Dynamic Models for Electroencephalography
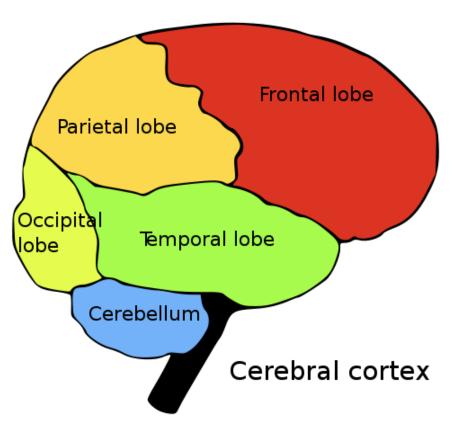
CASIS

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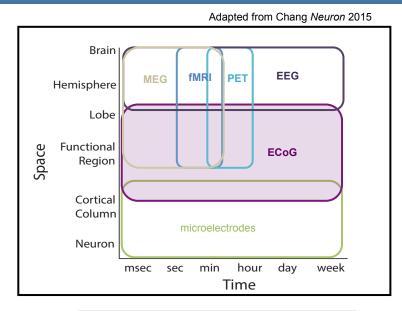May 18, 2016

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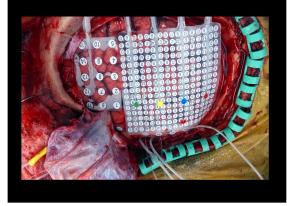
Brain Science

- **15 – 30 Billion neurons (cells)**
  - Axon carries electrical charge
  - Connected by synapses (thousands)
  - Connect to spinal cord

- **Highlights of the functional areas**
  - Cerebral cortex: thin outer layer
  - Frontal lobe: motion, memory
  - Parietal lobe: sensory integration
  - Temporal lobe: visual memories, hearing
  - Occipital lobe: vision
  - Cerebellum: coordination

Brain Imaging/Sensor Modalities

- MEG (Megnetoencephalography)

- Functional MRI (Magnetic Resonance Imaging)

- PET (Positron Emission Tomography)

- [Scalp] EEG (Electroencephalography)

- [Intracranial] EEG or ECoG
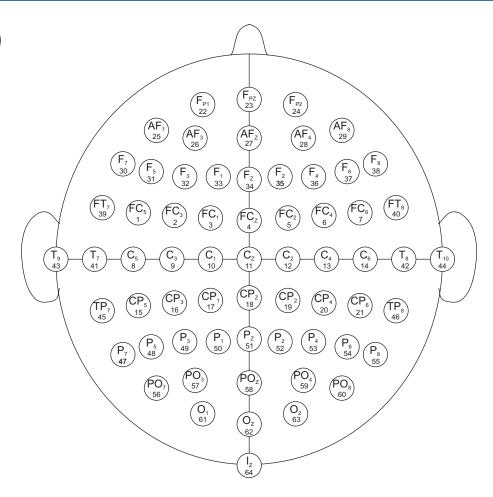
- Microelectrodes

Adapted from Chang *Neuron* 2015

Scalp EEG Montage

- 64 Electrodes (10-10 system)

- Each picking up activity of millions of neurons

- Local Field Potential (LFP) dependent on:
  - Orientation of neurons
  - Volumetric properties of the brain
  - Contact quality

Time/Frequency Analysis in EEG

- EEG frequency bands have been experimentally correlated with function

- Oscillatory behavior of neurons
  - Event-Related Desynchronization
  - Event-Related Synchronization

Band	Frequency	Example of Function
Delta	< 4 Hz	NREM sleep
Theta	4 – 7 Hz	Drowsiness, idling
Alpha	8 – 15 Hz	Relaxation, closed eyes
Beta	16 – 31 Hz	Active thinking, anxious
Gamma	> 32 Hz	Sensory processing
Mu	8 – 12 Hz	Motor neurons

Log-Normal Spectral Models

- Data from sensor array: $x_n(t)$

- Power spectral density: $y_{n,s}(f)$

n	channel
s	time bin
f	frequency bin

- Log-Normal model:

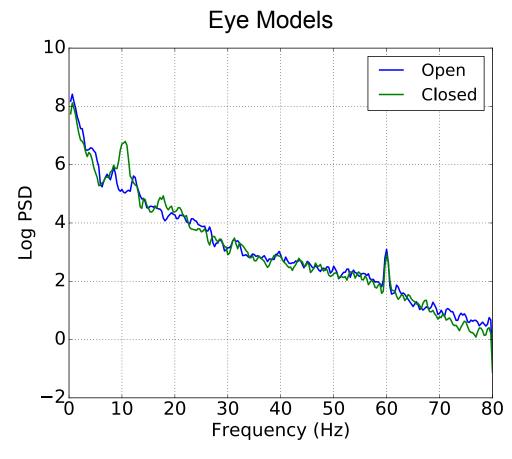$$\log y_{n,s}(f) \sim \mathcal{N}\left(\mu_f, \sigma_f^2\right)$$

- Resulting likelihood function: $\phi_f(\boldsymbol{y})$

- Parameter estimation:

$$\left(\mu_f, \sigma_f^2\right) = \underset{\mu_f, \sigma_f^2}{\arg\max}\, \phi_f(\boldsymbol{y})$$
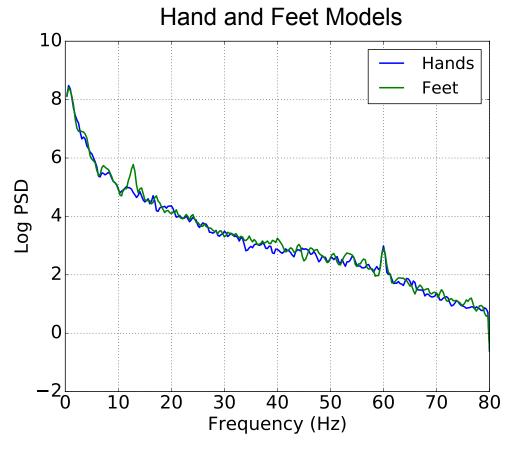
Spectral Characteristics

- **Scalp EEG**
  - 160 Hz sampling rate

- **STFT properties**
  - 2 second window with 1 second overlap
  - 0.5 Hz frequency resolution
  - 2 s temporal resolution

- **Estimate model parameters over corresponding data**
  - mean and variance for each frequency bin

Eye Models

Spectral Characteristics

- Scalp EEG
  - 160 Hz sampling rate

- STFT properties
  - 2 second window with 1 second overlap
  - 0.5 Hz frequency resolution
  - 2 s temporal resolution

- Estimate model parameters over corresponding data
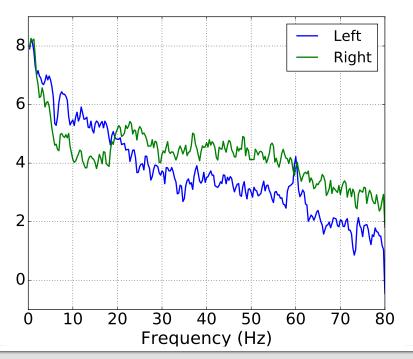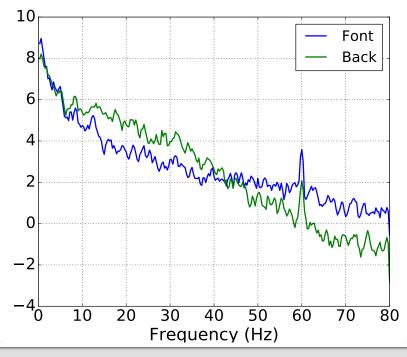 - mean and variance for each frequency bin

Hand and Feet Models

Adding Spatial Dynamics

- Channel dependent model:

$$\log y_{n,s}(f) \sim \mathcal{N}\left(\mu_{n,f}, \sigma^2_{n,f}\right)$$
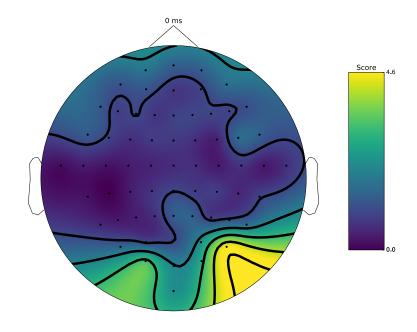
- Likelihood function: $\phi_{n,f}(\boldsymbol{y})$

Spatial Characteristics

- Train models for eye state (open and closed)
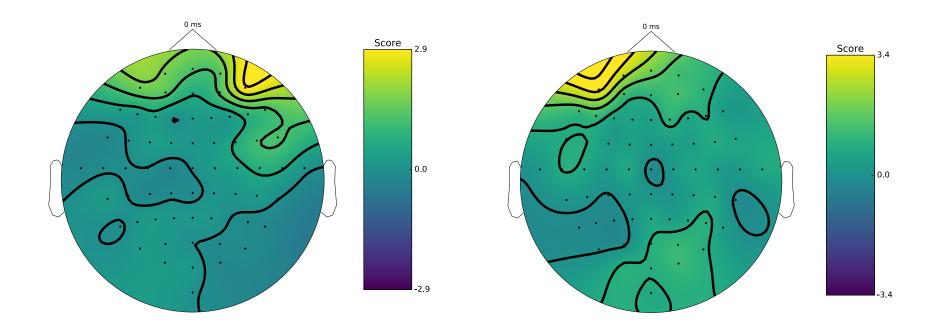
- Using new (test) data, compute:

$$\log \frac{\sum_f \phi_{n,f}^{\text{closed}}(\boldsymbol{y})}{\sum_f \phi_{n,f}^{\text{open}}(\boldsymbol{y})}$$

- Brain topography
  - Locate areas of activity
  - For specific task

Closed vs. Open

Spatial Characteristics

Hands vs. Feet

Left vs. Right

State Space Models

- Capture temporal evolution of the signals
  - States progress through time
  - State are not observed

- Basic formulation:

$$w_s \in \{1, 2, \ldots, M\}$$

$$w_{s+1} = g\left(w_s\right)$$

- State dependent likelihood functions:

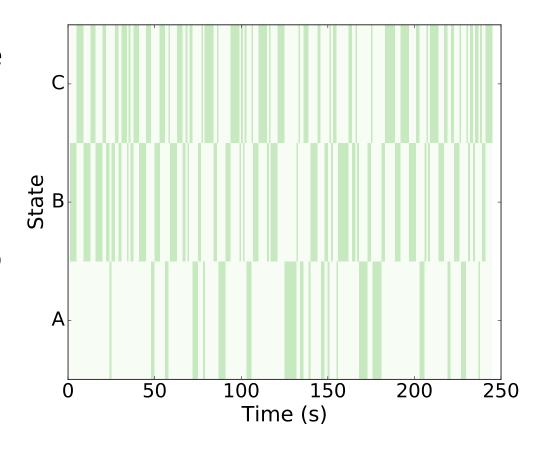$$\log y_{n,s}\left(f\right) \sim \mathcal{N}\left(\mu_{w_s,n,f}, \sigma^2_{w_s,n,f}\right)$$

- Markov transitions -> Hidden Markov Model

or $w_{s,n}$

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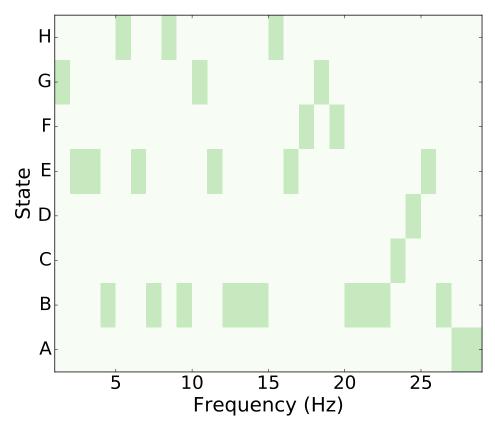LLNL-PRES-xxxxxx

National Nuclear Security Administration

State Space Behavior

- Train model on single run

- Compute most likely state sequence given the data

- Convert to binary matrix

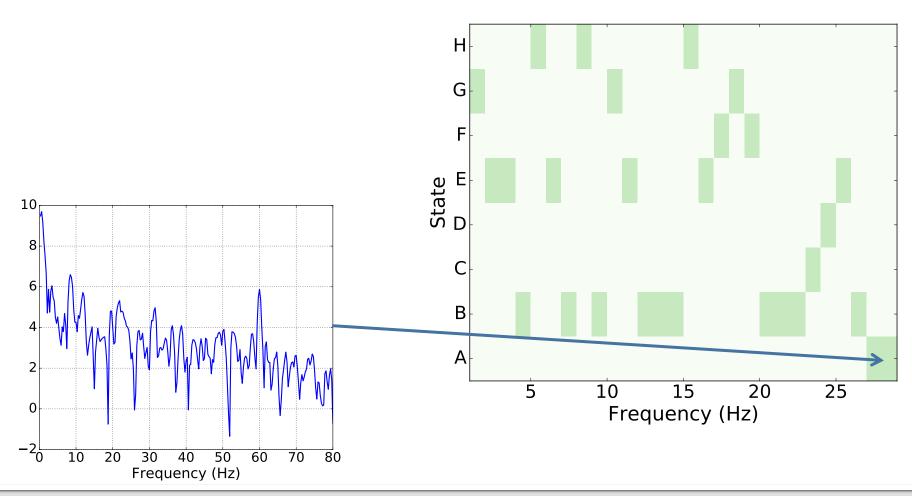- Discover temporal patterns corresponding to behavior

Investigating Discovered States

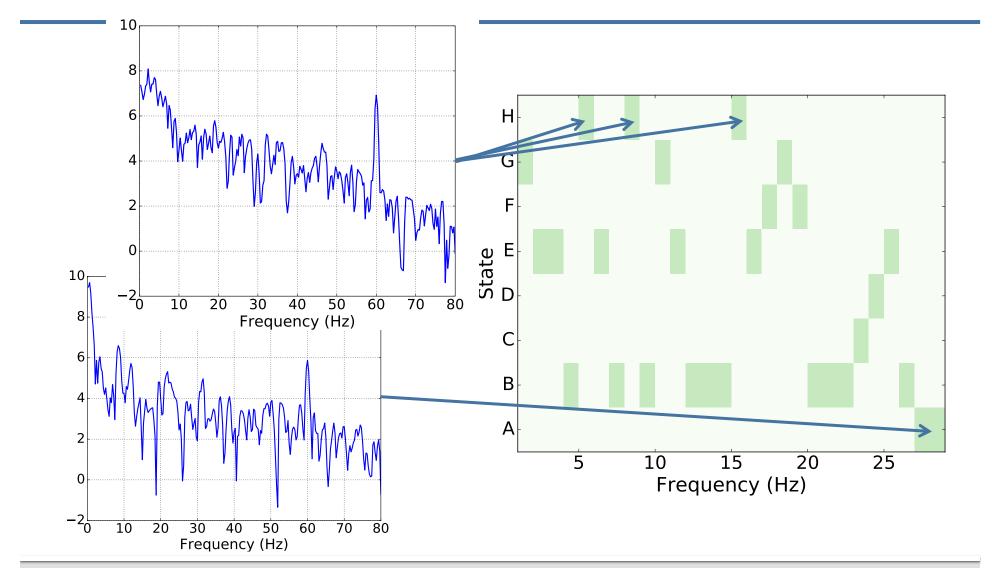- Resting State

- Each state-channel combination contains a log-Normal model over frequency bins

Investigating Discovered States

Investigating Discovered States

References

- Kubanek, Jan, and Gerwin Schalk. "NeuralAct: a tool to visualize electrocortical (ECoG) activity on a three-dimensional model of the cortex." Neuroinformatics 13.2 (2015): 167-174.

- S. Koelstra et al., "DEAP: A Database for Emotion Analysis Using Physiological Signals," in IEEE Transactions on Affective Computing, vol. 3, no. 1, pp. 18-31, Jan.-March 2012.

- Schalk, G., McFarland, D.J., Hinterberger, T., Birbaumer, N., Wolpaw, J.R. BCI2000: A General-Purpose Brain-Computer Interface (BCI) System. IEEE Transactions on Biomedical Engineering 51(6):1034-1043, 2004.