Lecture 2: EEG Basics

Introduction to Modern Brain-Computer Interface Design

Christian A. Kothe
SCCN, UCSD

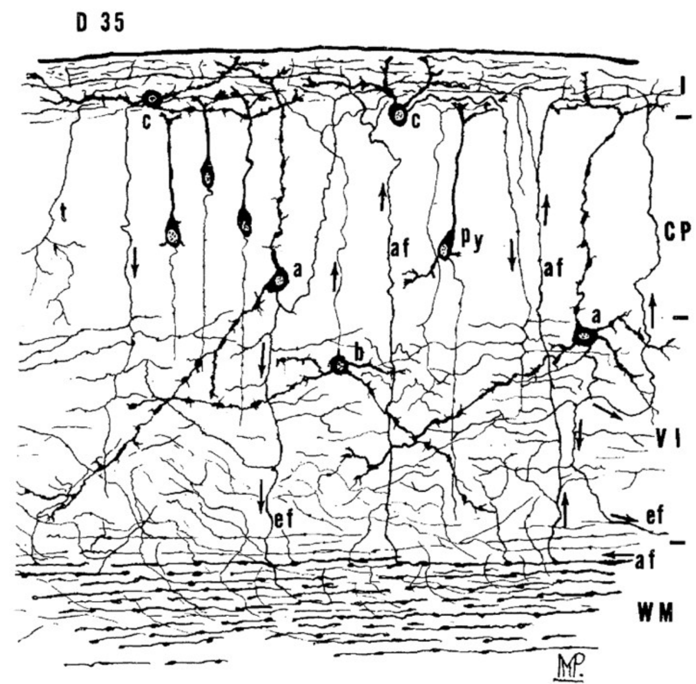
Outline

1. Underlying Brain Processes
2. Spatial Characteristics
3. Temporal Characteristics
4. Complex EEG Phenomena
5. Non-Brain Artifacts
6. Sensing and Acquisition

2.1 Underlying Brain Processes

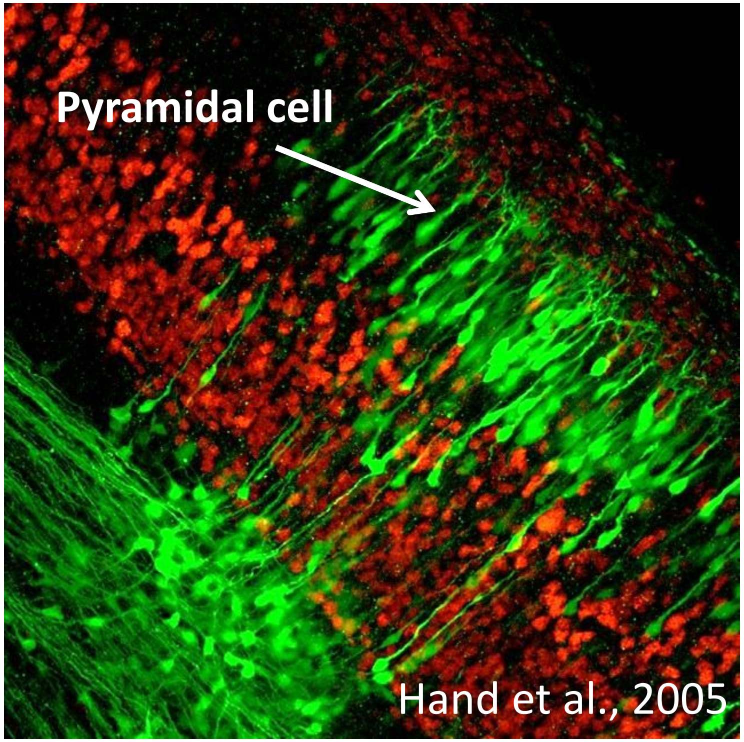
Underlying Neural Processes

- All BCIs have to operate on observable effects of brain activity
- Except for fMRI and fNIRS, they operate on effects of neural firing processes
- EEG, MEG and ECoG can only detect *large-scale* neural dynamics
- For example, 50.000 neurons firing in near-synchrony



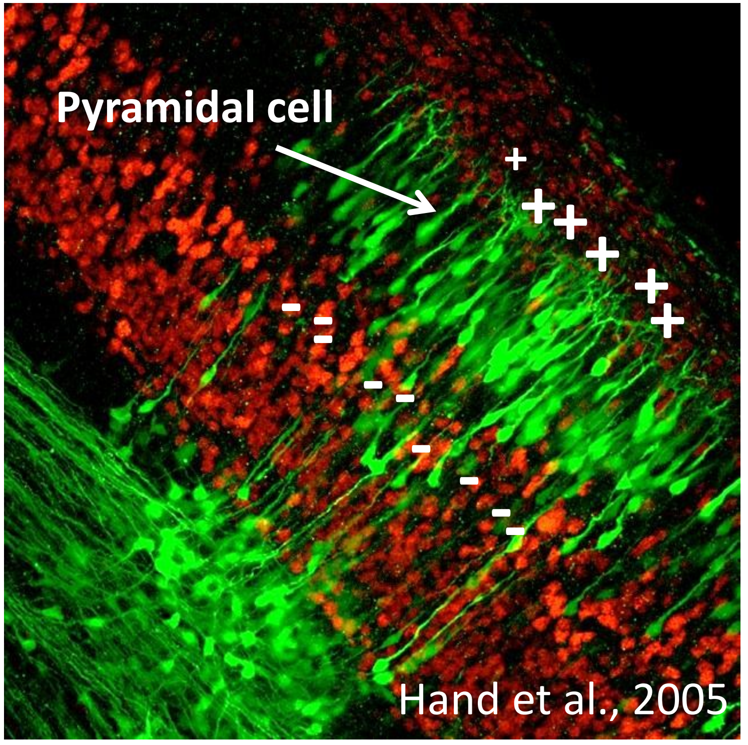
Underlying Neural Processes

- Largest contributors to the EEG are the pyramidal cells
- Radially oriented in the cortex (orthogonal to the surface)



Underlying Neural Processes

- Largest contributors to the EEG are the pyramidal cells
- Radially oriented in the cortex (orthogonal to the surface)
- Electromagnetic fields of co-aligned and co-activated neurons **add up**

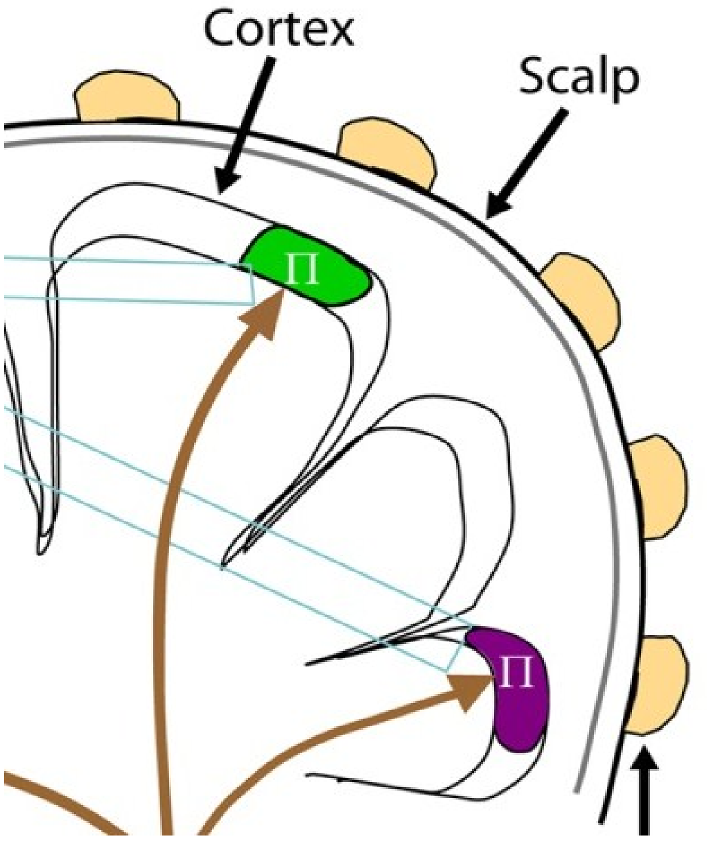


Large-Scale Brain Processes

- When would 50.000 neurons fire near-synchronously?
  - An external event triggers a cascade of related neural processes (e.g., in perception)
  - An internal event triggers a cascade of related neural processes (e.g., sudden “aha!”)
  - Neural populations enter a synchronized steady-state firing pattern (e.g., idle oscillations)
- Event-Related Potentials (ERPs) and Oscillatory Processes are the two major BCI-detectable EEG/MEG phenomena

Signal Detectability

- Root cause might not be directly observable (e.g., dopaminergic system, deep brain structures, few neurons)
- Widely scattered neural populations are unlikely to exhibit synchrony (unless connected by fiber tracts)
- Spatially compact populations are more likely to have coordinated timing
- Electromanetic fields can cancel each other out (e.g., in the Amygdala)



Makeig 2007

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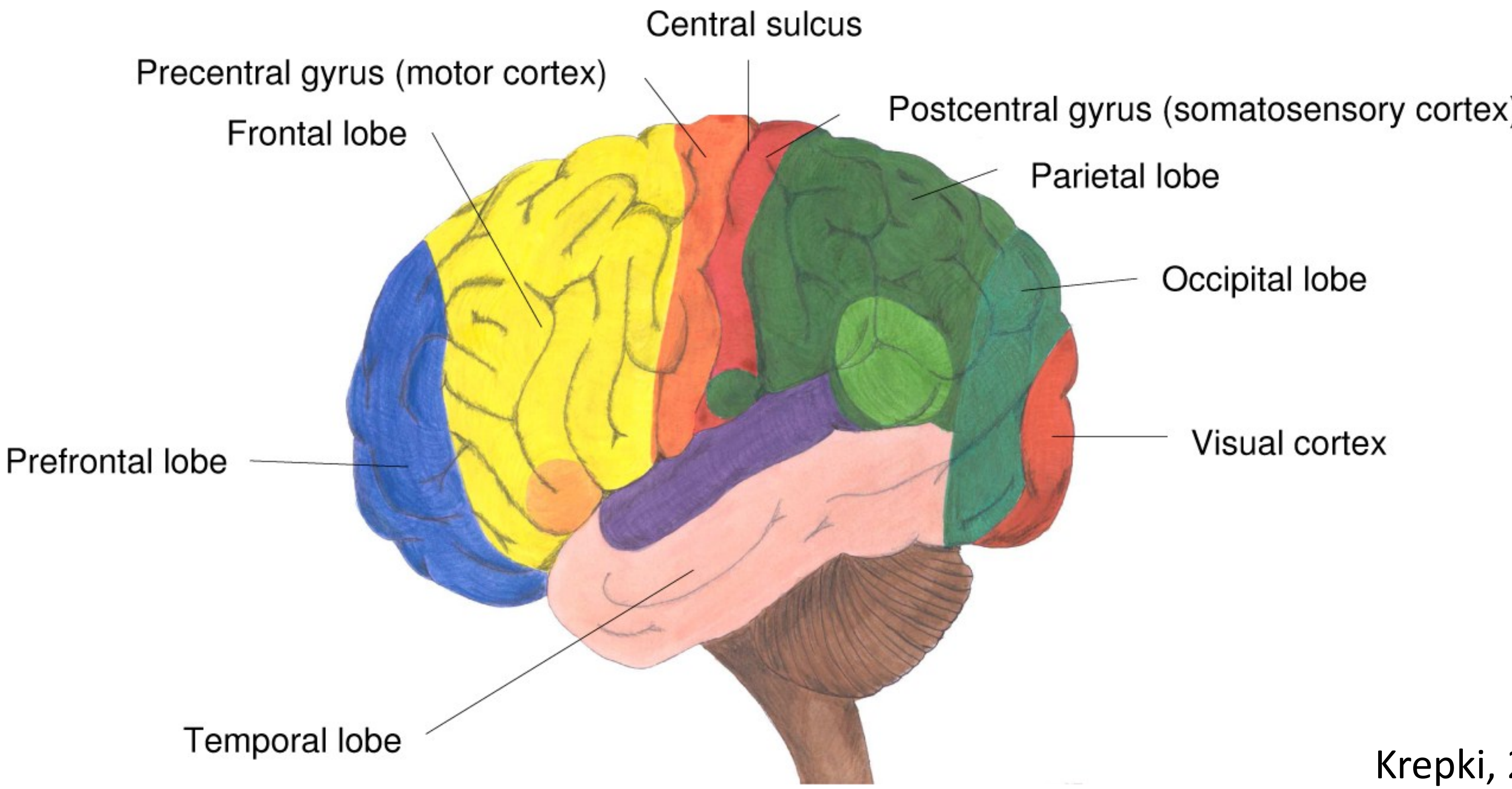
2.2 Spatial Characteristics

Anatomical Regions

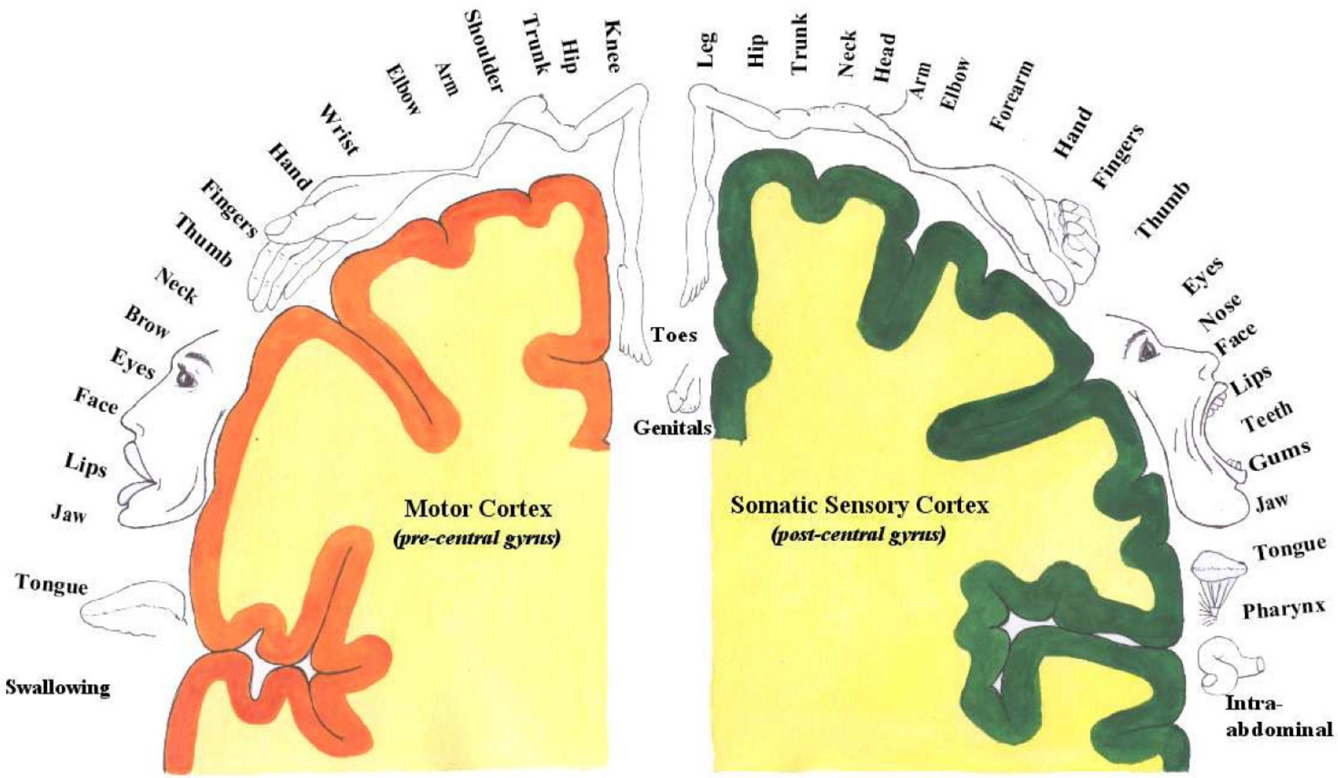
- Some notable large-scale brain features are the hemispheres, lobes, gyri and suci



Krepki, 2004

Functional Mapping

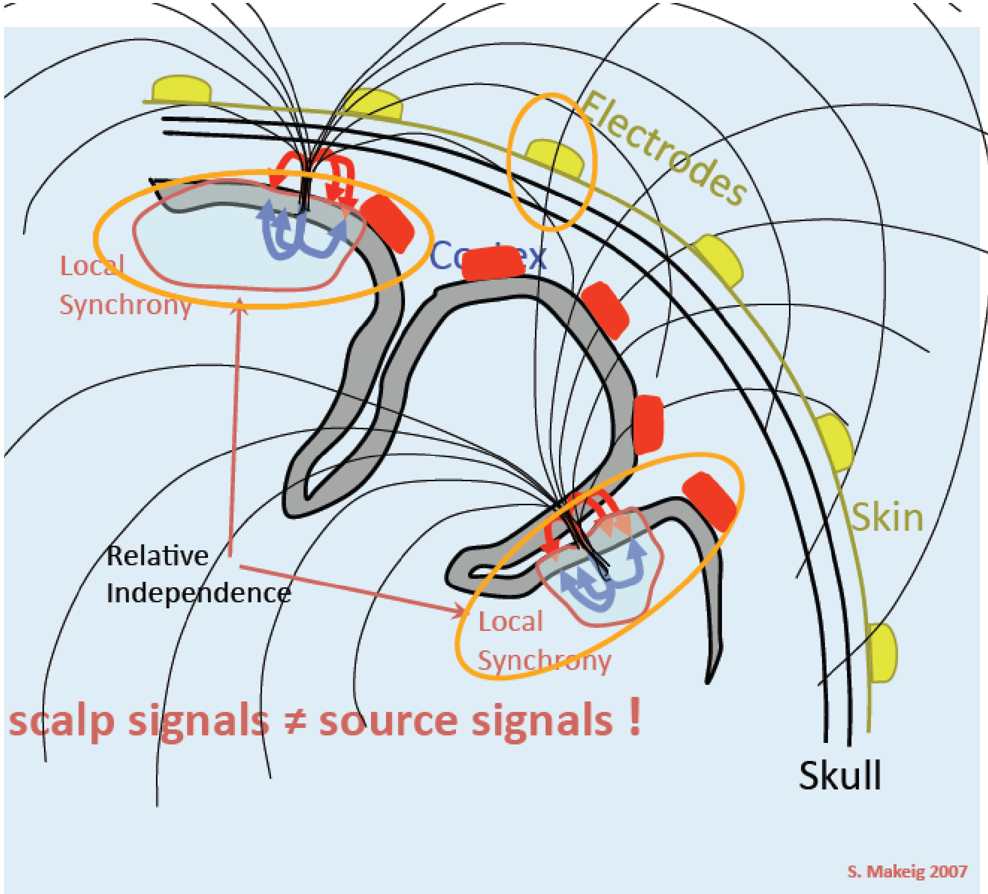
- For most regions more or less well known functional associations exist – the motor cortex is one of the best examples:



Krepki, 2004

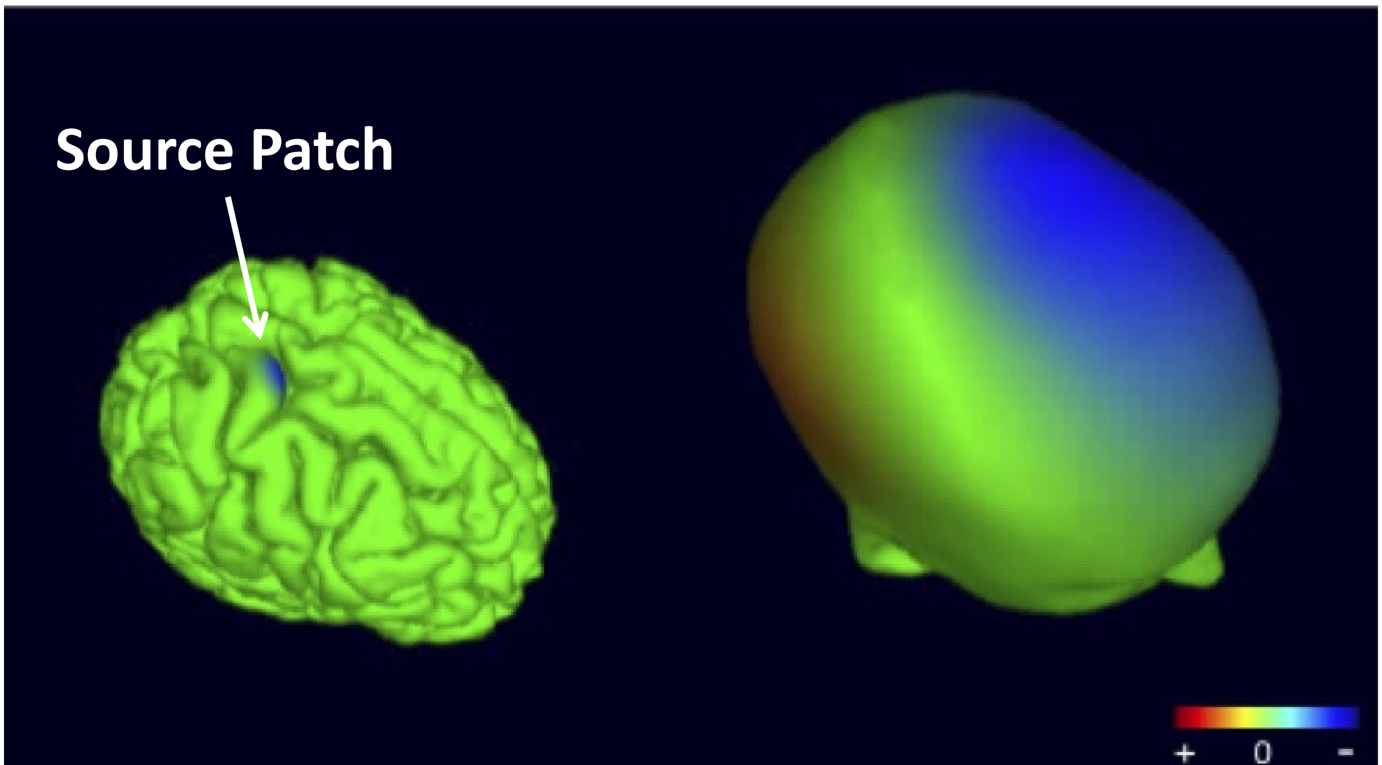
Volume Conduction

- Neural activity is conducted through the brain volume to the scalp and sensors by *Volume Conduction*
- Volume conduction is linear
- Each sensor measures a (weighted) sum of each neuron's activity



Volume Conduction

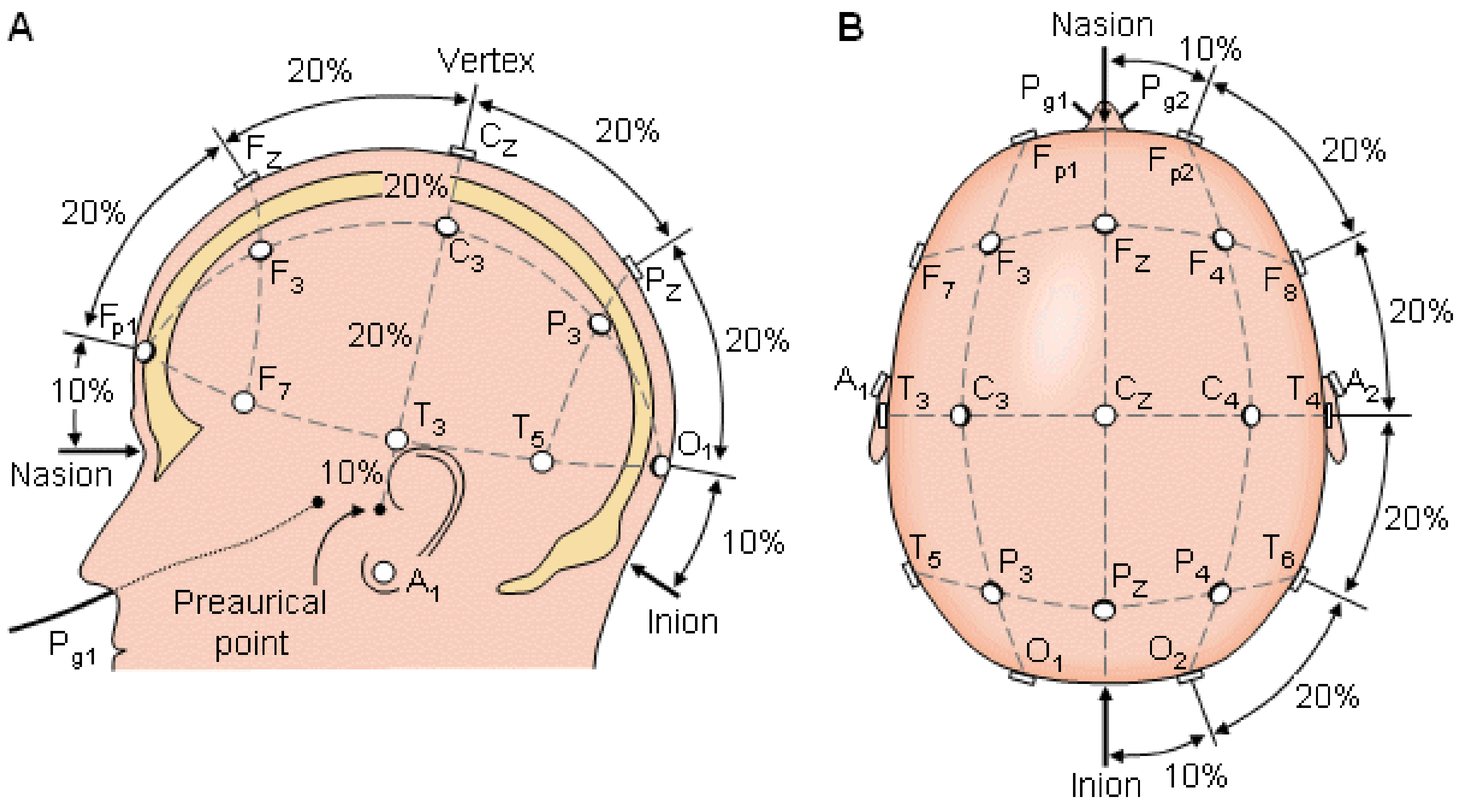
- Note: the point-spread function from a source patch to the scalp is extremely broad



Akalin Acar et al., 2011

Measurement Sites

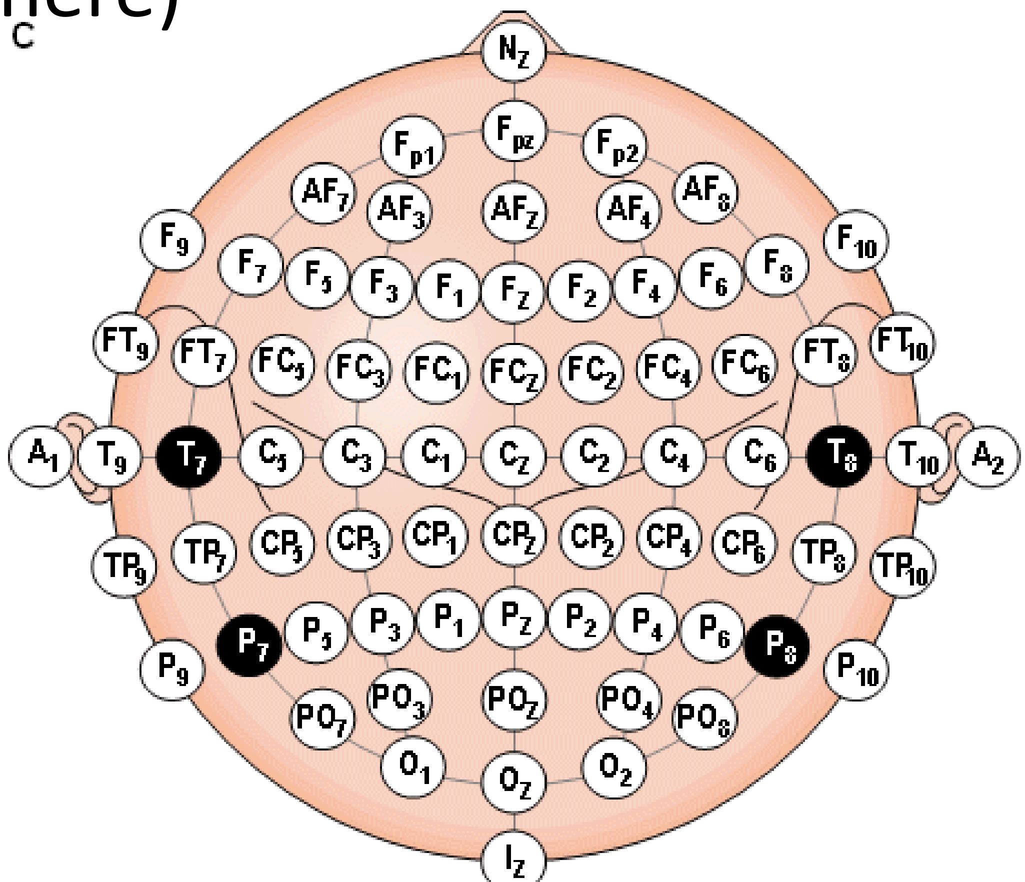
- Standardized location system (10-20 system)
- Saves a lot of hassle vs. custom labels



Malmivuo and Plonsey, 1995

Measurement Sites

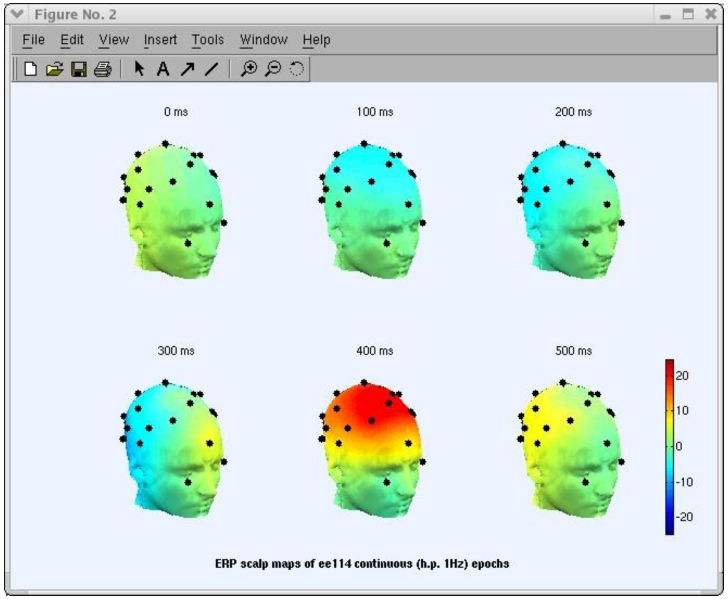
- Defined also at much higher resolutions (not shown here)



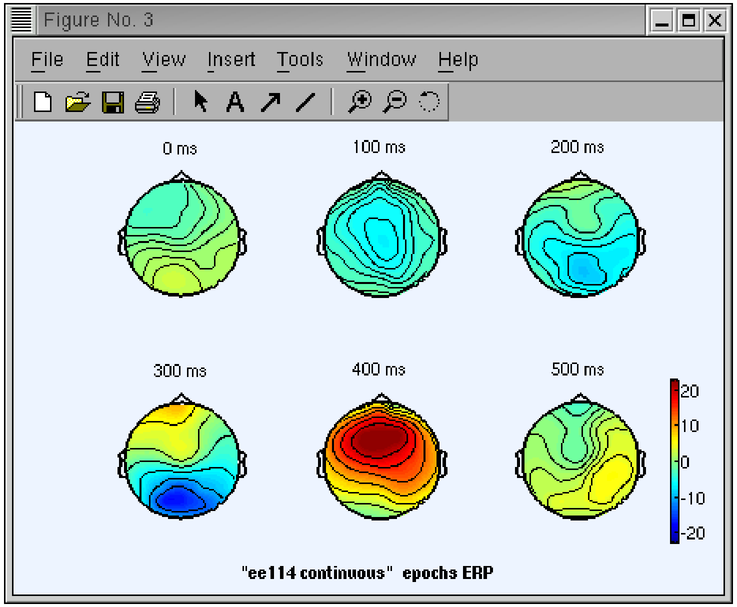
Malmivuo and Plonsey, 1995

Actual Scalp Maps

- Scalp maps (observed voltages at scalp sites) allow for source localization
- Single-source scalp maps are rarely observed in the raw signal, but can be obtained by signal processing (more later)



3d head visualization



Corresponding 2d scalp maps

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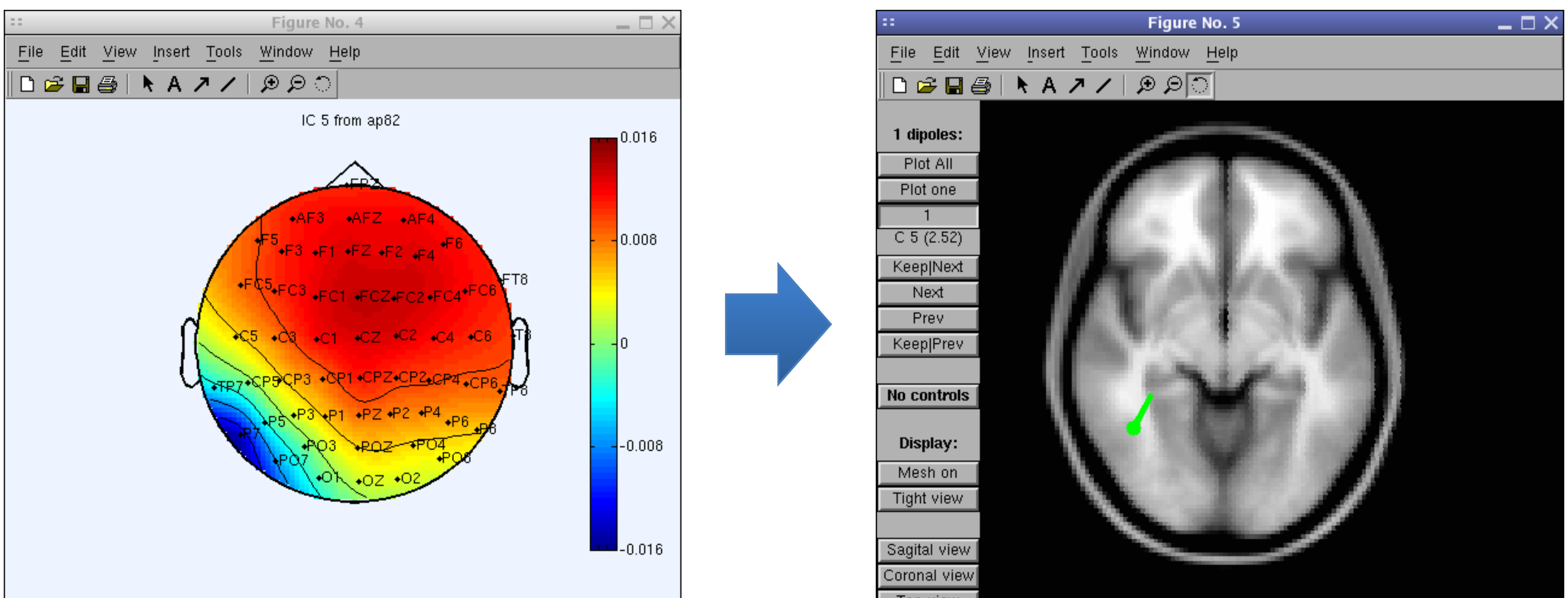
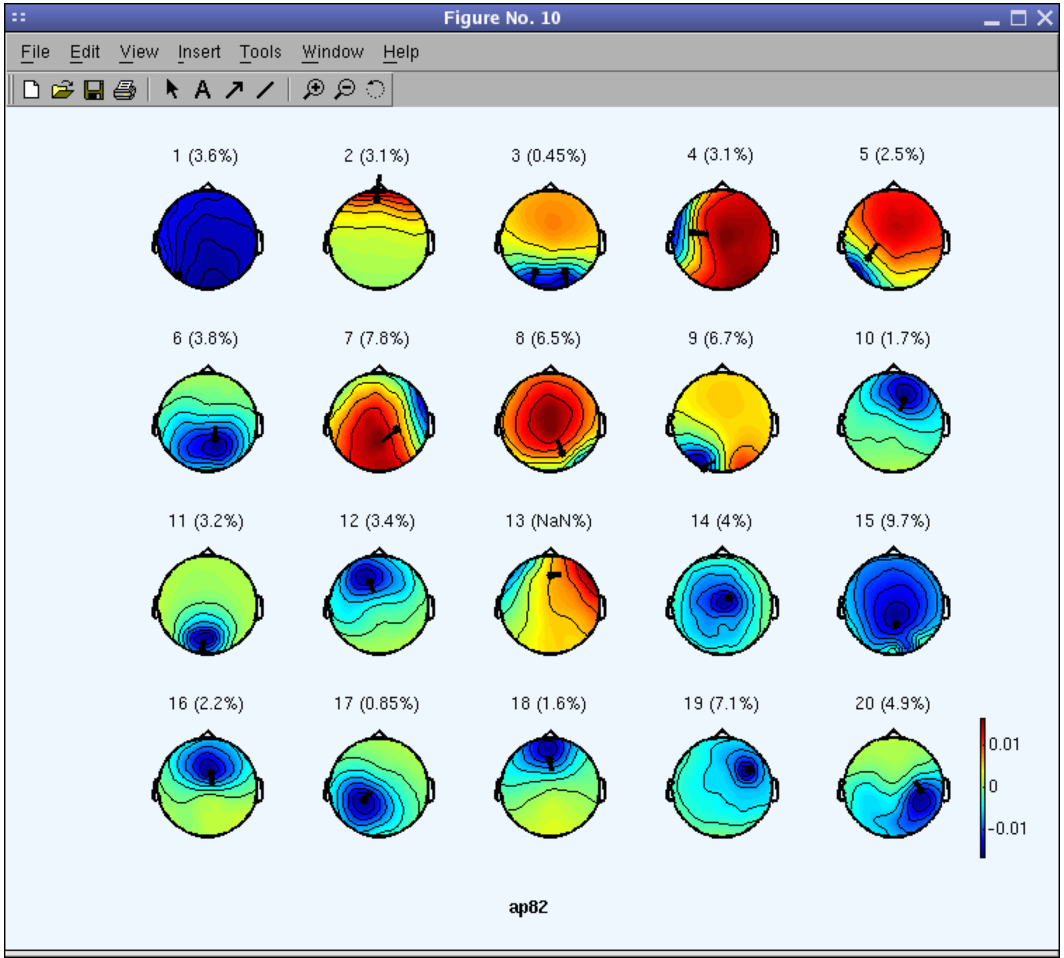
Equivalent Dipole Model

- Electromagnetic field sustained by a *compact collection of neurons* (e.g., 1 cm2) can be modeled as a *single equivalent dipole*
- This facilitates localization of the field source



Equivalent Dipole Tour

- Further scalp maps and associated dipole fits

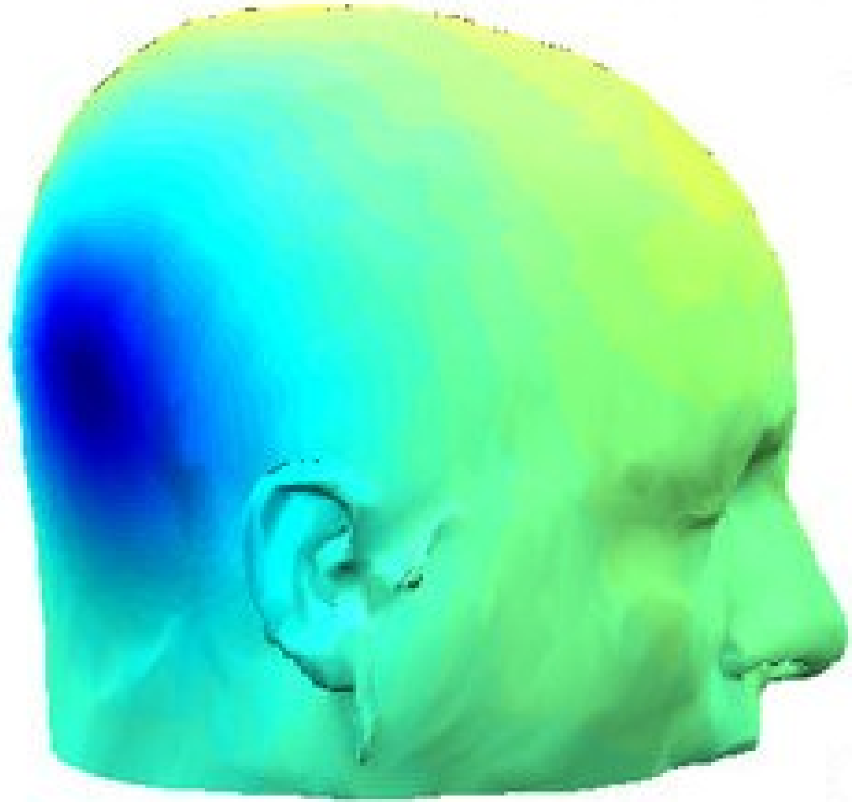


Dipole Modeling Problems

- High-quality fits are hard to achieve
  - Requires knowledge about sensor locations
  - Requires assumptions about conductivities of scalp, skull, cerebrospinal fluid (CSF), brain tissue
  - Requires knowledge of the folding of the cortex (candidate dipoles) unless simplistic spherical model is used
  - Some brain tissue has anisotropic conductance (white matter)
  - Scalp maps are usually not perfect (arise from data processing) – fit accuracy suffers
  - Scalp maps can be a sum of multiple dipole sources – requires a distributed source model

Distributed Source Modeling

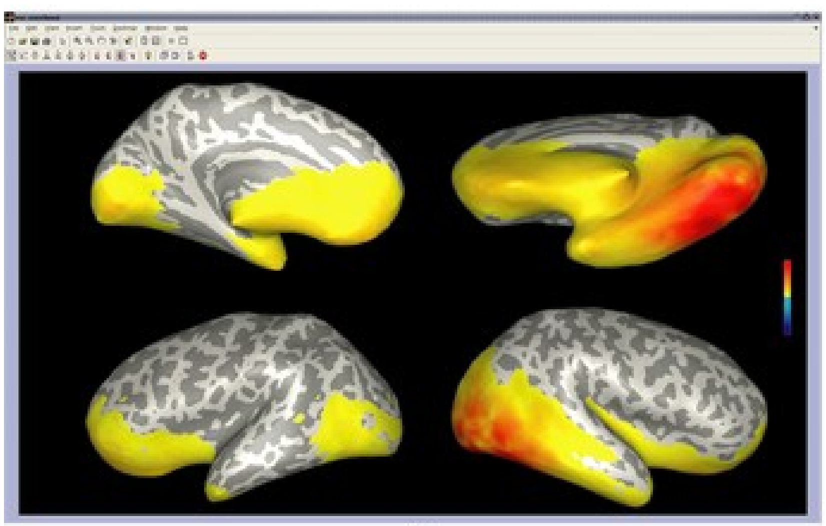
- Allow to recover and image *distributed* cortical support of given scalp maps



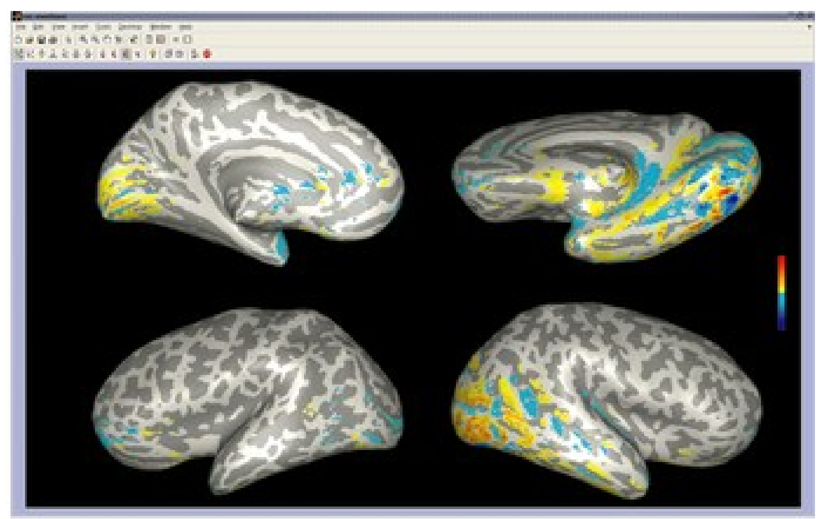
Subsequent images:
Rey Ramirez (Scholarpedia)

Distributed Source Modeling

- Wide range of methodologies and underlying assumptions (sLORETA, Beamforming, Sparse Bayesian Learning, …)
- Prone to finding only locally optimal solutions



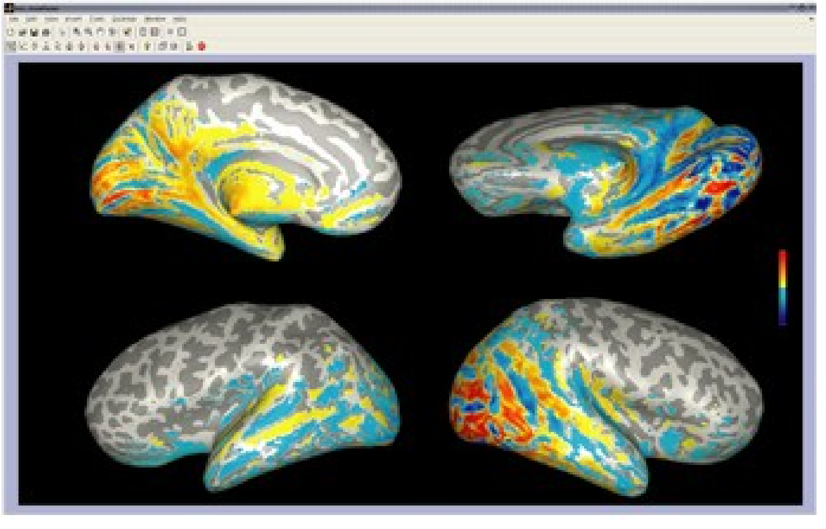
LCMV Beamforming



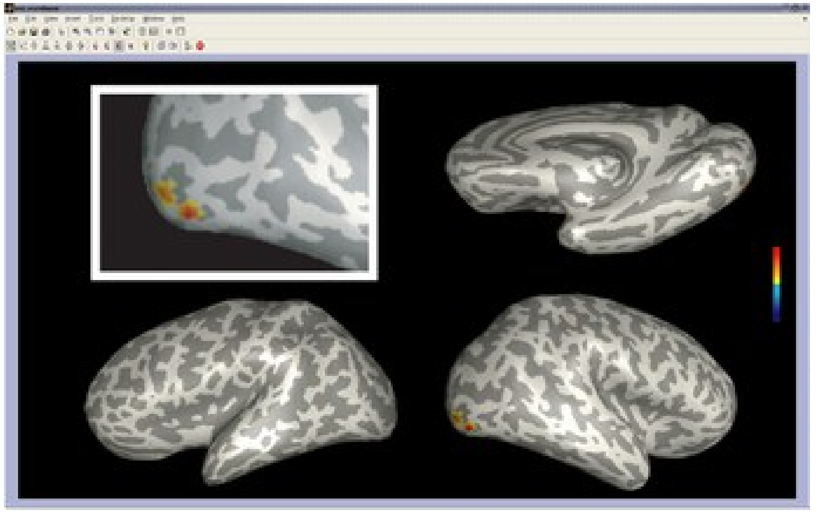
Anatomically Constrained Beamforming

Distributed Source Modeling

- Wide range of methodologies and underlying assumptions (sLORETA, Beamforming, Sparse Bayesian Learning, …)
- Prone to finding only locally optimal solutions



sLORETA



Sparse Bayesian Learning

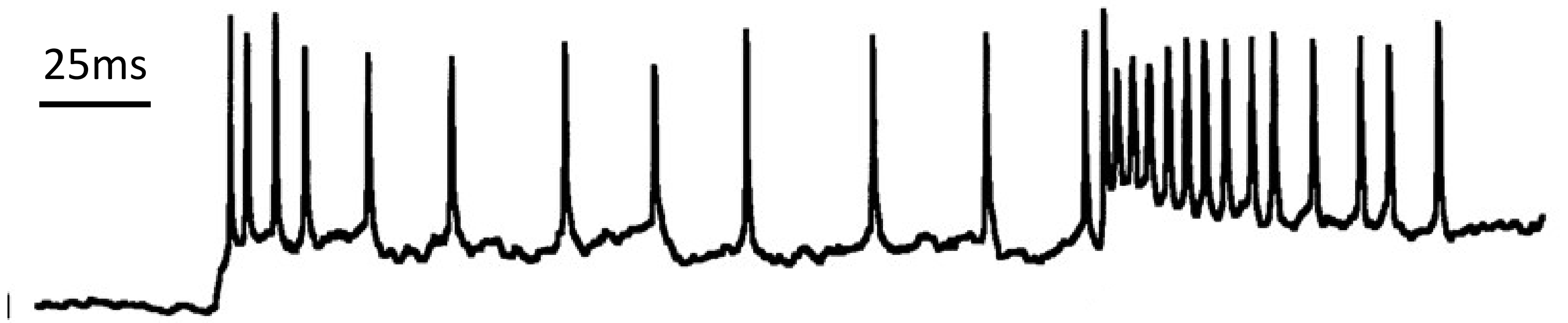
Distributed Source Modeling

(Video)

2.3 Temporal Characteristics

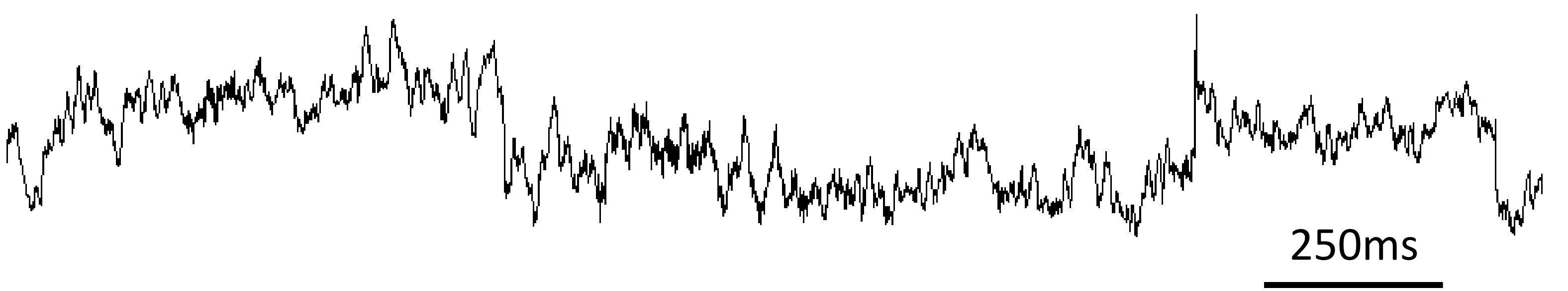
Neural vs. Scalp Activity

- Typical spiking behavior of a single neuron



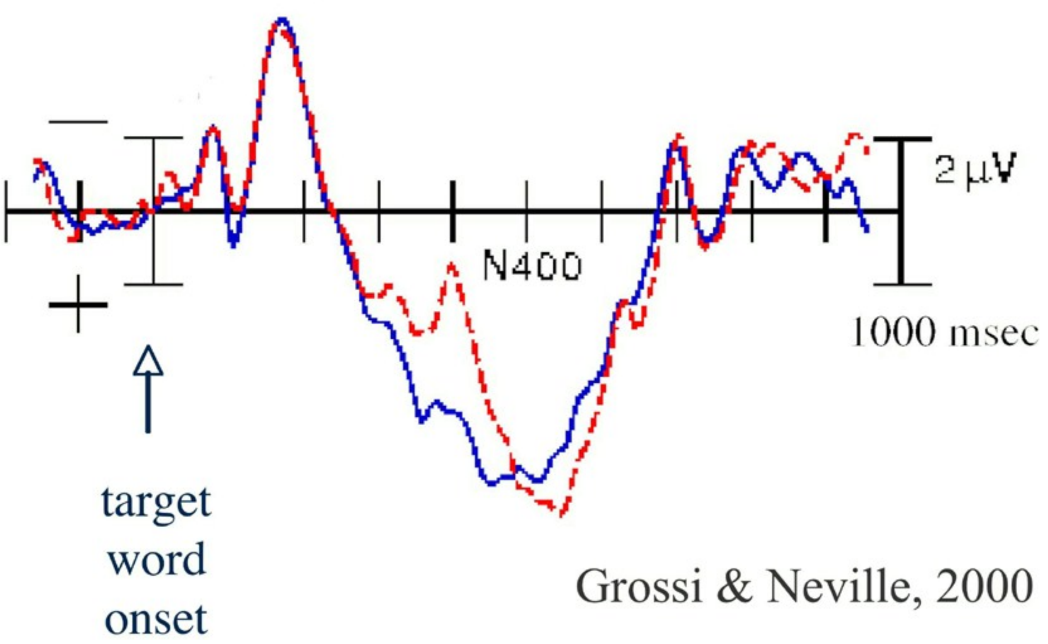
Tsodkys, 1997

- Typical signal measured at a scalp site



Event-Related Potentials (ERPs)

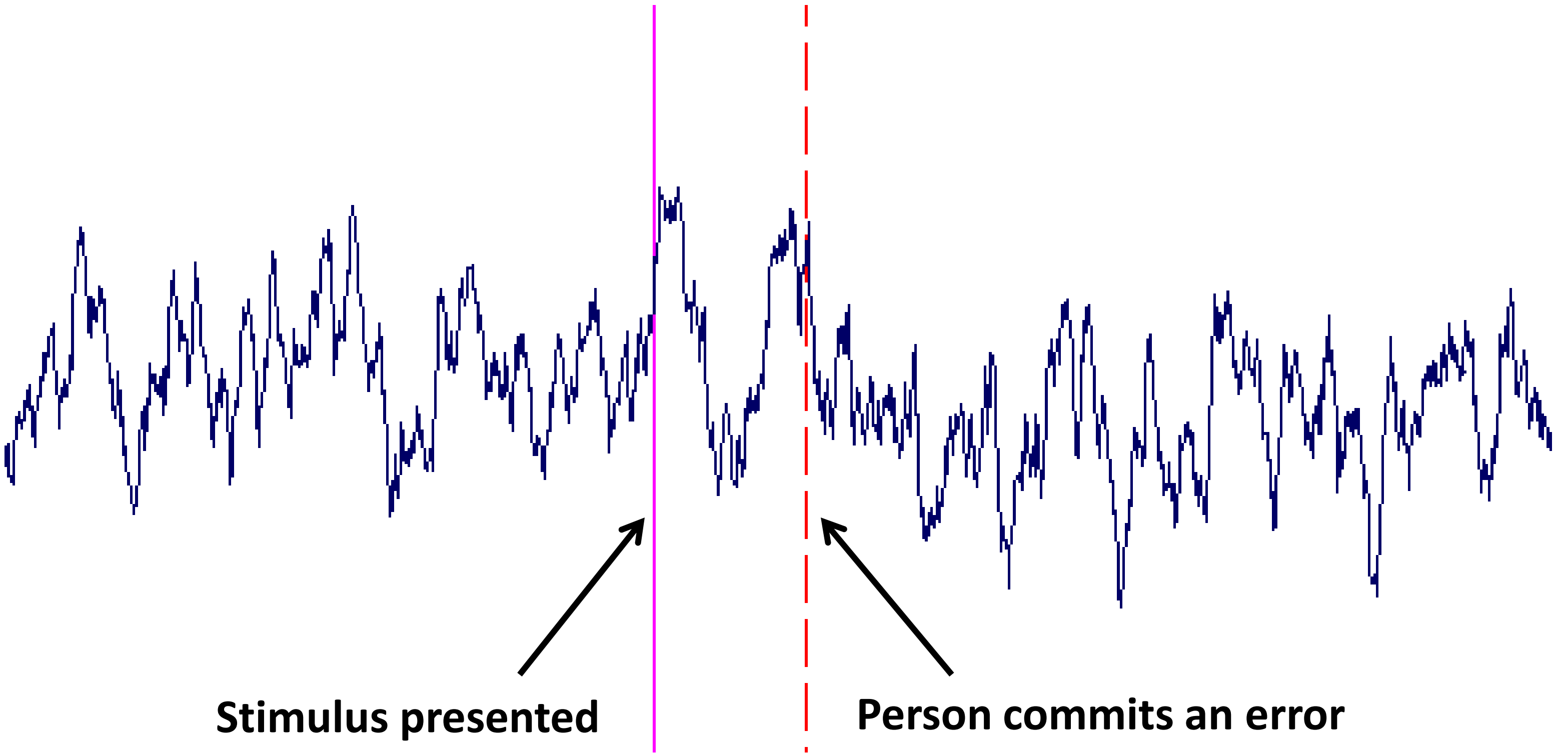
- Averaging EEG activity relative to an event results in primarily event-induced activity (trial-to-trial variability averaged out)



Grossi & Neville, 2000

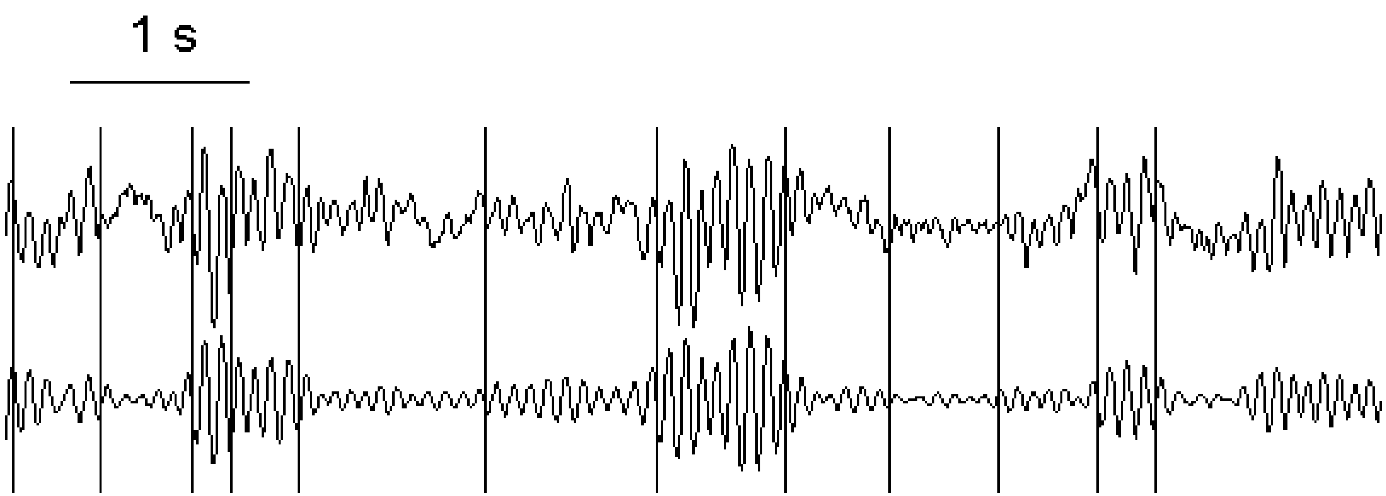
Event-Related Potentials (ERPs)

- Single-trial ERPs are much harder to identify



Oscillatory Processes

- EEG is permeated by oscillatory processes, such as the alpha rhythm (pictured)
- Standard names for such rhythms are *delta* (0-4Hz), *theta* (4-7Hz), *alpha* (8-13Hz), *beta* (12-30Hz), and *gamma* (25-100Hz)



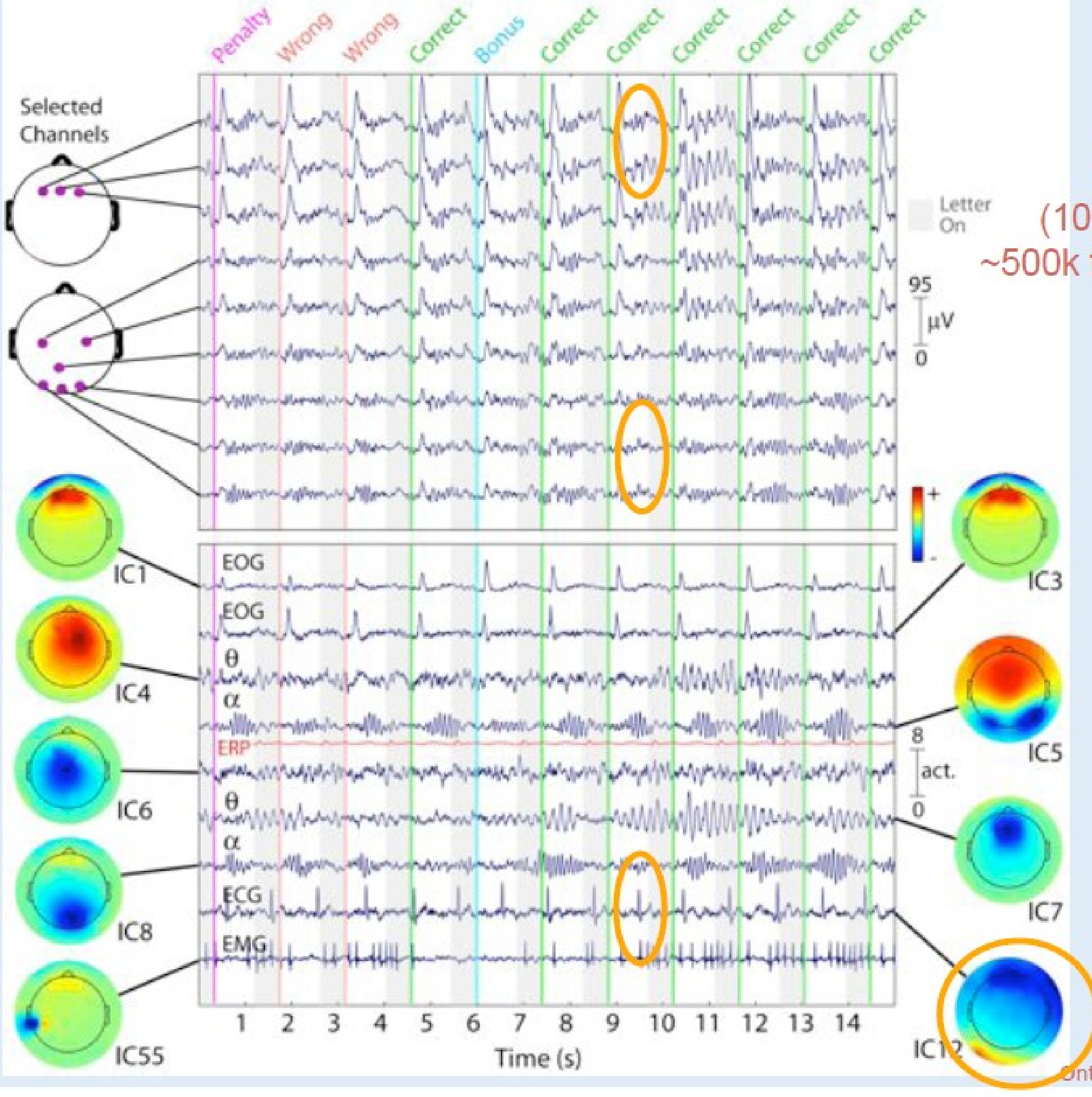
Kaplan et al., 2000

Oscillatory Processes

- **Alpha:** Sensory areas (visual cortex, auditory cortex) and Motor areas (motor cortex) exhibit strong alpha-band oscillations when “idle” in most subjects
- **Beta:** Motor cortex often generates also beta-band oscillations
- **Theta:** Known to occur in “bursts” relative to events in certain brain areas (e.g. frontal midline, lateral frontal, …)

2.4 Complex EEG Phenomena

EEG Sources Separated via ICA



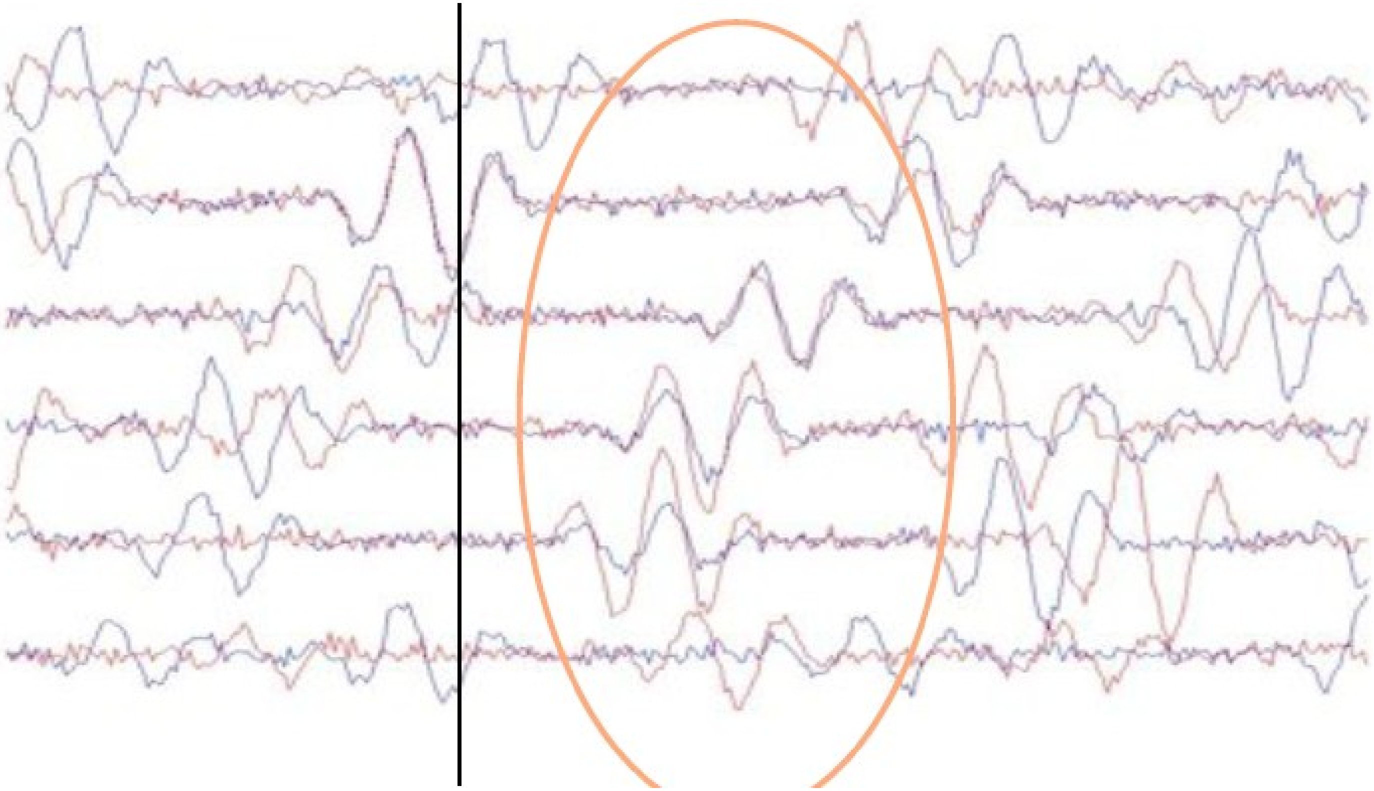
ICA in practice

(100 channels, ~500k time points)

Onton & Makeig, 2006

Higher-Order Phenomena

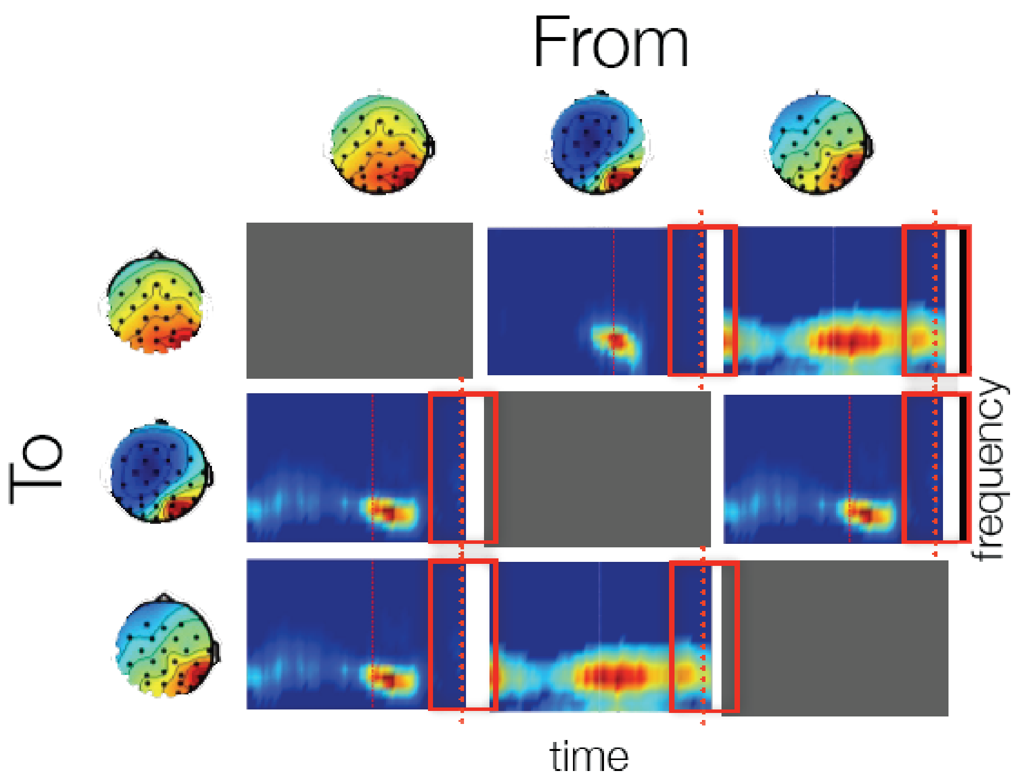
- *Event-Related Coherence* between two signal components (here simulated data)

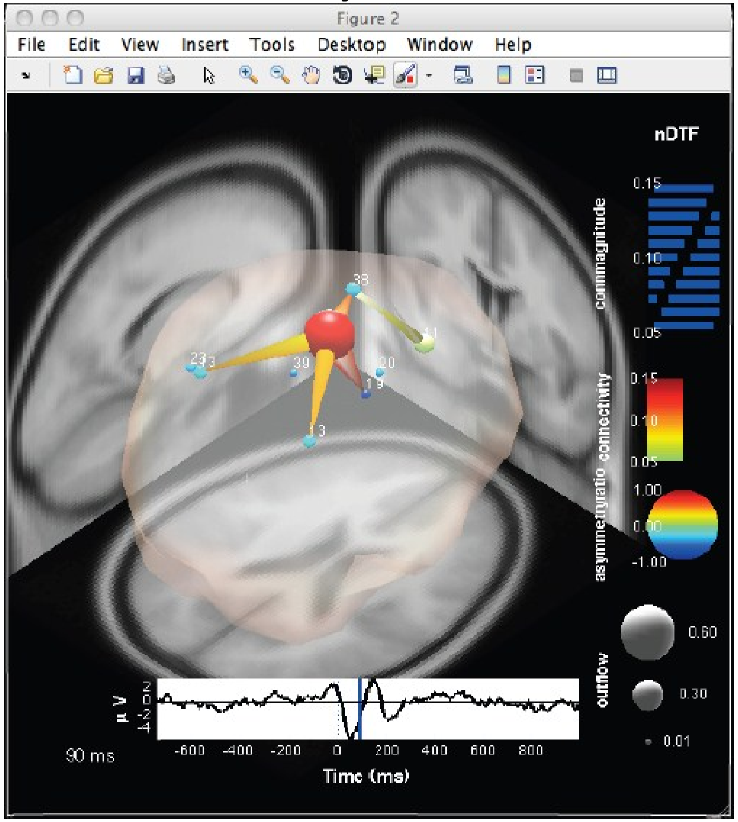


Makeig 2007

Effective Connectivity

- Sophisticated measure of interaction between multiple signals (“information flow”)





Mullen et al., 2011

Effective Connectivity

(Video)

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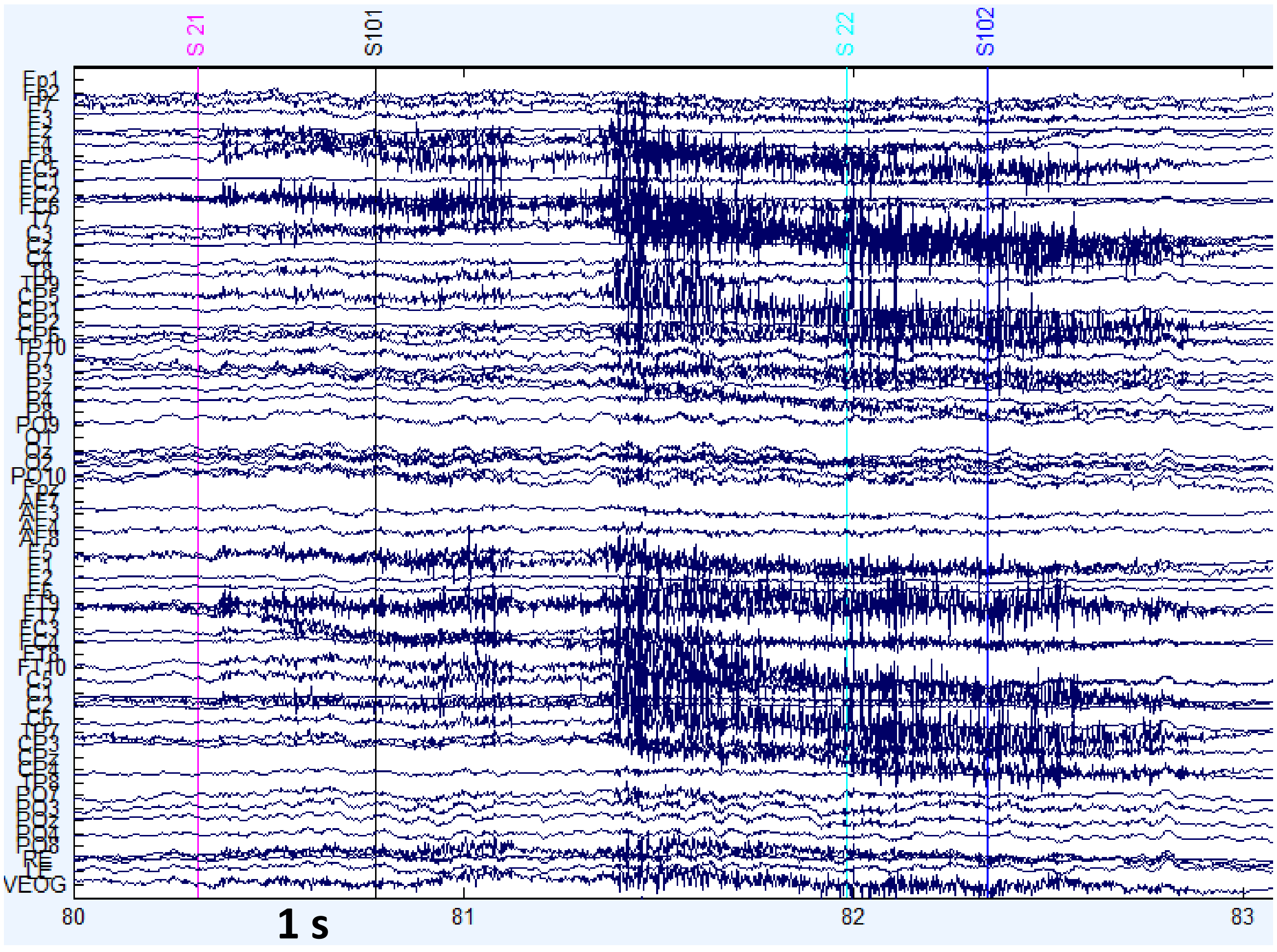
2.5 Non-Brain Artifacts

Non-Brain Artifacts

- Often far outscale the brain processes in the EEG (when present)
- **Internally generated:** neck, face and eye muscles, eye dipoles, heart activity
- **Externally generated:** 50/60Hz line noise, EM spikes from equipment
- **Sensor-related:** DC offset drifts, cable sway, thermal noise, quantization noise

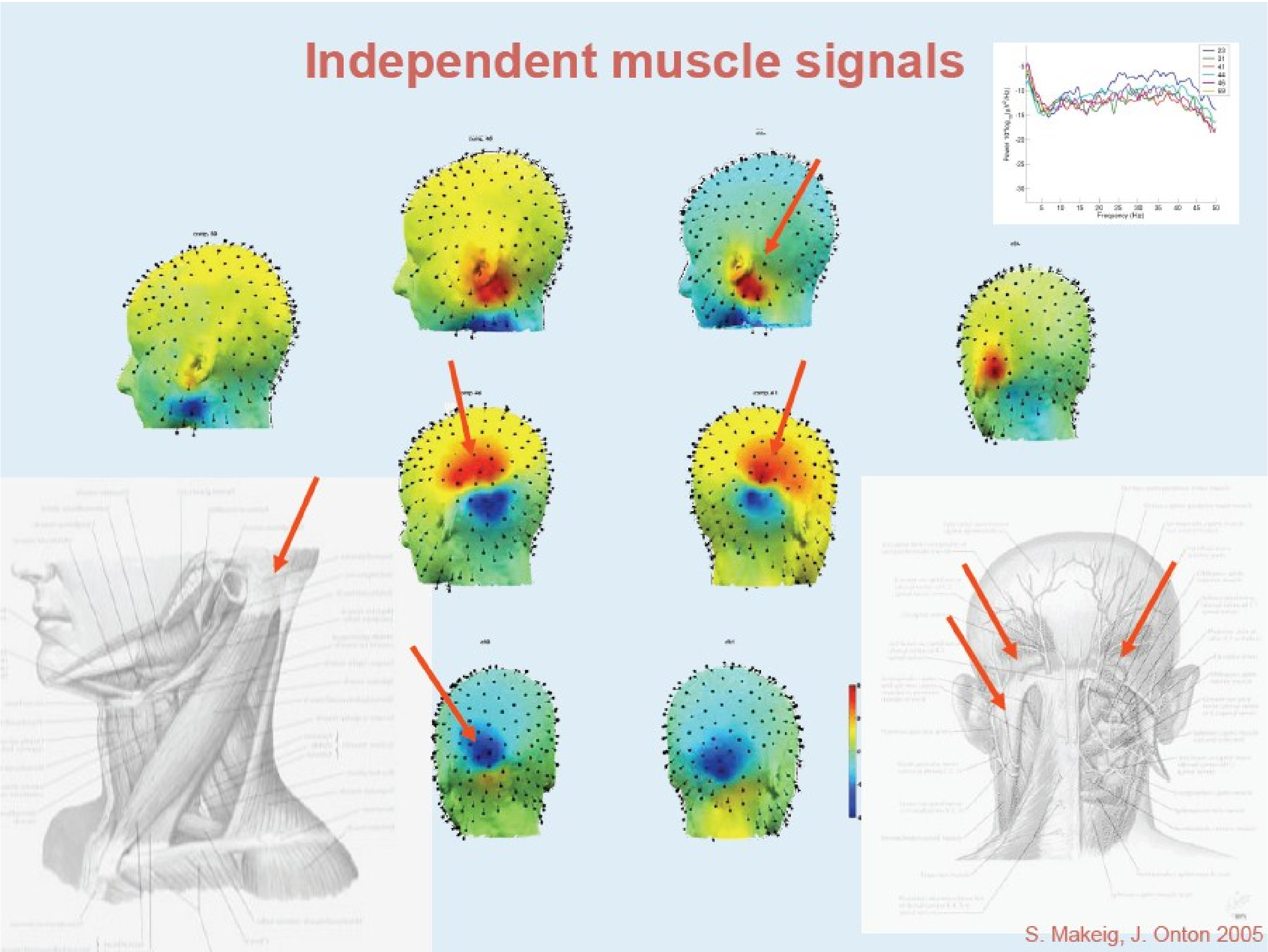
Muscle Artifacts

- High-frequency / broadband, large amplitude



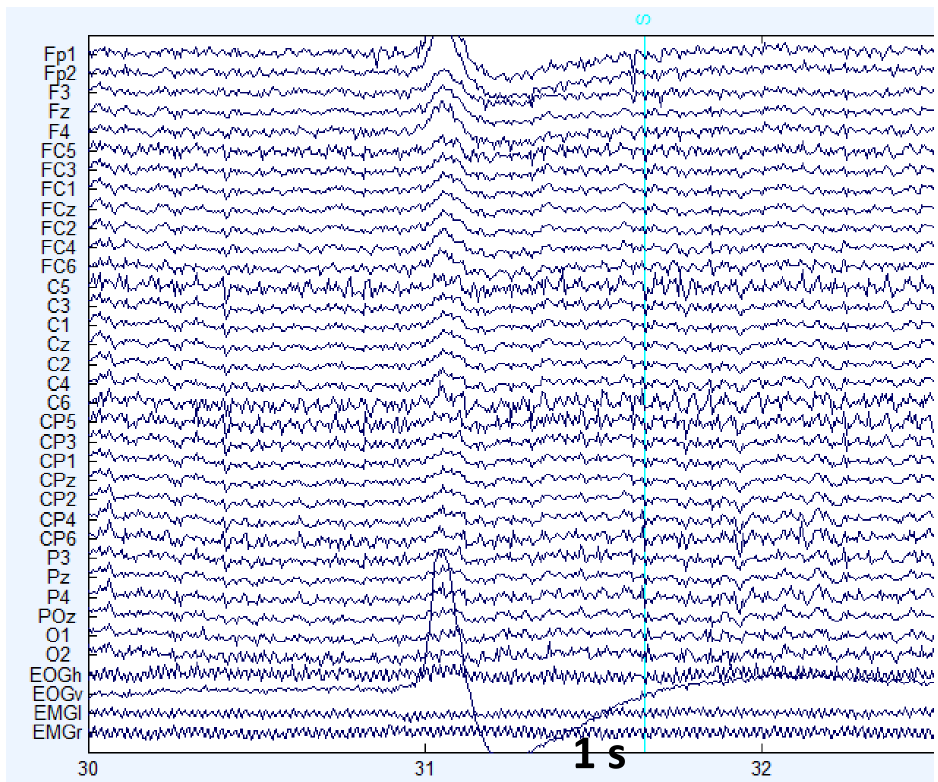
Muscle Artifacts

- Scalp projections are spatially stereotyped



Eye Blinks

- Large low-frequency peak and rebound, mainly frontal
- Can also incurs non-linear effects in occipital cortex



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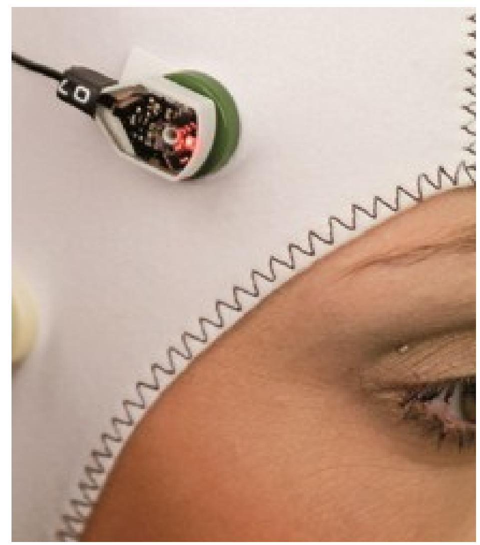
2.6 Sensing and Acquisition

EEG Sensor Designs

- Most EEG systems are gel-based
- Nowadays mostly using active electrodes

Passive, gel-based
(EasyCap)



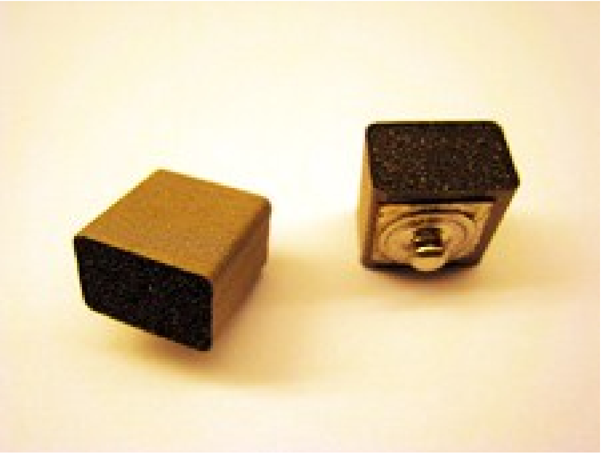
Active, gel-based
(Brain Products)

EEG Sensor Designs

- Dry (gel-free) systems are emerging quickly

Pins
(g.SAHARA)

Spring-loaded Pins
(NCTU)

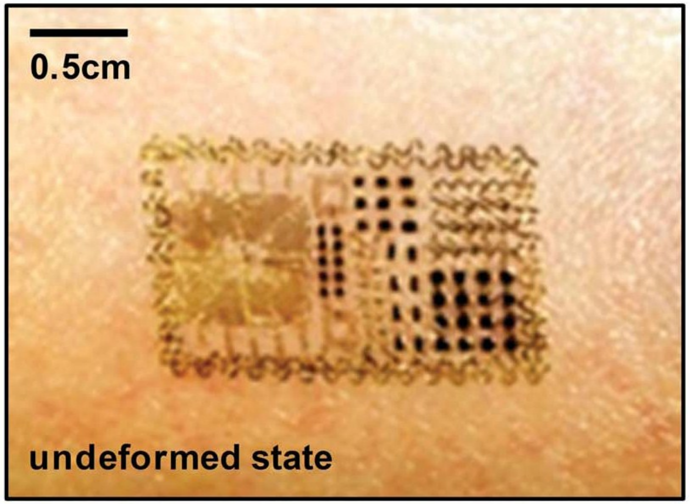


Foam-based sensors
(NCTU)

EEG Sensor Designs

- Recent Prototypes

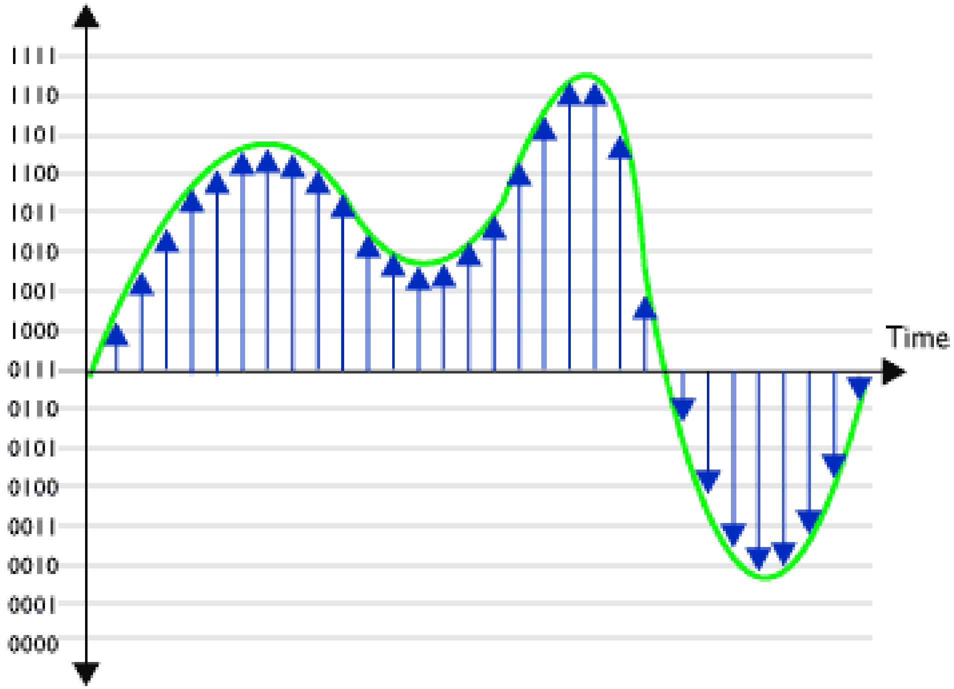
Bristle Sensors
(Grozea et al., 2011)



Epidermal Electronics
(Kim et al., 2011)

Digitization

- After amplification (e.g., 50000x), signal is low-pass filtered using an analog filter, then digitally sampled at fixed rate



Ottewill

Sampling Theorem

- If the signal is band-limited below the Nyquist frequency B (i.e., contains no higher frequency than B), it can be exactly reconstructed using the interpolation function:

$$g(t) = \frac{\sin 2\pi Bt}{2\pi Bt} \quad s(t) = \sum_{n=-\infty}^{\infty} s\left(\frac{n}{F_s}\right) g\left(\frac{t-n}{F_s}\right)$$

- The Nyquist Frequency is ½ sampling rate

Computer-based Access

- The data is made accessible through:
  - Vendor-specific recording programs (BrainVision Recorder, ActiView, g.Recorder, …)
  - Vendor-specific system drivers (Emotiv SDK, BioSemi driver, …)
  - Generic system interfaces (e.g., Bluetooth serial port, A/D cards, TCP, …)
- Almost all EEG systems support real-time signal access (except for some gadgets)

L2 Questions?