ECoG-Based Brain Computer Interfaces and Applications in Chronic Stroke

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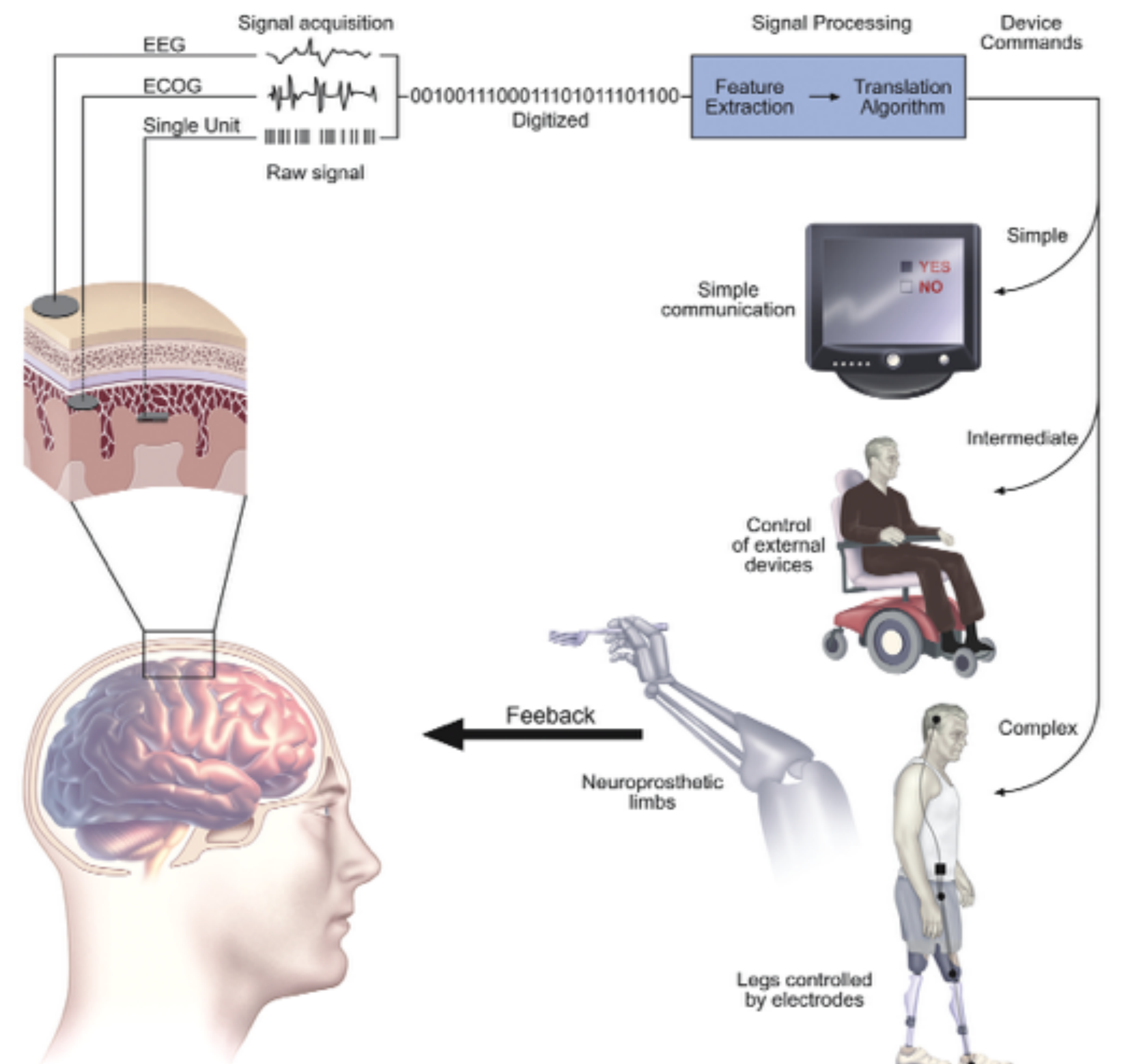
Neuroprosthetics:

A Brain Computer Interface, or BCI, is device that can monitor and decode the electrical signals of the user's thoughts and convert that information into some type of overt machine control



Leuthardt et al, Neurosurgery, 2006

Lecture Overview

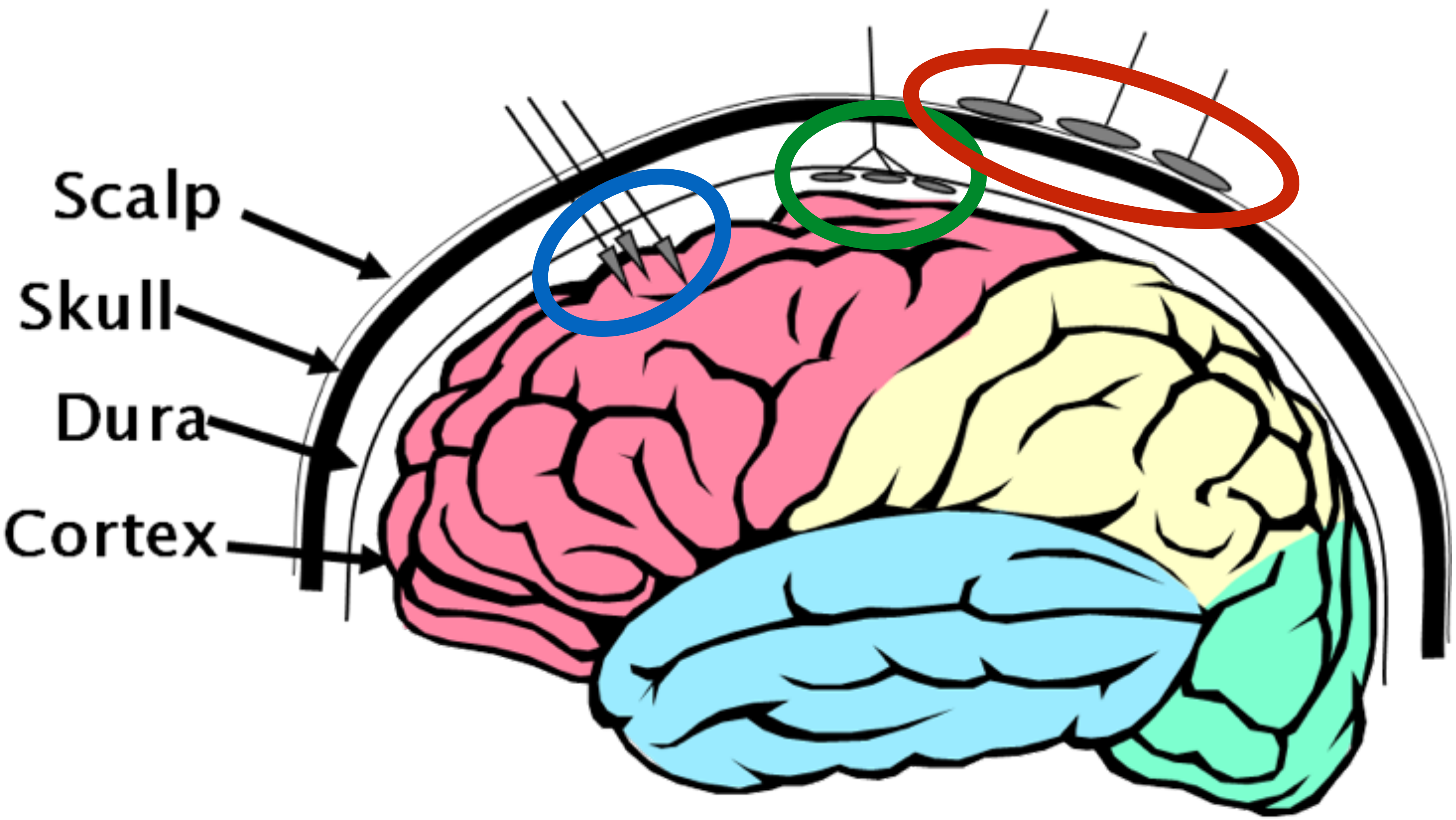
- BCI Overview
  - Signal modalities
  - ECoG Physiology
  - Exemplar ECoG BCI studies
- BCIs for Stroke
- Biomimetic BCI
  - Single-unit physiology
  - Evaluation of ECoG Correlates of 3-dimensional reaching

Signal Modalities

Microelectrodes
- -100 µm spacing
- -Spikes/LFPs
- ~100 mV
- -Highly Invasive

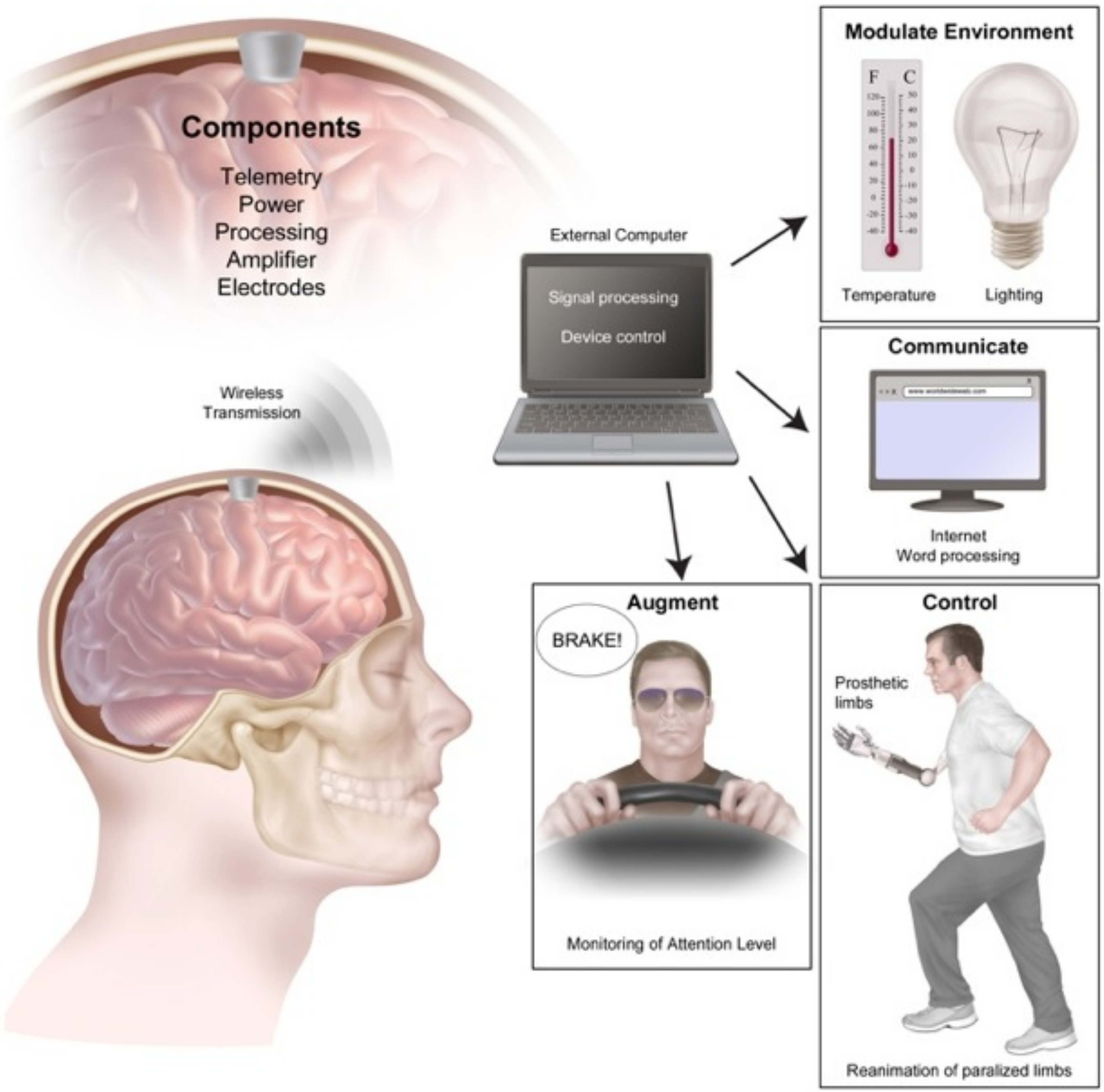
ECoG
- -0.1-1.0 cm spacing
- -LFPs 0-400+ Hz
- ~100 µV
- -Moderately invasive

EEG
- -3.0-5.0 cm spacing
- -LFPs <40 Hz
- ~10 µV
- -Non-invasive



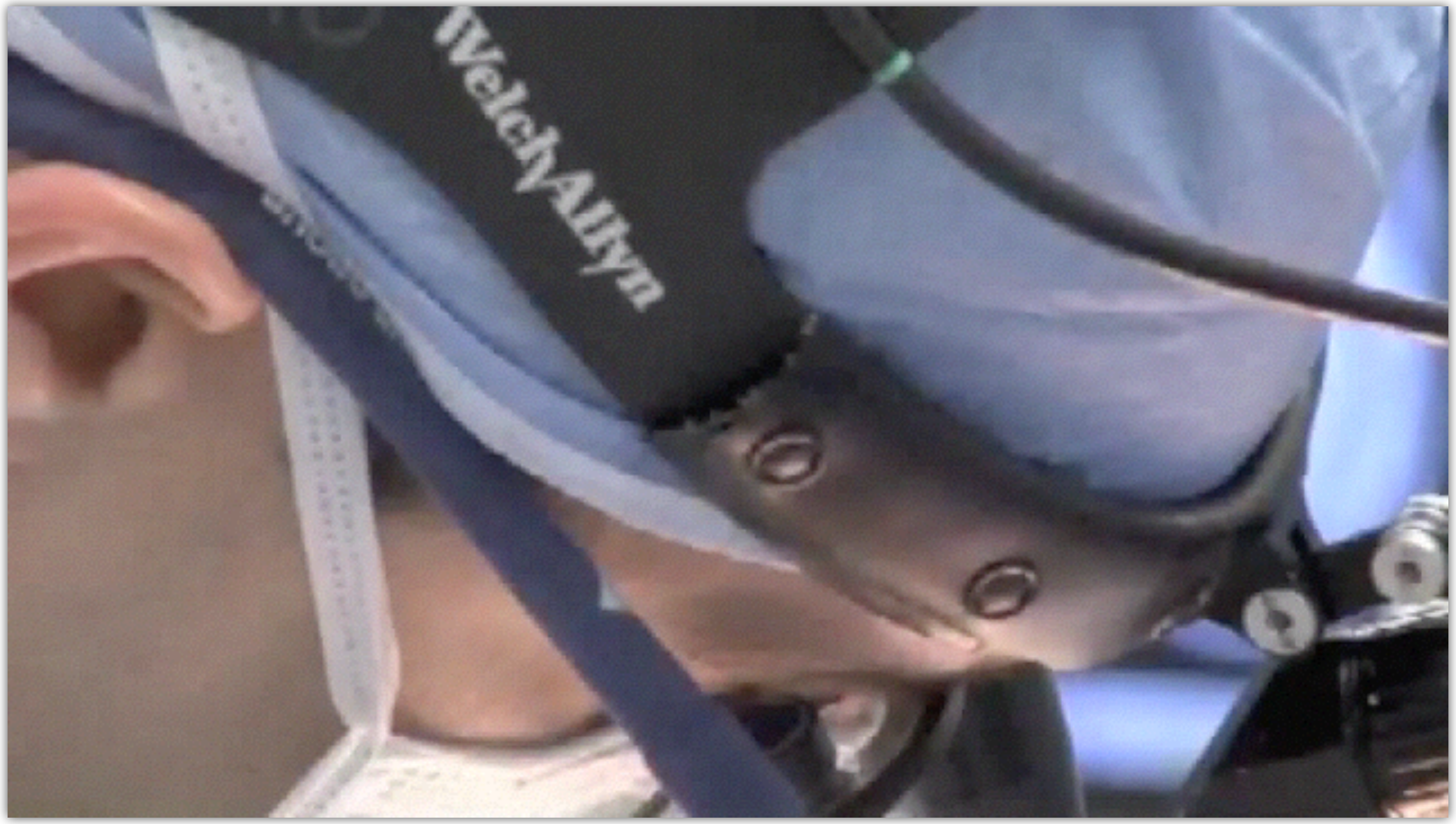
ECoG Recordings

Long-Term Goal

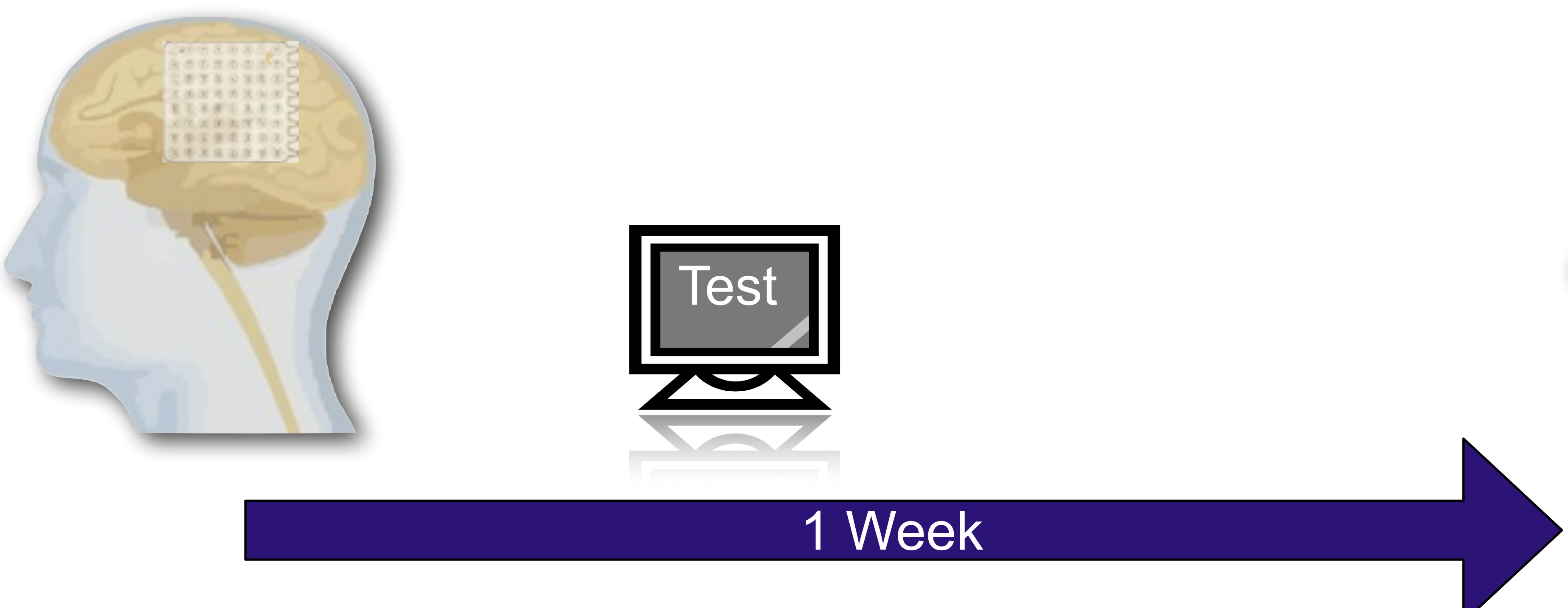


Schalk and Leuthardt, IEEE, *in press*

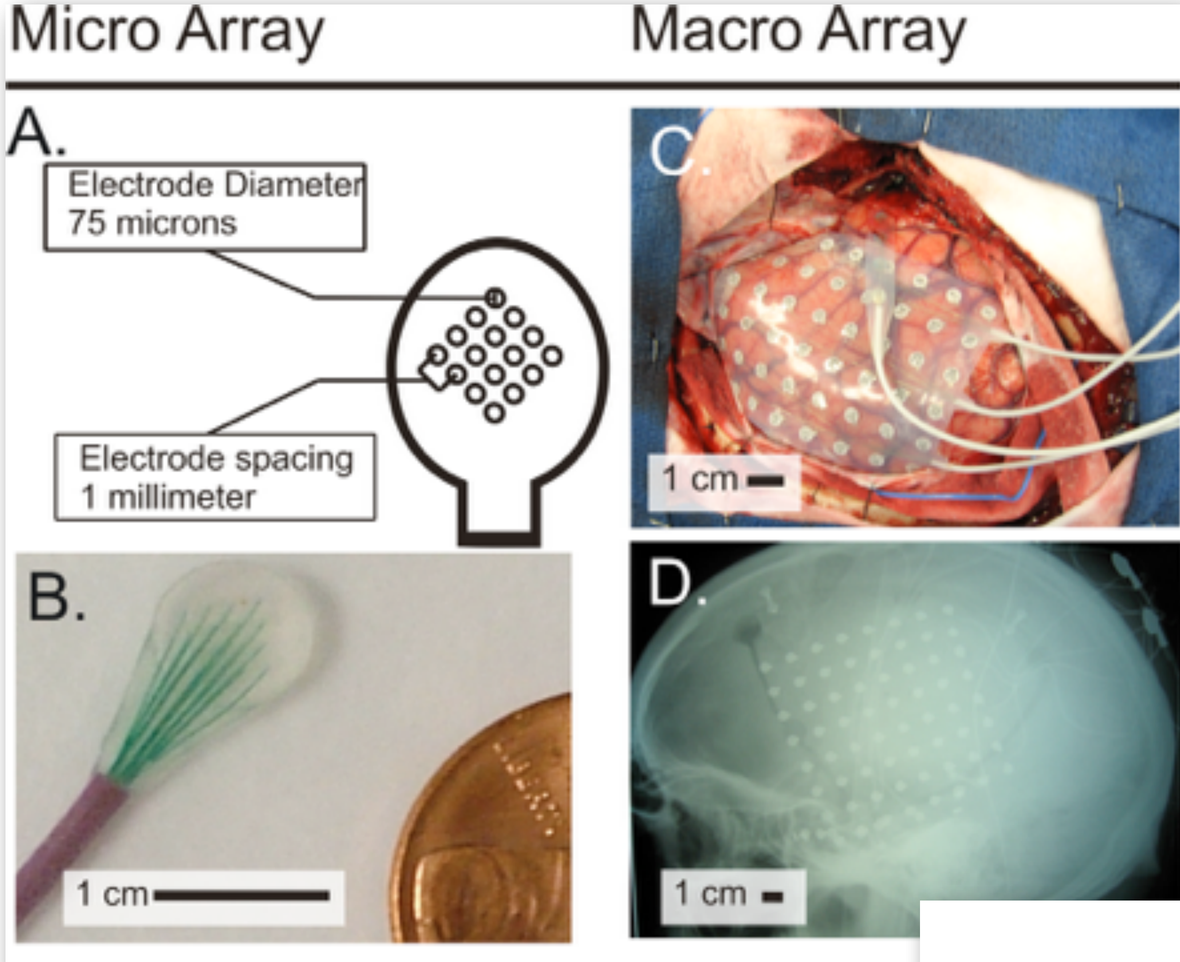
Current Research Model



- Utilizes patient with intractable epilepsy
- Superimposes research on clinical model
- Unique access to human cortex and cognitive processes

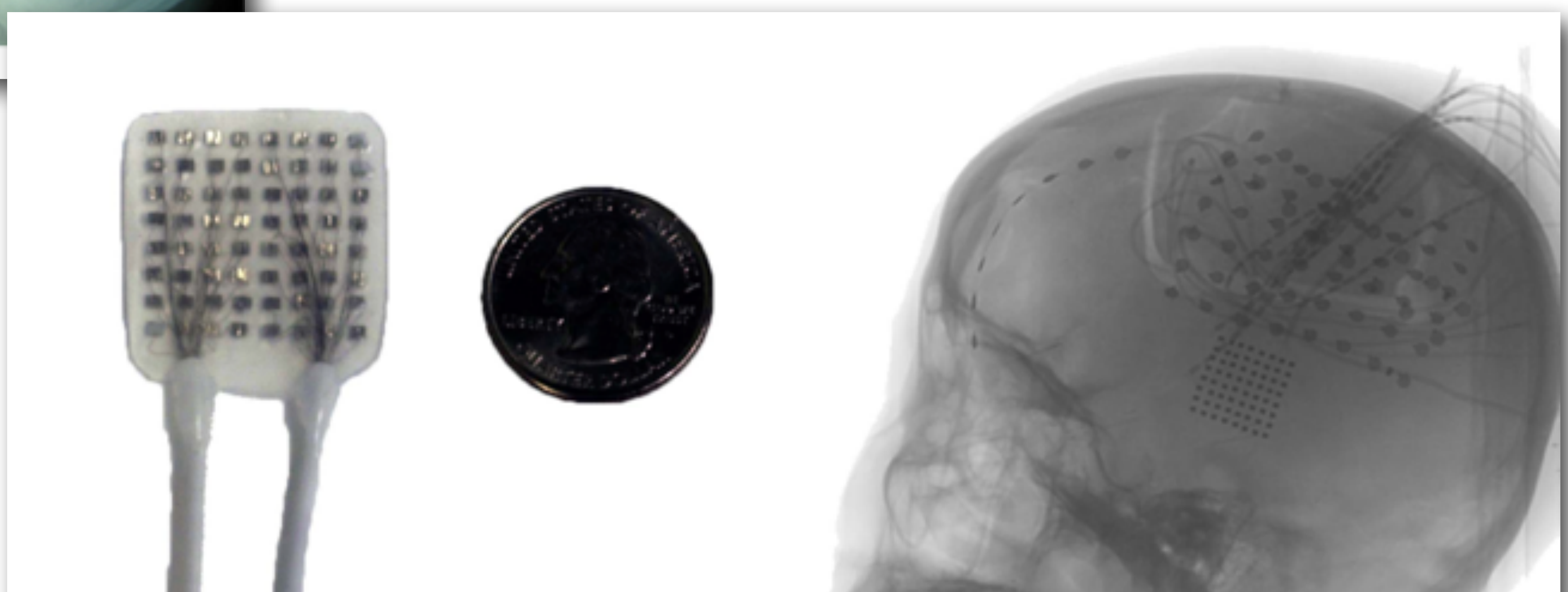


Electrodes



Leuthardt, J Neural Engineering, 2011

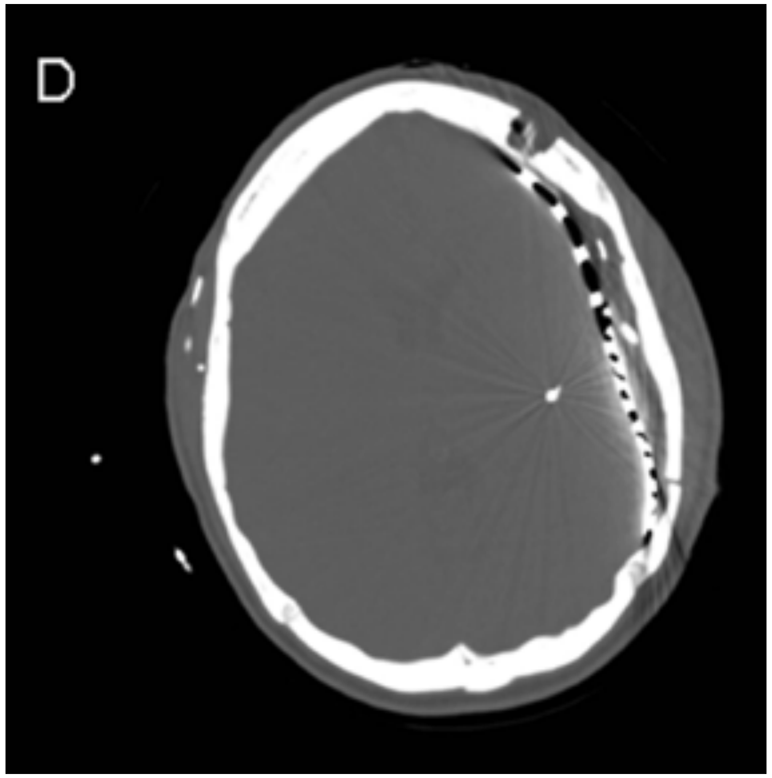
- Clinical Arrays typically 2.3 mm and 1 cm inter-electrode distances
- Research arrays varied in size and dimension



Blakely, *IEEE, 2009*

Clinical Considerations

- Patients participating have had a major neurosurgical procedure.
  - Ability to participate **fluctuates**
    - pain, seizures, personal/social needs
- Participation limited to duration of monitoring
  - Ongoing studies - which are required for BCI paradigms - can be challenging



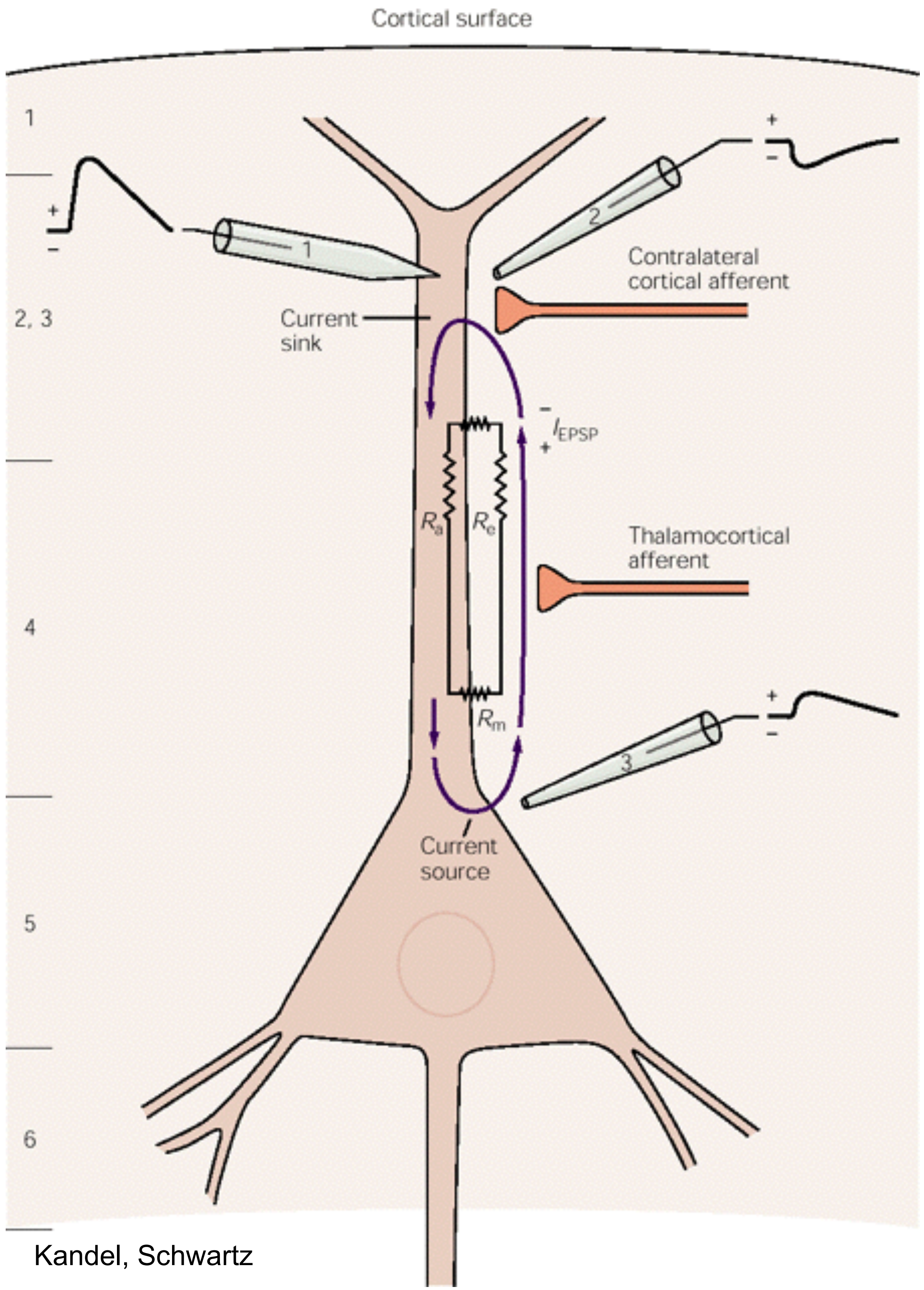
Albert G. et al., J Neurosurg. 2010

Limitations - Research Paradigm

- Clinical Constraints of the research paradigm
  - Clinical needs ***always take priority over research goals***
  - Limited amount of time to work with patients (1-2 hours per day for several days
  - Cognitive capability variable -- due to acute medical factors (pain,seizures, medication) and chronic issues (impaired cognition due to epilepsy)
- Noisy environment
  - electric beds, pressurized stockings, IV Systems
- **Bottom line:**
  - **Human ECoG recordings represent a unique and important source for neuroscience experiments**
  - **Personnel needs ready to run experiments whenever the opportunity arises**
  - **Researchers must understand that these patients are donating their time during a very stressful clinical experience. A sensitivity to their needs and a respect for their willingness to participate is paramount**

Signal Physiology

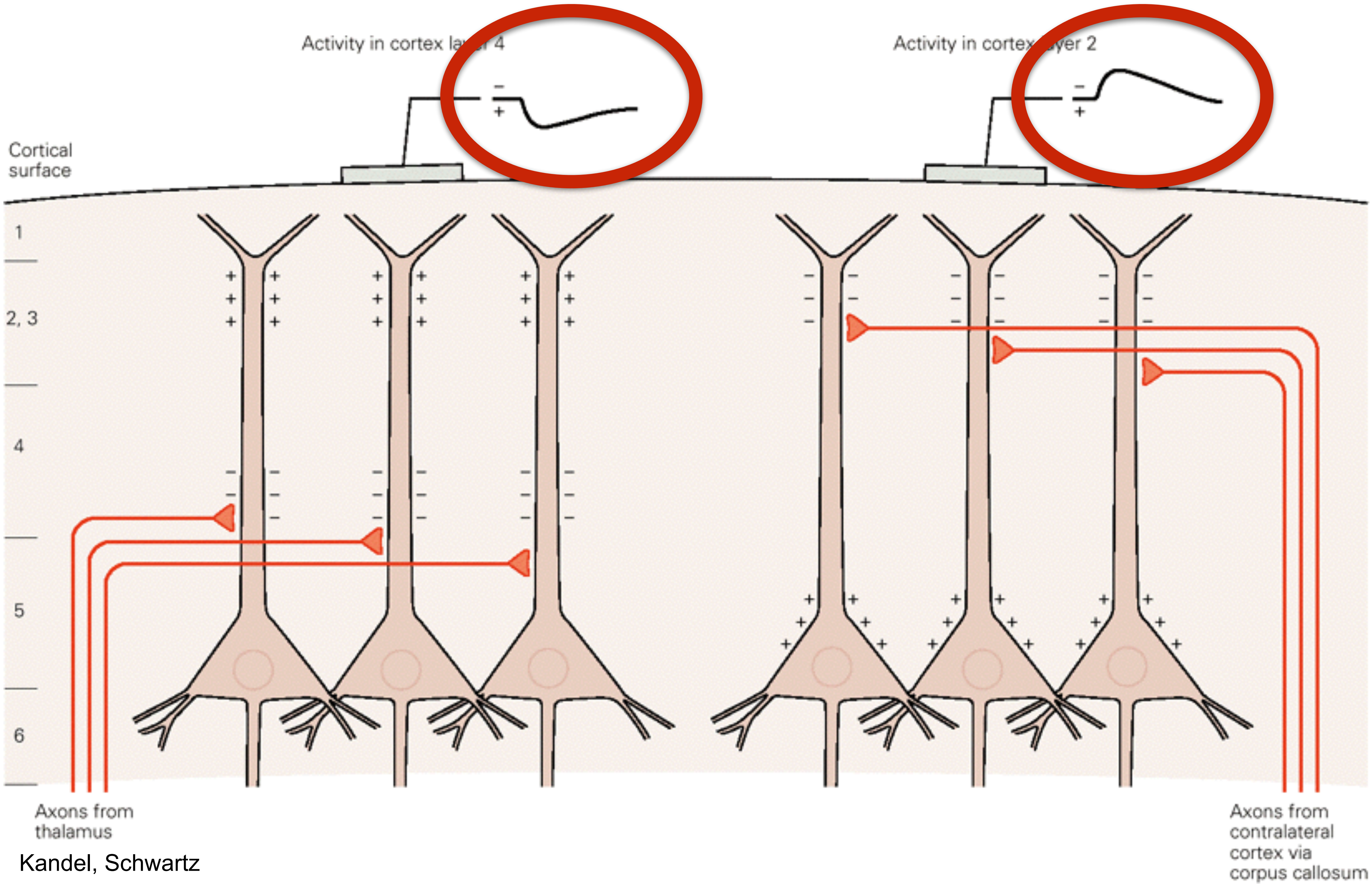
Physiology of Field Potentials



Kandel, Schwartz

- Activity detected by electrodes near apical dendrites during EPSPs is dependent on electrode location
  - Extracellular electrodes at the sink and source have opposite polarities
  - Intracellular potentials have the same polarity regardless of location

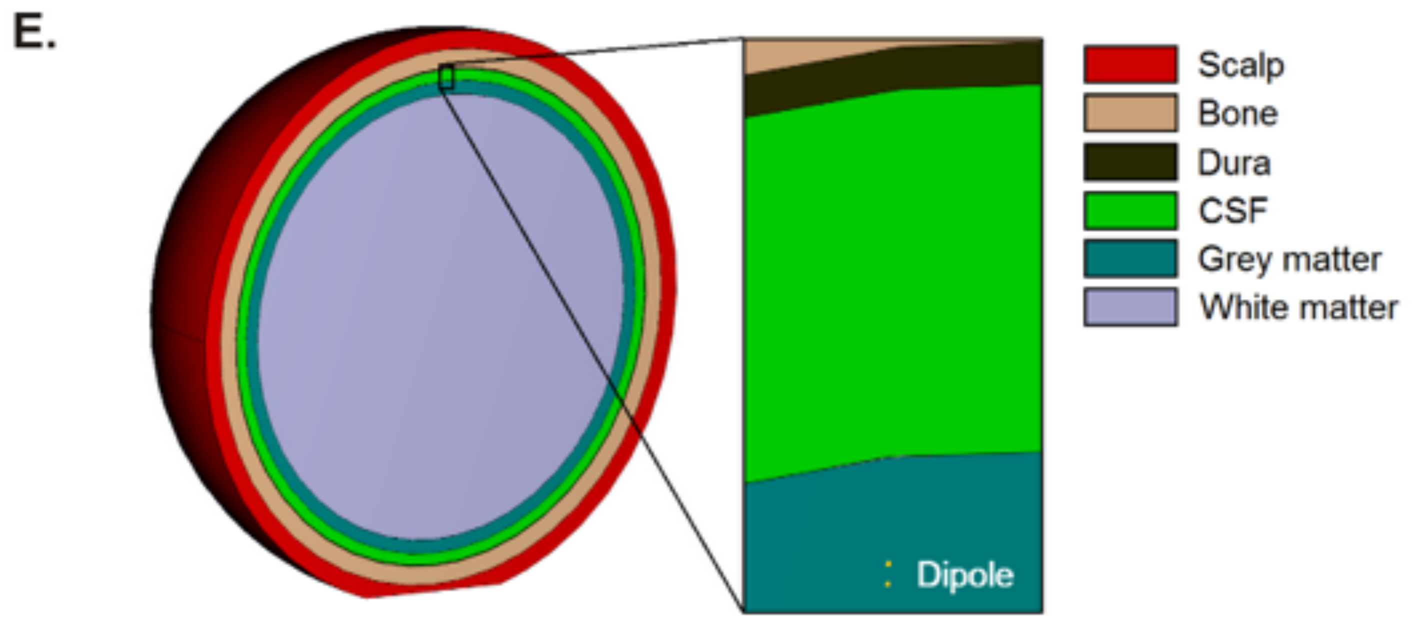
Physiology of Surface Potentials Can be Ambiguous

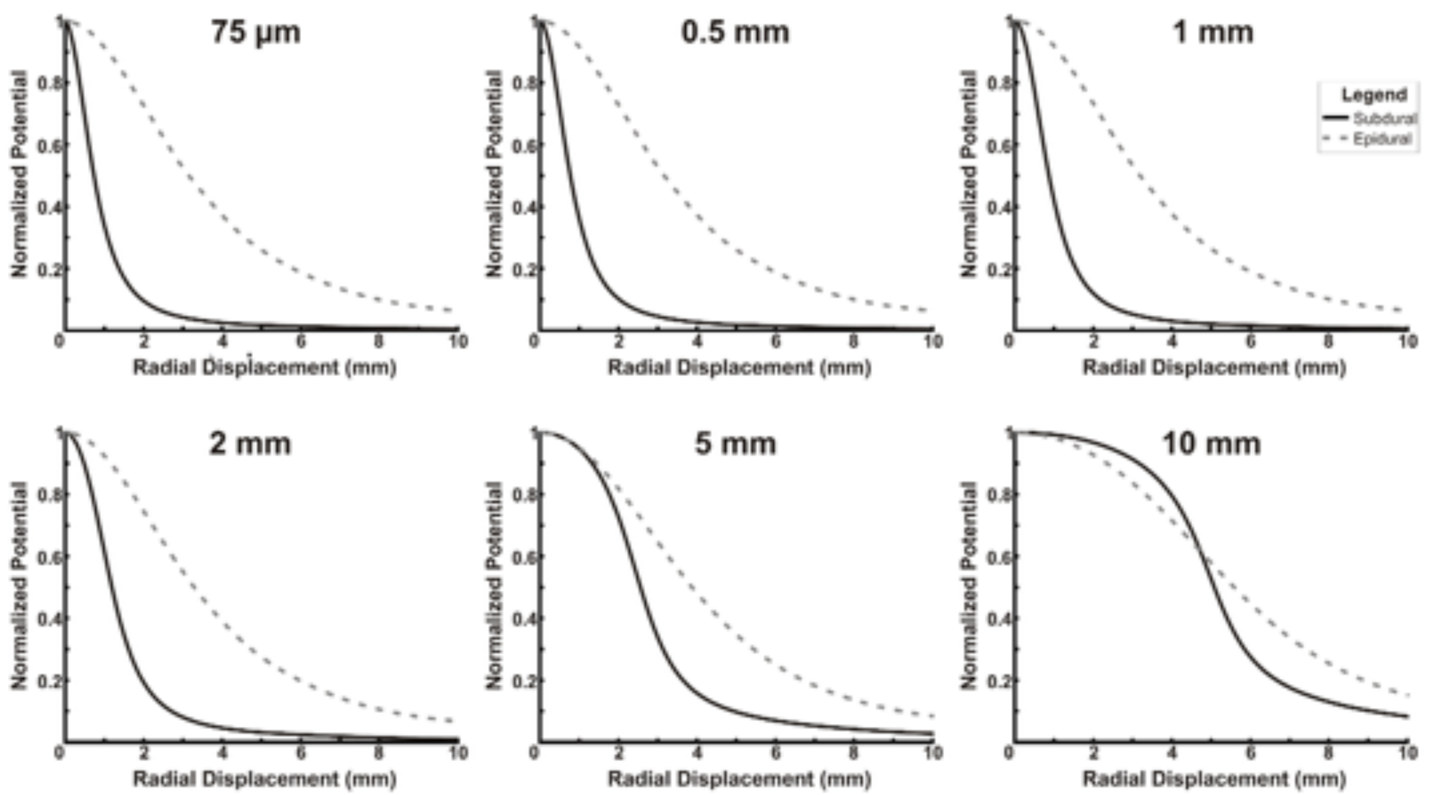


Kandel, Schwartz

Spatial Spread of Neural Activity

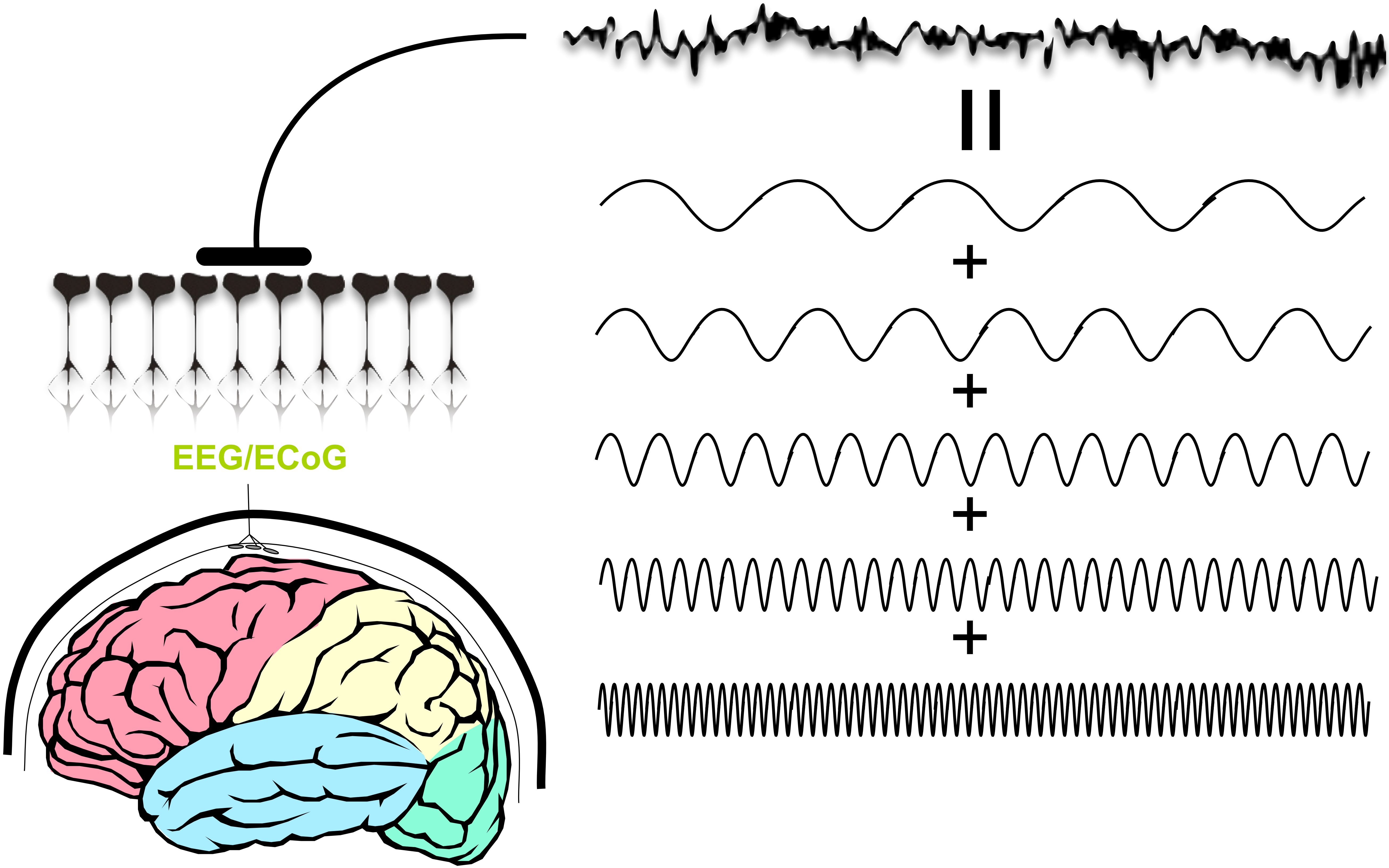
- Finite-element analysis of electrodes of various sizes demonstrate that ECoG recordings represent broad populations of cortex



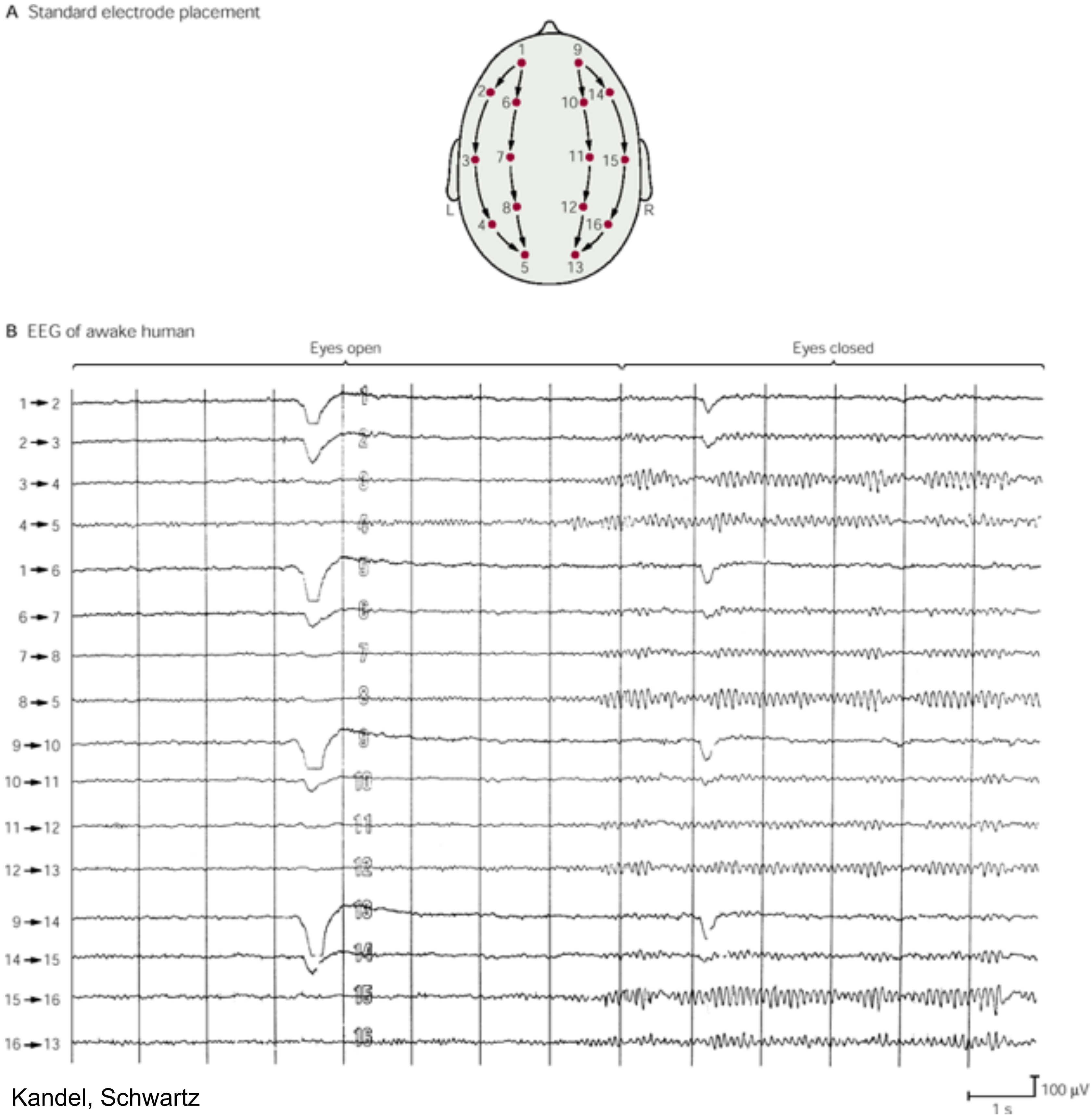


Bundy, JNE (in press)

Superimposed Physiologies



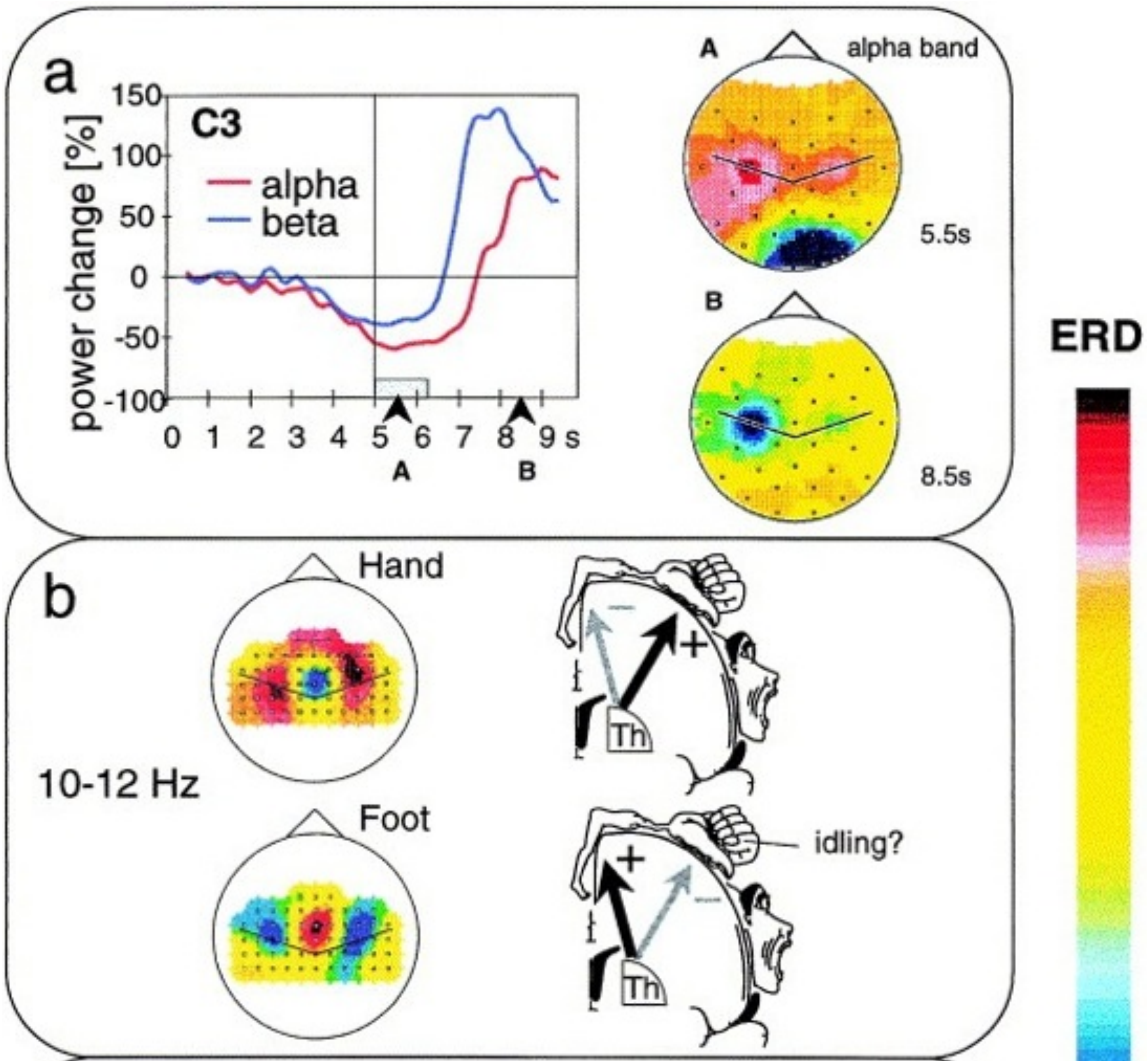
Alpha Waves



Kandel, Schwartz

- EEG was first demonstrated in humans by Hans Berger in 1924
- He was the first to describe different waves or rhythms
  - i.e. Alpha (7-13 Hz) rhythm that is suppressed when a subject opens their eyes.

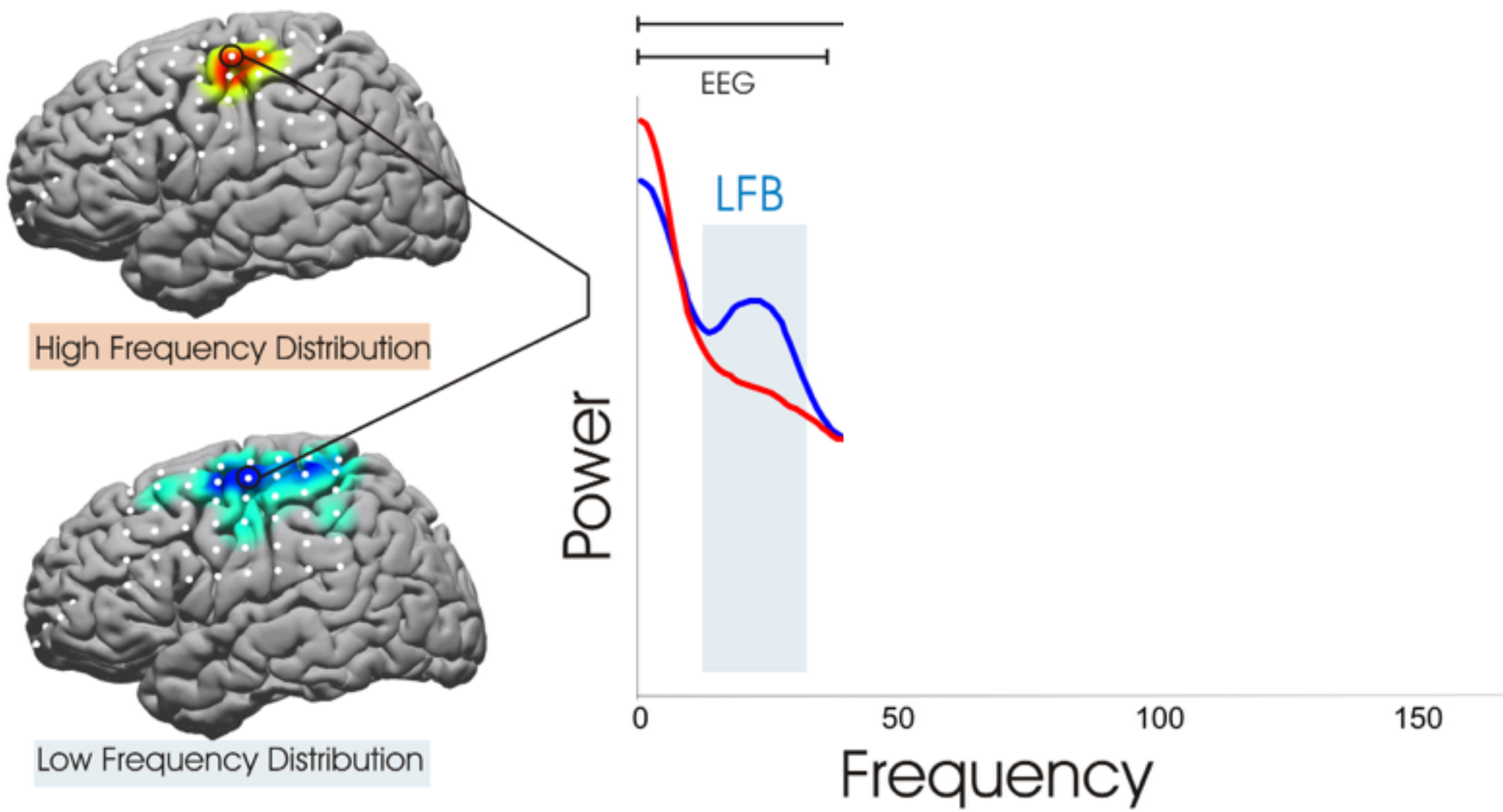
Event-Related Desynchronization



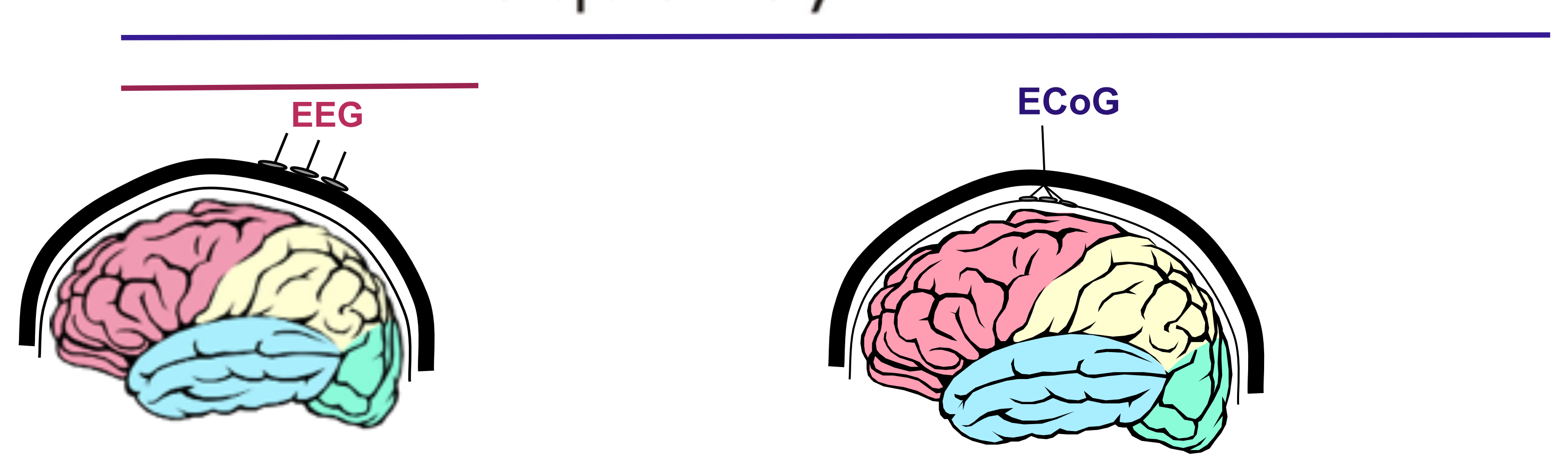
Pfurtscheller & Lopes de-Silva, 1993

- Pfurtscheller demonstrated a decrease in Alpha/Mu (10-12Hz) and Beta (13-30Hz) immediately before and during execution of motor movements.
  - Event-related desynchronization (ERD)
- After movement there is a period of increased power
  - Event-related synchronization (ERS)

Anatomic Distribution of Frequencies



Leuthardt et al, Neurosurgery, 2006



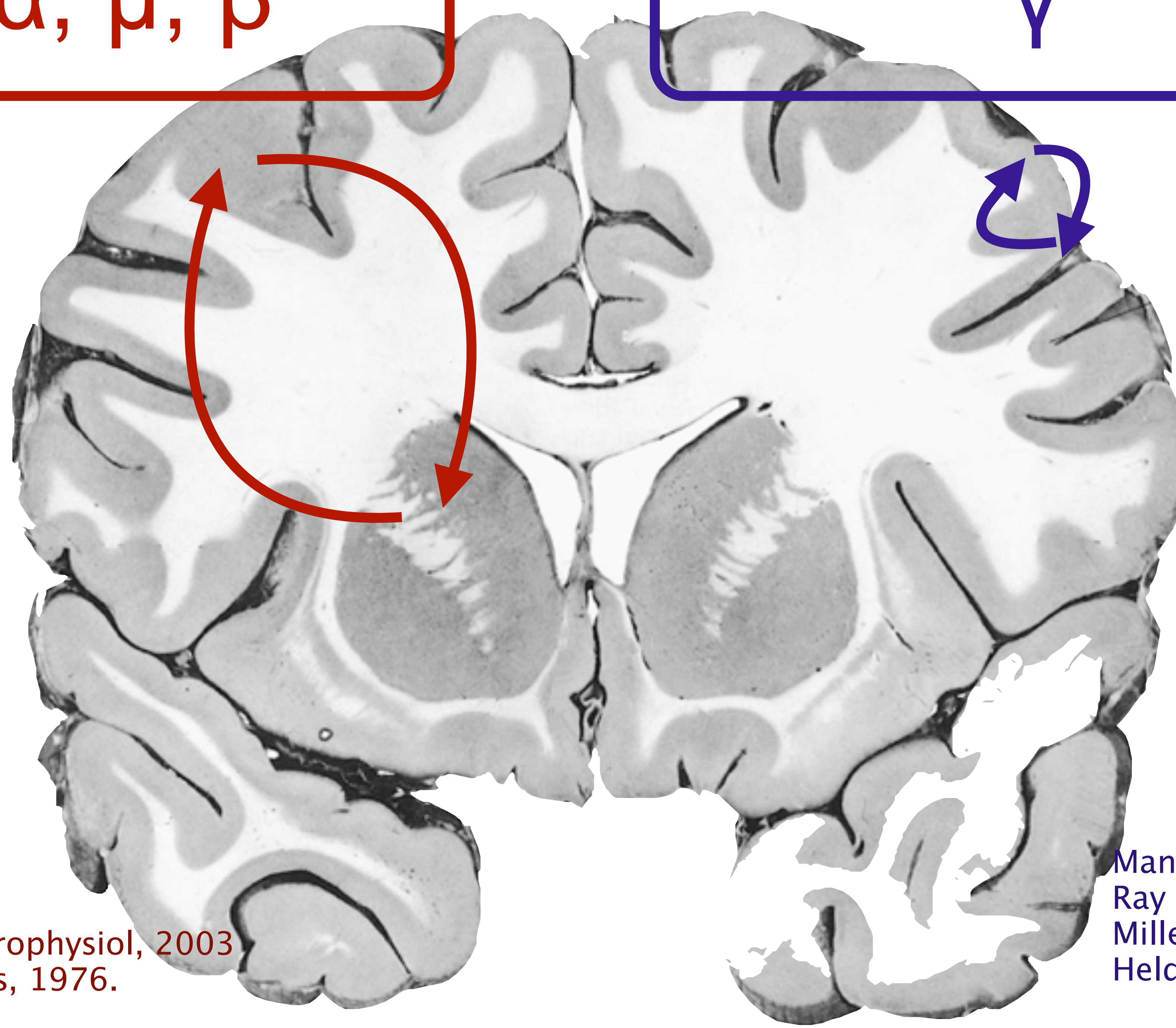
Sources

Lower Frequency Bands (< 30 Hz)

Θ, α, μ, β

Higher Frequency Bands (>30 Hz)

γ



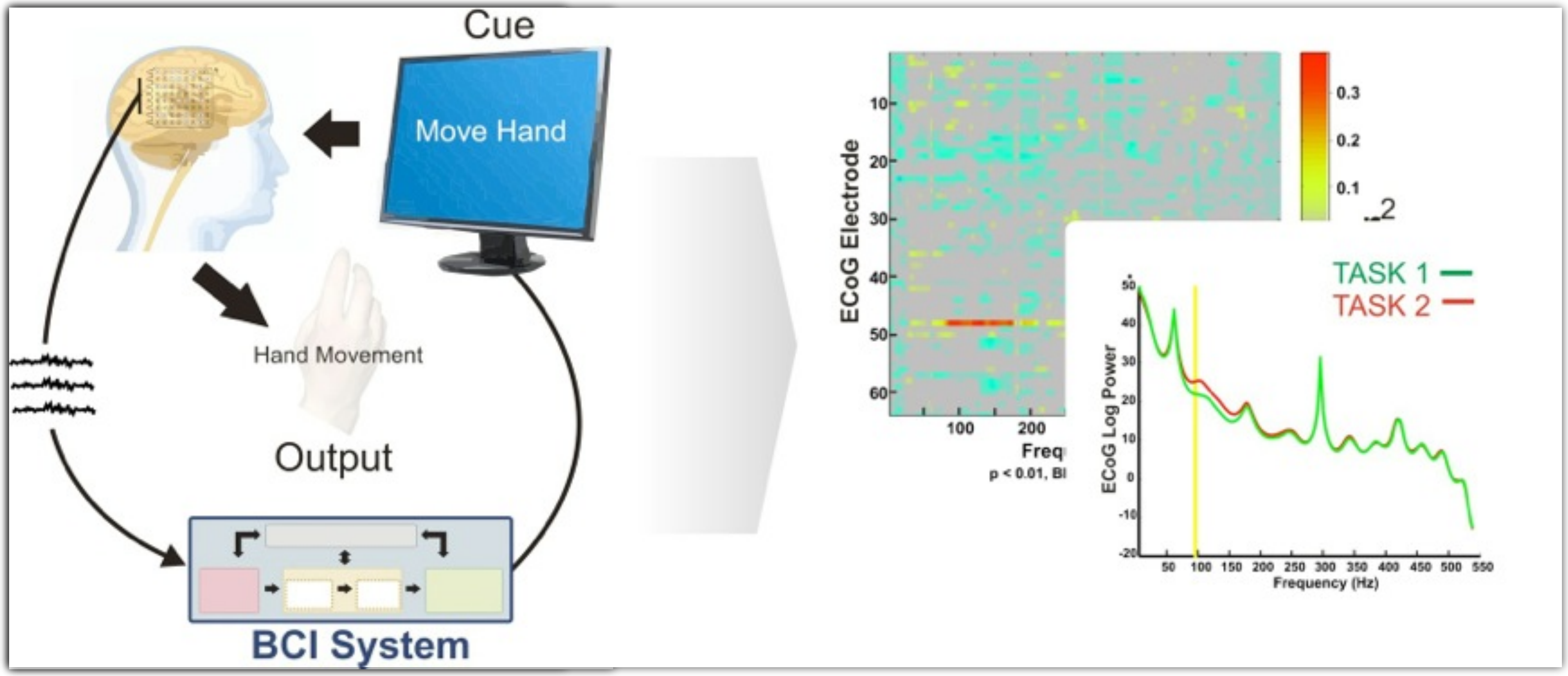
Pfurtscheller, e al. Clin Neurophysiol, 2003
Lopes da Silva, et al Brain Res, 1976.

Manning, et al J Neurosci, 200
Ray et al J Neurosci, 2008.
Miller, et al J Neurosci, 2009.
Heldman et al, IEEE, 2006.

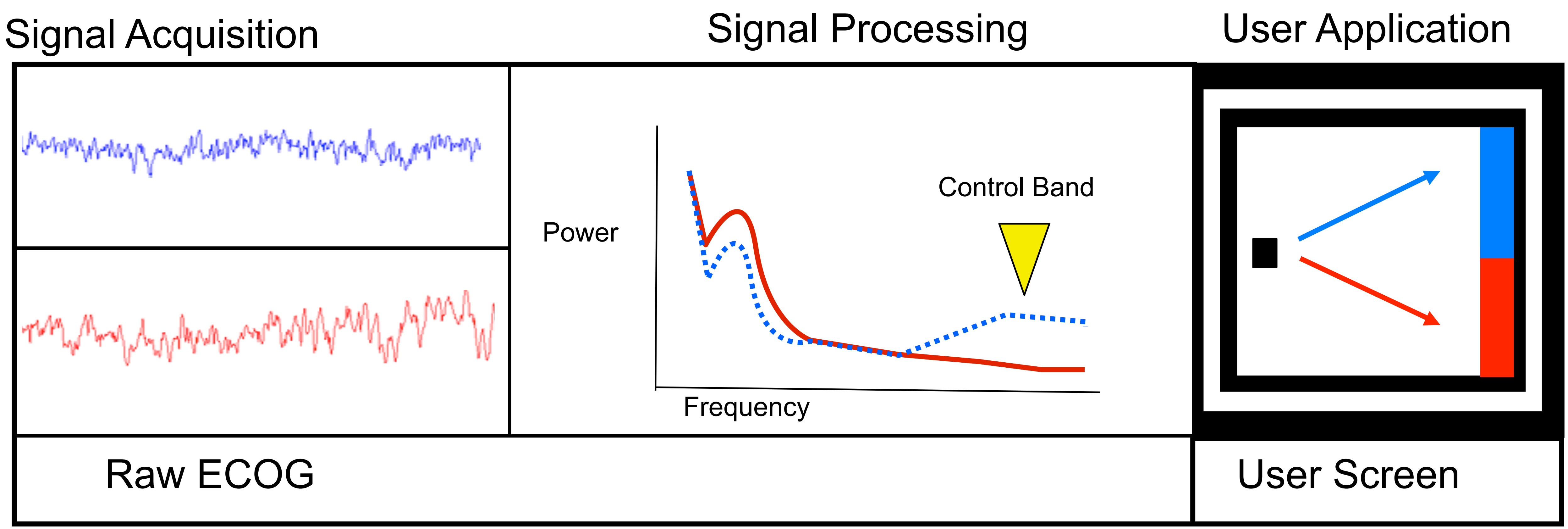
Online BCI Examples

Typical Protocol Design

- Two Stages:
  - Offline Screening
  - Online BCI Control



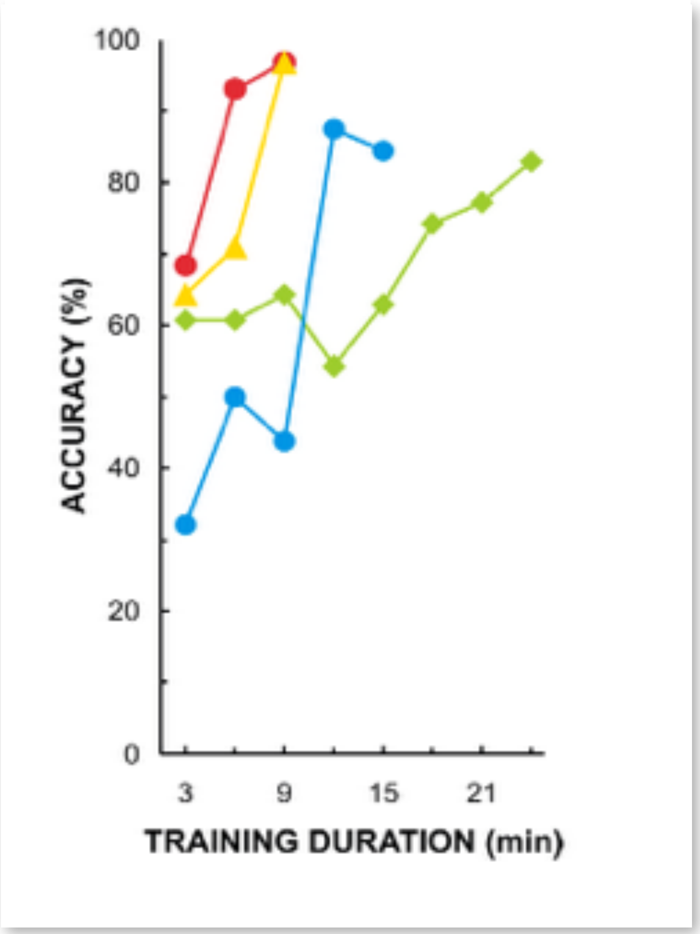
Online BCI Control



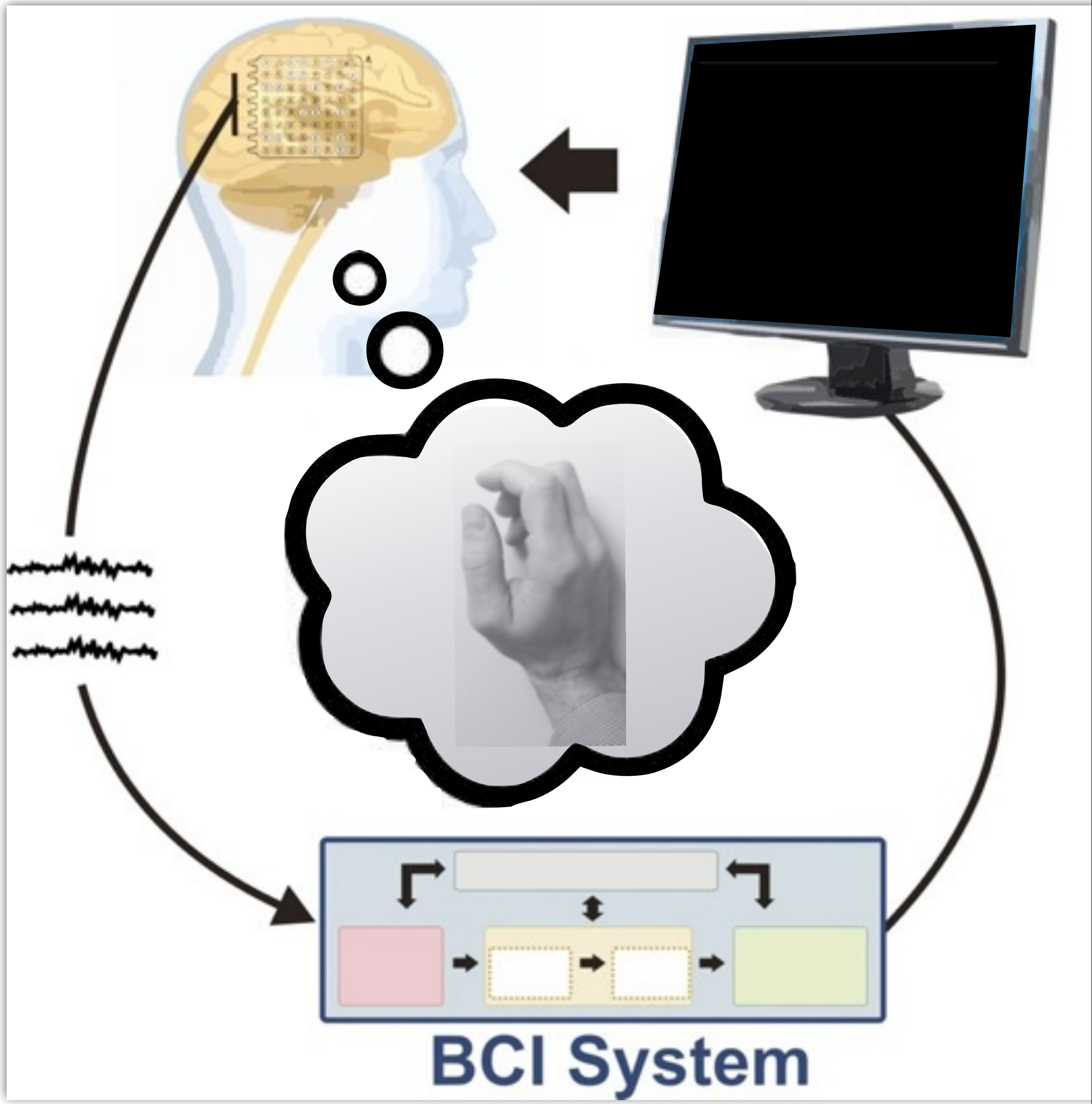
Condition 1. Imagine movement, directs cursor upwards
Condition 2. Rest, directs cursor downward

Early Studies - Motor Signal Derived BCIs

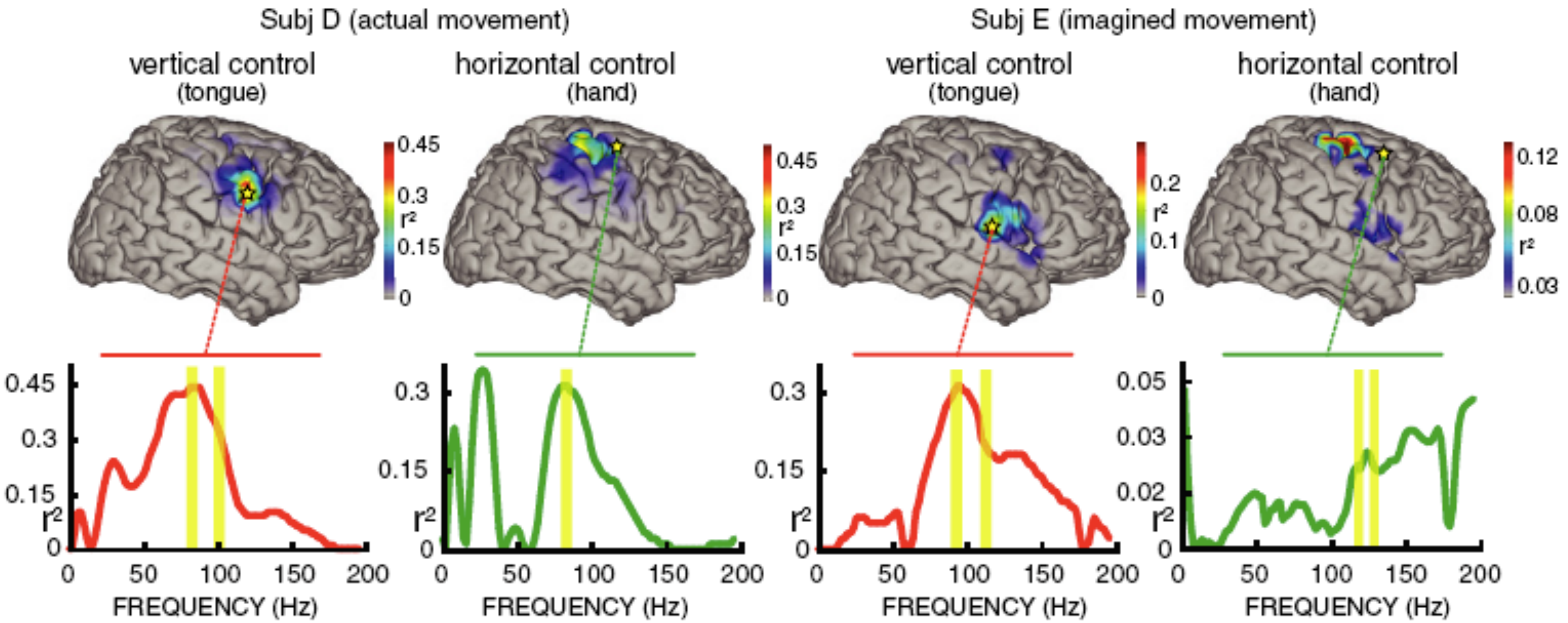
- **Leuthardt et al., 2004**
  - First demonstration of ECoG for BCI
  - Demonstrated rapid ability to achieve control



Leuthardt et al. *J, Neural Engineering*, 2004



Two Dimensional BCI Control

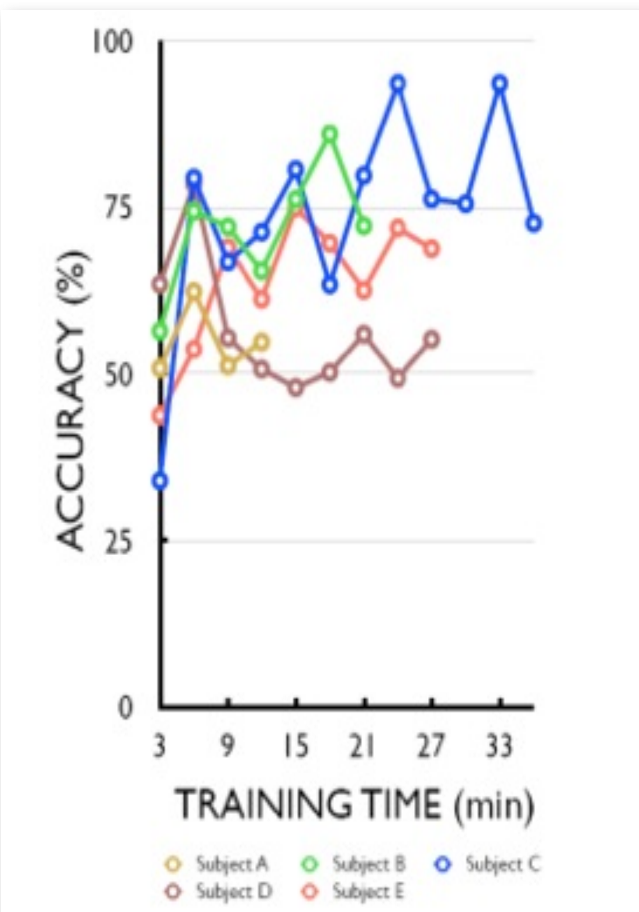


Schalk et al, J Neural Engineering, 2008

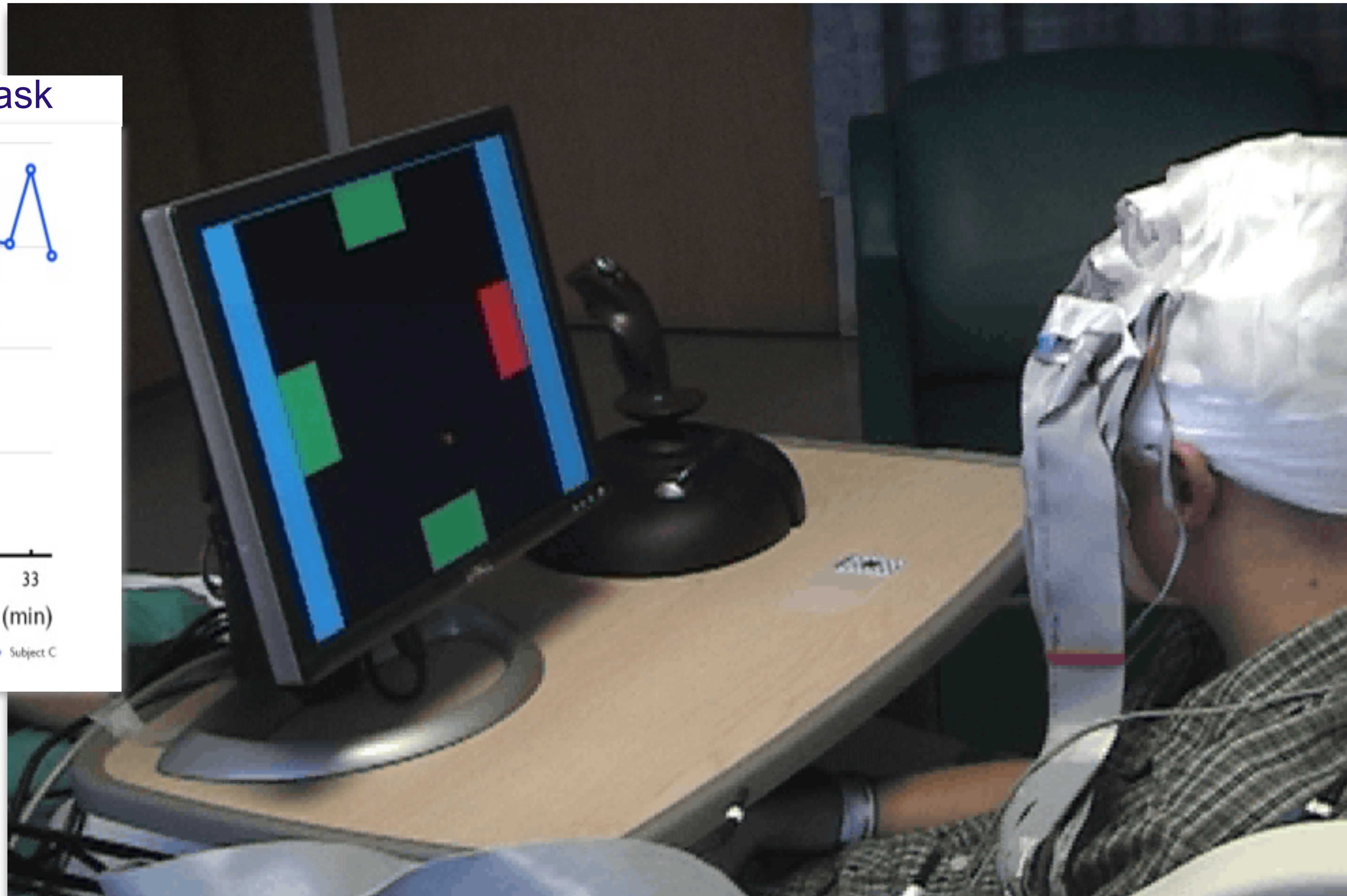
Higher Frequencies Have Higher Anatomic Resolution

ECoG Used for 2D BCI Control

2 D Control Task

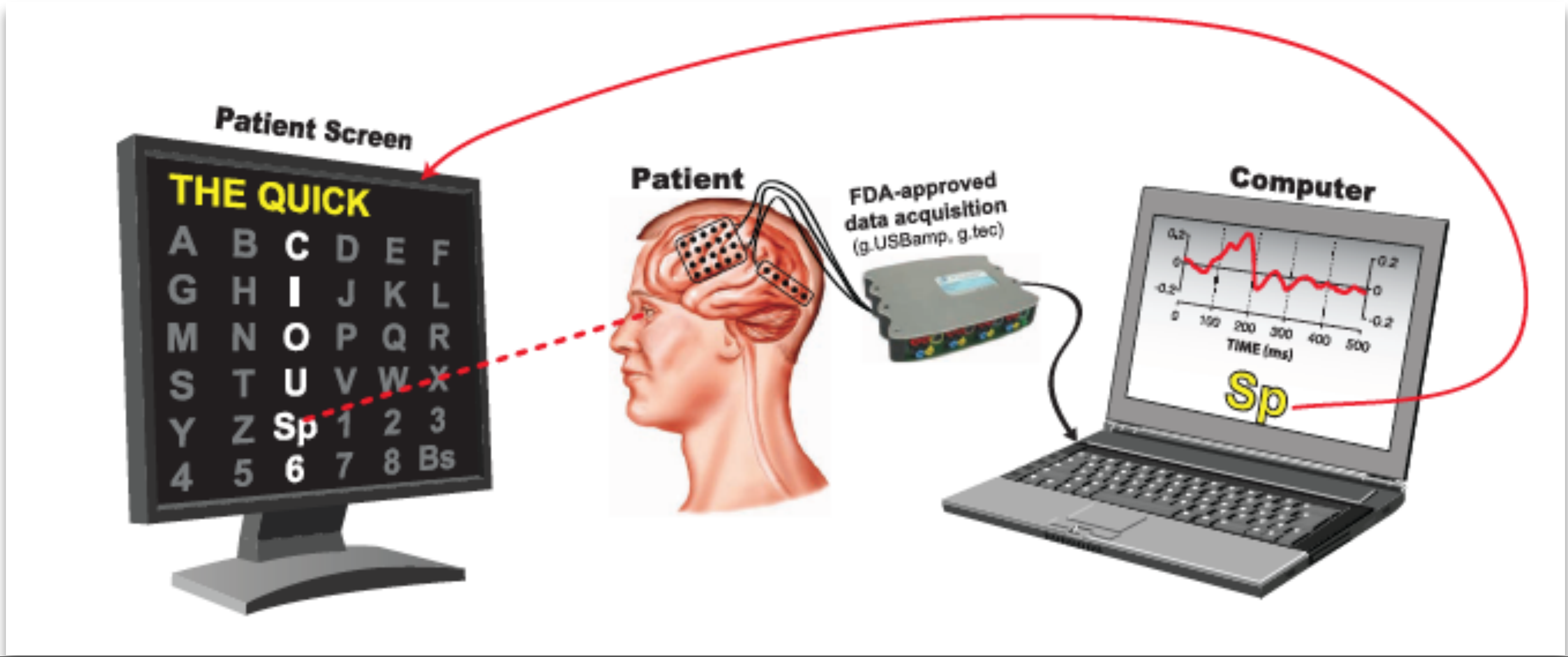


Schalk et al *J. Neural Engineering*, 2008



Non-motor modalities:
Event Related Potentials

- **Brunner, et al., Frontiers in Neuroscience, 2011**
- Used event related potentials (primarily from visual cortex) to control a matrix speller
- Subject sustained a rate of 17 characters/min (i.e., **69 bits/min**), and achieved a peak rate of 22 characters/min (i.e., **113 bits/min**)
- Fastest ECoG BCI to date
- Confirmed by similar studies



Non-motor modalities:
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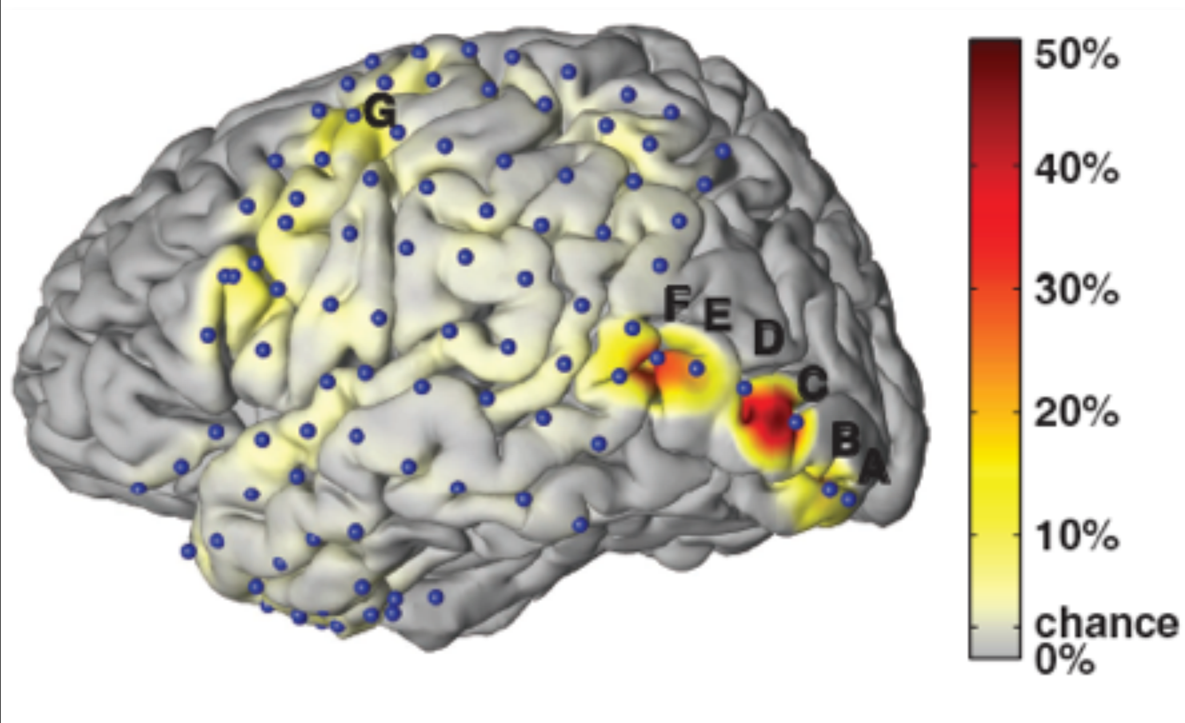
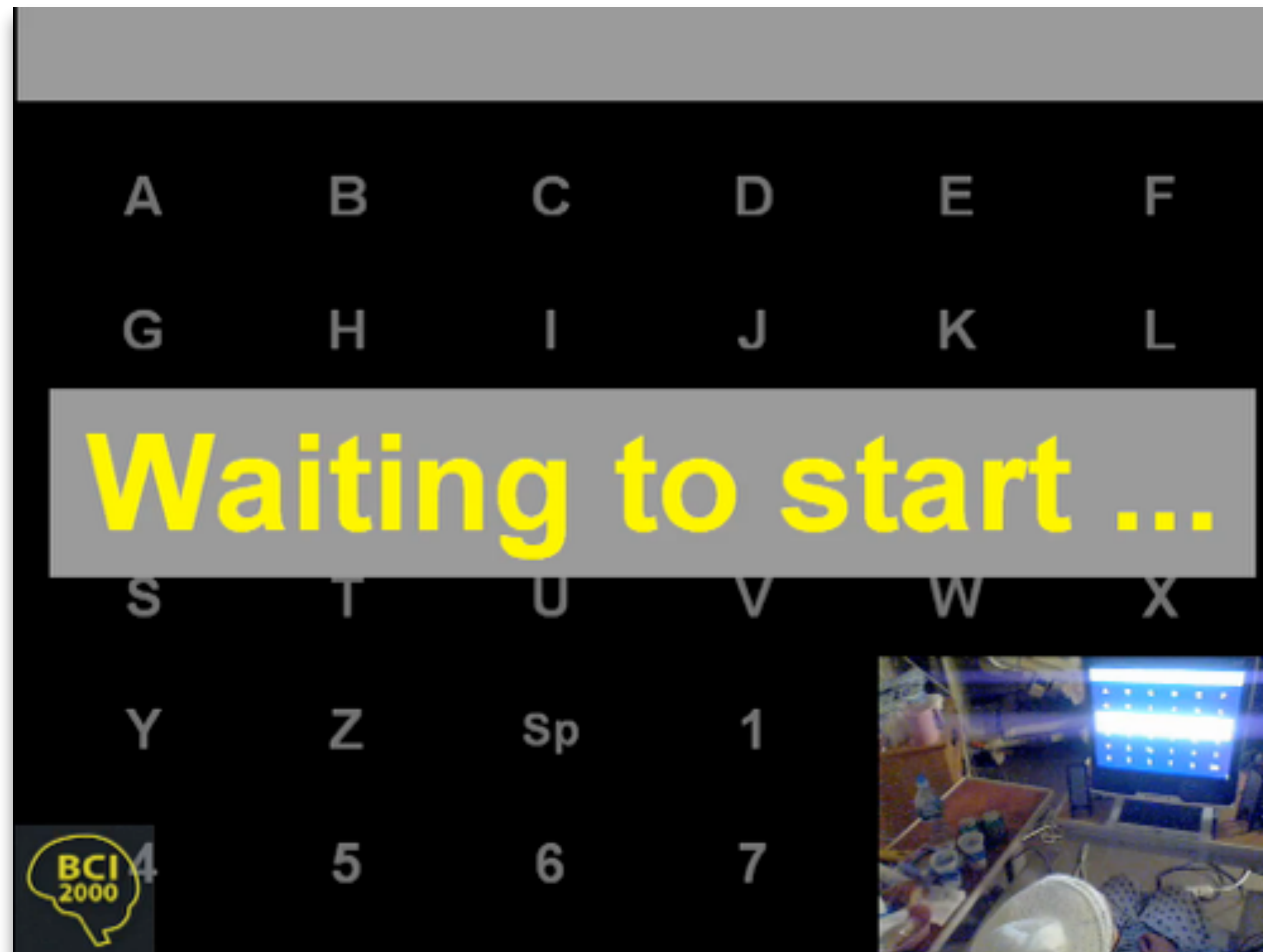
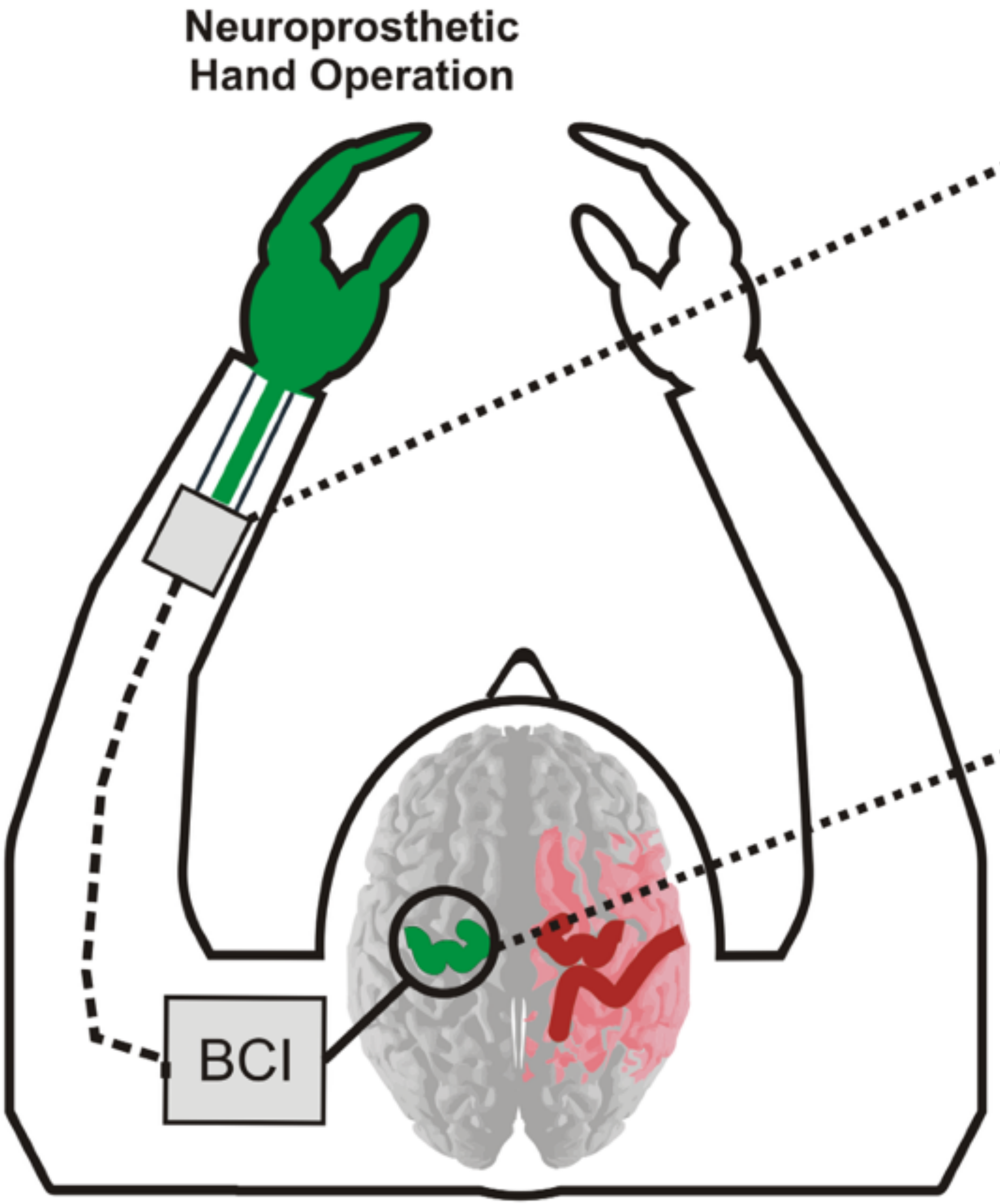




Brunner, et al. Frontiers in Neuroscience, 2011

BCI in Chronic Stroke

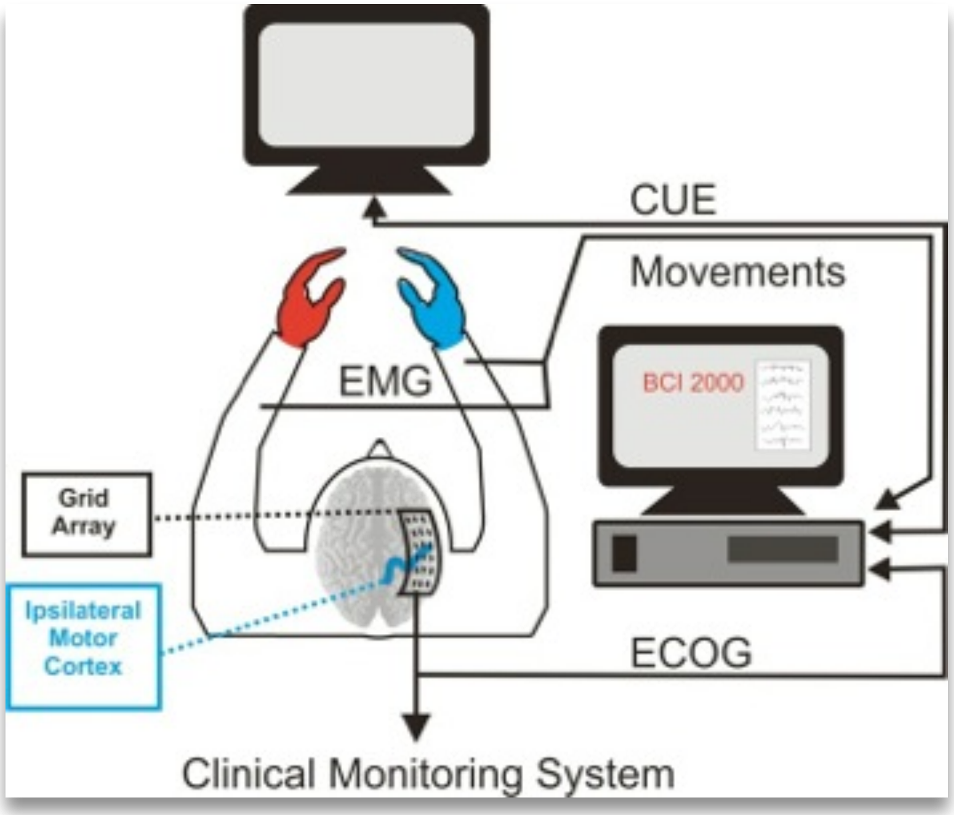
C. Neuroprosthetic Restoration

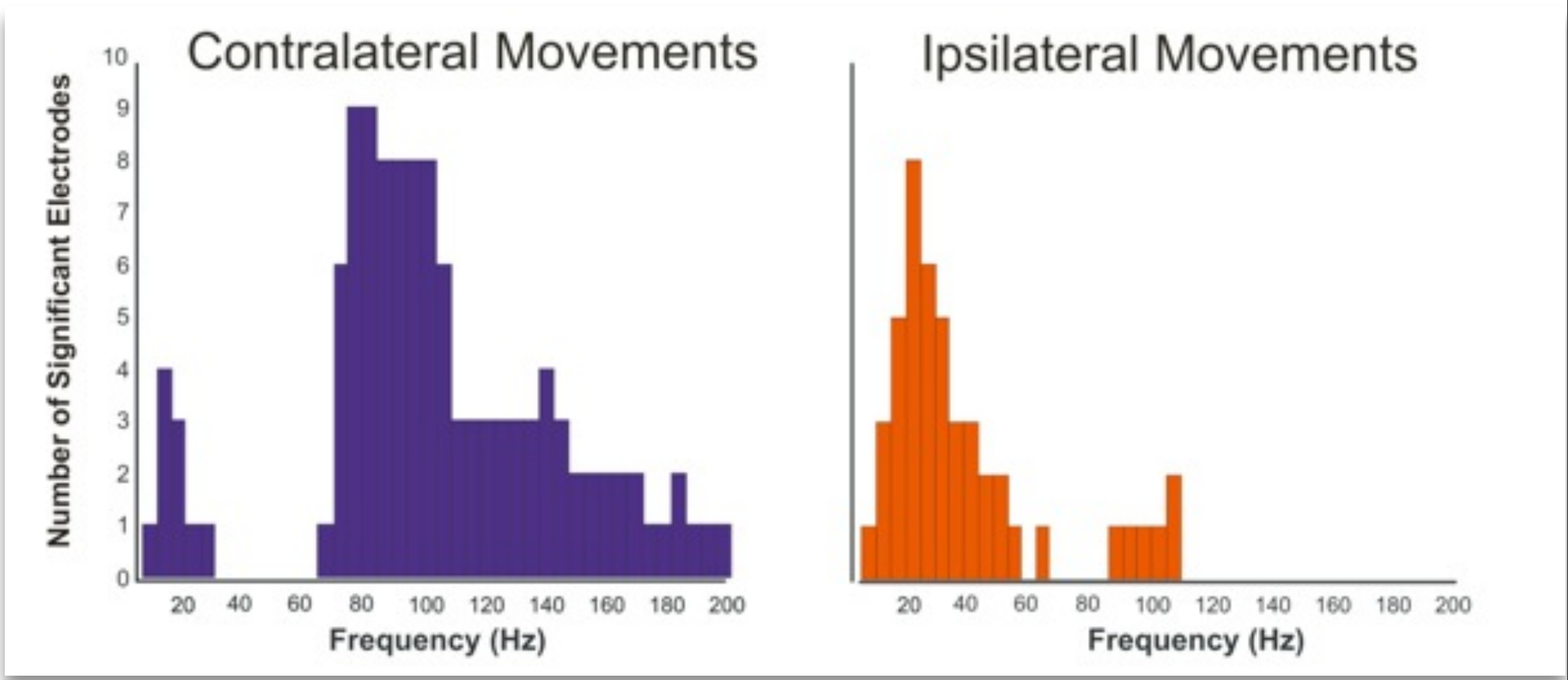


External Effector to Paretic Hand (e.g. robotic glove or functional electric stimulation of nerves and muscles of the hand)

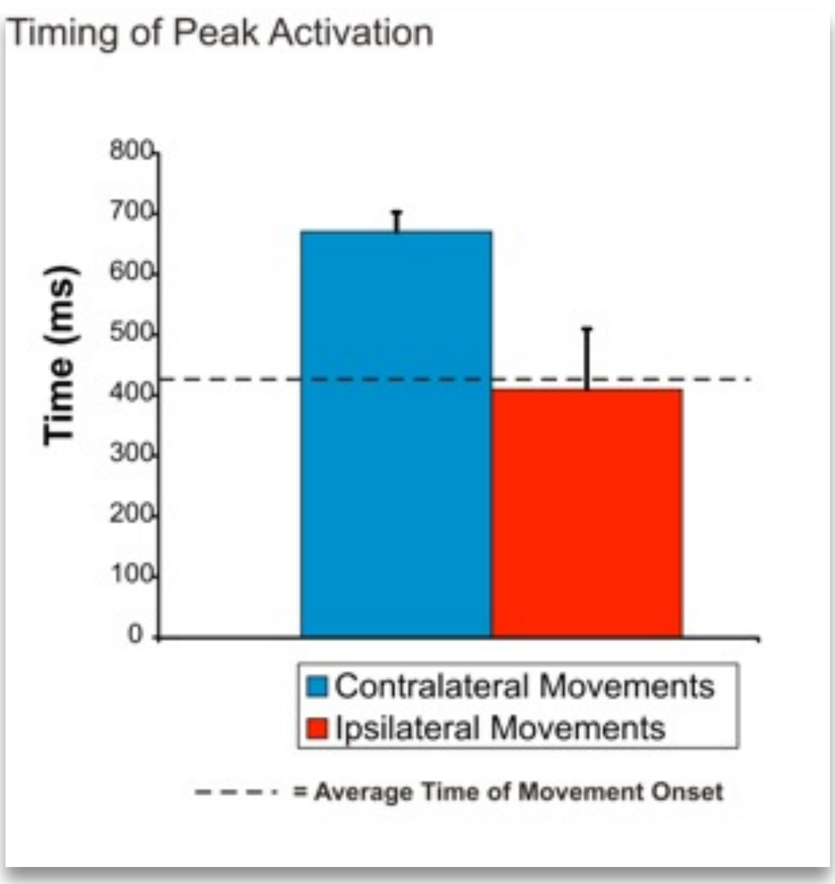
Brain Computer Interface
Detects Ipsilateral Premotor Signals And Actuates Motor Commands Through External Effectors

Leuthardt, et al, Neurosurgical Focus, 2009

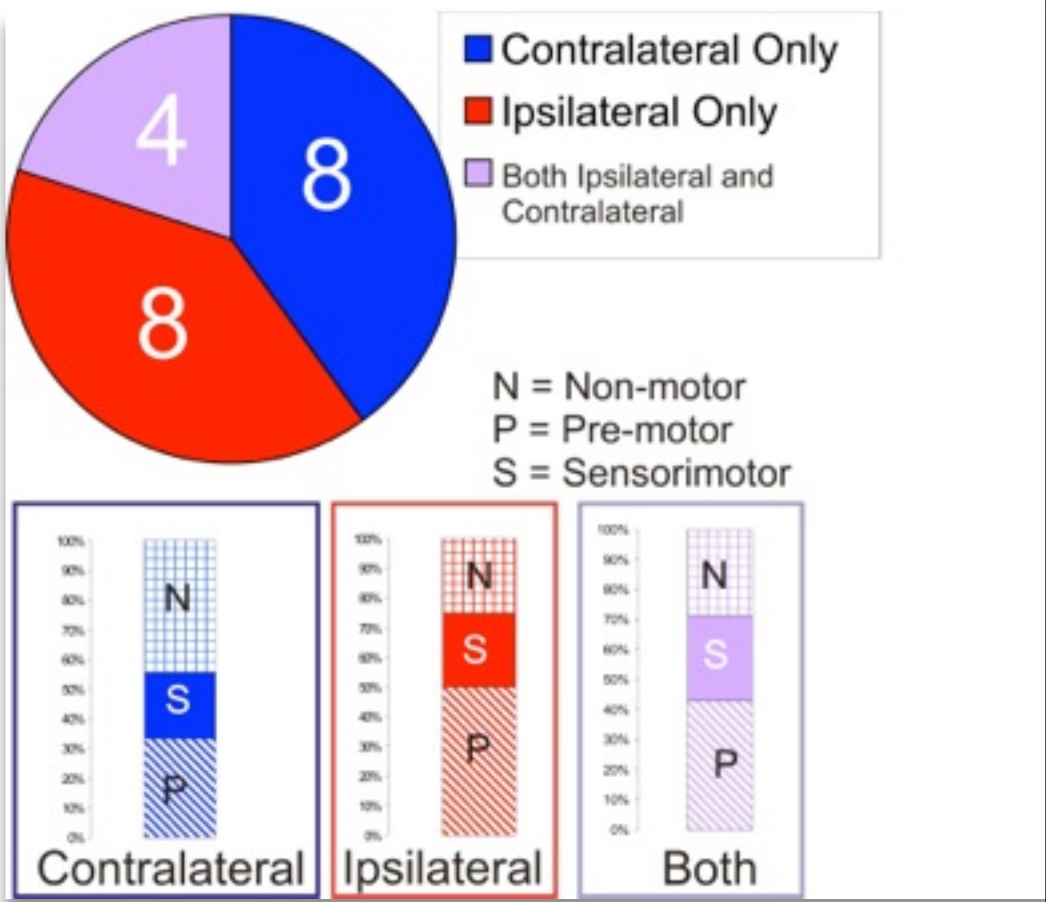




Distinct Frequency Spectra



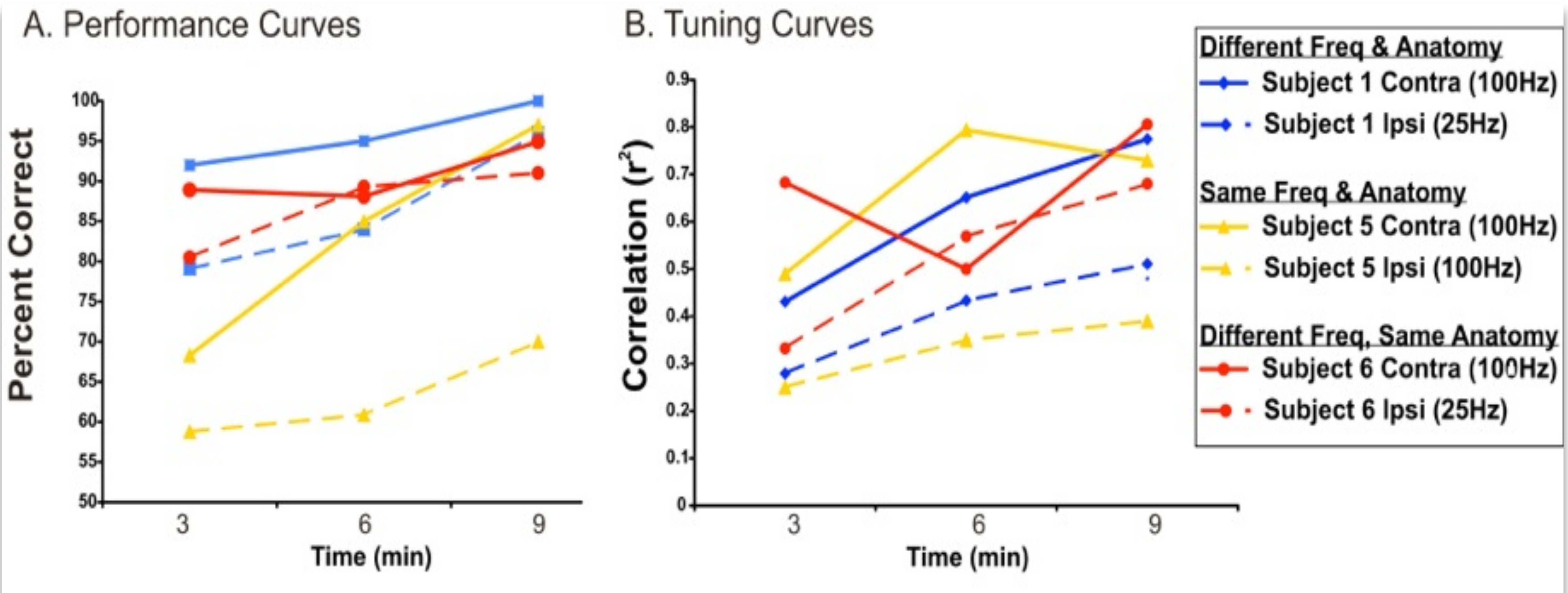
Distinct Timing



Distinct Anatomy

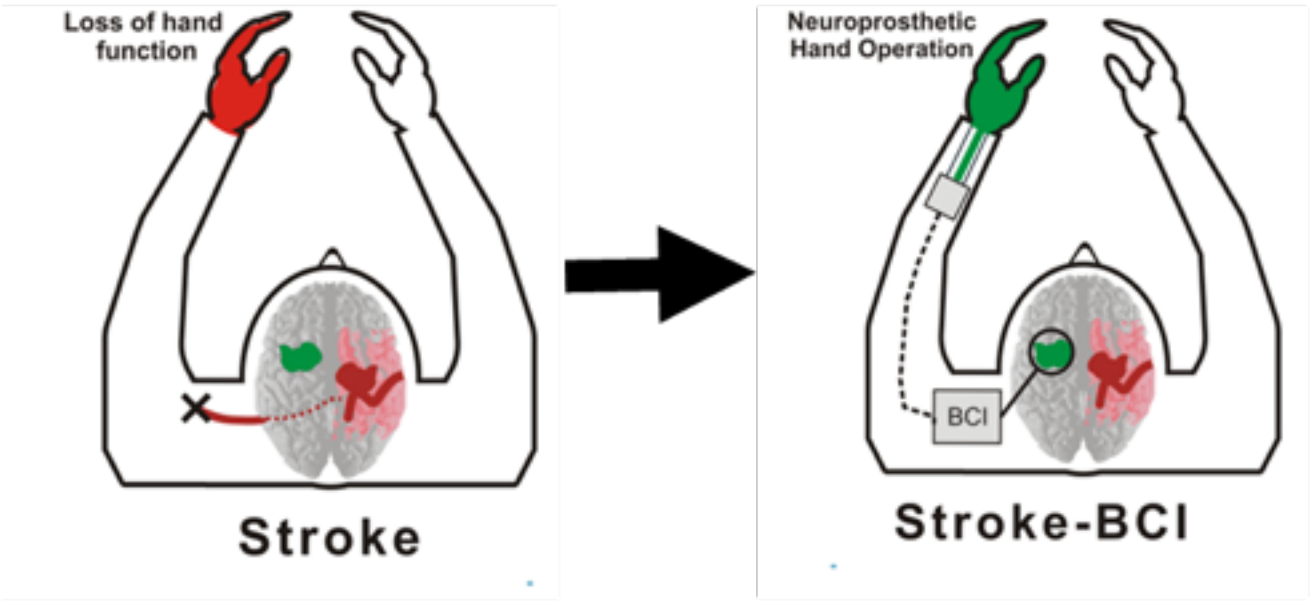
Wisneski et al., Stroke, 2008

Using Ipsilateral Motor Signals for BCI

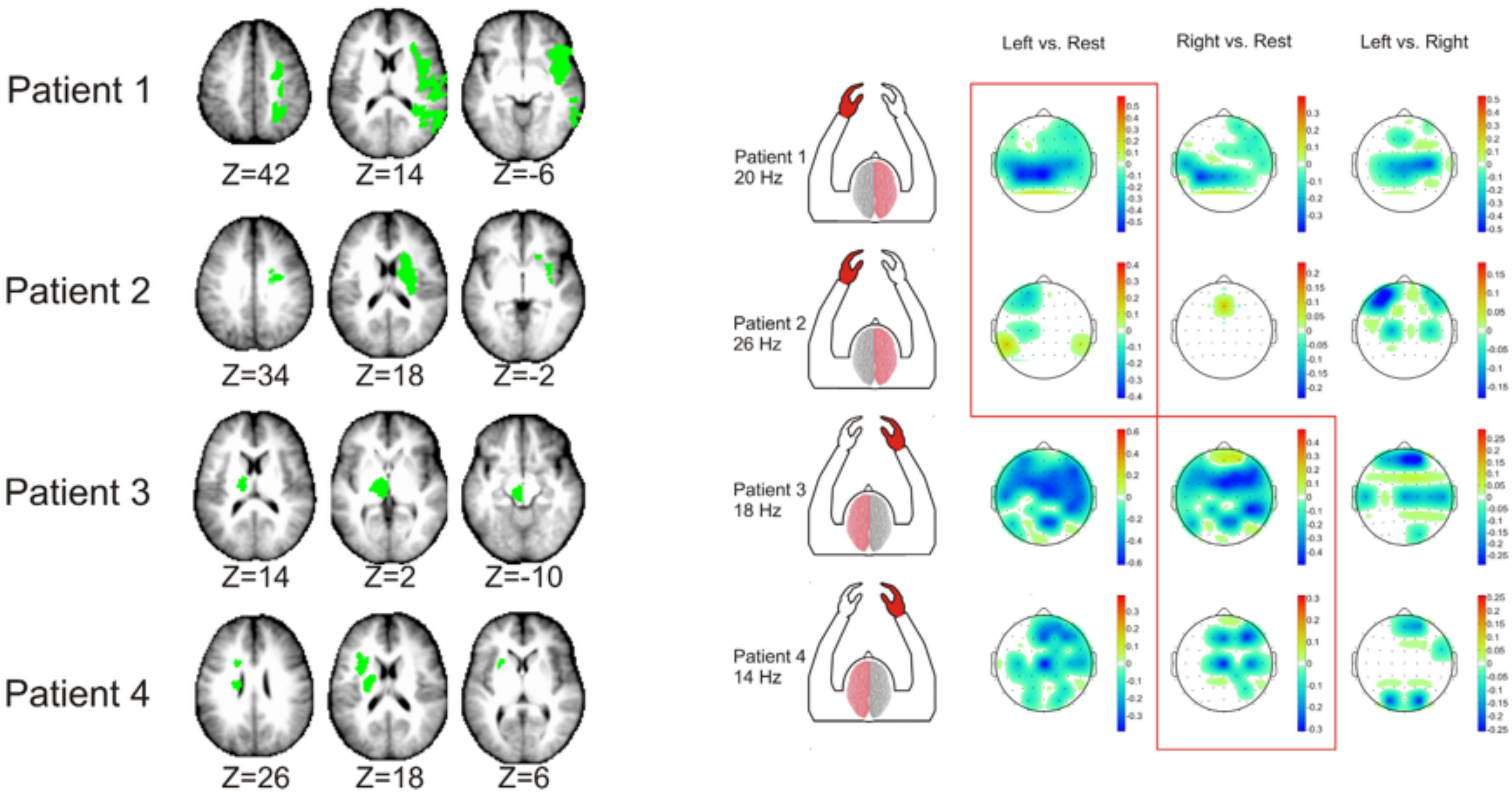


Wisneski et al., Stroke, 2008

Can stroke survivors use their unaffected hemisphere to control a BCI?

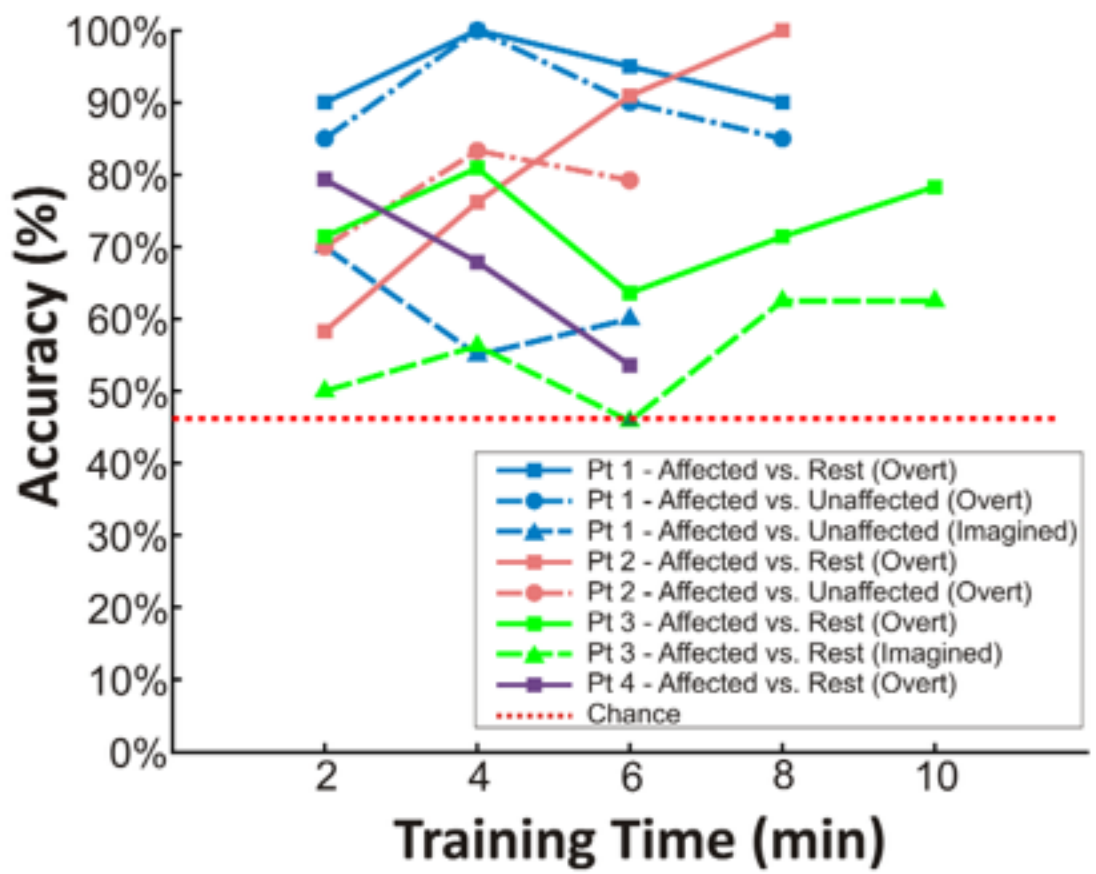


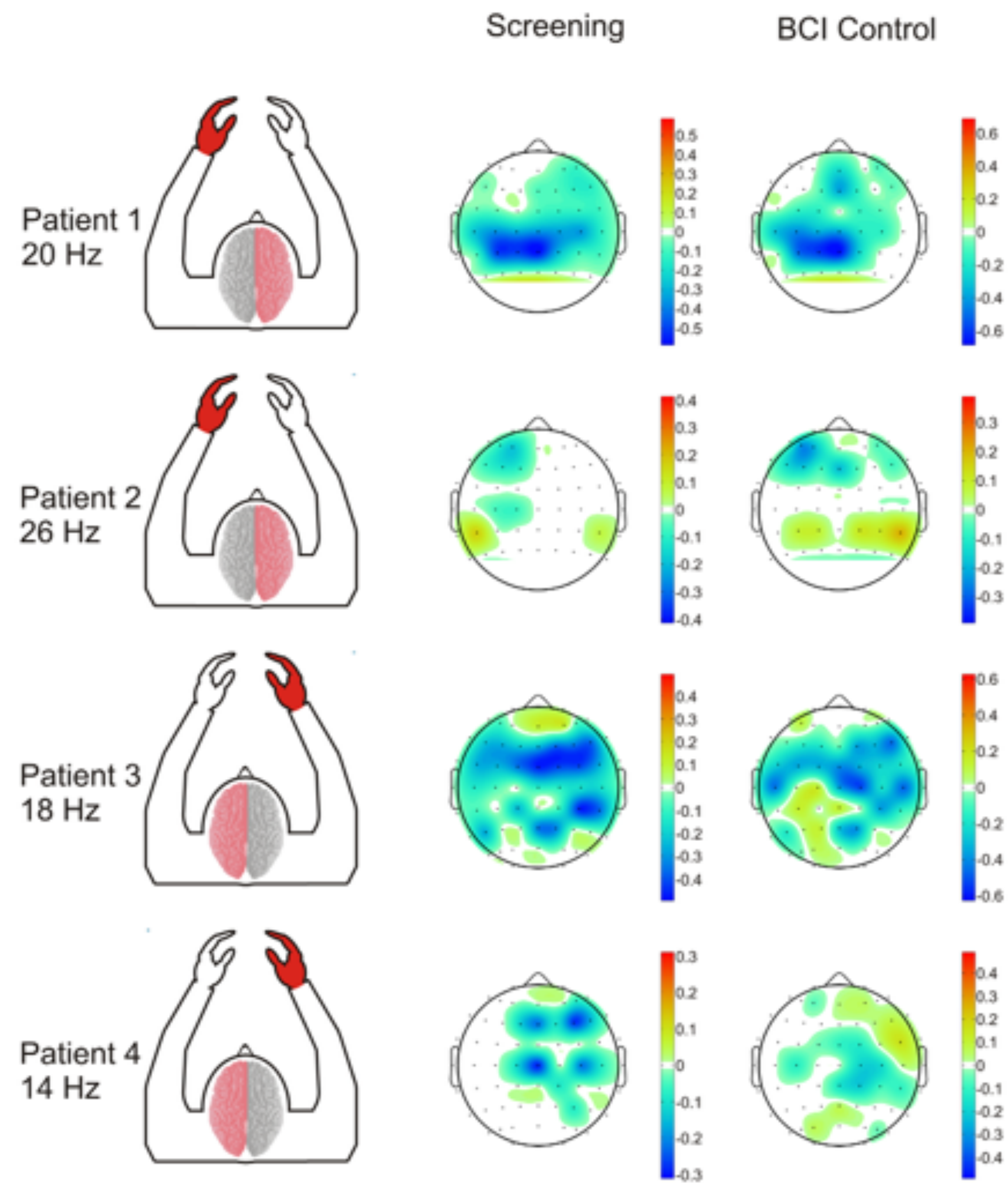
Ipsilateral, Contralesional Motor Activity after Chronic Stroke



Bundy et al., JNE 2012

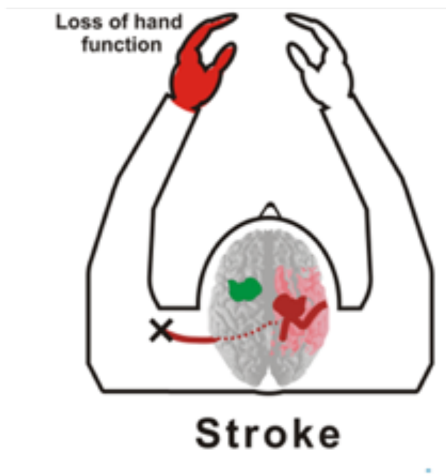
Ipsilateral BCI after Stroke

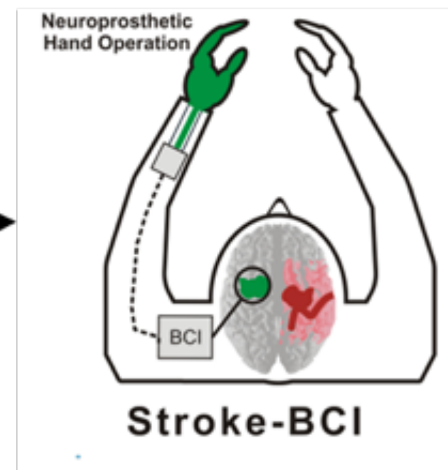


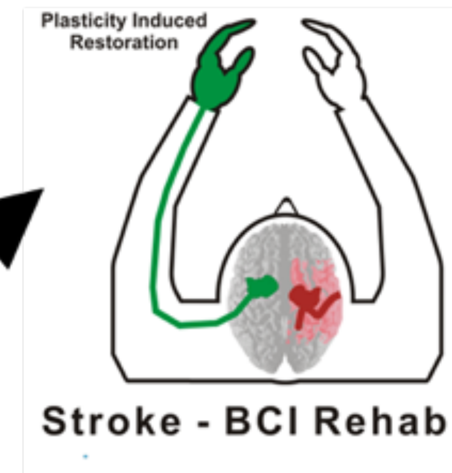


Bundy et al., JNE 2012

Pathways to Translation







BCI Rehabilitation

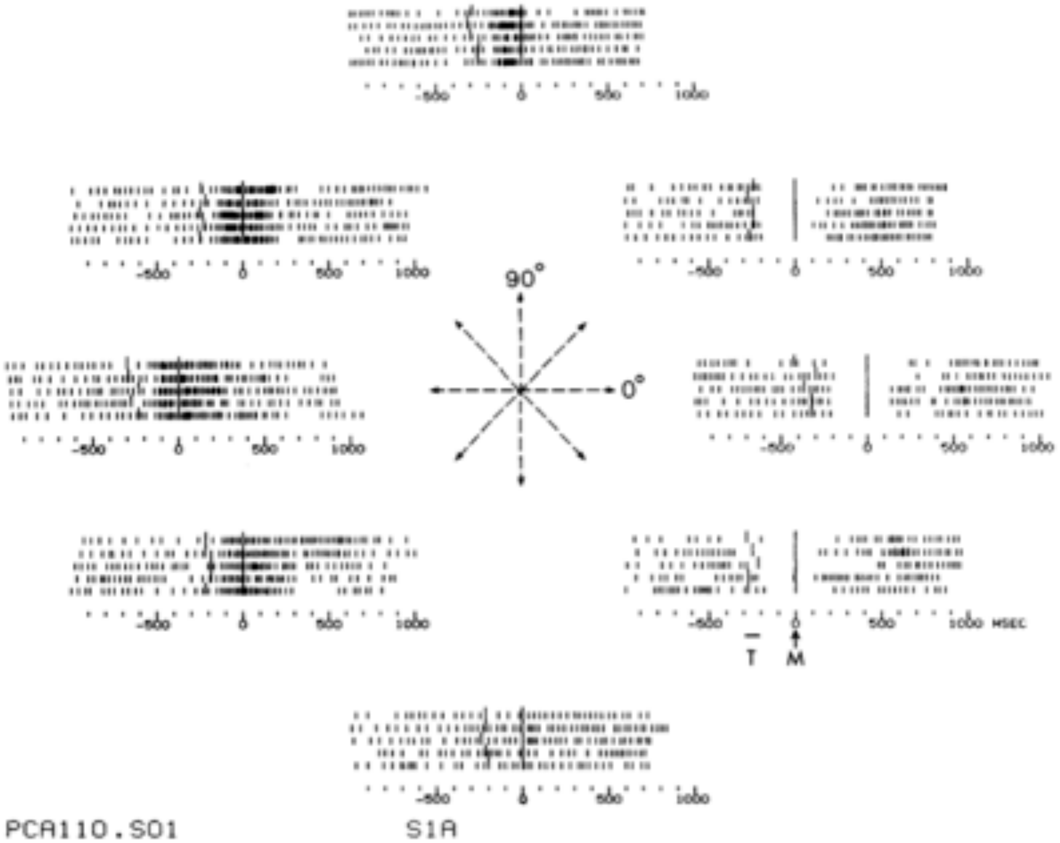
- Fast training
- Stable control signal
- Non-invasive

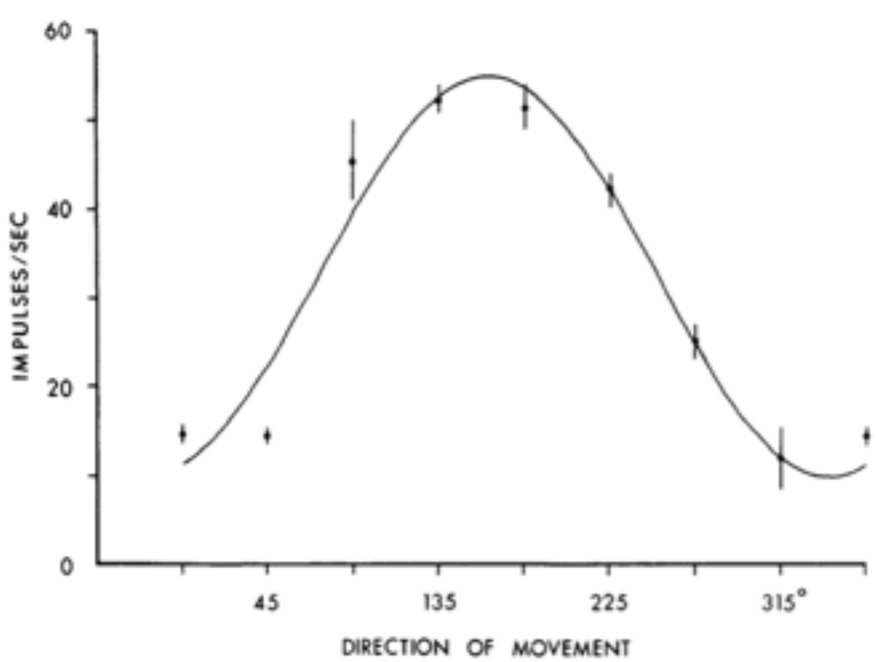
Long-Term Device Operation

- Chronically stable signal
- High degree of information
- Functionally relevant output

Biomimetic BCI

Cosine Tuning in Single Units





Georgopoulos et al, 1982

- The relationship between motor-neuron firing and movement direction was described by Georgopoulos.
- Moran and Schwartz extended the description to both speed and direction

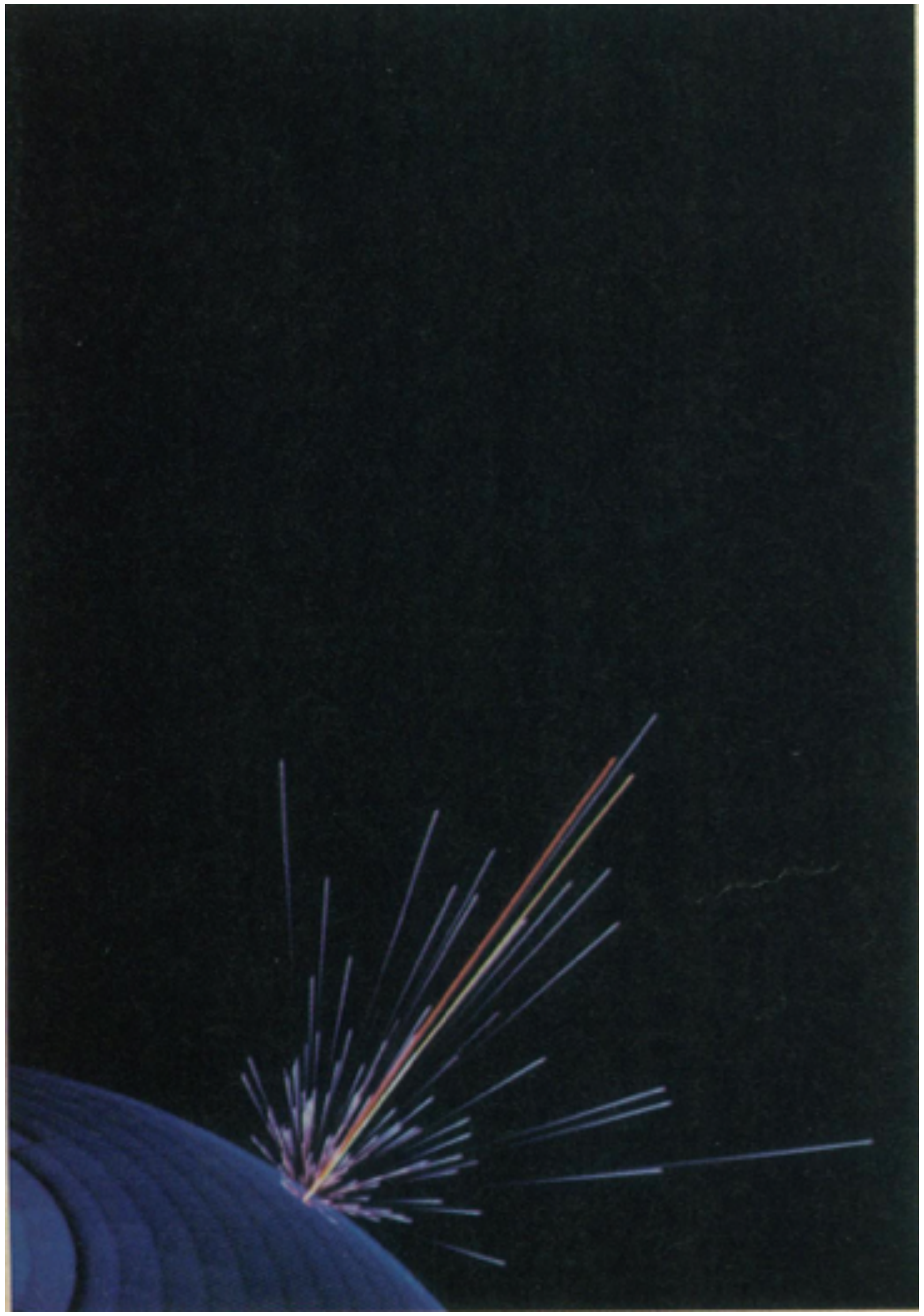
$$D(t-\tau) - b_0 = \|\vec{V}(t)\|(b_n + b_y \sin[\theta(t)] + b_x \cos[\theta(t)])$$

- D = firing rate
- V=velocity
- θ =direction of movement
- b_x and b_y = regression coefficients

Population Vectors

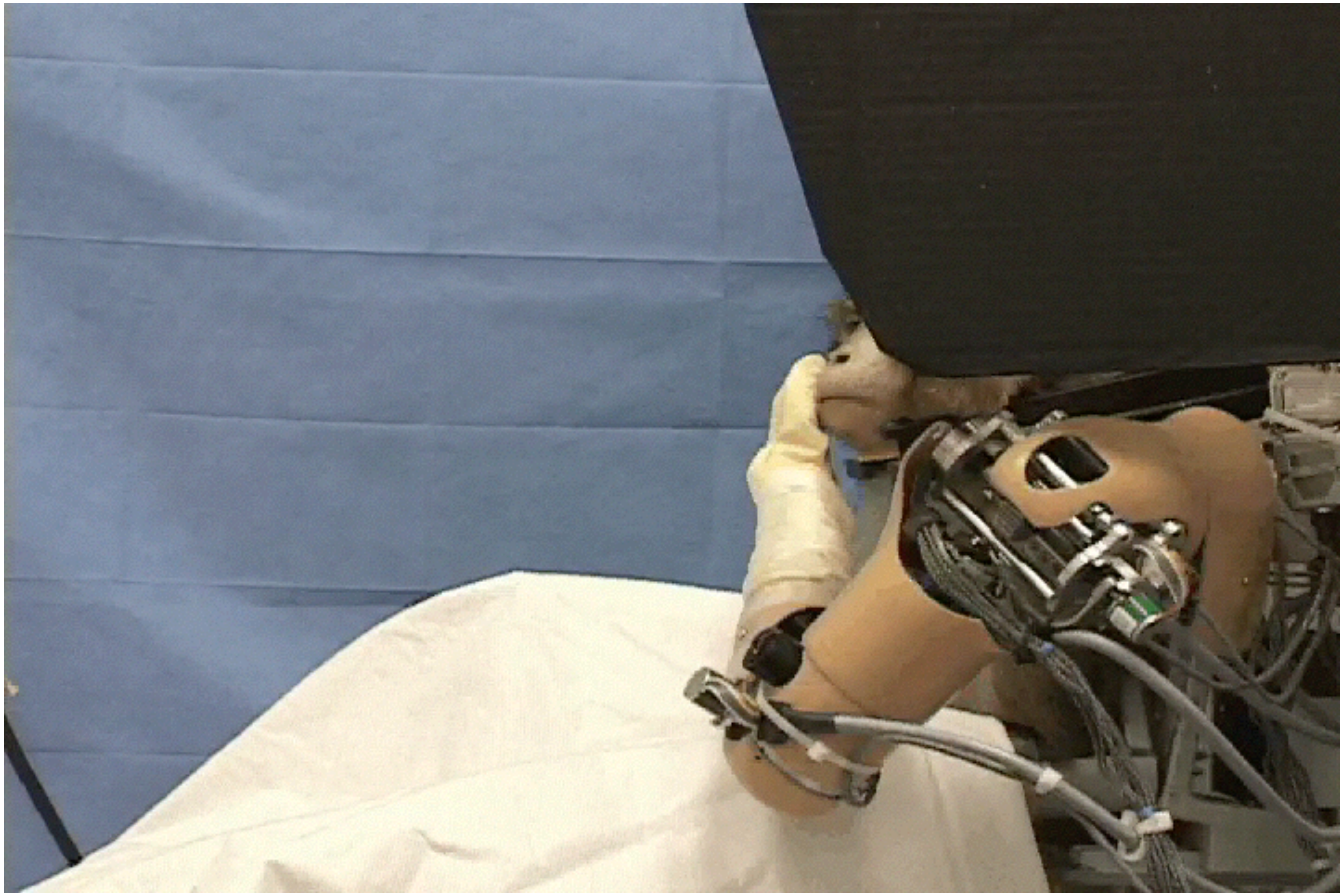
- By combing the the activity of a population of neurons a population vector can be calculated to accurately predict kinematics:

$$PV_{y,j}(t) = \sum_{i=1}^{\text{num cells}} \frac{D_{i,j}(t-\tau) - A}{M} \cdot \frac{B_{y,i}}{M}$$



Georgopoulos et al, 1986

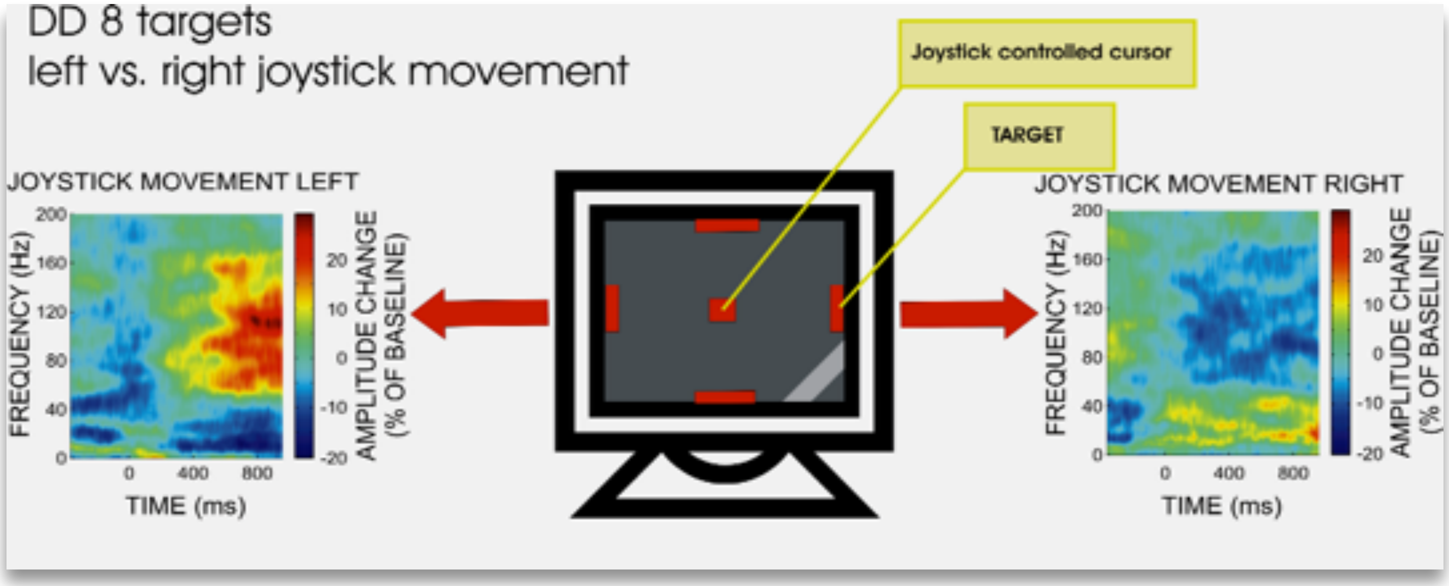
Robotic Limb Control



Biomimetic studies in ECoG

Two Dimensional Prediction with ECoG

- Electrodes demonstrating modulation of spectral activity with kinematics can be located.
- Using the modulation of ECoG activity with movement direction, the following model can be regressed:

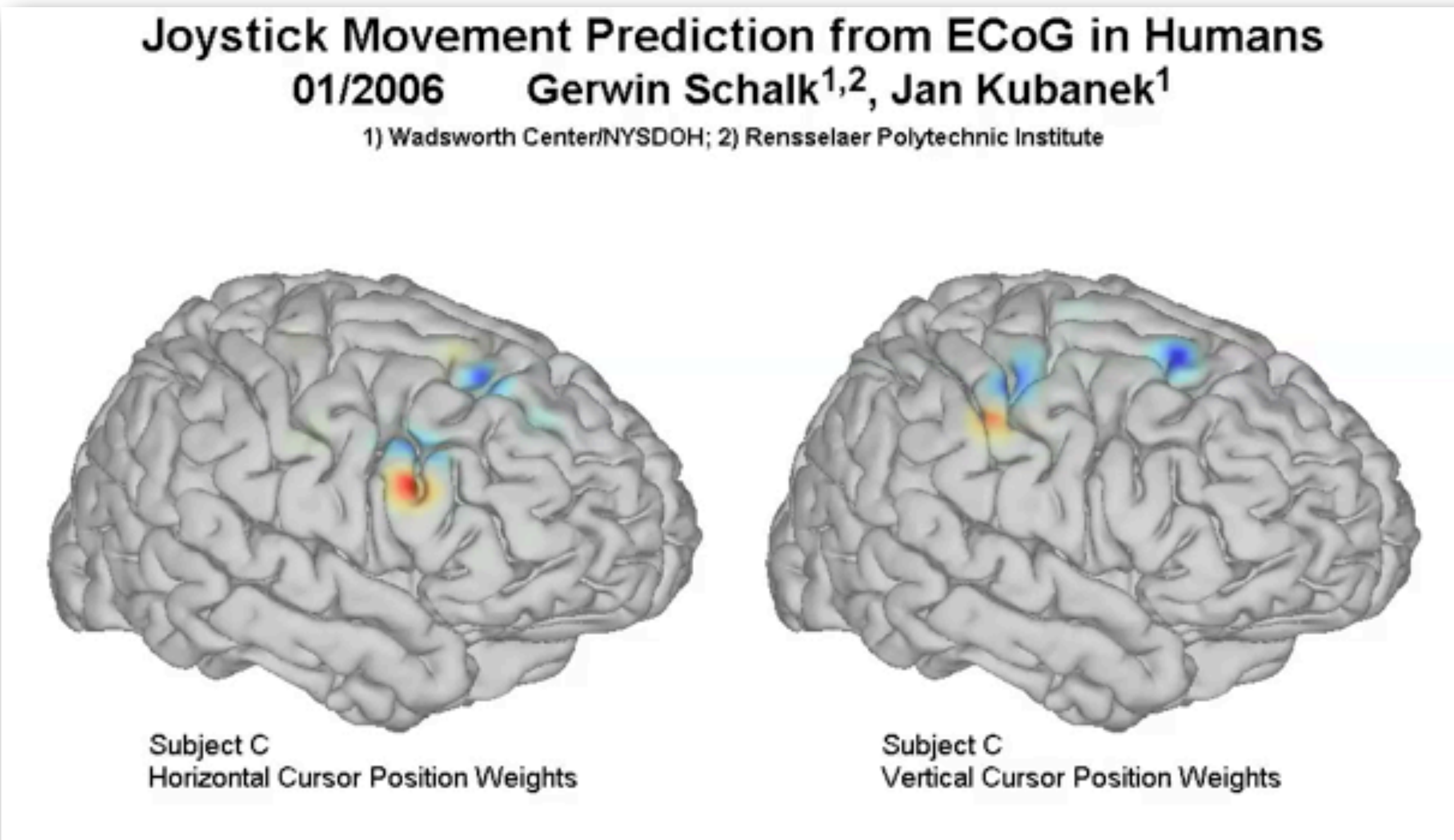


Leuthardt et al , J Neural Engineering, 2004

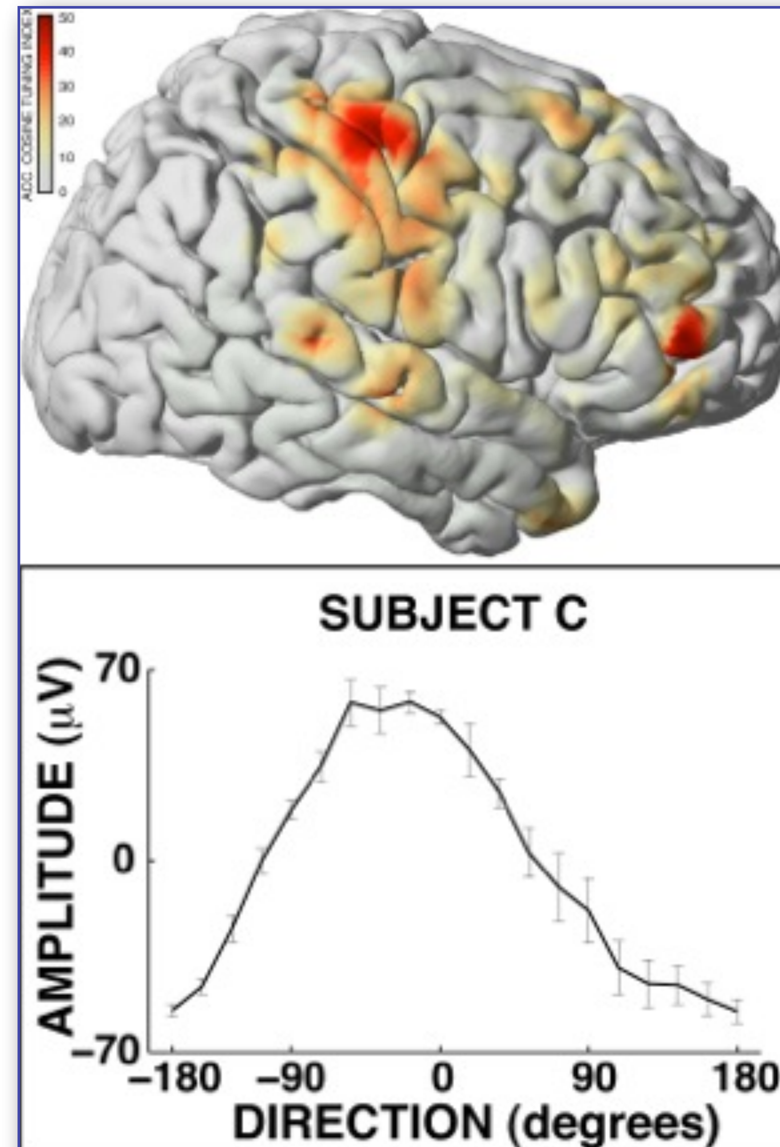
$$\overline{P} = B_{p,0} + B_{p,x}\overline{x} + B_{p,y}\overline{y} + B_{p,z}\overline{z}$$
$$\overline{P} = B_{v,0} + B_{v,x}\overline{\dot{x}} + B_{v,y}\overline{\dot{y}} + B_{v,z}\overline{\dot{z}}$$

- P is the average spectral amplitude, $B_{p:x,y,z}$ and $B_{v:x,y,z}$ are the regression coefficients with (B_{px},B_{py},B_{pz}) and (B_{vx},B_{vy},B_{vz}) the position gradient and preferred direction respectively

ECoG Signals Encode Directional Motor Kinematics



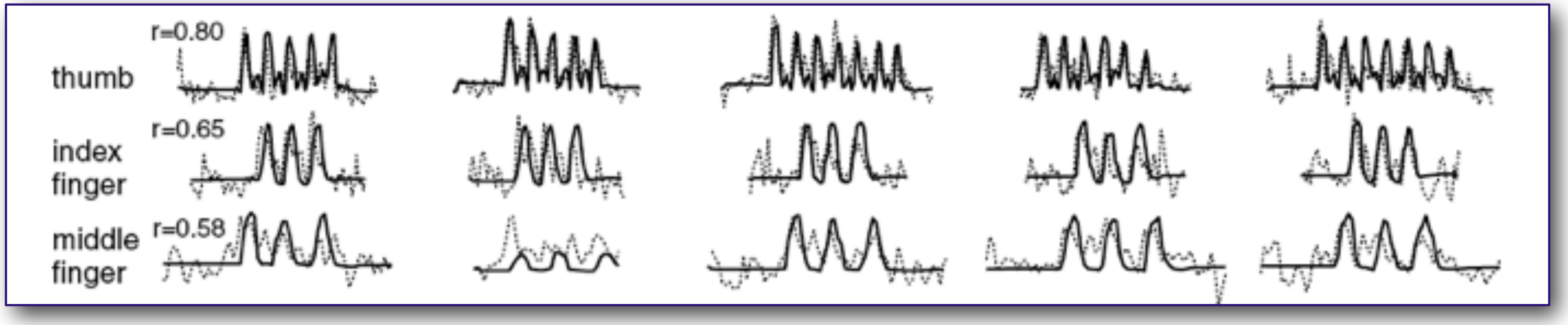
Large Cortical Populations



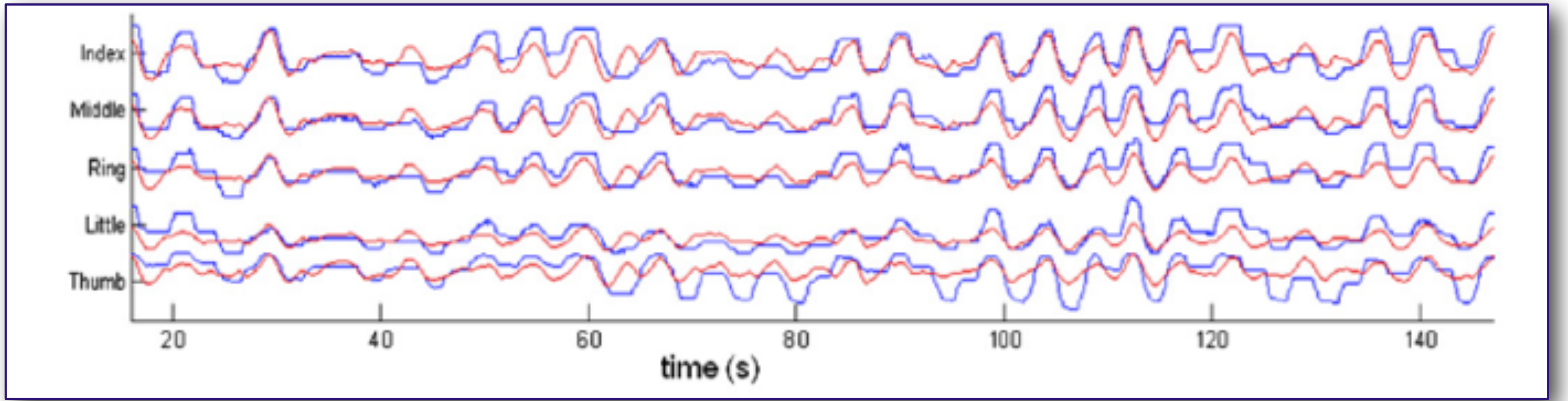
Schalk, et al, *J Neural Engineering*, 2007

Local Motor Potential (LMP) Encode Finger Movements

- Finger Movements

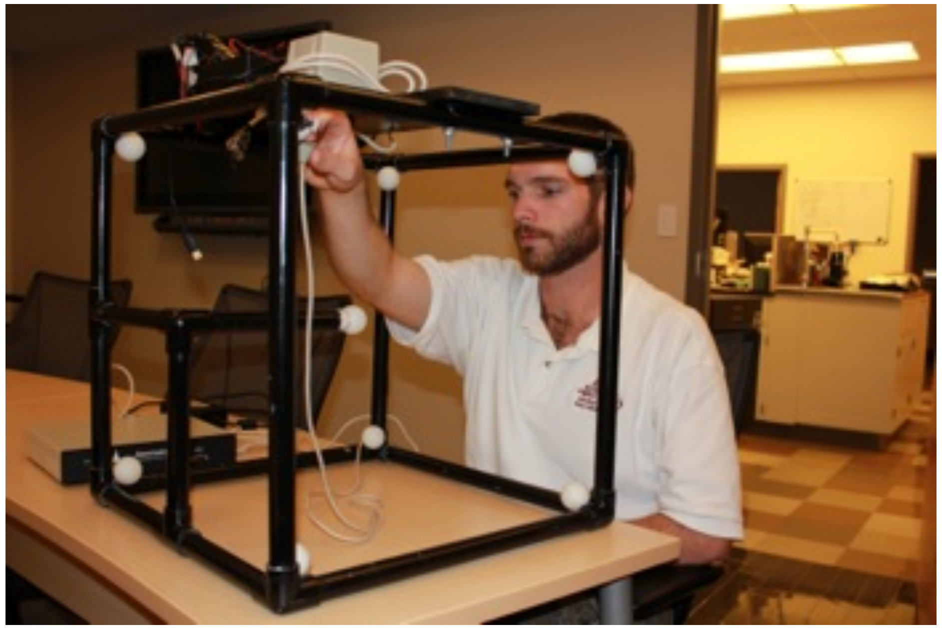


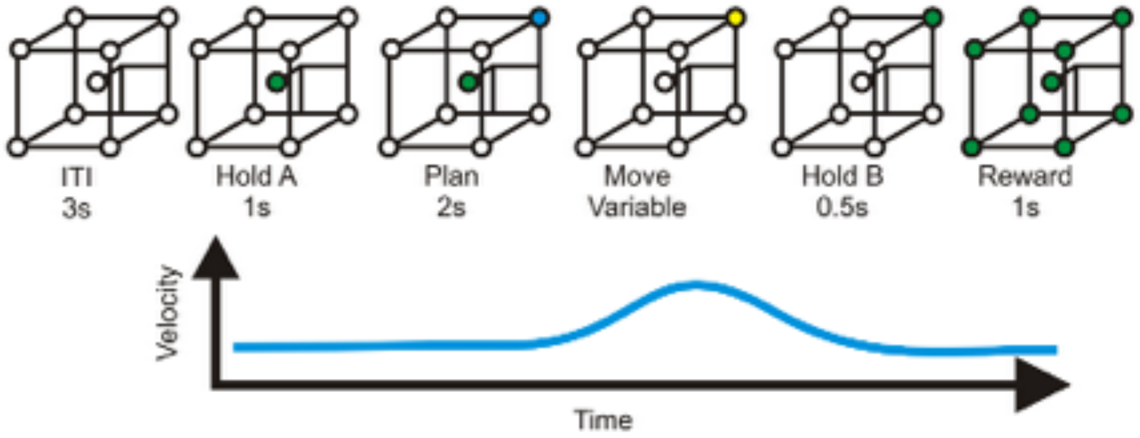
Kubanek, et al *J Neural Engineering*, 2009



Acharya, et al *J Neural Engineering*, 2010

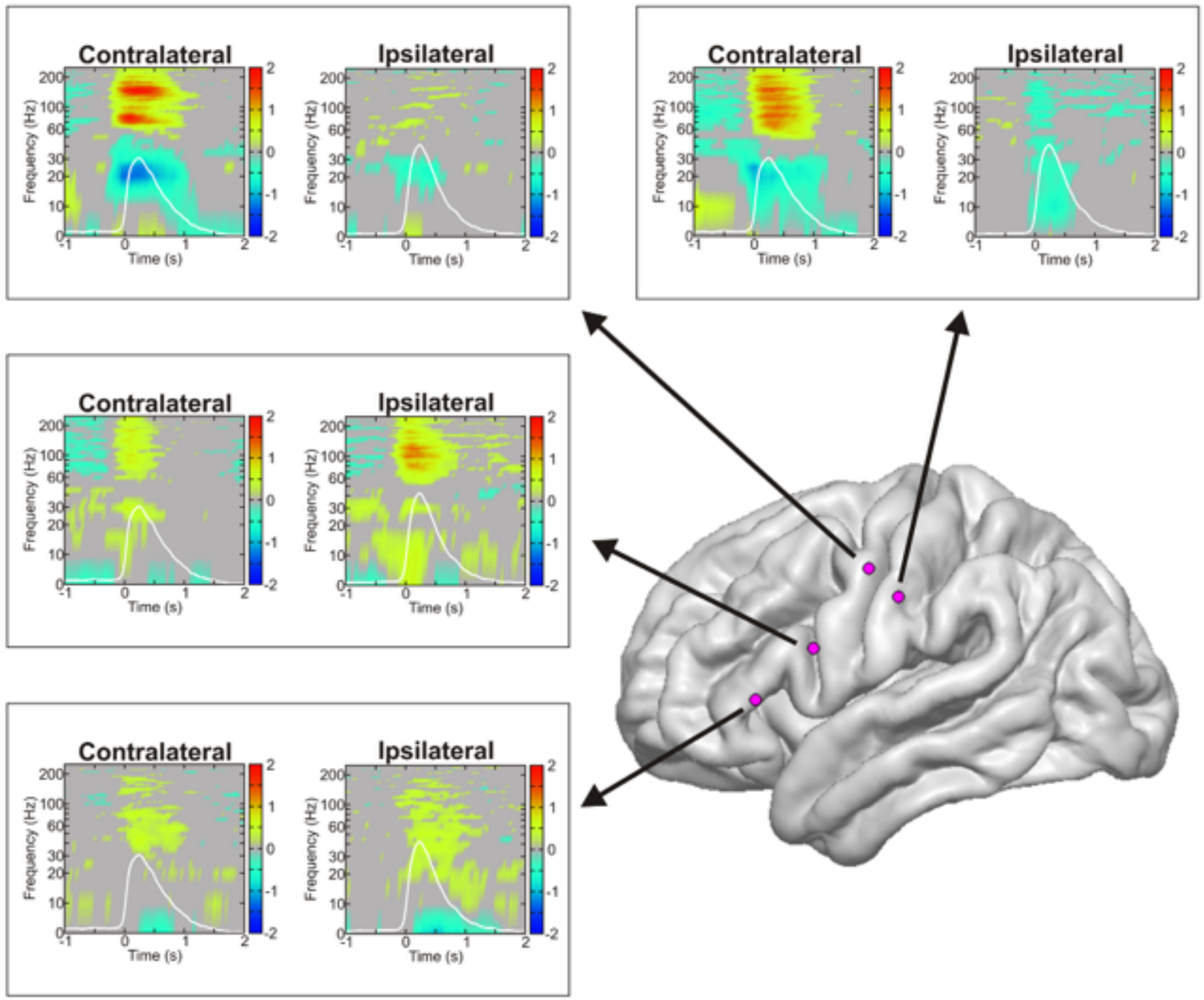
Task Design



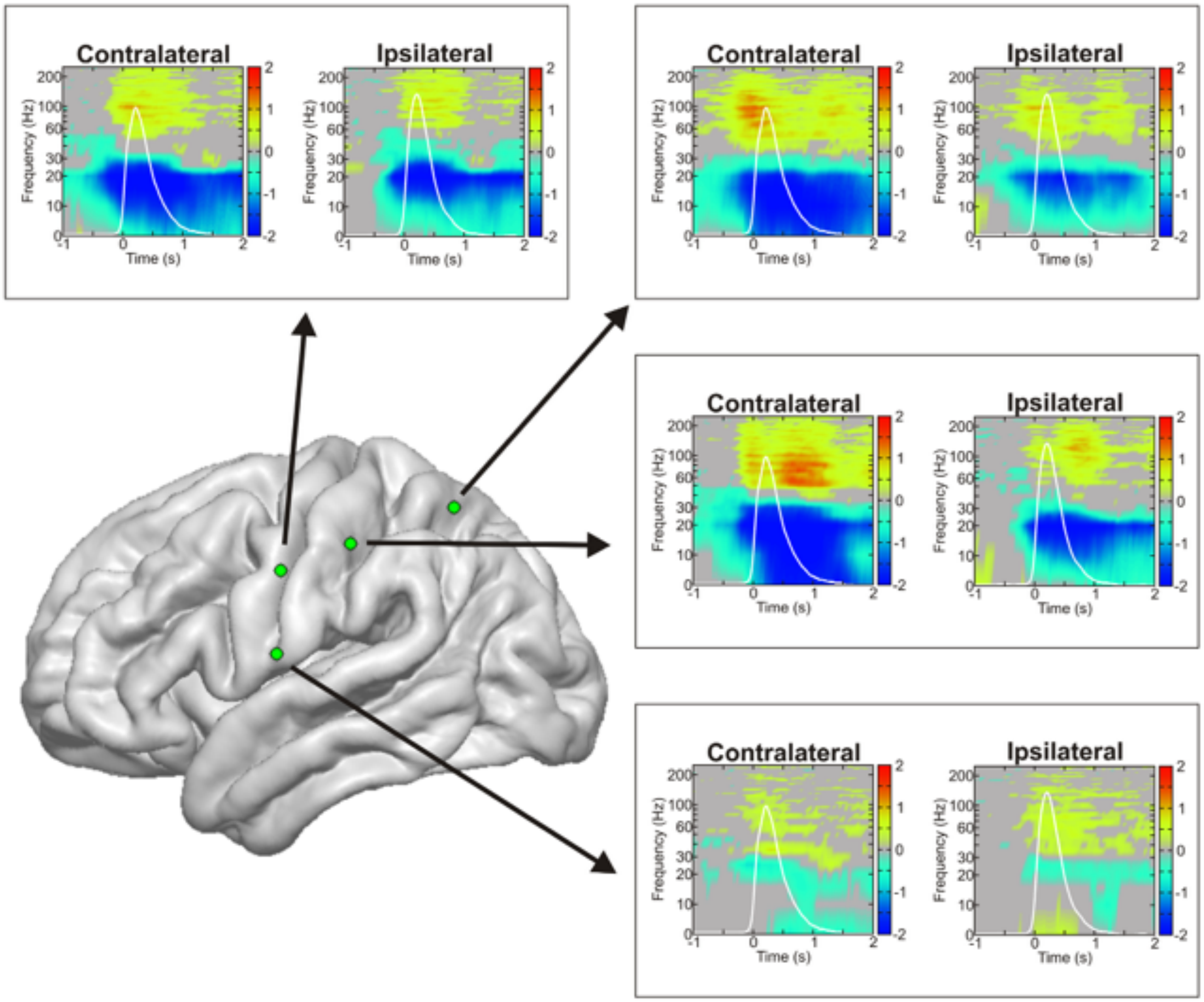


- A center-out reaching task was designed to evaluate the extent of information that can be decoded from ECoG signals
- ECoG recordings and 3D hand position are simultaneously recorded during task performance
- Separate planning and movement periods allow for separation of planning and execution of motor movements

Exemplar Cortical Activations: Electrode Location and Limb



Exemplar Cortical Activations: Electrode Location and Timing



Machine Learning Methods

L1-Regularized Least-Squares Linear Regression:

Fit a regression equation:

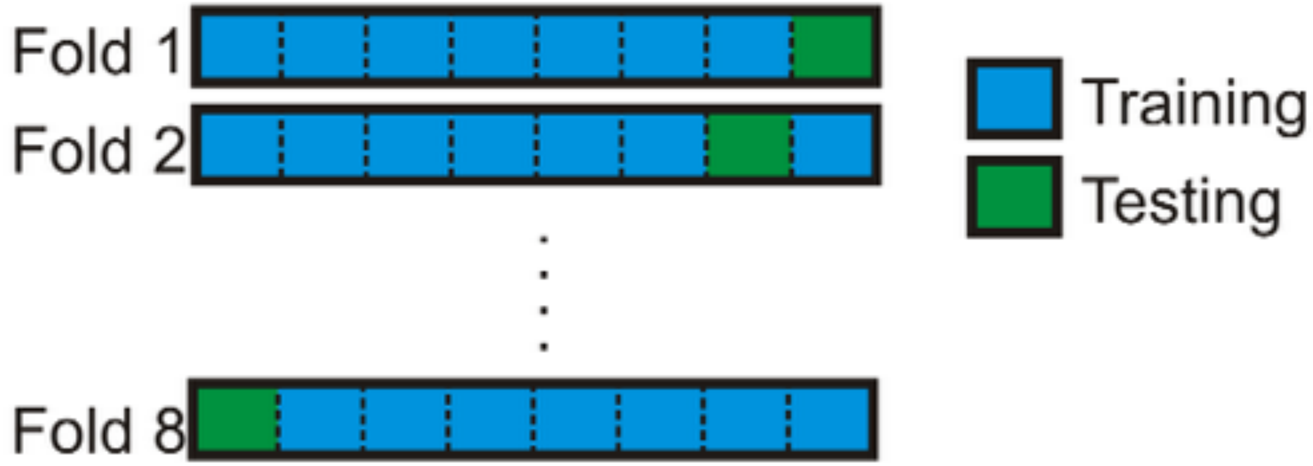
$$y_i = w_o + \sum_{j=1}^{NumChan} w_j x_{ij} + \varepsilon_j$$

Subject to the constraint:

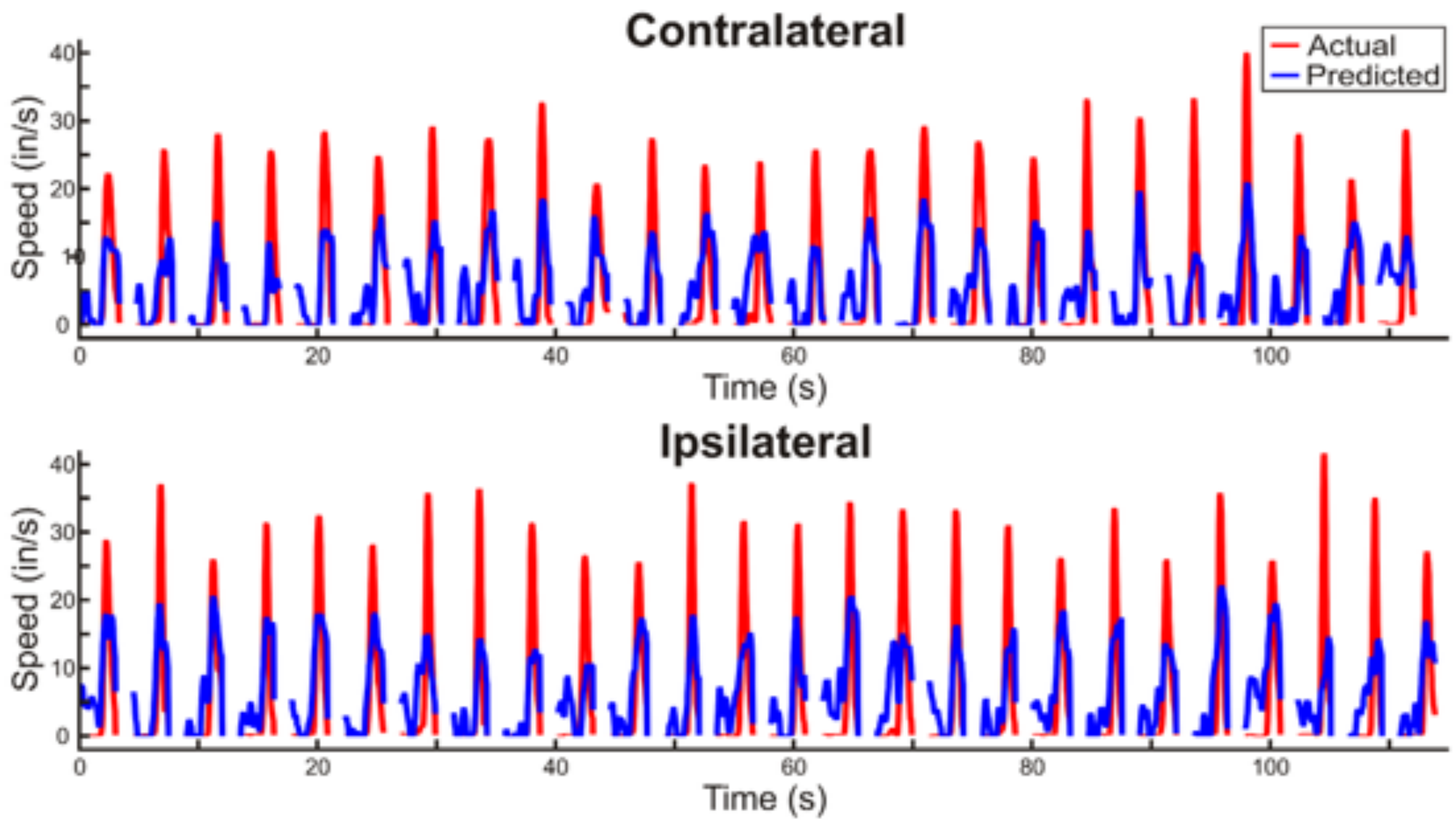
$$RSS = \sum_{i=1}^{n} \left(y_i - w_o - \sum_{j=1}^{NumChan} w_j x_{ij} \right) + \lambda \|w\|_1$$

This forces a sparse solution and minimizes overfitting

Cross-Validation Testing:



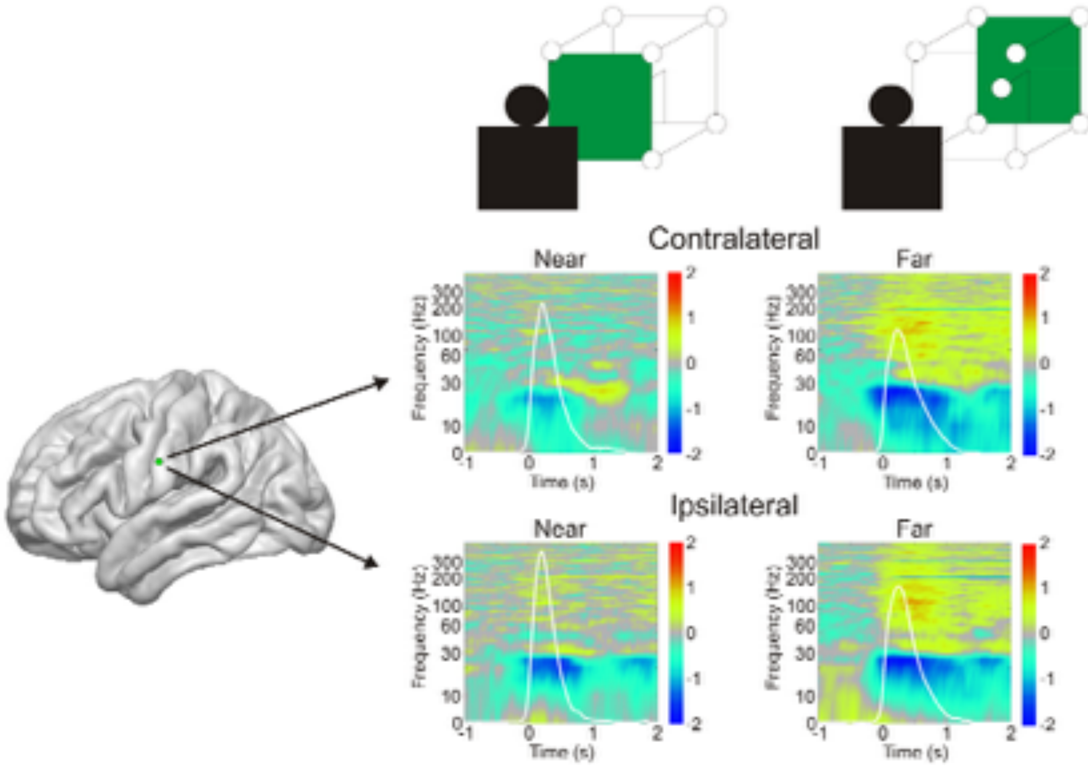
Velocity Prediction



Patient	Hand	Trials (n)	Average Cross-Validation R-Value
1	Contra	245	**0.31137**
	Ipsi	119	**0.3692**
2	Contra	76	**0.47546**
	Ipsi	187	**0.55427**
3	Contra	104	**0.57189**
	Ipsi	-	**-**
4	Contra	221	**0.71699**
	Ipsi	177	**0.64601**
5	Contra	202	**0.70715**
	Ipsi	208	**0.69751**

Directional Specificity: Single Channels

- As in previous work single channels can be found with spectral power modulated by direction.
- As electrode locations are dependent upon clinical needs, the presence of electrodes with this directional modulation varies.
- Utilizing spatial combinations of electrodes, we can obtain more information about movement kinematics



Common Spatial Patterns

Given signals X with covariance C:

$$C = \frac{XX'}{tr(XX')}$$

Mean covariances from two classes of data can be combined to form:

$$C_C = C_1 + C_2$$

With Eigen-decomposition

$$C_C = U_C \lambda_C U_C'$$

A whitening transform using this combined covariance can be calculated

$$P = \sqrt{\lambda_C^{-1}} U_C'$$

Applying this transform to each class of data, we have

$$S_1 = P C_1 P', \; S_2 = P C_2 P'$$

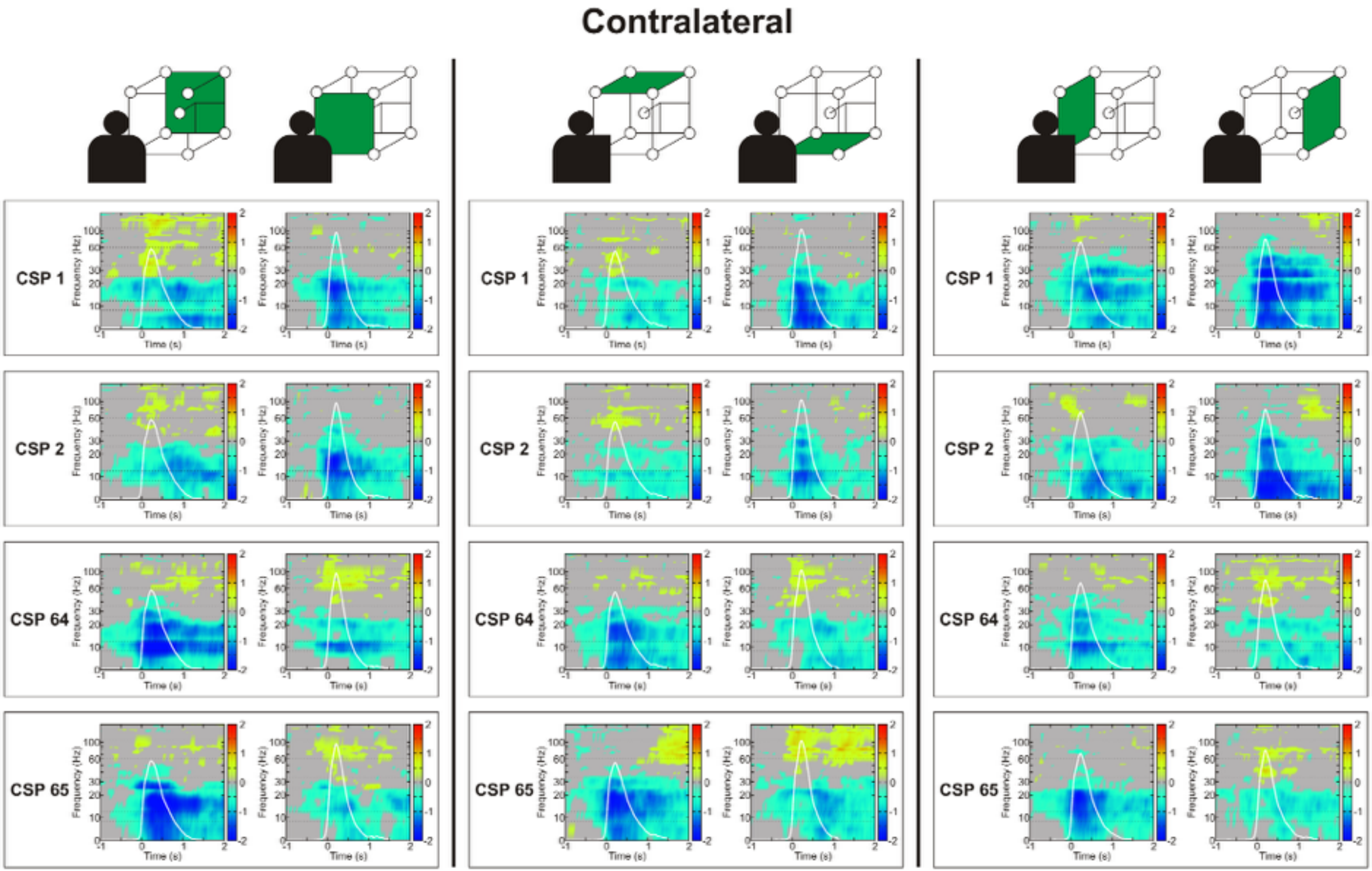
with property:

$$S_1 = B \lambda_1 B' \; and \; S_2 = B \lambda_2 B, \; where \; \lambda_1 + \lambda_2 = I$$

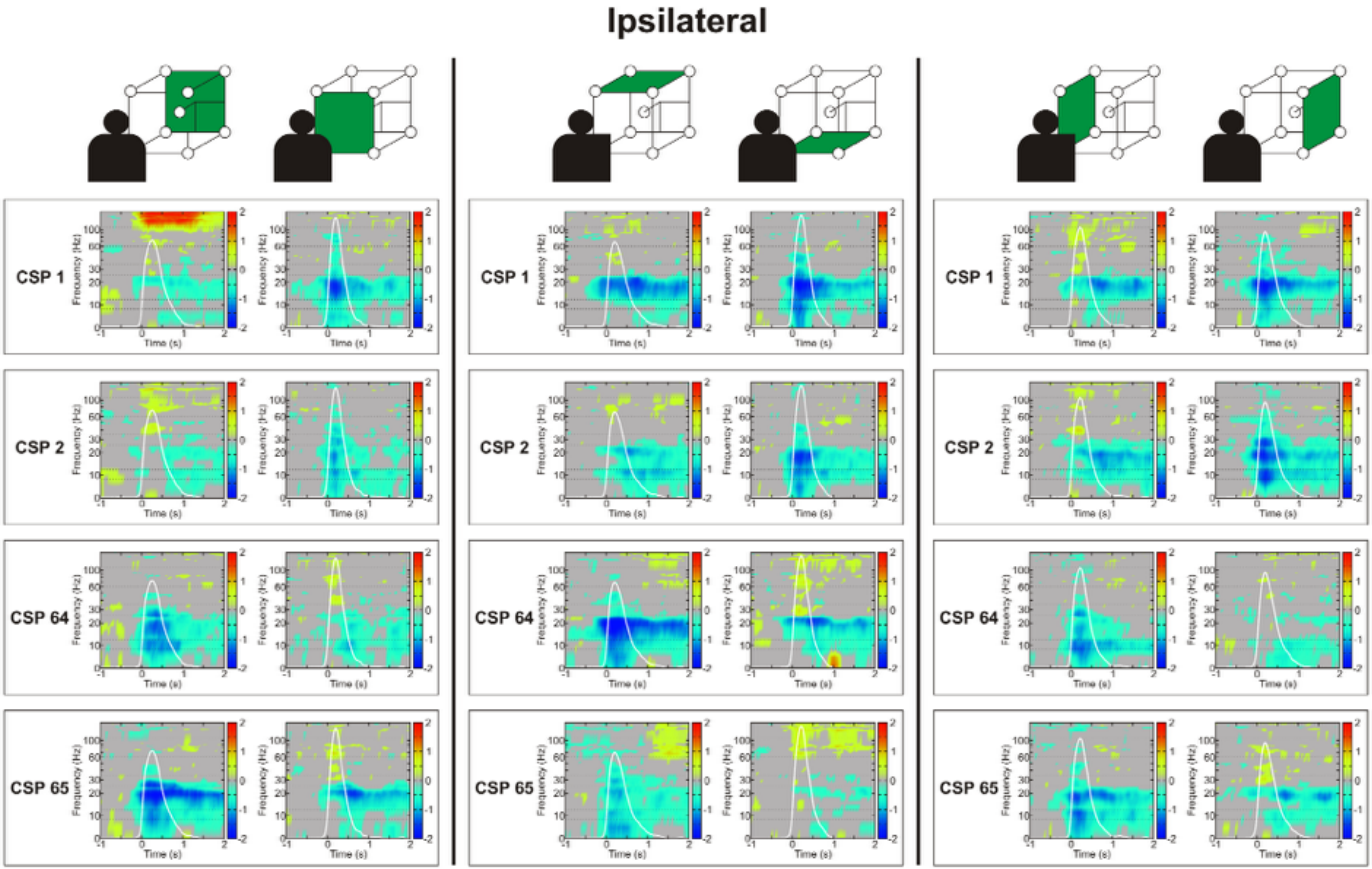
Therefore, we can apply the eigenvectors of S1/S2 as **spatial filters** designed to **maximize/minimize the variance** in our two classes

$$Z = WX = (B'P)'X$$

Encoding of Directional Information: Contralateral



Encoding of Directional Information: Ipsilateral



Future Directions

- ECoG Recordings contain information related to planning and execution of motor movements
  - Speed can be predicted with a high-degree of accuracy
  - ECoG signals also appear to encode directional kinematics
- Future work will further investigate the utilization of ECoG for off-line prediction of directional kinematics and on-line BCI control based upon this prediction.

Questions?