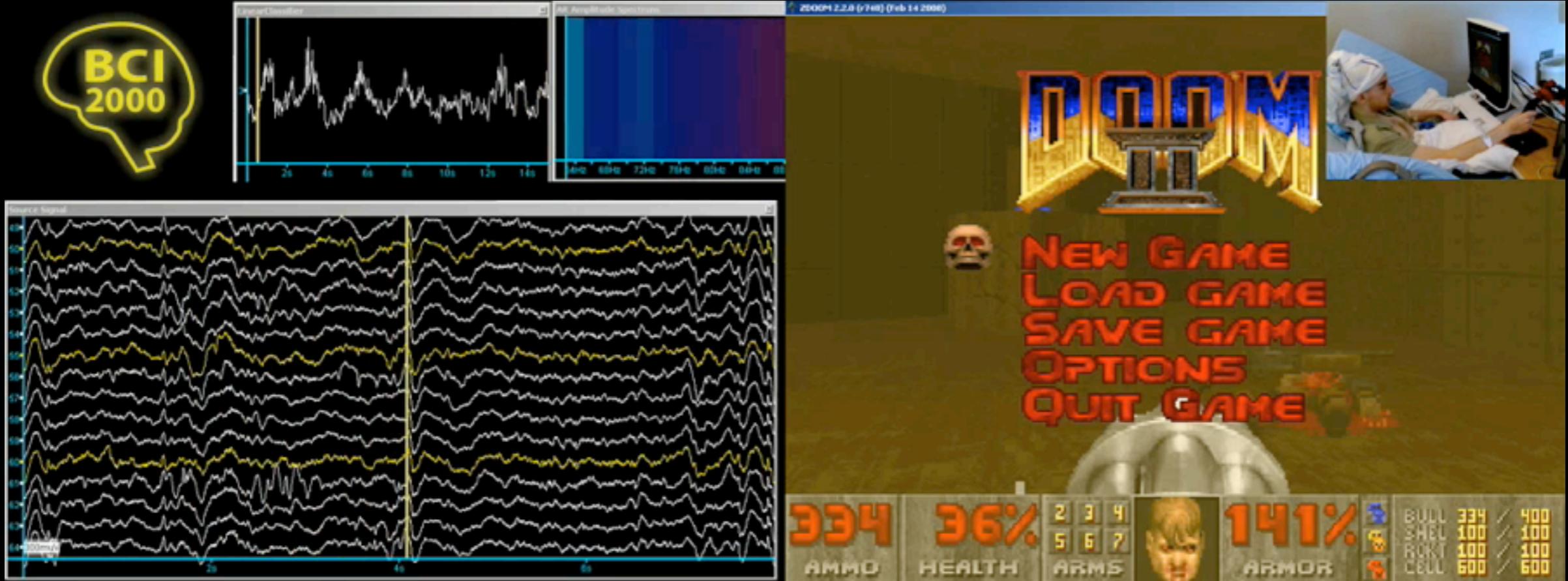
Triggering Action with the Brain: Clint Eastwood, 1982



Triggering Action with the Brain: Brunner, Ritaccio, Schalk, 2009

Triggering Action with the Brain:

Brunner, Ritaccio, Schalk, 2009



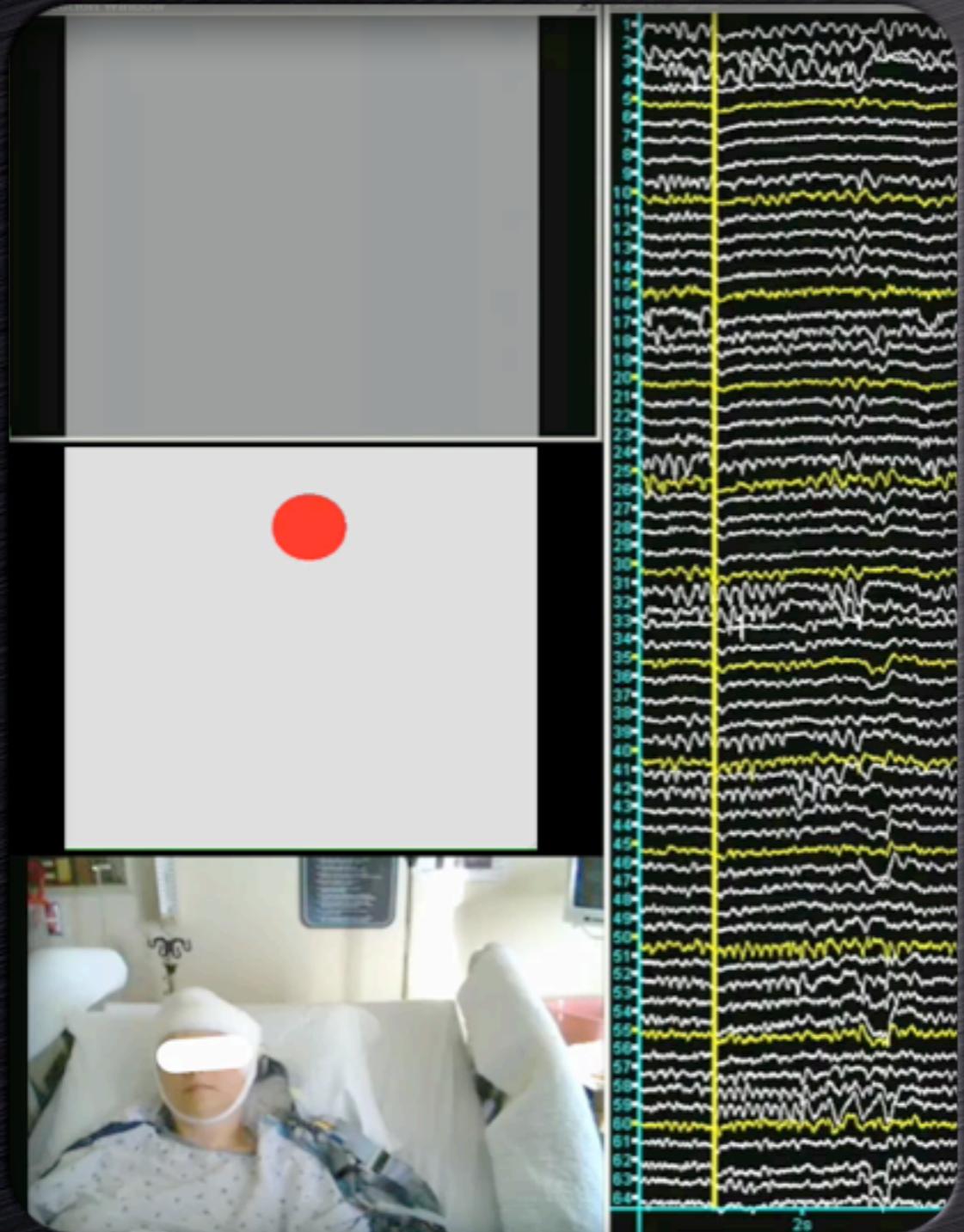
Using Imagined Vowels for Silent Communication



powered by
BCI2000

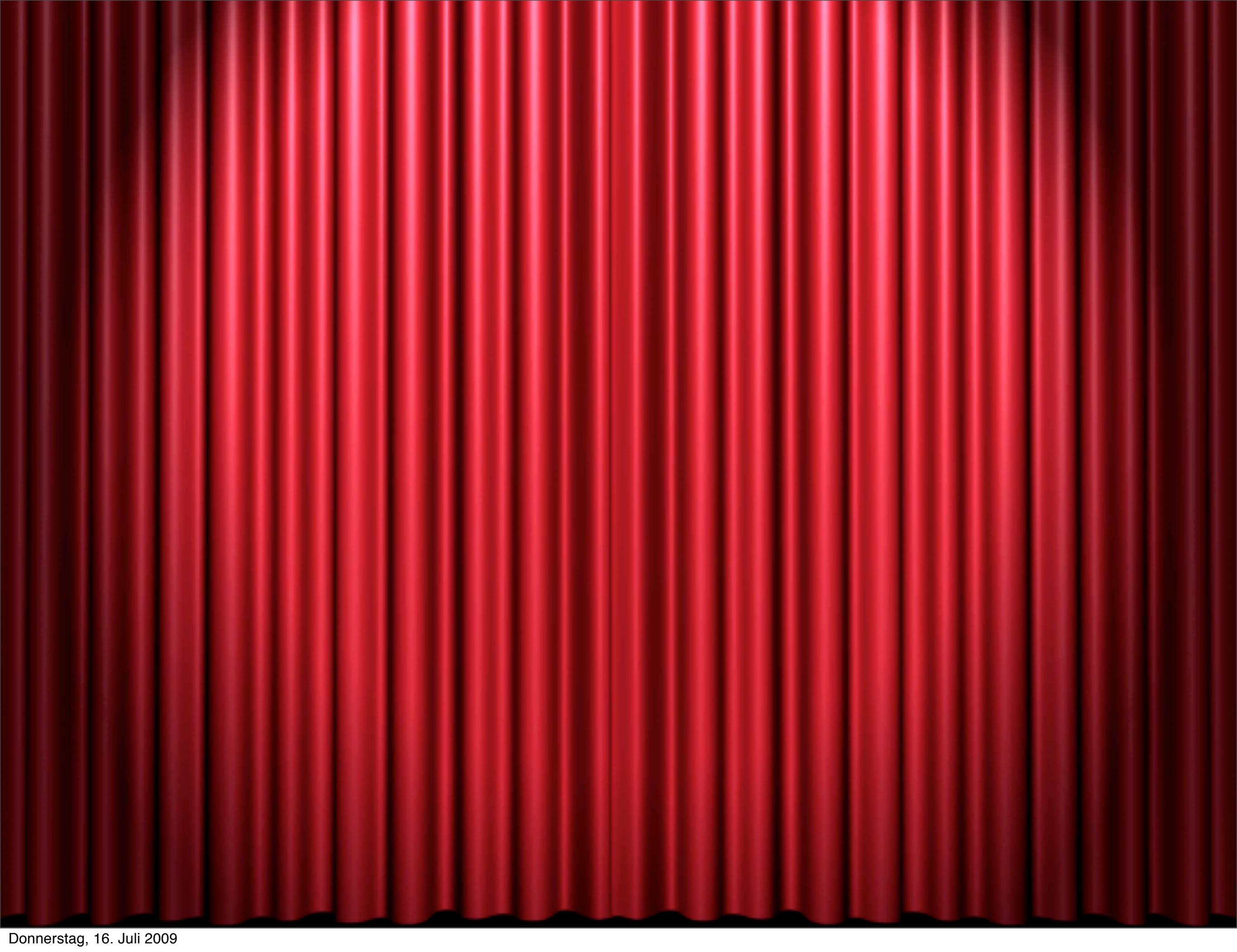
In collaboration with Eric Leuthardt, WashU

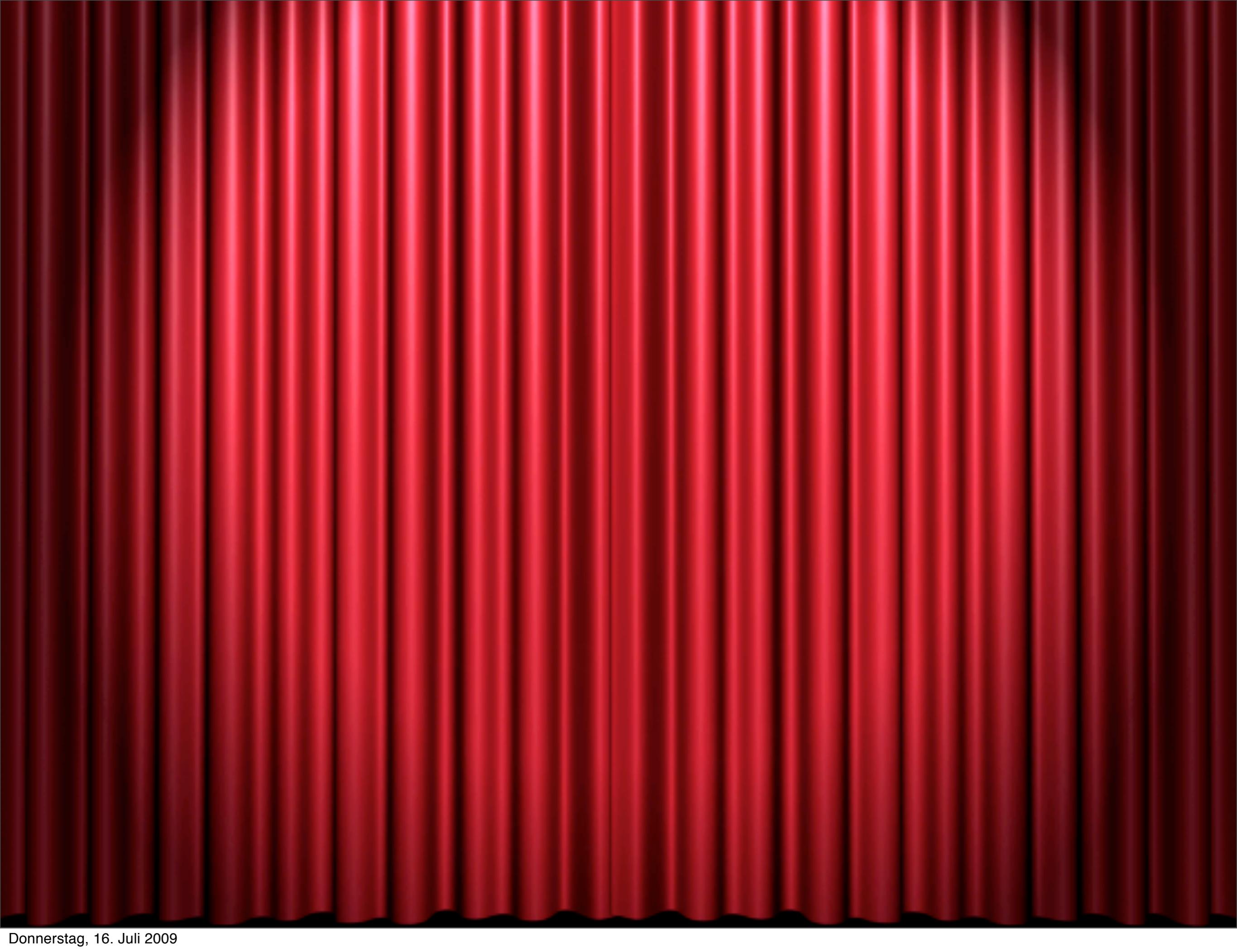
Using Imagined Vowels for Silent Communication



powered by
BCI2000

One more thing ...





Brunner, Ritaccio, Schalk, Wadsworth/AMC, 2009

A

B

C

D

E

F

G

H

I

J

K

L

Waiting to start ...

S

T

U

V

W

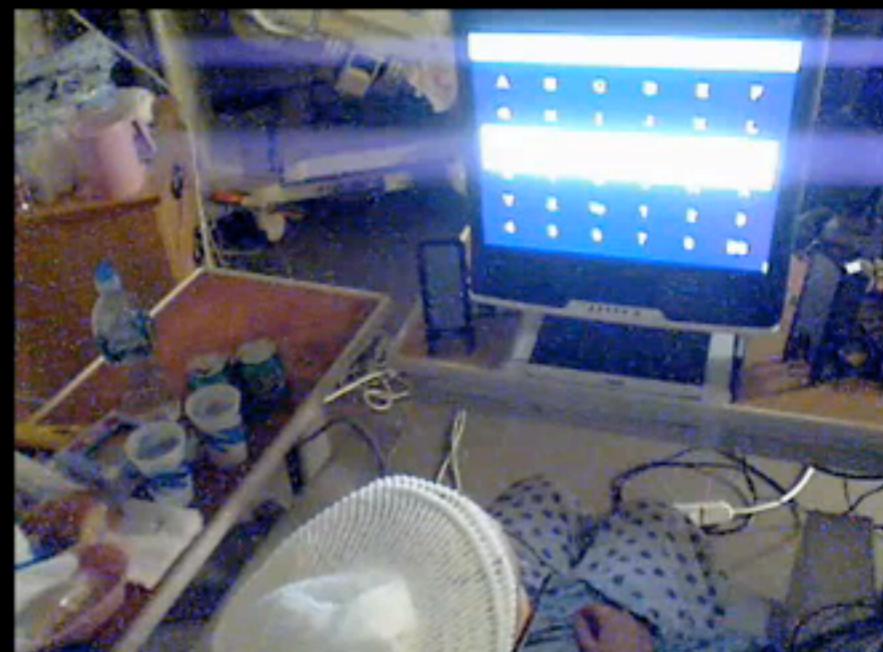
X

Y

Z

Sp

1



5

6

7

Brunner, Ritaccio, Schalk, Wadsworth/AMC, 2009

Electrocorticographic Signals (ECoG) in Humans

Relationship

Characteristics

ECoG

BCI Control

Diagnosis

Open Questions

Future Directions

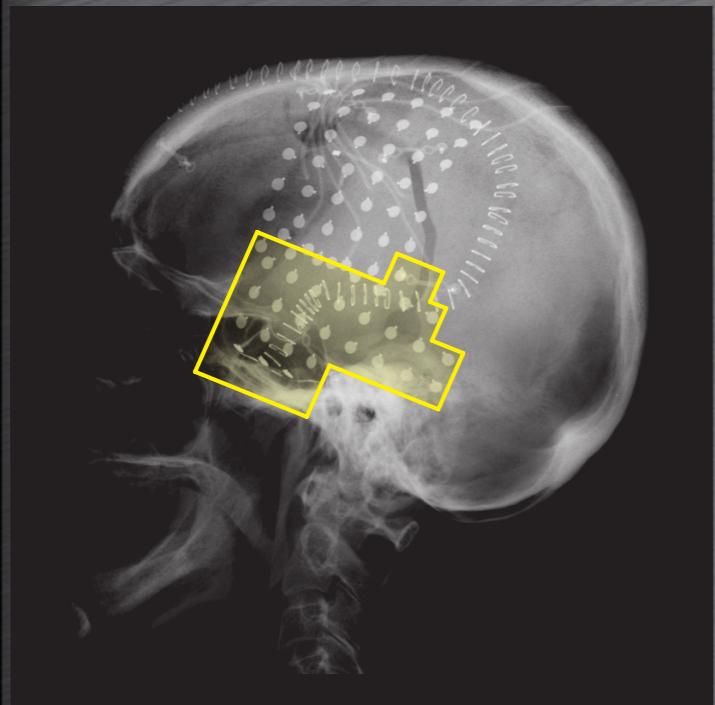
Functional Mapping

- Invasive brain surgery (e.g., for epilepsy or tumors) requires mapping of function
- Several techniques for functional mapping exist (e.g., fMRI, PET, electrical stimulation)
- All have substantial problems
- We use ECoG and our BCI techniques (BCI2000, SIGFRIED algorithm) for real-time mapping

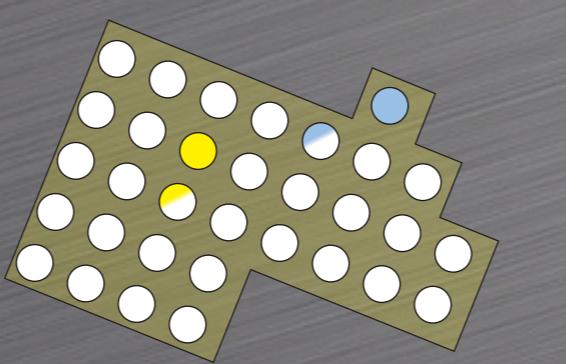
Schalk et al., *J Neurosci Meth*, 2008; Schalk et al., *NeuroImage*, 2008
Brunner, Ritaccio, Schalk et al., *Epilepsy and Behavior*, 2009

Real-Time Mapping Example #1

Lateral X-Ray
and ECoG Grids

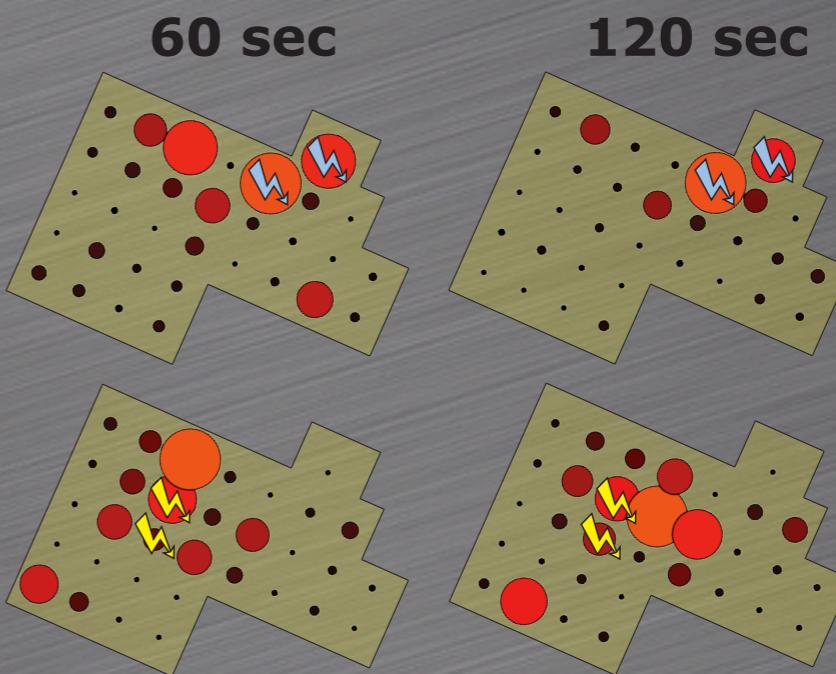


Language Localization
Using ECS Mapping
(5 hours)



● RECEPTIVE APHASIA
● ANOMIA

Language Localization
Using SIGFRIED Mapping
(several minutes)

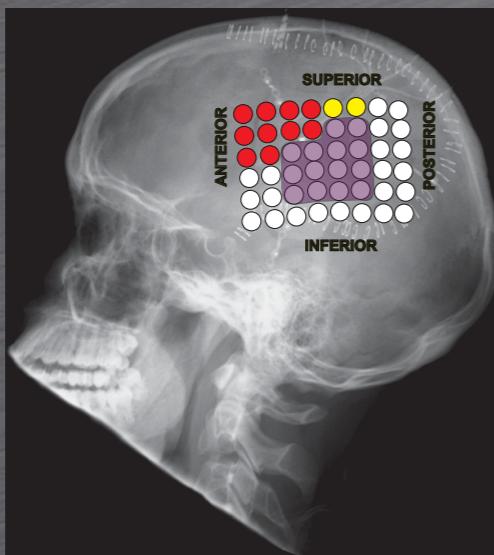


RECEPTIVE
LANGUAGE

NAMING

Real-Time Mapping Example #2

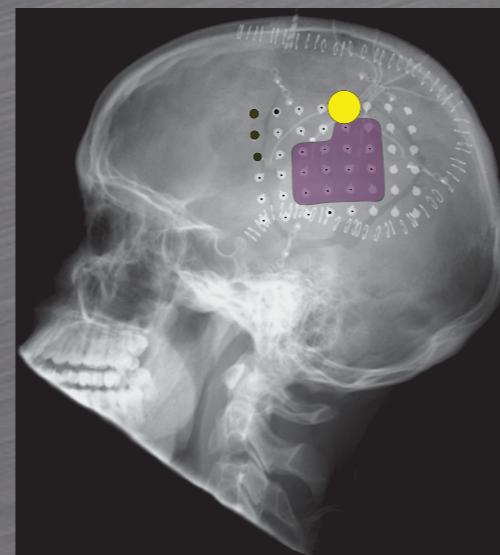
Motor Localization
Using ECS Mapping (5 hours)



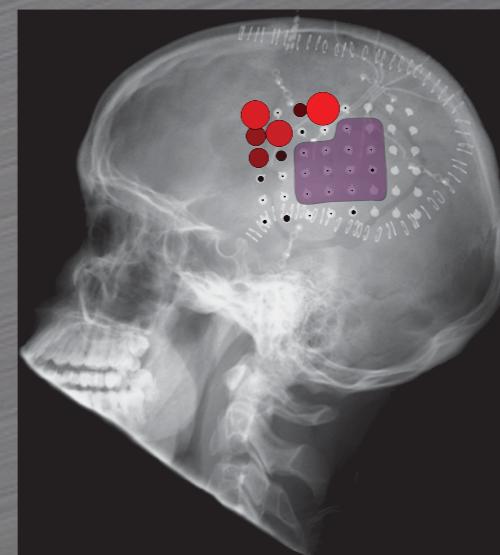
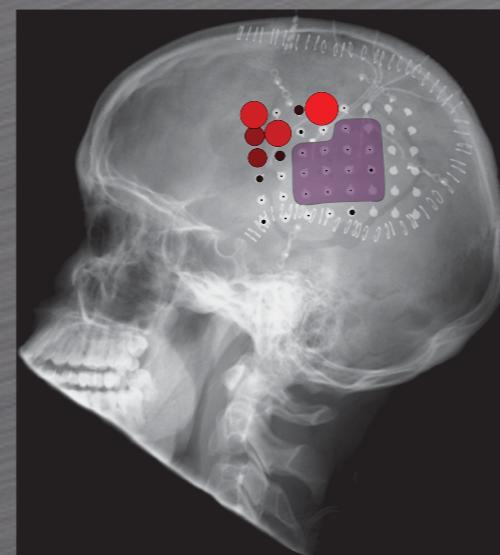
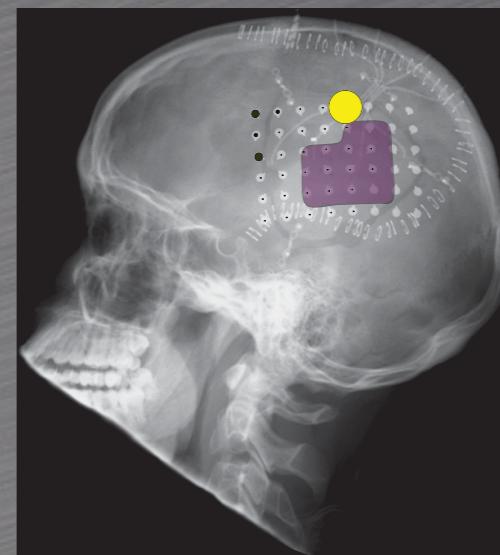
- HAND MOTOR
- FACE MOTOR
- TUMOR

Motor Localization Using SIGFRIED Mapping
(several minutes)

60 sec



120 sec

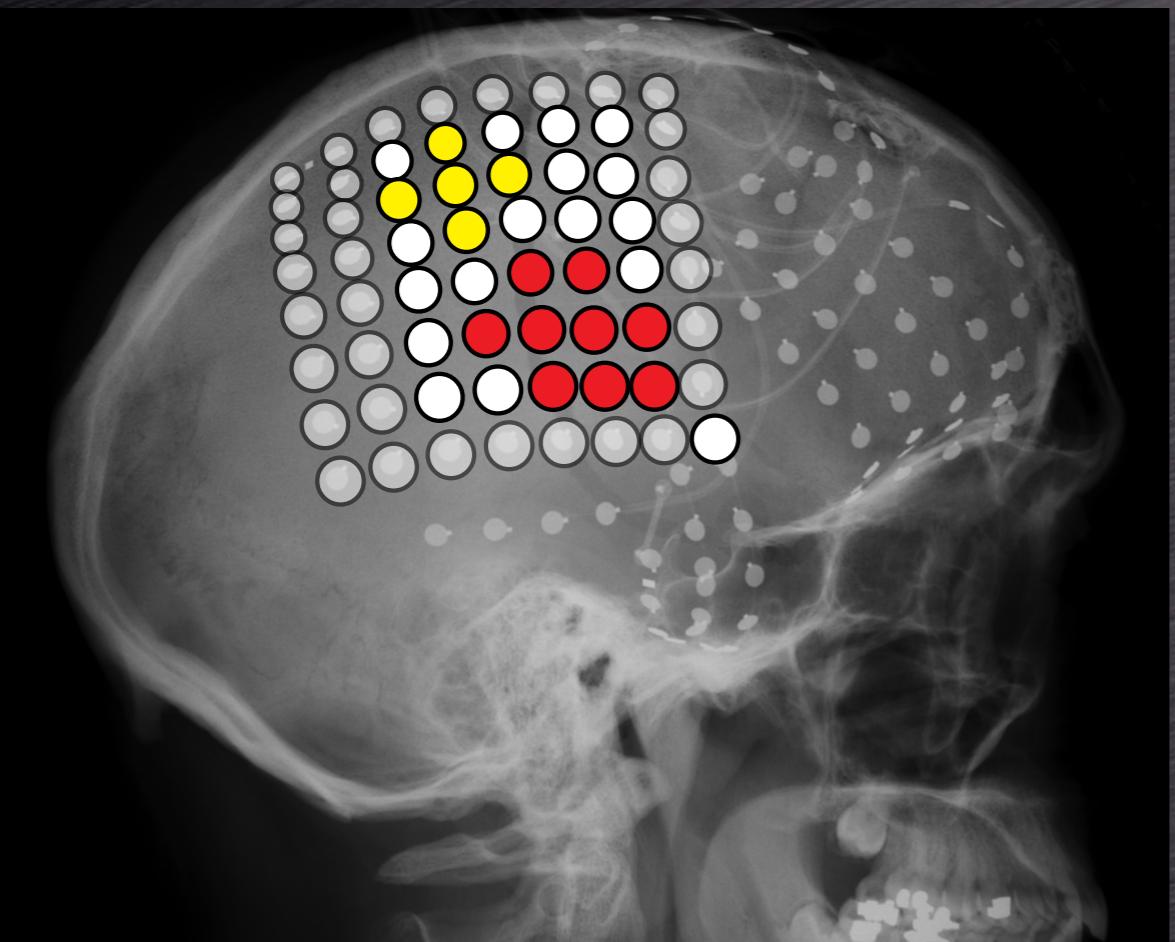


Example applications to date include motor, expressive / receptive language, and naming.

Real-Time Mapping Example #3

Real-Time Mapping Example #3

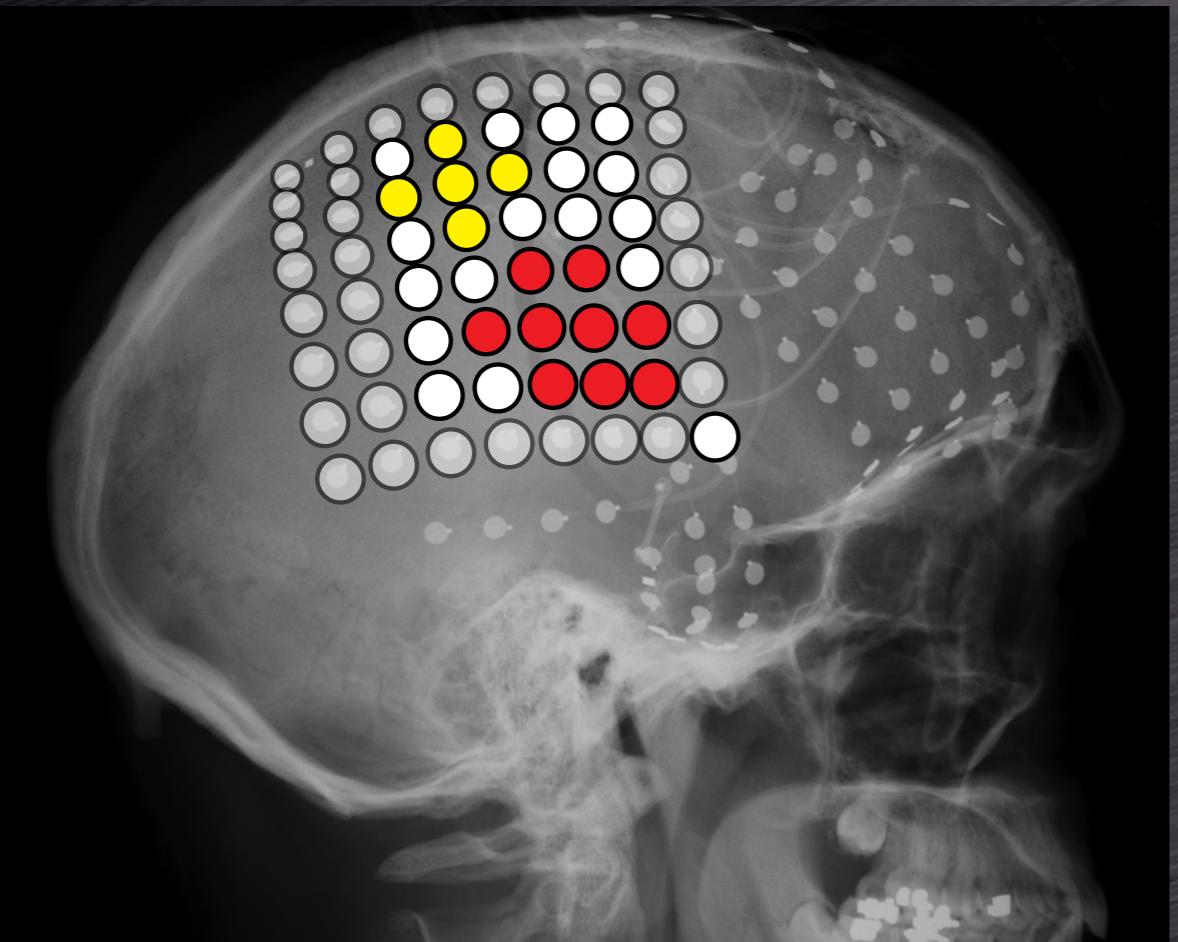
Results from ECS after 2.5 hours



- Hand
- Tongue

Real-Time Mapping Example #3

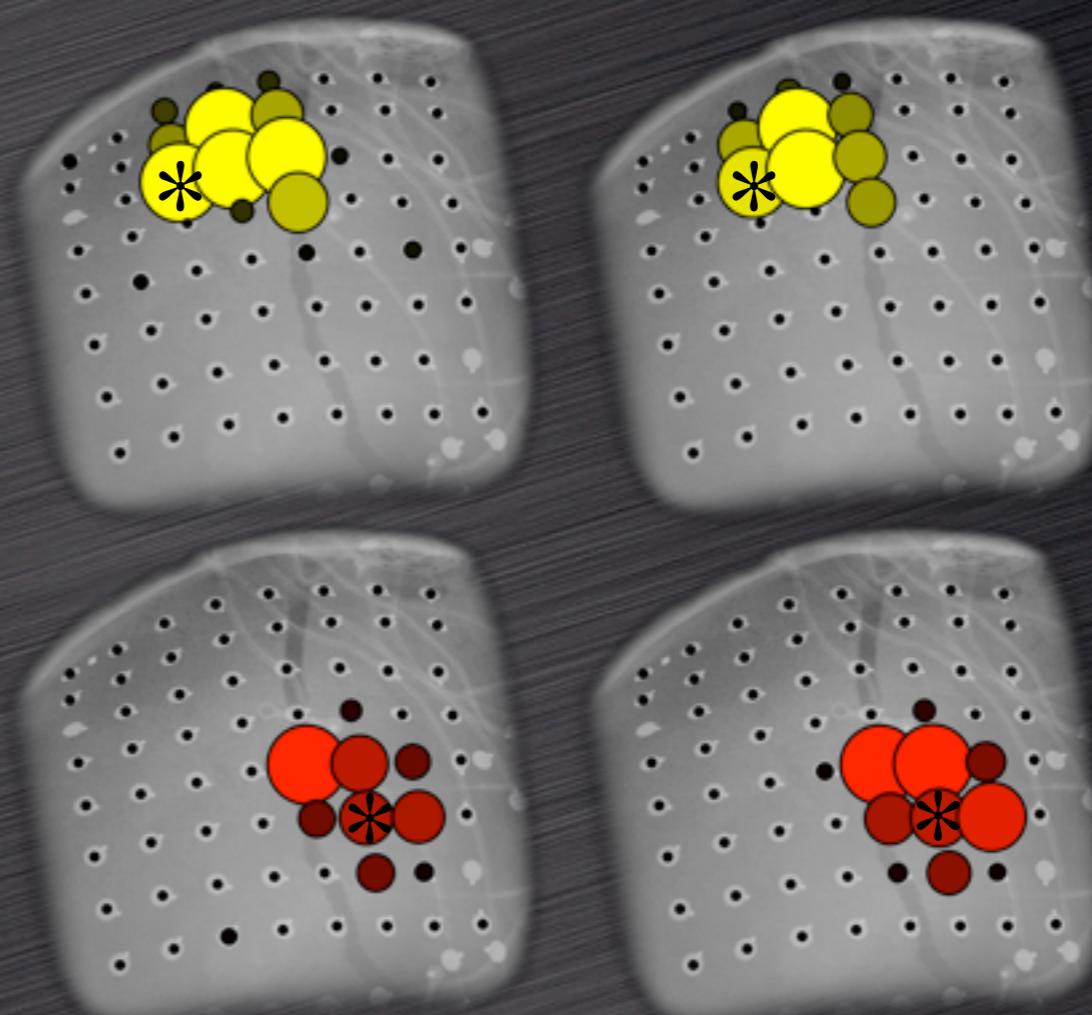
Results from ECS after 2.5 hours



● Hand

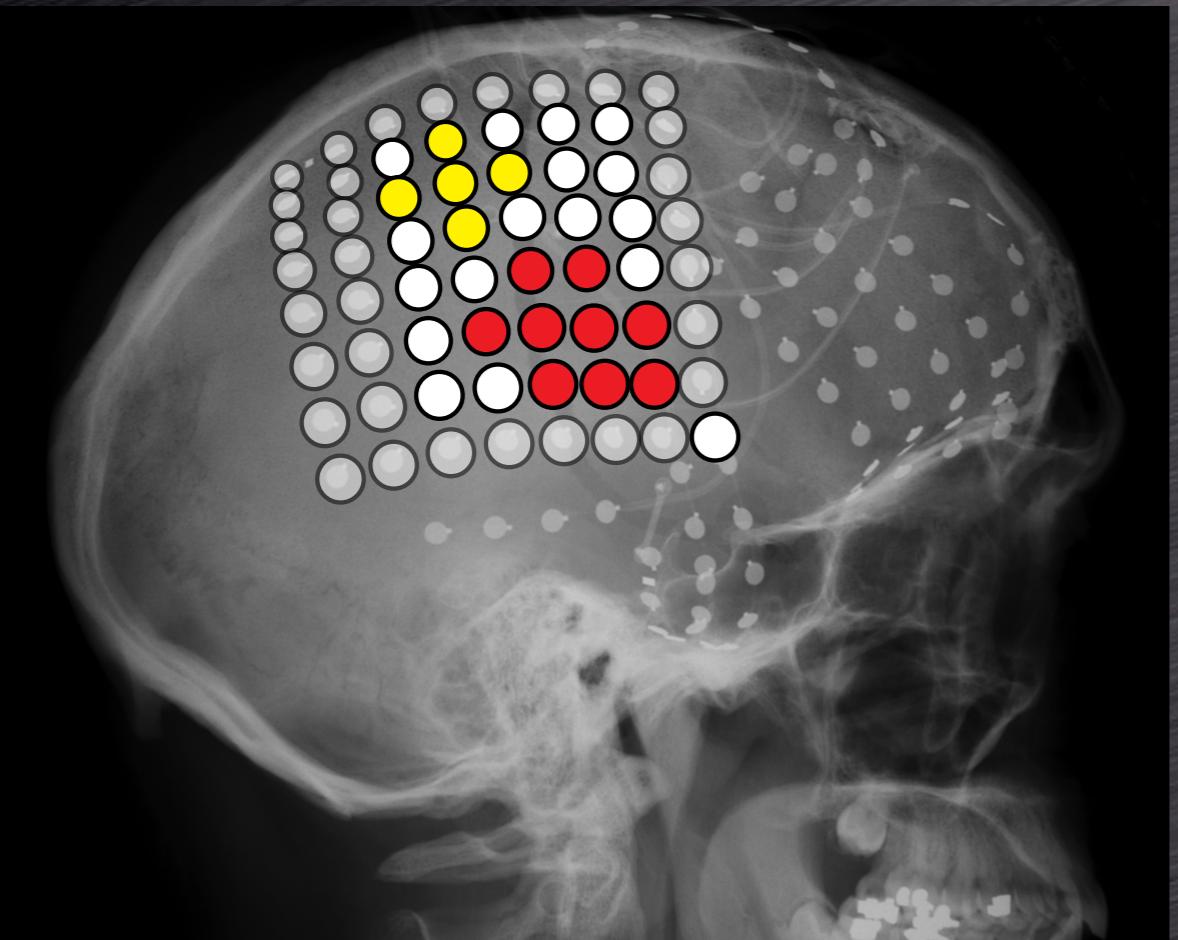
● Tongue

Results from SIGFRIED
after 60 sec after 180 sec



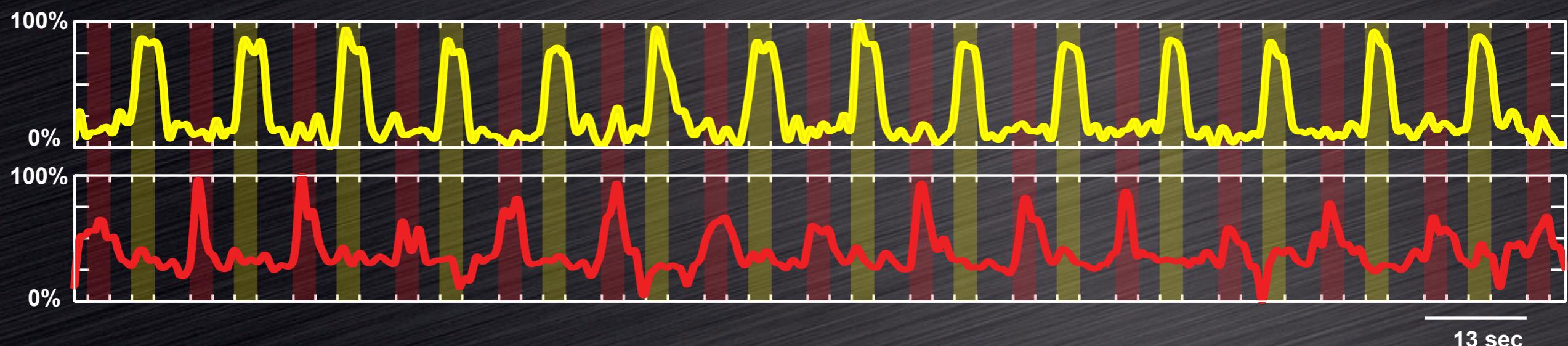
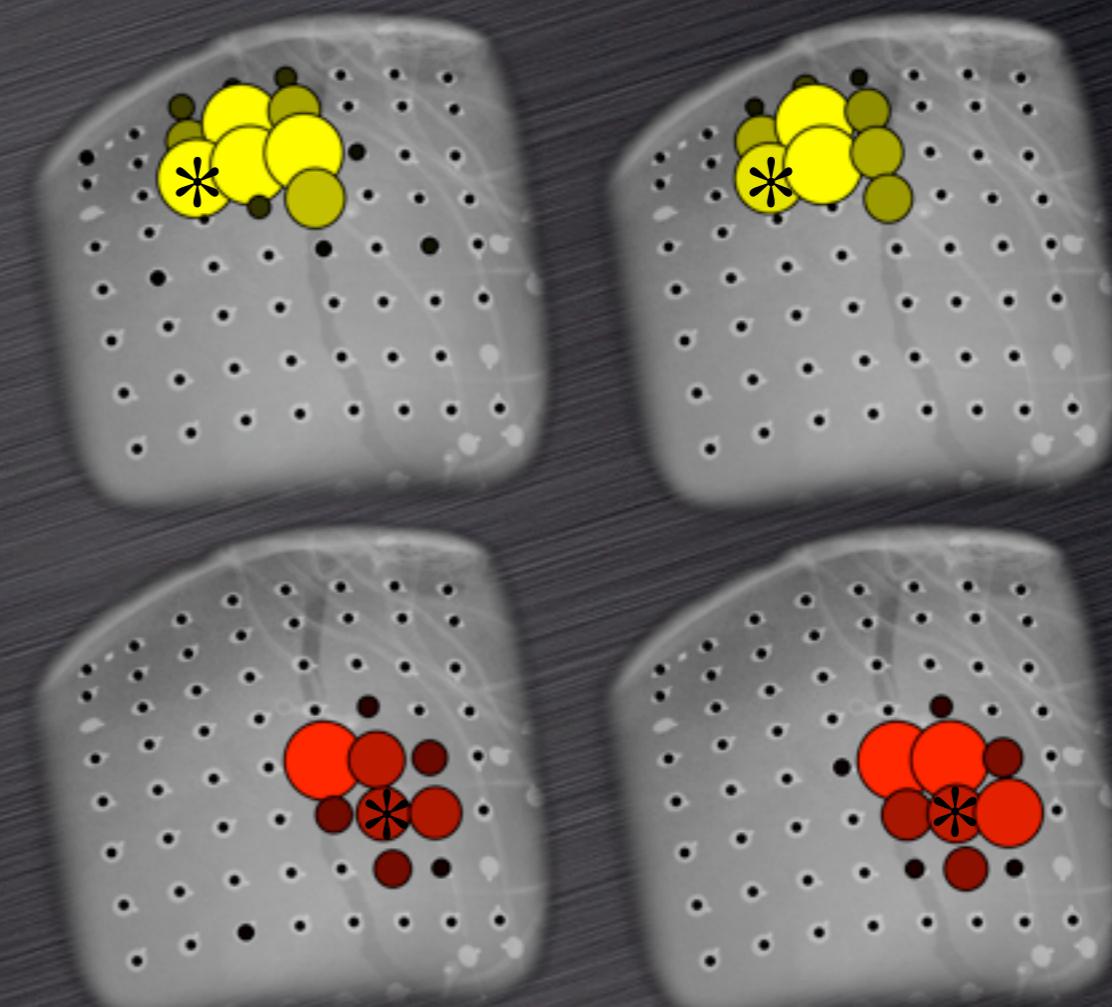
Real-Time Mapping Example #3

Results from ECS after 2.5 hours



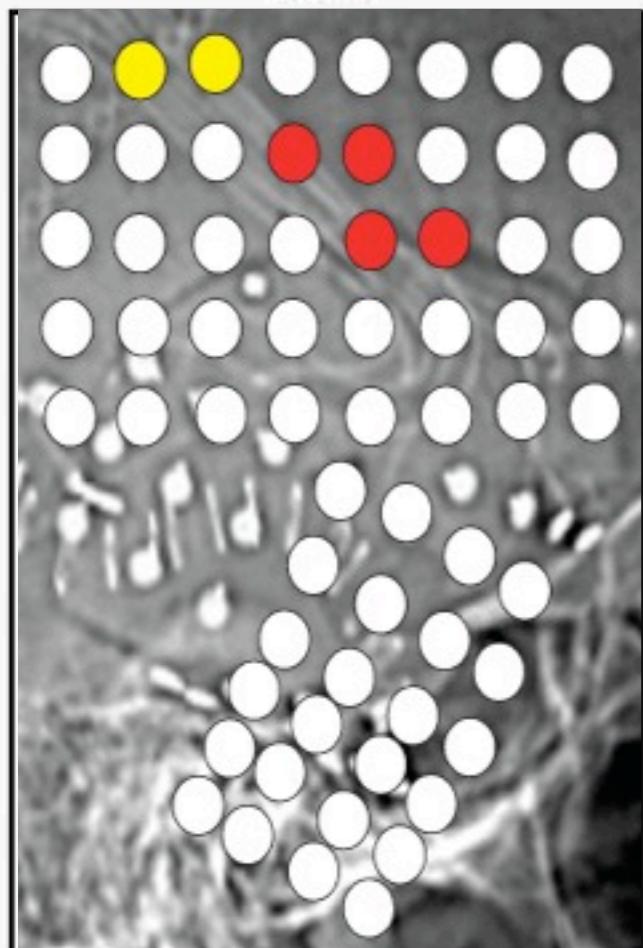
● Hand ● Tongue

Results from SIGFRIED
after 60 sec after 180 sec

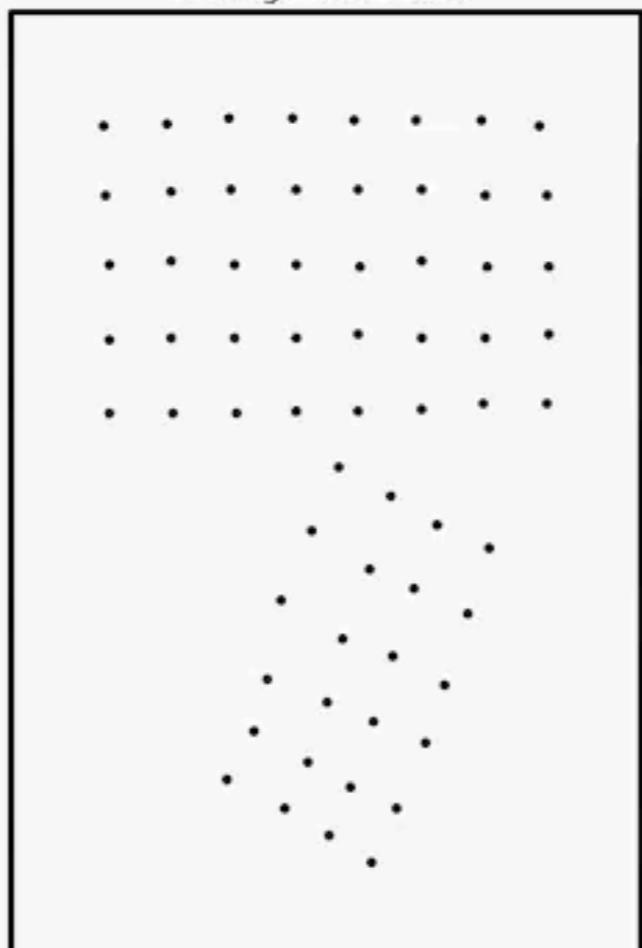


SIGFRIED Score Topography (gamma)

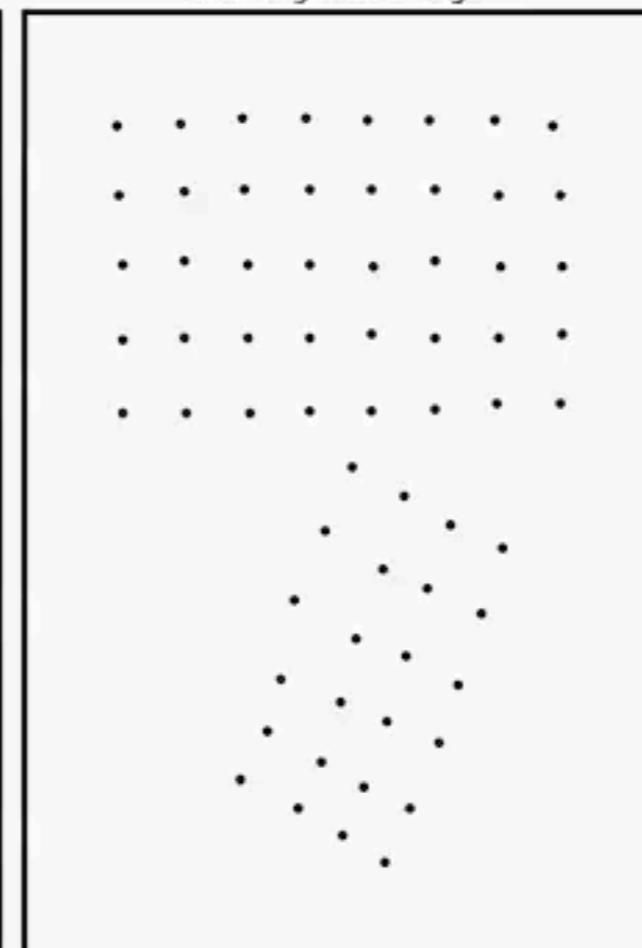
realtime



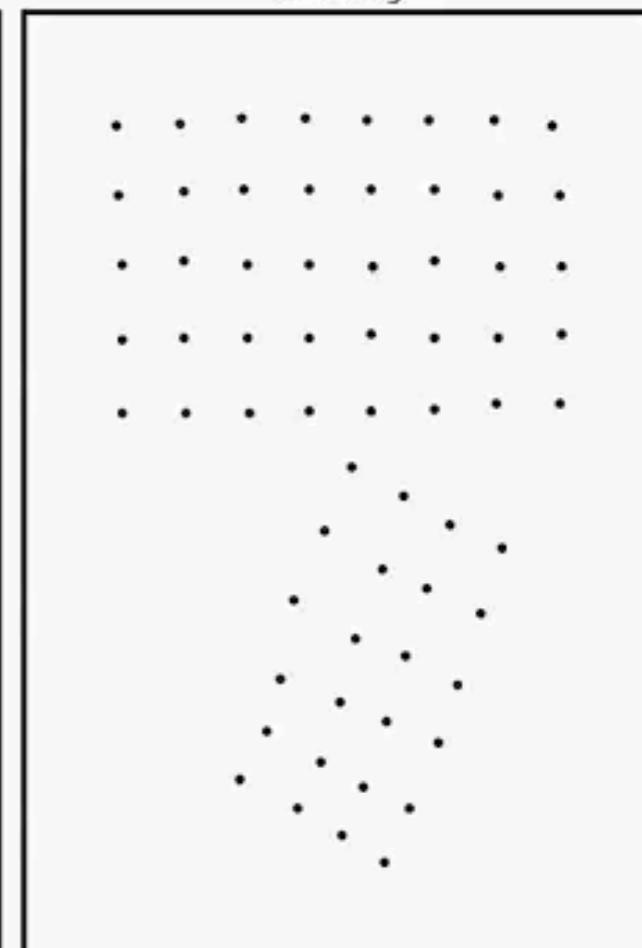
solving rubik's cube



sticking out toungue



listening



BCI2000/Operator 2.0 - Running 00:00 s

File View Help

Function 1 Function 2 Function 3 Function 4

Config → Set Config → Suspend

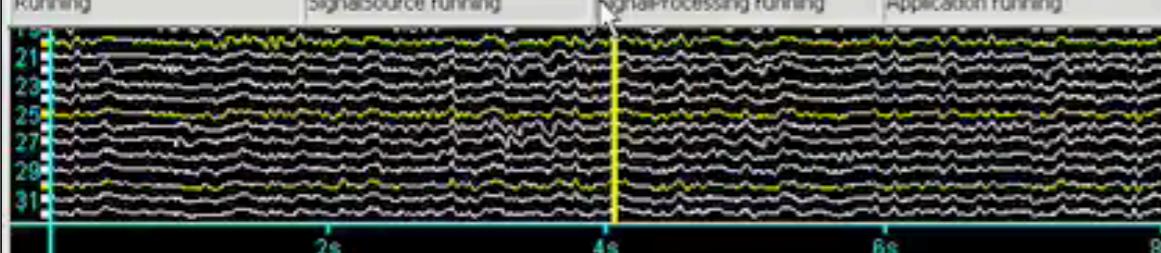
Quit

Running

SignalSource running

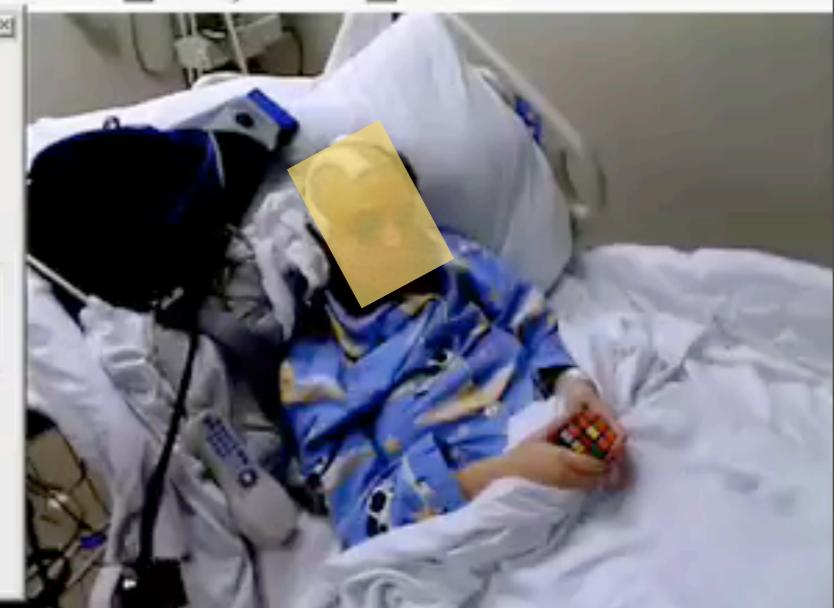
SignalProcessing running

Application running



Application Window

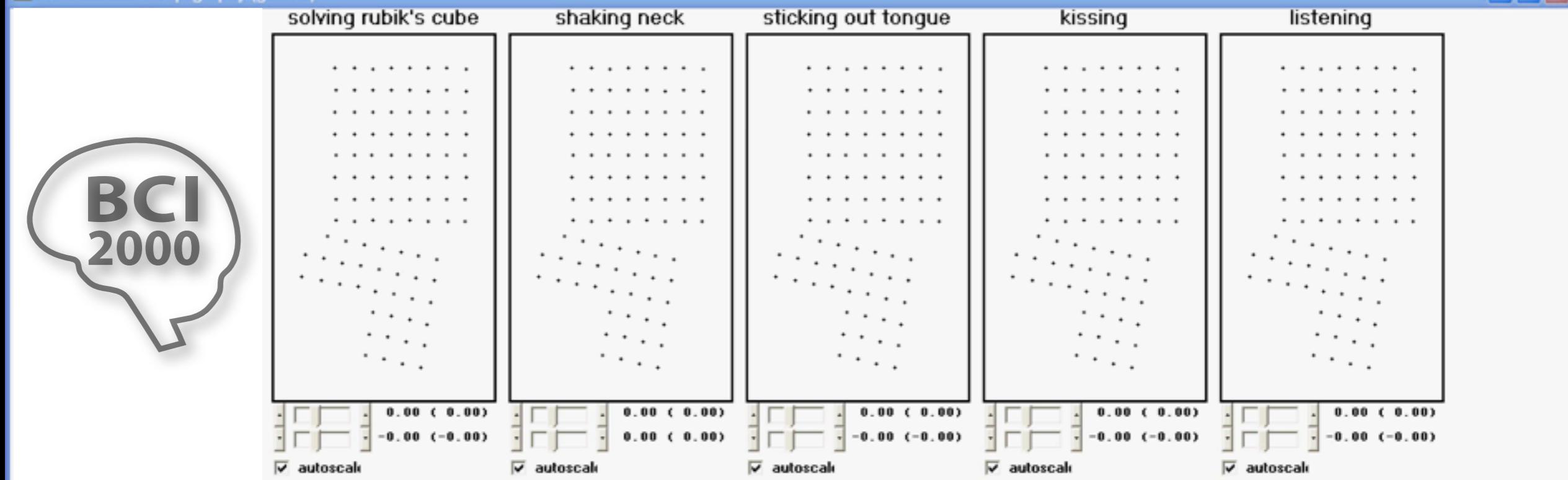
Waiting to start ...



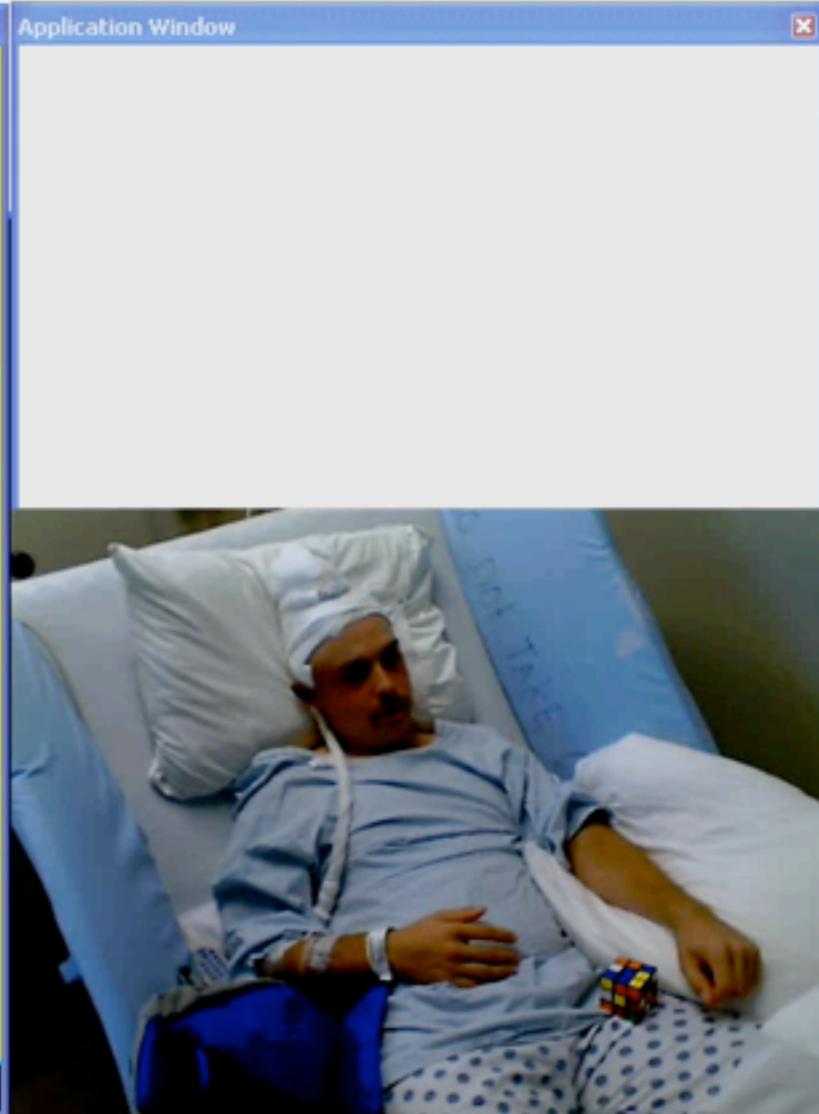
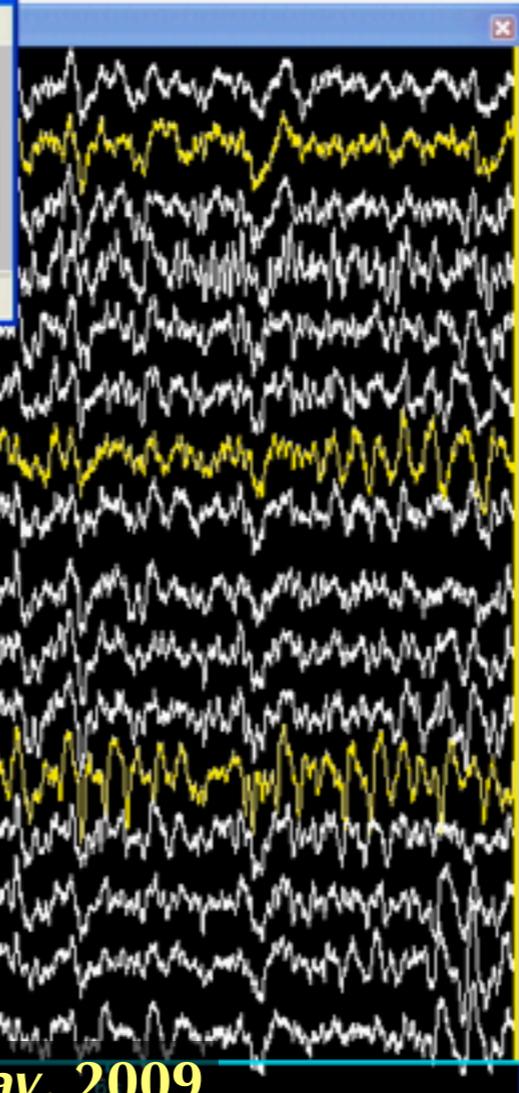
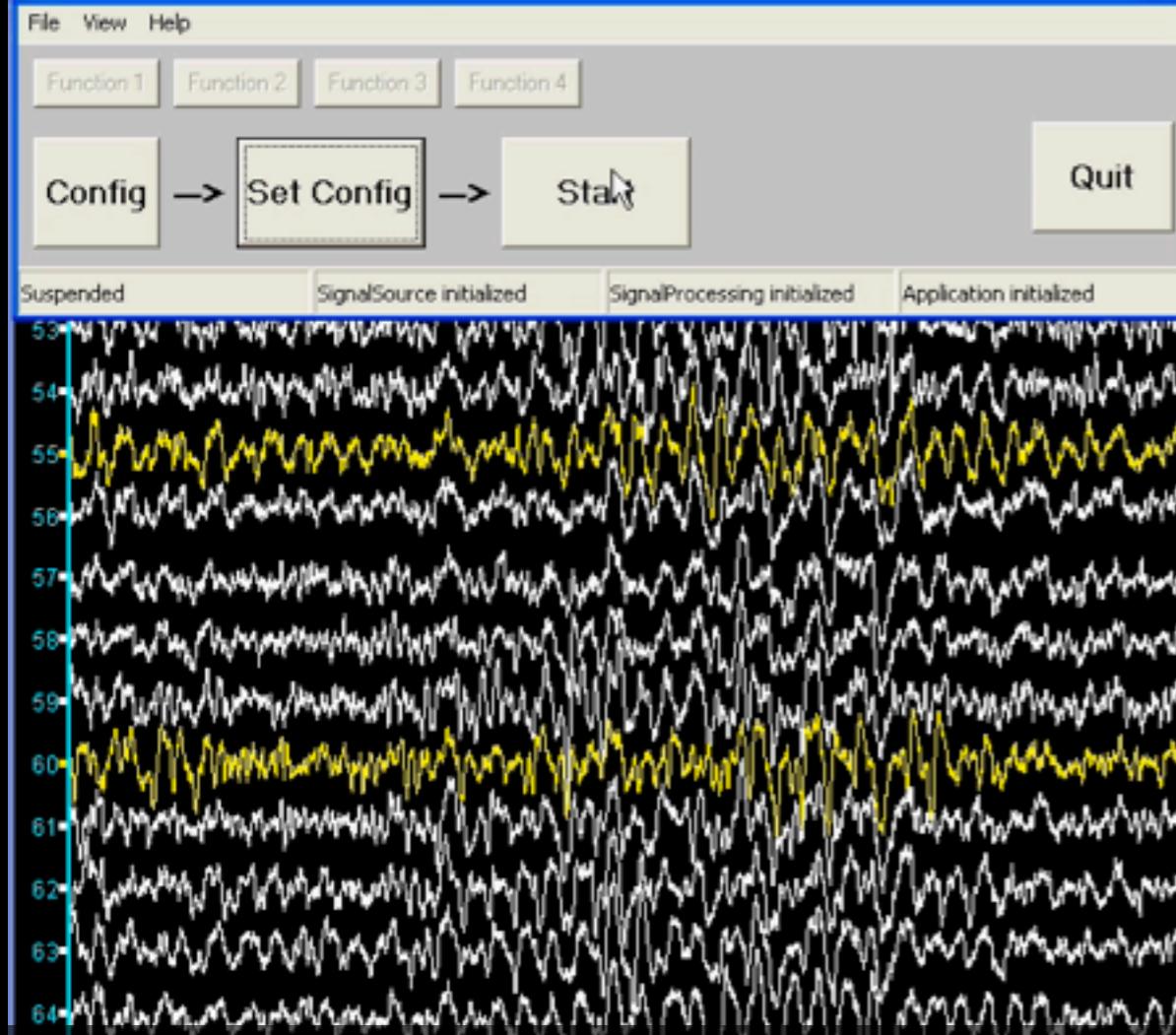
BCI
2000

powered by BCI2000 and SIGFRIED technologies

SIGFRIED Score Topography (gamma)



BCI2000/Operator 2.0 - Suspended 01:08 s



Electrocorticographic Signals (ECoG) in Humans

Relationship

BCI Control

Characteristics

Diagnosis

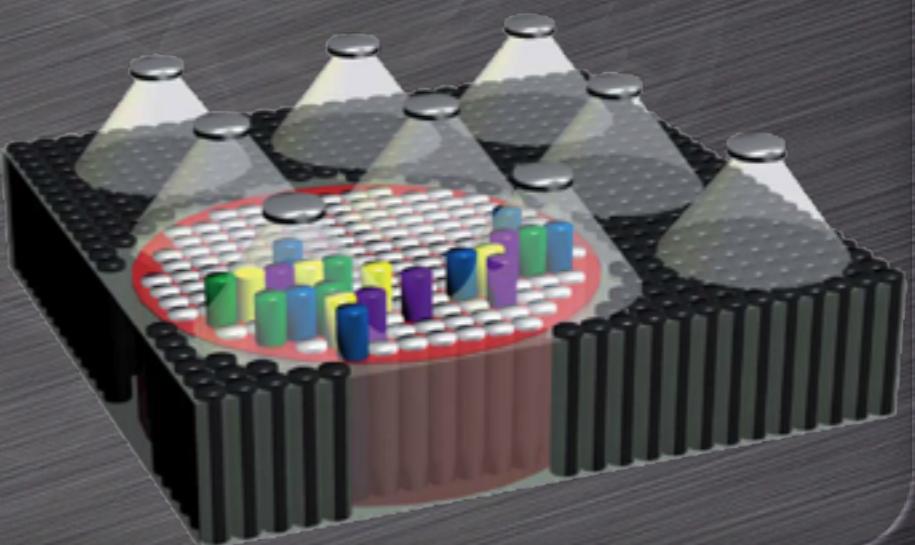
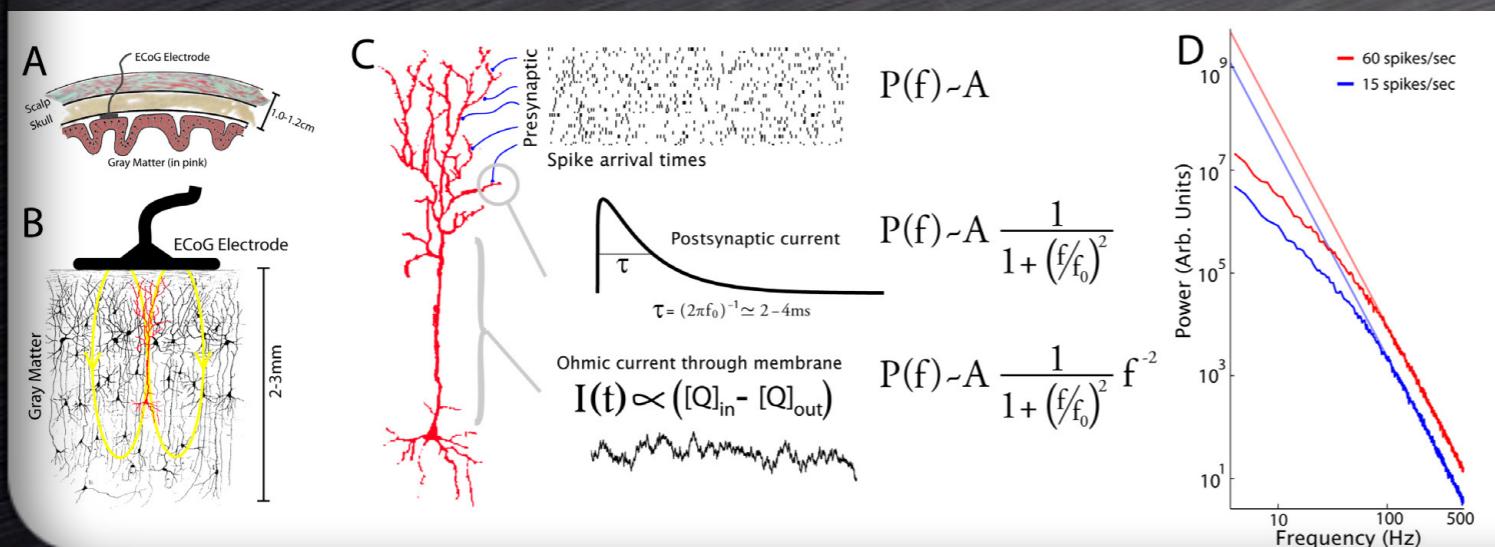
ECoG

Open Questions

Future Directions

Question 1: What is Gamma?

- Candidate 1:
One oscillation (such as the mu rhythm)
- Candidate 2:
“Brain Noise” with power-law characteristics
- Candidate 3:
Many local oscillations



Question 2: What is the LMP?

Question 2: What is the LMP?



Question (Set) 3: What is the best ...

- **Location?**
- **Scale?**
(subdural, epidural, scull screws)
- **Inter-electrode distance?**
- **Task?**
(decoding kinematic parameters vs. feedback)

Electrocorticographic Signals (ECoG) in Humans

Relationship

BCI Control

Characteristics

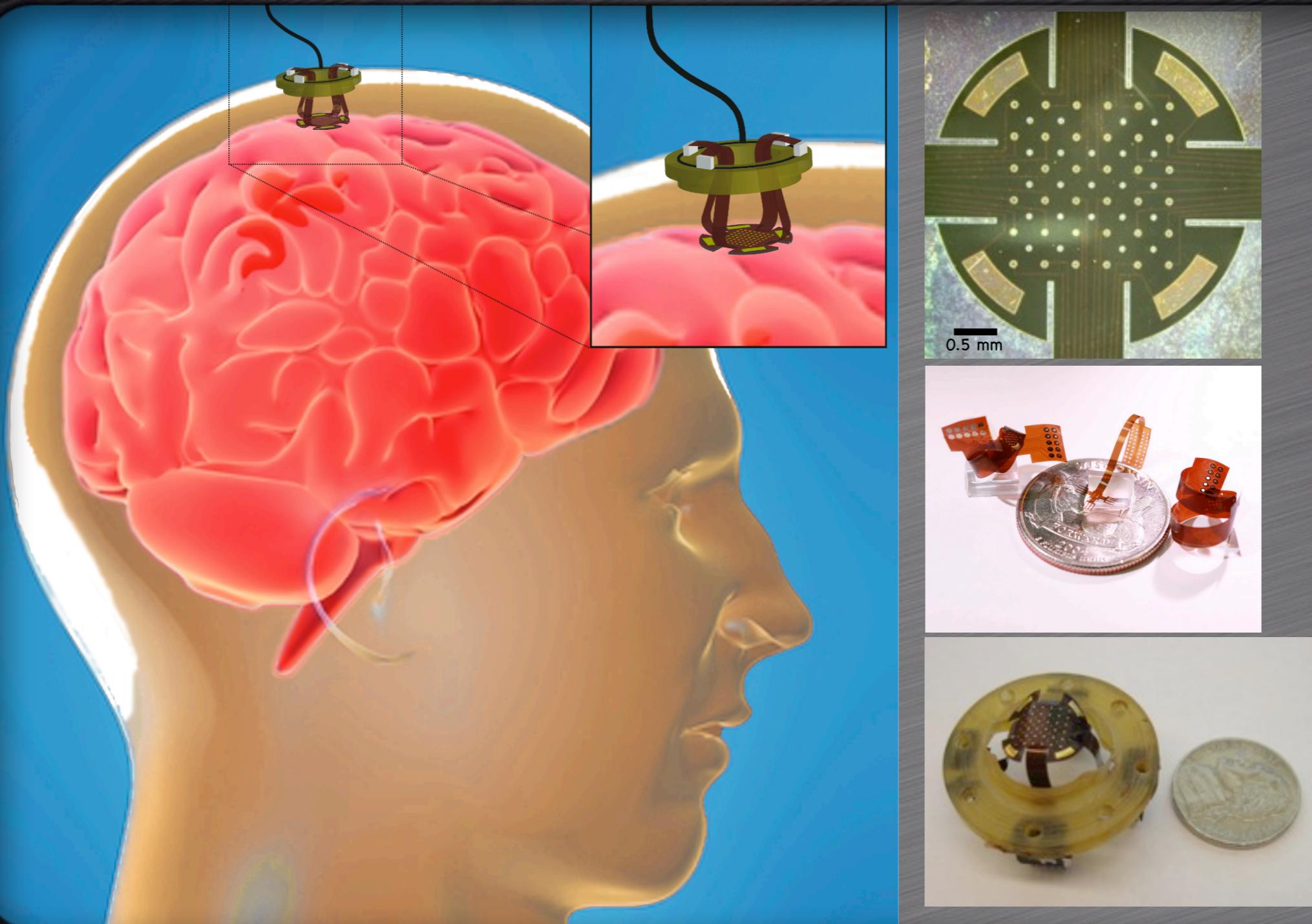
Diagnosis

ECoG

Open Questions

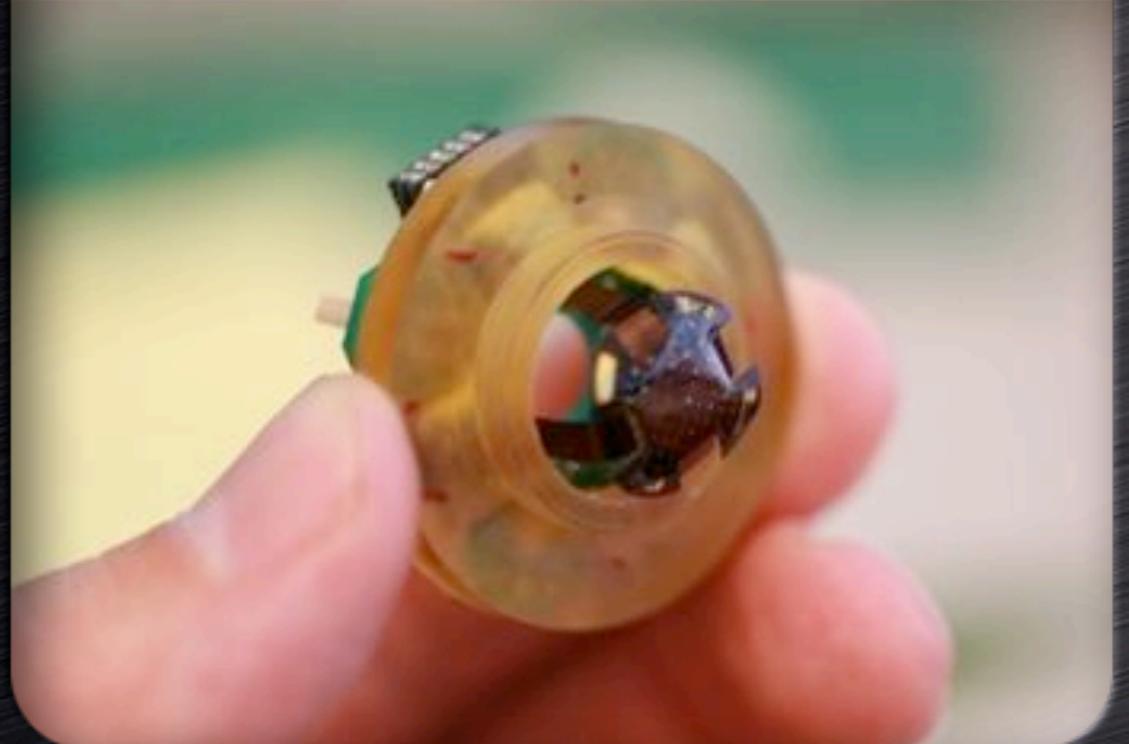
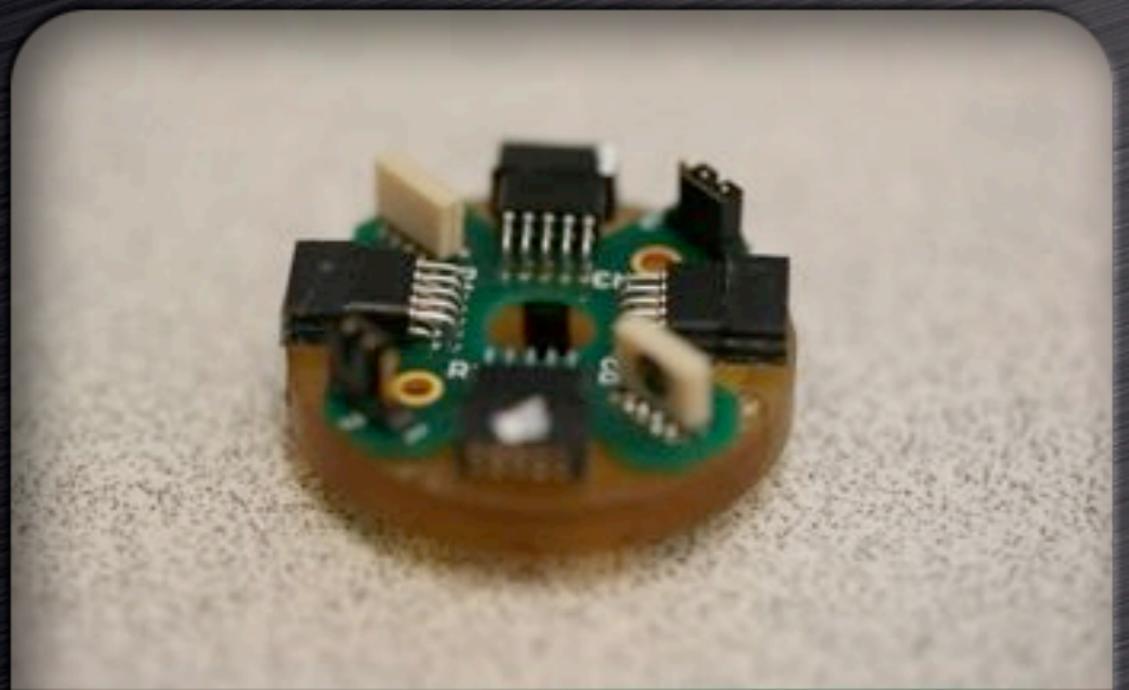
Future Directions

Current μ ECoG



Justin Williams, University of Wisconsin

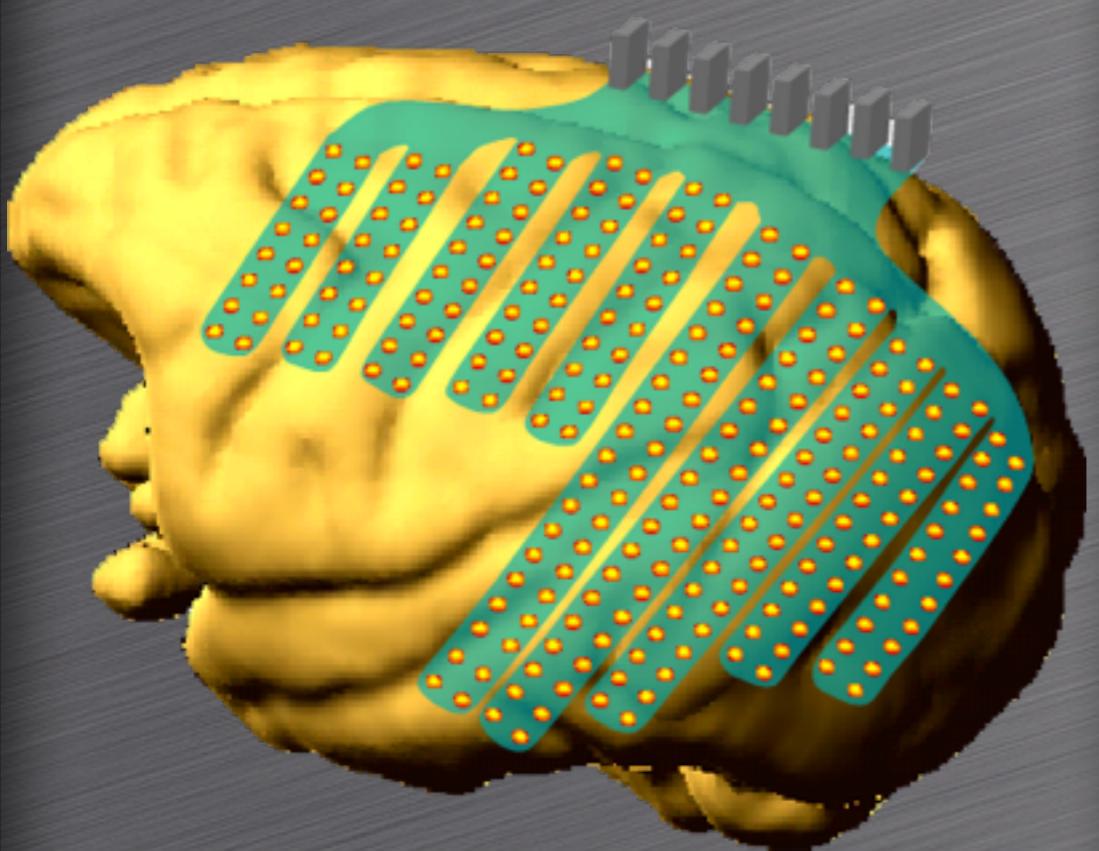
Next Generation μ ECoG



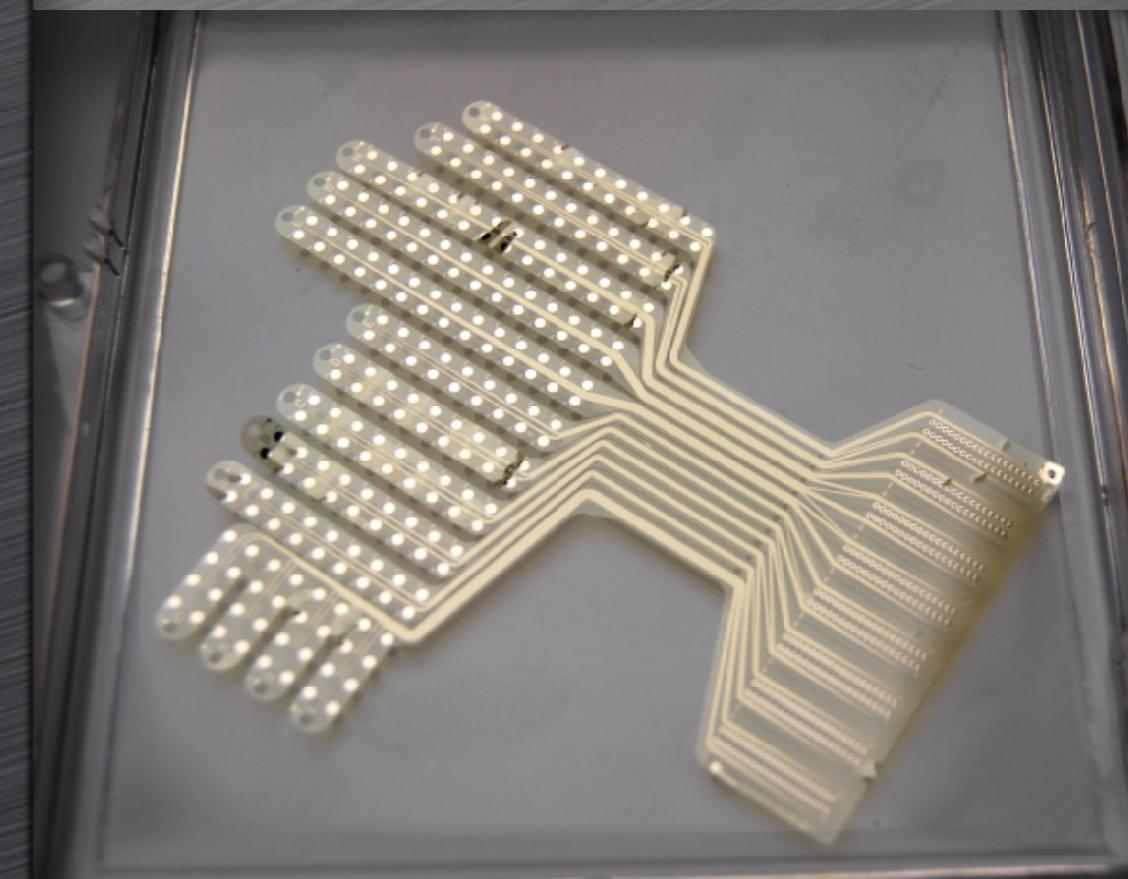
- Electronics integrated into platform

Justin Williams, University of Wisconsin

Different Design ...



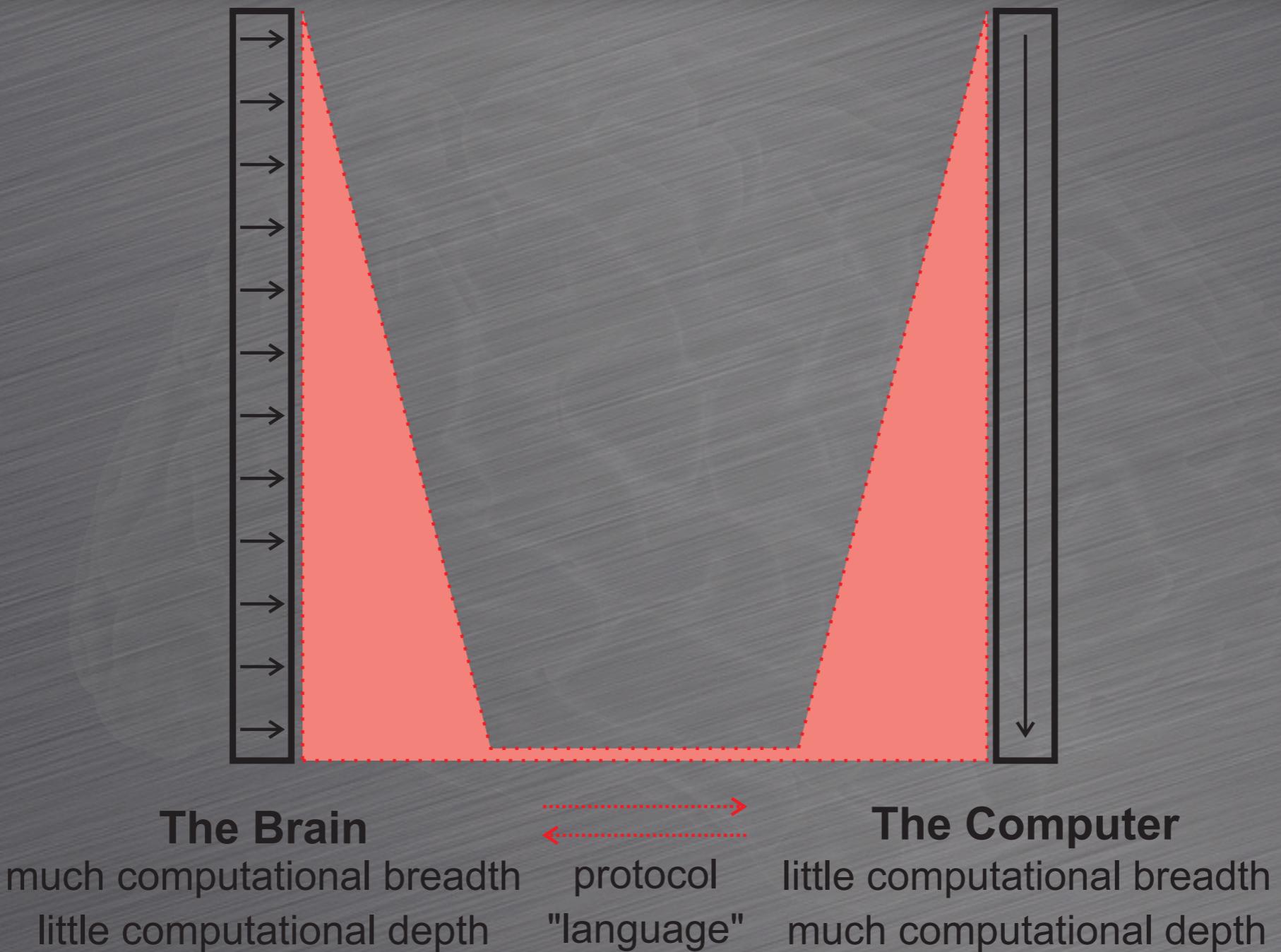
Pascal Fries, Nijmegen



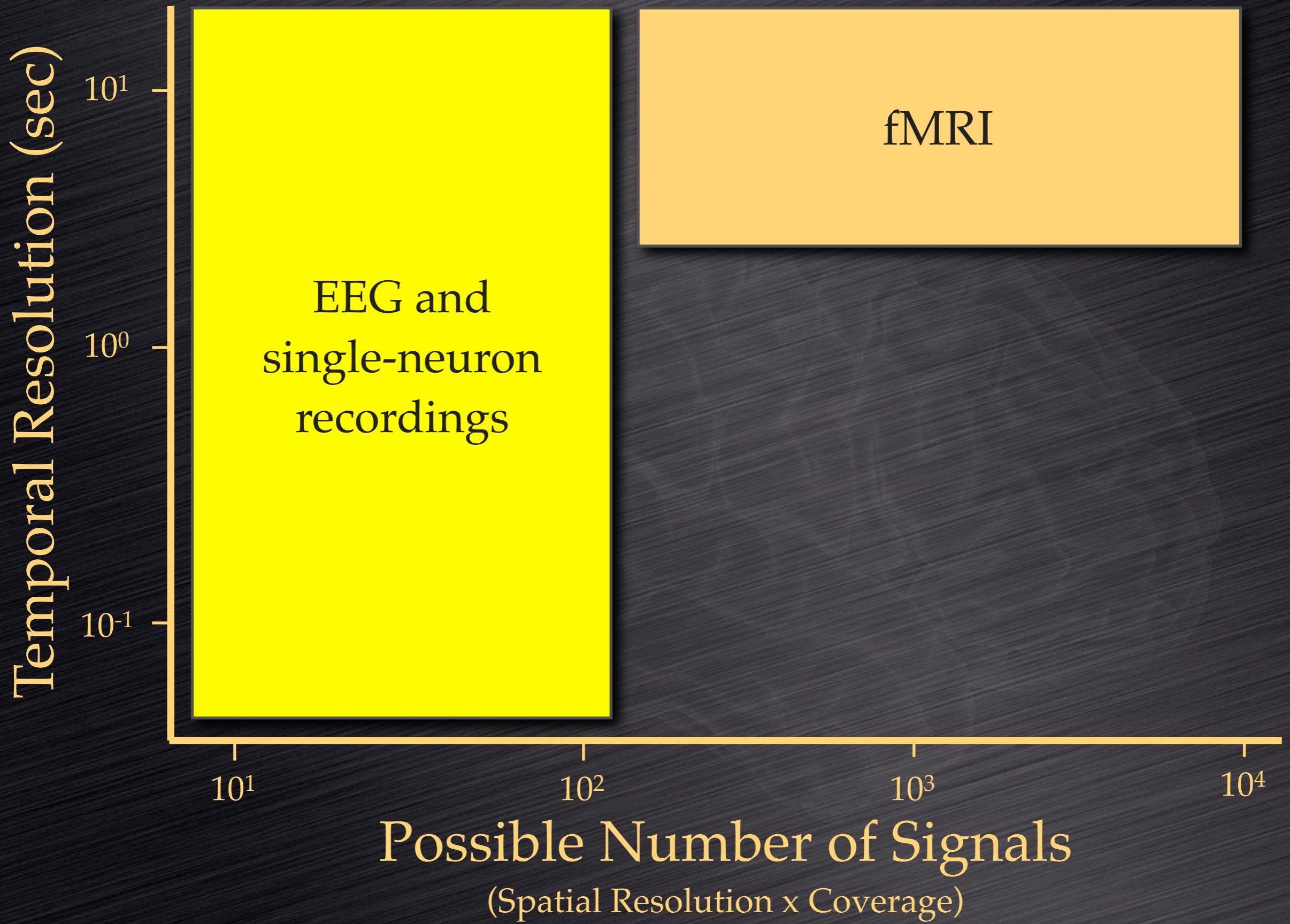
Thomas Stieglitz, Freiburg

What does all this mean?

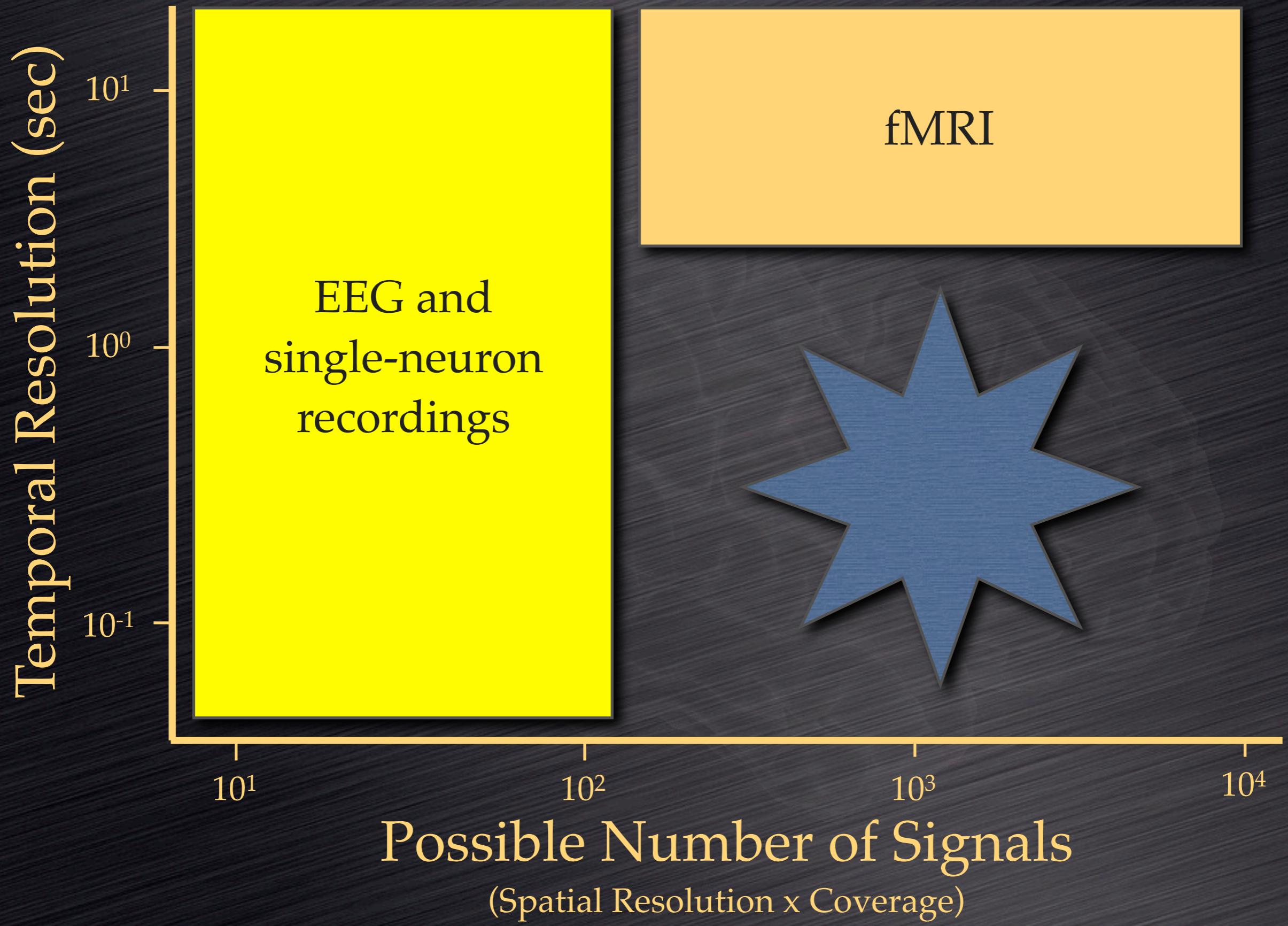
The Communication Problem



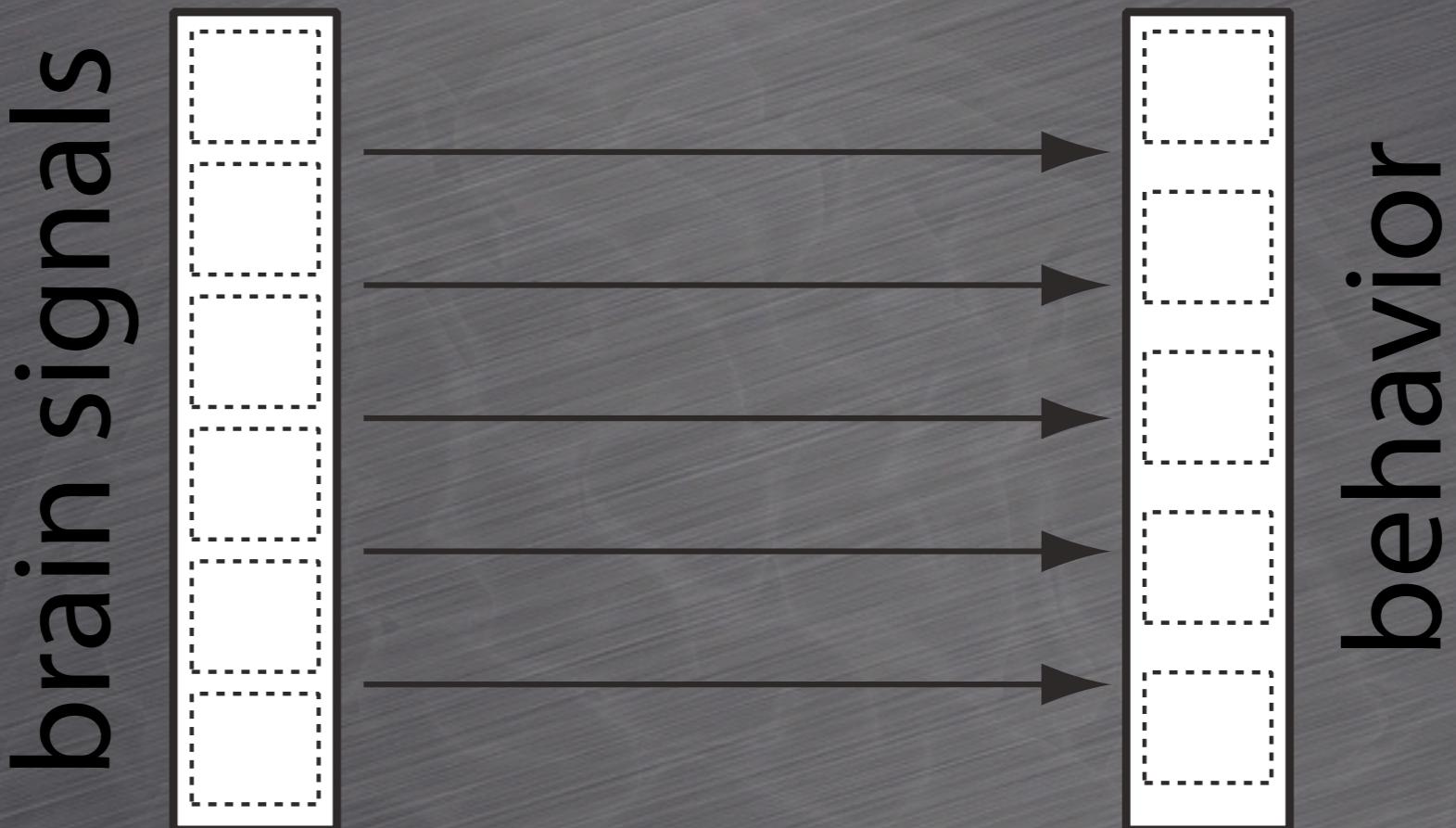
Req. 1: Better Access to Brain Signals



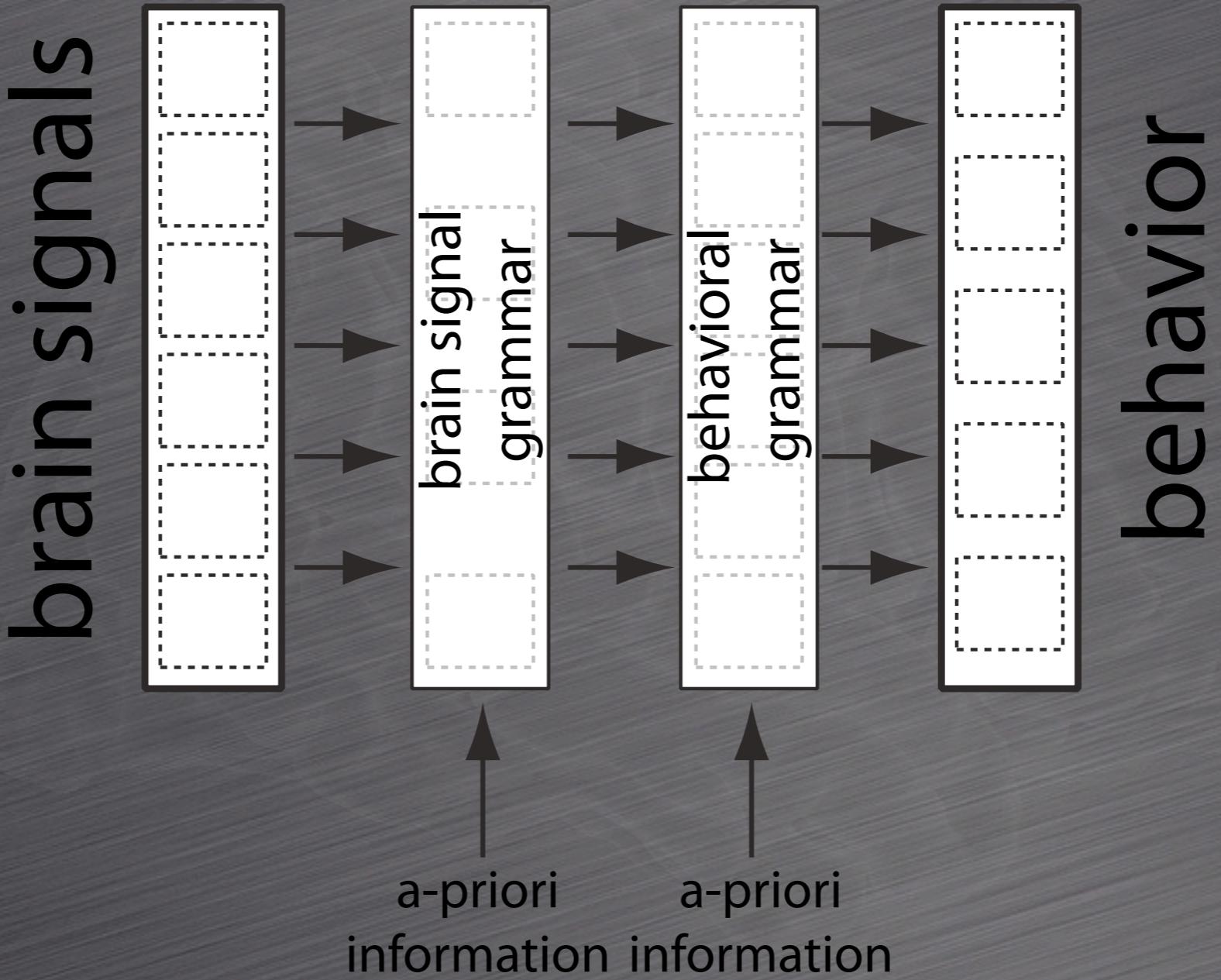
Req. 1: Better Access to Brain Signals



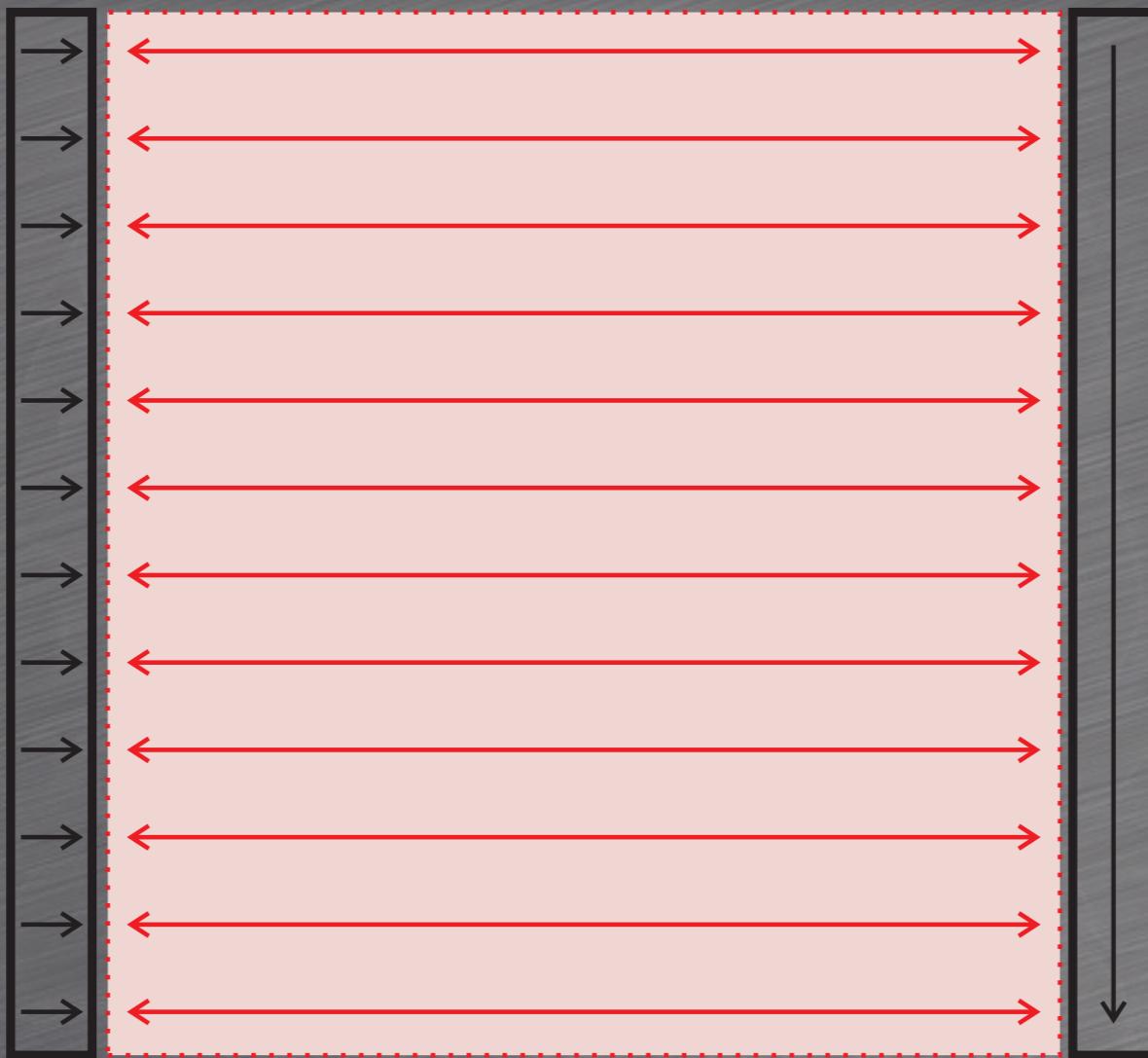
Req. 2: Better Interpretation



Req. 2: Better Interpretation



The Communication Problem Solved



The Brain and The Computer
much computational breadth
much computational depth

The hope is that, in not too many years, human brains and computing machines will be coupled together very tightly, and that the resulting partnership will think as no human brain has ever thought and process data in a way not approached by the information-handling machines we know today.

J.C.R. Licklider, *Man-Computer Symbiosis*, March 1960

The hope is that, in not too many years, human brains and computing machines will be coupled together very tightly, and that the resulting partnership will think as no human brain has ever thought and process data in a way not approached by the information-handling machines we know today.

J.C.R. Licklider, *Man-Computer Symbiosis*, March 1960

Schalk, G.
Brain-Computer Symbiosis
J. Neural Eng. 5:1-15, 2008

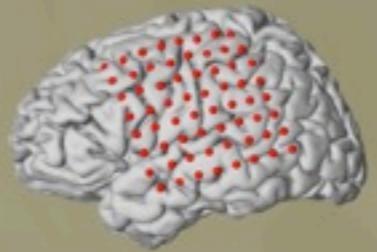
Conclusions

ECoG presents an exciting opportunity for:

- Brain-computer interfaces
- Neuroscience research
- Clinical diagnosis

5th BCI2000 Workshop

Intl. Workshop on Advances in Electrocorticography



October 1-3, 2009
The Sagamore Conference Center
Bolton Landing, New York, USA

<http://www.bci2000.org>

Invited Speakers

| | |
|-------------------|---|
| Peter Brunner | Wadsworth Center |
| Nathan Crone | Johns Hopkins Hospital |
| Christoph Guger | g.tec Medical Engineering, Inc. |
| Jeremy Hill | Max-Planck-Institute for Biological Cybernetics |
| Eric Leuthardt | Washington University School of Medicine |
| Robert Oostenveld | Radboud University Nijmegen |
| Anthony Ritaccio | Albany Medical Center |
| Steven Schachter | Harvard Medical School |
| Gerwin Schalk | Wadsworth Center |
| William Stacey | University of Pennsylvania |
| Jonathan Wolpaw | Wadsworth Center |

Wadsworth Center
New York State Department of Health

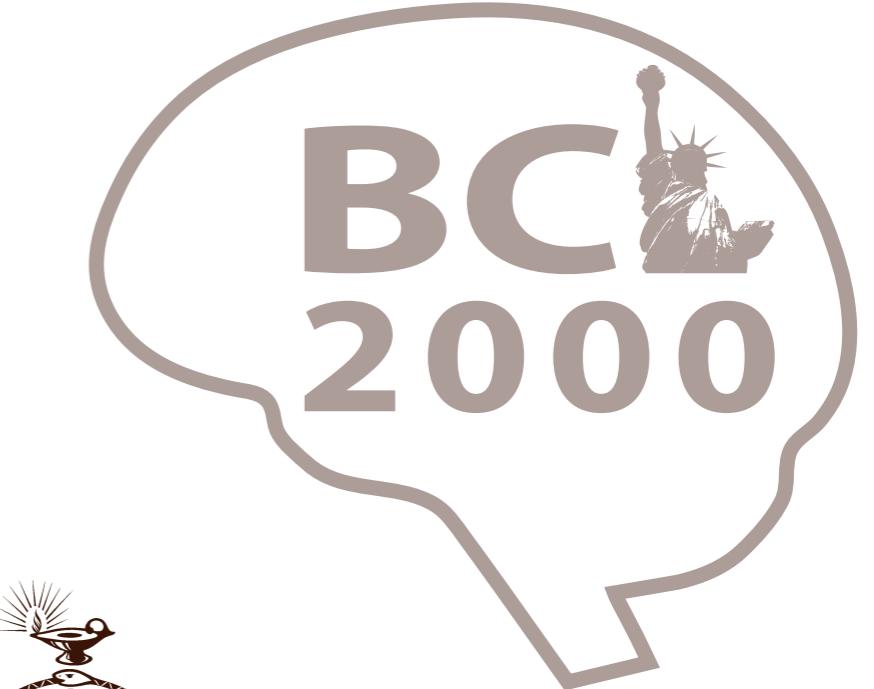


Registration and Contact
Jennifer Price
PriceJ@mail.amc.edu

Organization

Research Chair
Gerwin Schalk
Wadsworth Center

Clinical Chair
Anthony Ritaccio
Albany Medical Center



Wadsworth Center

New York State Department of Health



Credits

Wadsworth Center, Albany

Sam Briskin, BS

Peter Brunner, MS

Aysegul Gunduz, PhD

Xiao-mei Pei, PhD

Adam Wilson, PhD

Albany Medical College, Albany

Anthony Ritaccio, MD

Timothy Lynch, MD

Joseph Emrich, MD

Washington University in St. Louis

Eric C. Leuthardt, MD

Daniel Moran, PhD

New York University, New York

Bijan Pesaran, PhD

University of Wisconsin, Madison

Justin Williams, PhD

University Medical Center, Utrecht

Erik Aarnoutse, PhD

Nick Ramsey, PhD

University of Washington, Seattle

Kai J. Miller, PhD

Jeffrey G. Ojemann, MD

Rensselaer Polytechnic Inst., Troy

Lester A. Gerhardt, PhD

University of Tübingen, Germany

Jürgen Mellinger, ME

Niels Birbaumer, PhD

US Army: W911NF-07-1-0415, W911NF-08-1-0216

NIH: R01-EB006356-01, R01-EB000856-06