Introduction to Electroencephalogram

Tzyy-Ping Jung

Center for Advanced Neurological Engineering and
Swartz Center for Computational Neuroscience and
University of California San Diego, USA
and
Department of Computer Science
National Chiao-Tung University, Hsinchu, Taiwan

Outline

- History of EEG
- Why measure EEG
- Basic Physics of EEG
- EEG data collection
- Challenges in EEG analysis
- Analysis of EEG
  - Response averaging
  - Time-frequency analysis

History of EEG

- In 1875, Richard Caton observed the EEG from the exposed brains of rabbits and monkeys.
- In 1912, Russian physiologist, Vladimir Vladimirovich Pravdich-Neminsky published the first animal EEG and the evoked potential of the mammalian (dog).
- In 1914, Napoleon Cybulski and Jelenska-Macieszyna photographed EEG-recordings of experimentally induced seizures.
- In 1924, Hans Berger used his ordinary radio equipment to amplify the brain's electrical activity measured on the scalp.
- In 1934, Adrian and Matthews verified concept of "human brain waves" and identified regular oscillations around 10 to 12 Hz which they termed "alpha rhythm".

Why Measure the EEG ?

The greatest advantage of EEG is its **temporal resolution**. EEG can determine the relative strengths and positions of electrical activity in different brain regions.

According to R. Bickford (1987) research and clinical applications of the EEG in humans and animals are used to:

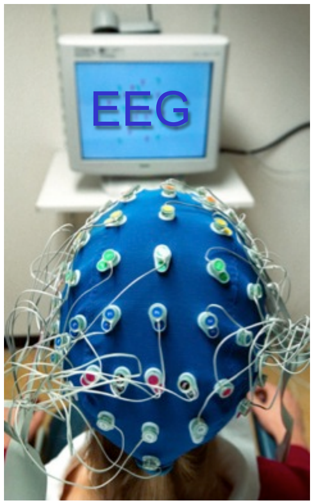
(1) monitor alertness, coma and brain death;
(2) locate areas of damage following head injury, stroke, tumor, etc.;
(3) test afferent pathways (by evoked potentials);
(4) monitor cognitive engagement (alpha rhythm);
(5) produce biofeedback situations, alpha, etc.;
(6) control anesthesia depth (“servo anesthesia”);
(7) investigate epilepsy and locate seizure origin;
(8) test epilepsy drug effects;
(9) assist in experimental cortical excision of epileptic focus;
(10) monitor human and animal brain development;
(11) test drugs for convulsive effects;
(12) investigate sleep disorder and physiology.

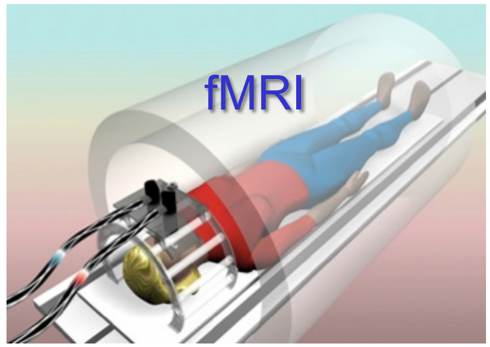
R.D. Bickford. Electroencephalography. In: Adelman G. ed. *Encyclopedia of Neuroscience*, 371-3, 1987.
M. Teplan, Fundamental of EEG Measurement, In: *Measurement Science Review*, 2, 2002.

BIOE 280A

Current Neuroimaging Modalities

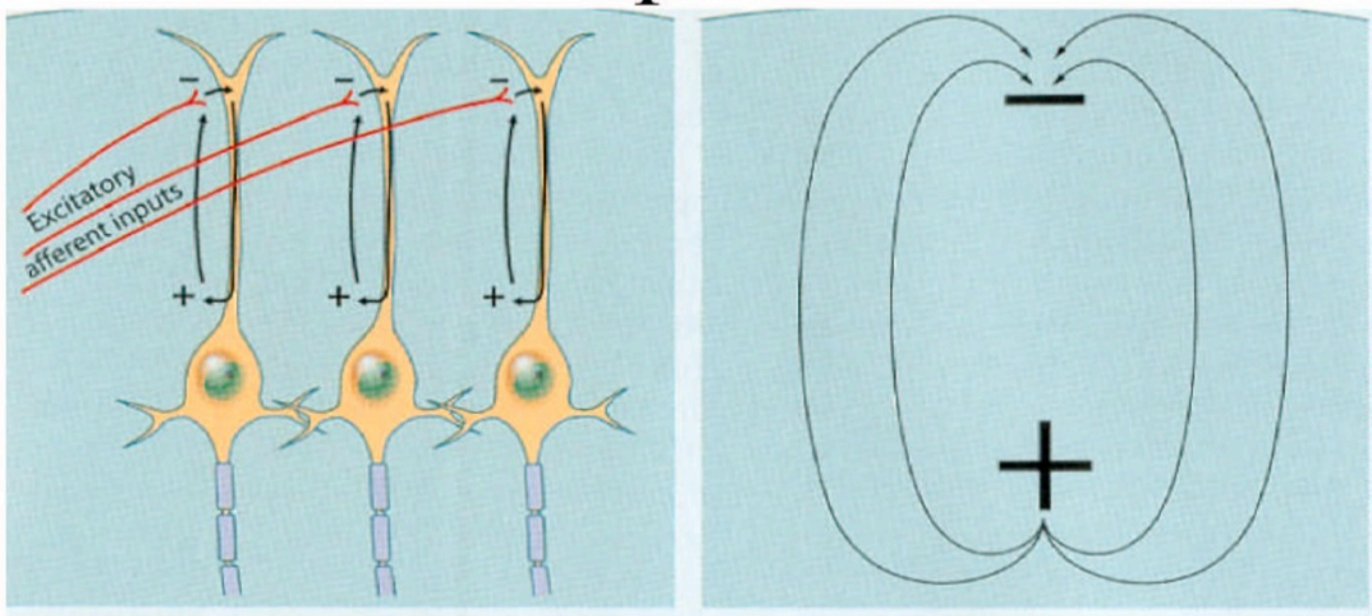
UCSD





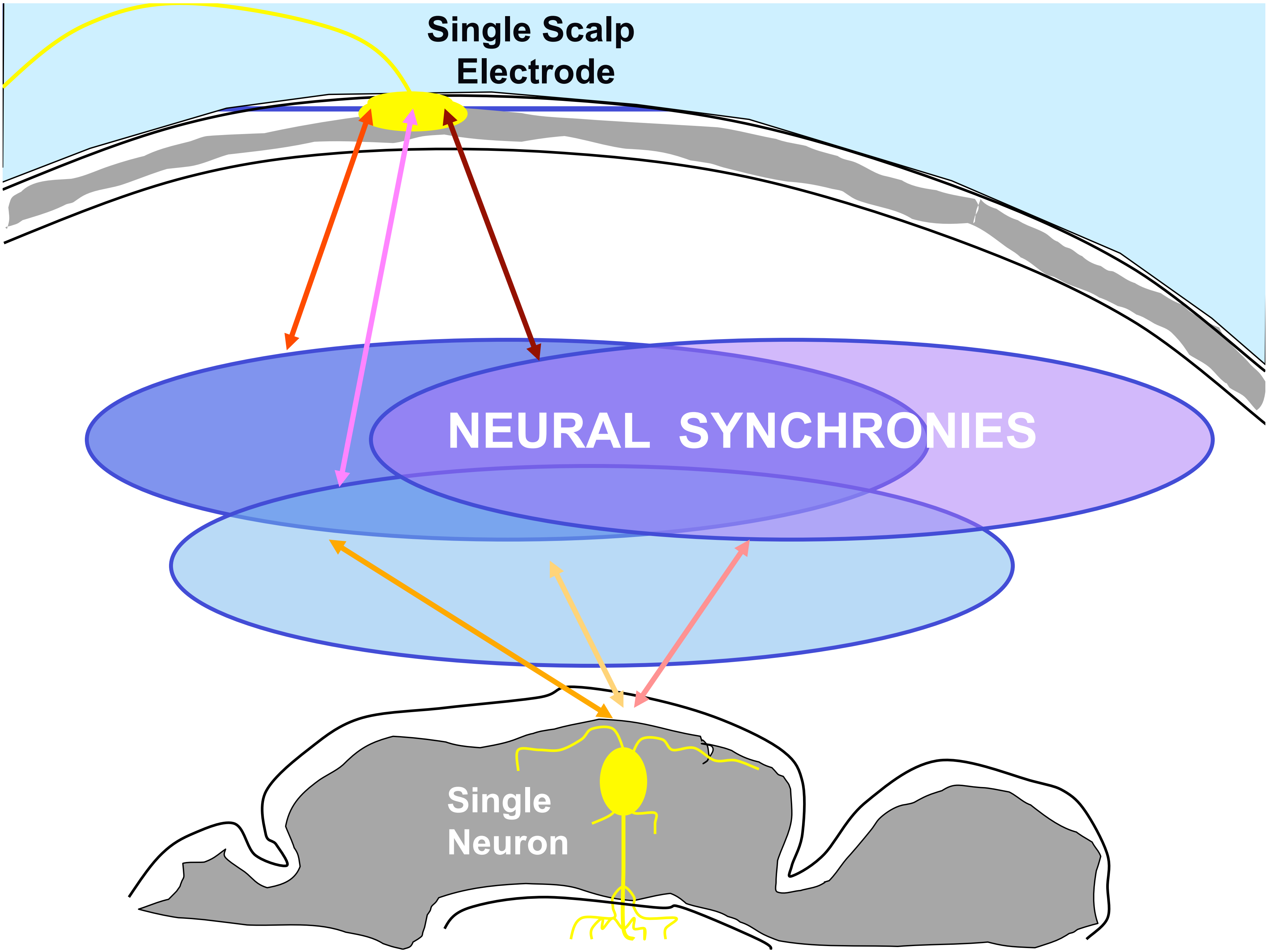
- In all modalities but EEG, the sensors are heavy.
- EEG is the only modality that does not require the head/body to be fixed.
- EEG might enable the monitoring of the brain functions of unconstrained participants performing normal tasks in the workplace and home.

Dipoles



- When neurons are activated, local currents are produced.
- EEG measures the current that flow during the excitations of the dendrites of many pyramidal neurons in the cerebral cortex.
- Potential differences are caused by summed postsynaptic potentials from pyramidal cells that create diploes between soma and apical dendrites.
- Necessary conditions: Aligned neurons and synchronous activity.

Figure is from Gazzaniga et al., *Cognitive Neuroscience: The biology of the mind Norton and Company,* 2009.


Single Scalp
Electrode
NEURAL SYNCHRONIES
Single
Neuron

EEG Acquisition

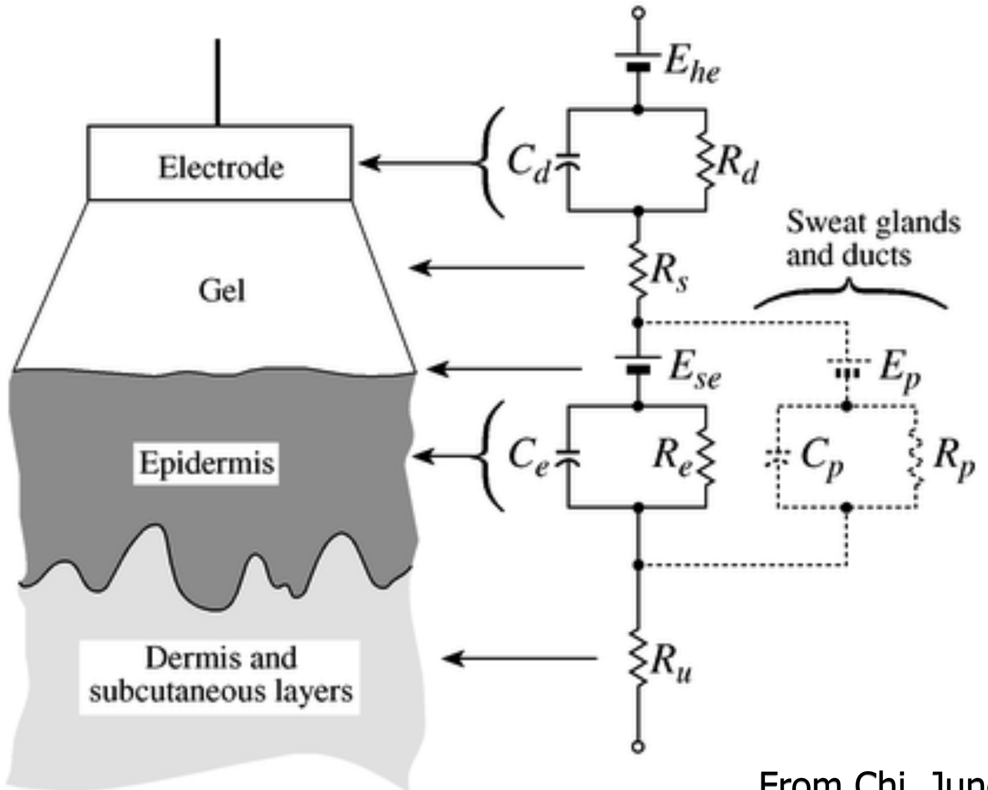
- Electrode caps, conductive jelly, ruler, injection and aid for disinfection.
- EEG amplifier unit, PC/laptop

EEG Electrodes

In common applications, EEG signals are measure by an electrode with electrolyte gel placed directly on the skin.

The coupling between skin and electrode can be described as a layered conductive and capacitive structure, with series combinations of parallel RC elements.

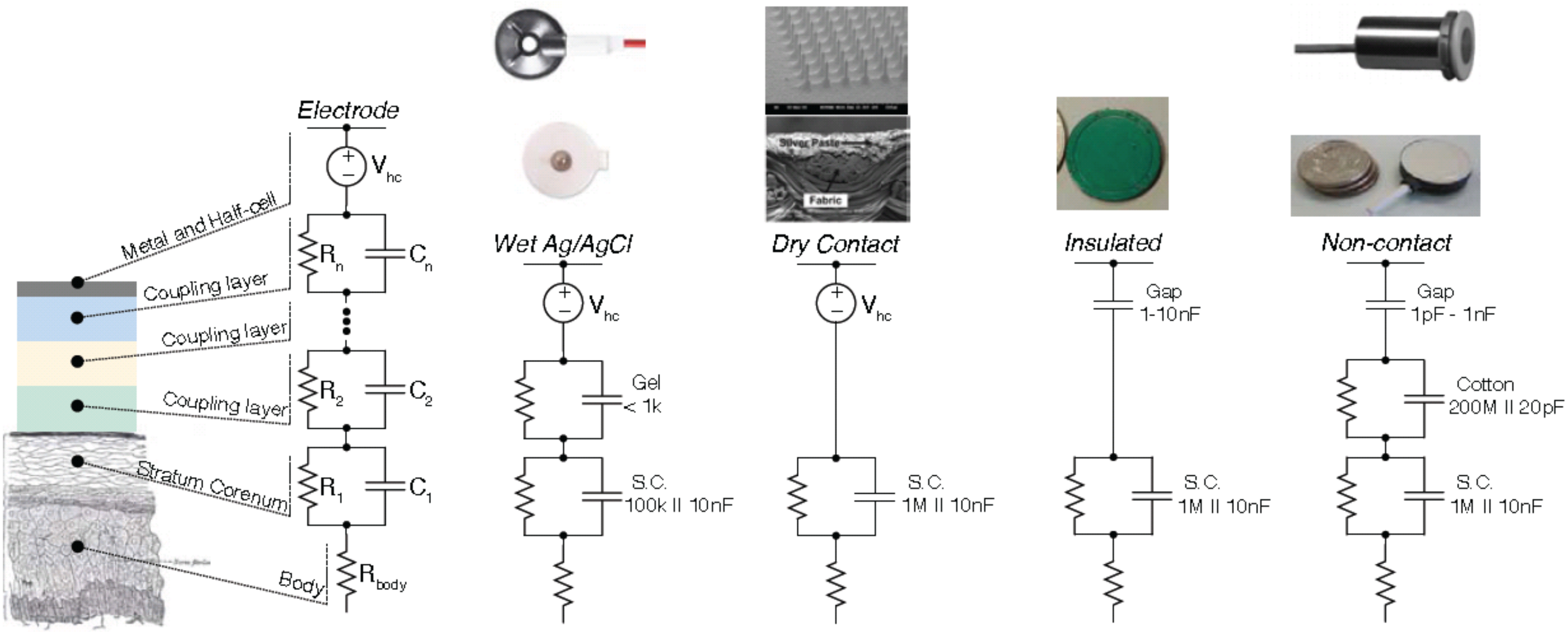
Equivalent circuit



From Chi, Jung & Cauwenberghs, 2010.

EEG Electrodes

Comparison of electrical coupling of the skin-electrode interface between electrodes

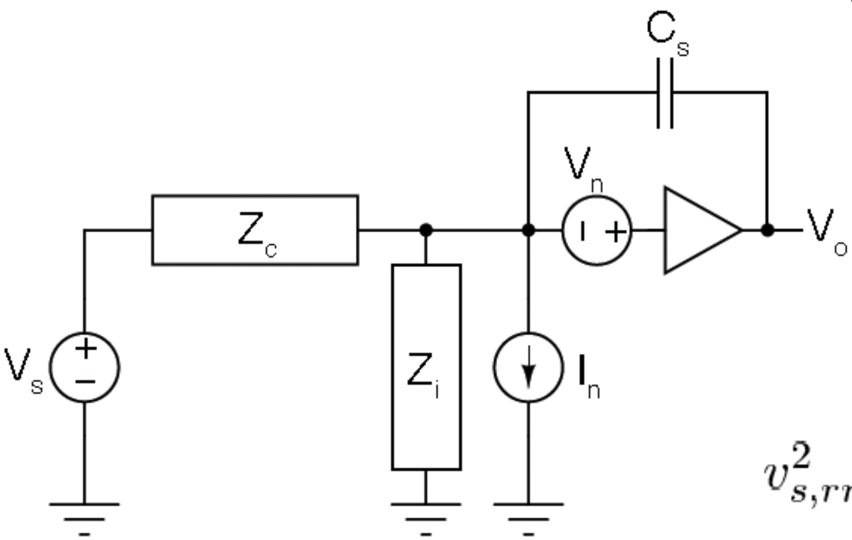


Typically, one of the RC sections dominates and the electrical coupling may be simply represented as a single element with conductance g_c in parallel with capacitance C_c , $Y_c(j\omega) = g_c + j\omega C_c$.

From Chi, Jung & Cauwenberghs, 2010.

EEG Electrodes

The conventional notion that low resistance (high conductance) is essential for good electrode performance could be misleading in certain cases.



Source input-referred noise power density

$v_s(j\omega)$	signal source on skin surface;
$v_o(j\omega)$	signal recorded at amplifier output;
$v_{i,n}(j\omega)$	input referred amplifier voltage noise;
$i_{i,n}(j\omega)$	net current noise at amplifier input;
$Y_c(j\omega)$	$g_c + j\omega C_c$, skin-electrode coupling admittance;
$Y_i(j\omega)$	$g_i + j\omega C_i$, amplifier input admittance;
C_s	active shield to electrode capacitance;

$$v_{s,rms}^2 \approx \frac{4kT\, g_c}{|Y_c(j\omega)|^2} = \frac{4kT}{g_c + \frac{\omega^2 C_c^2}{g_c}}.$$

$V_{s,\, rms}$ can be reduced to zero in two limits: either infinite coupling conductance (low-resistance contact sensing), or infinite coupling impedance (capacitive noncontact sensing). This presents a rather interesting dichotomy—either of the two extreme cases of zero resistance and infinite resistance of skin-electrode contact are actually optimal for low-noise signal reception

From Chi, Jung & Cauwenberghs, 2010.

Practical Design Considerations

- To abrade the skin to obtain a low contact resistance (5–10kΩ).
- To employ an amplifier with very high input impedance such that the skin-electrode impedance becomes negligible.

From Chi, Jung & Cauwenberghs, 2010.

Comparison for EEG Electrodes

Standard wet electrodes : low skin impedance, and buffer the electrode against mechanical motion. But, they may be messy, time-consuming, irritating during preparation and cleaning, and the signal quality degrades over time.

Rigid metal electrodes: subject to motion artifacts

Dry foam electrode (Gruetzmann *et al.*, 2007): comfortable and stable with increased resistance to motion artifact, but difficult to assess hair-bearing sites.

MEMS sensors: low skin impedance. But, they may be irritating and difficult to penetrate the hairs.

Microprobe electrodes: sensitive to motion artifacts.

Non-contact sensors: sensitive to motion artifacts, poor settling times. Friction between the electrode and insulation can cause large voltage excursion at the sensitive input.

Epidermal electrodes (Kim eta al., 2011): very comfortable and stable with increased resistance to motion artifact, but difficult to assess hair-bearing sites.

BIOE 280A

Wearable EEG Devices

UCSD

(a)

Emotiv

(b)

NeuroSky

(c)

Zeo

(d)

Starlab

(e)

EmSense

(f)

nia Game Controller

(g)

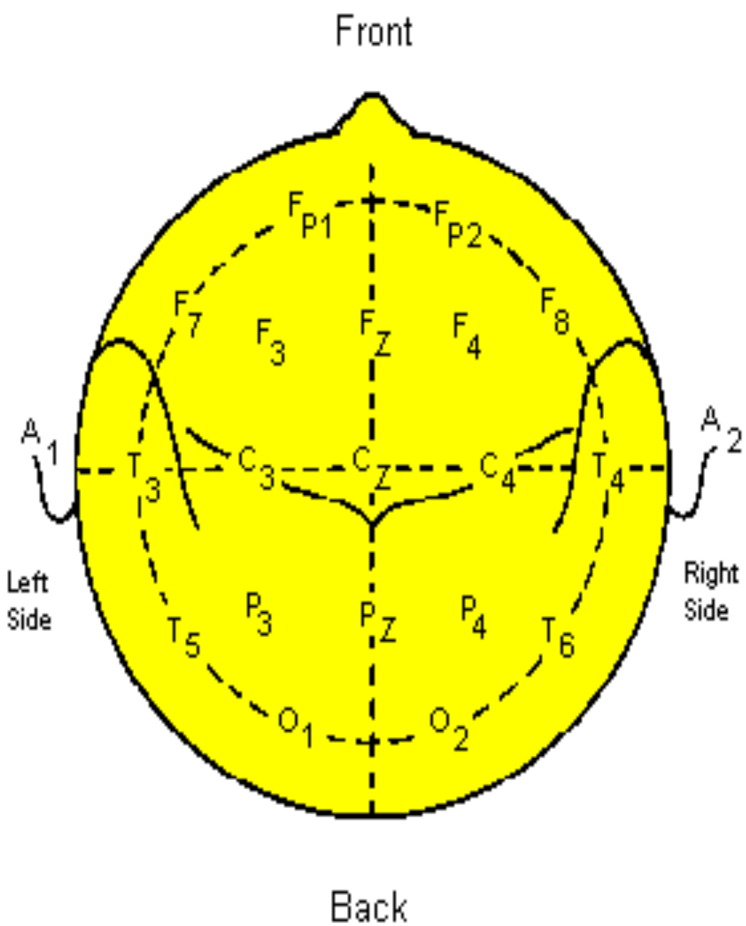
Mindo 4

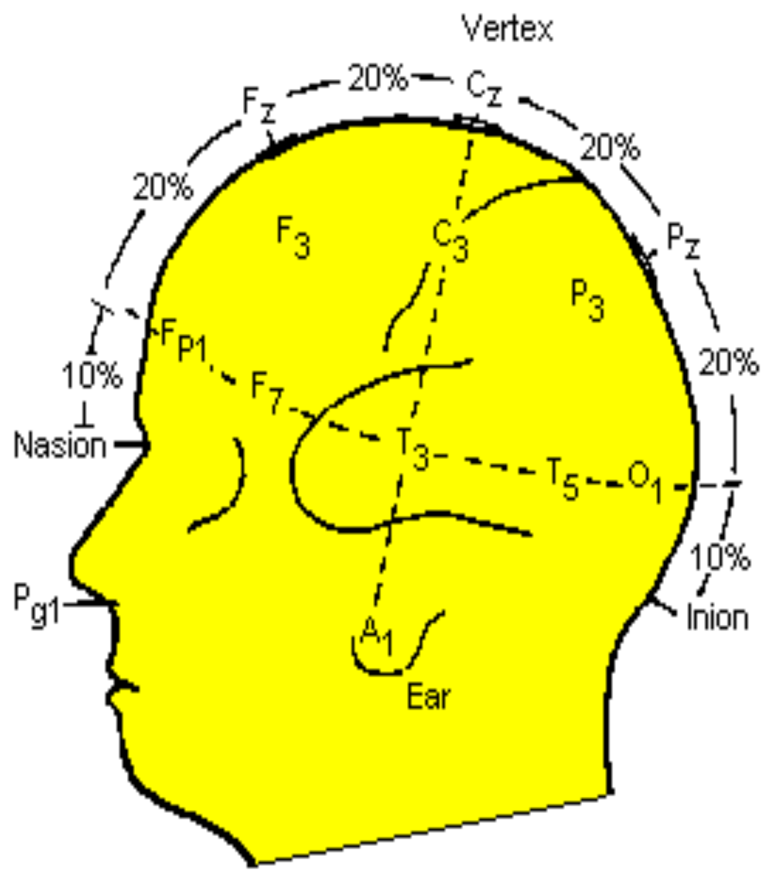
(h)

Mindo 16

EEG Montage

International 10-20 system

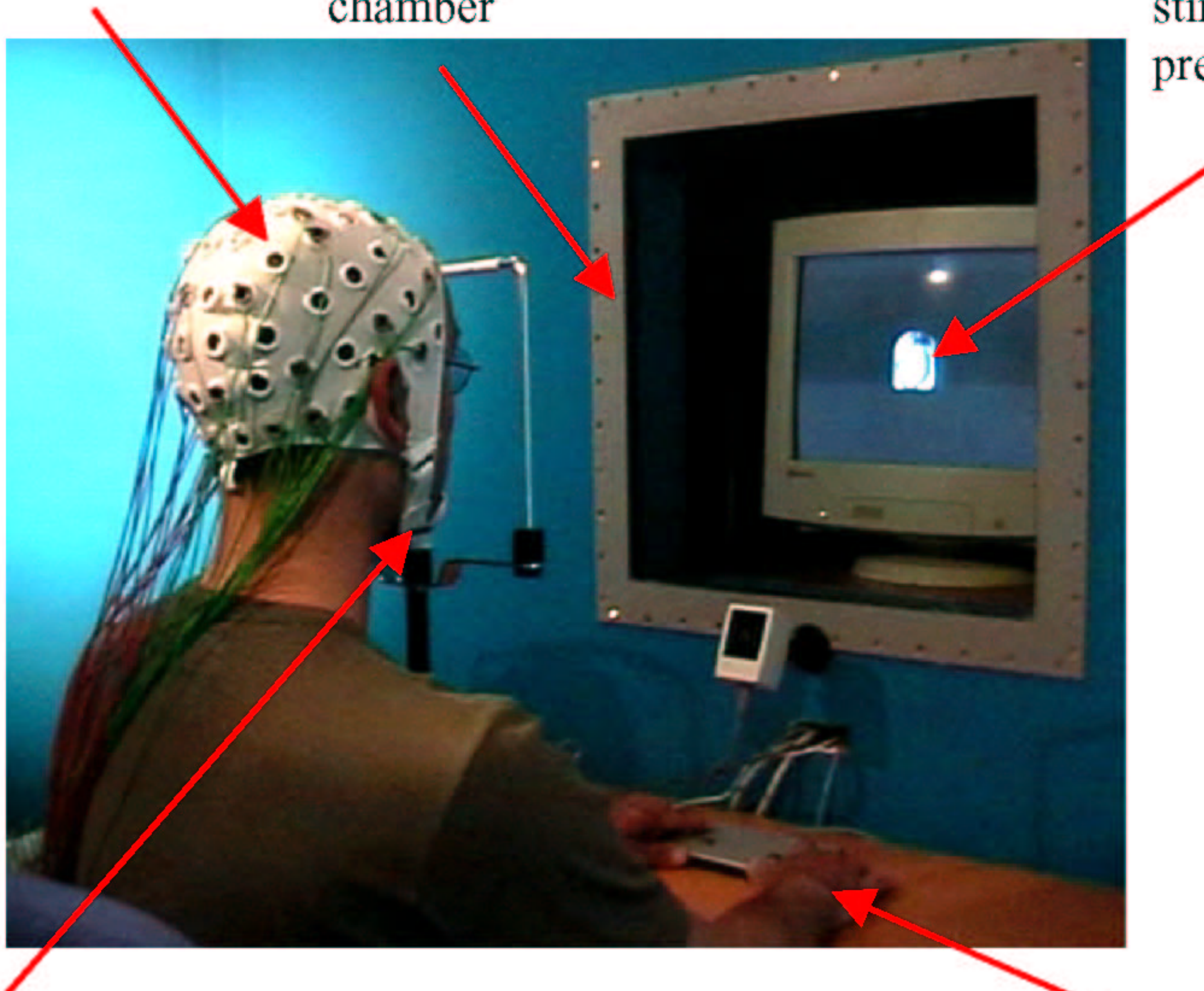




Head cap with inserted Ag/AgCl electrodes

Electromagnetically shielded recording chamber

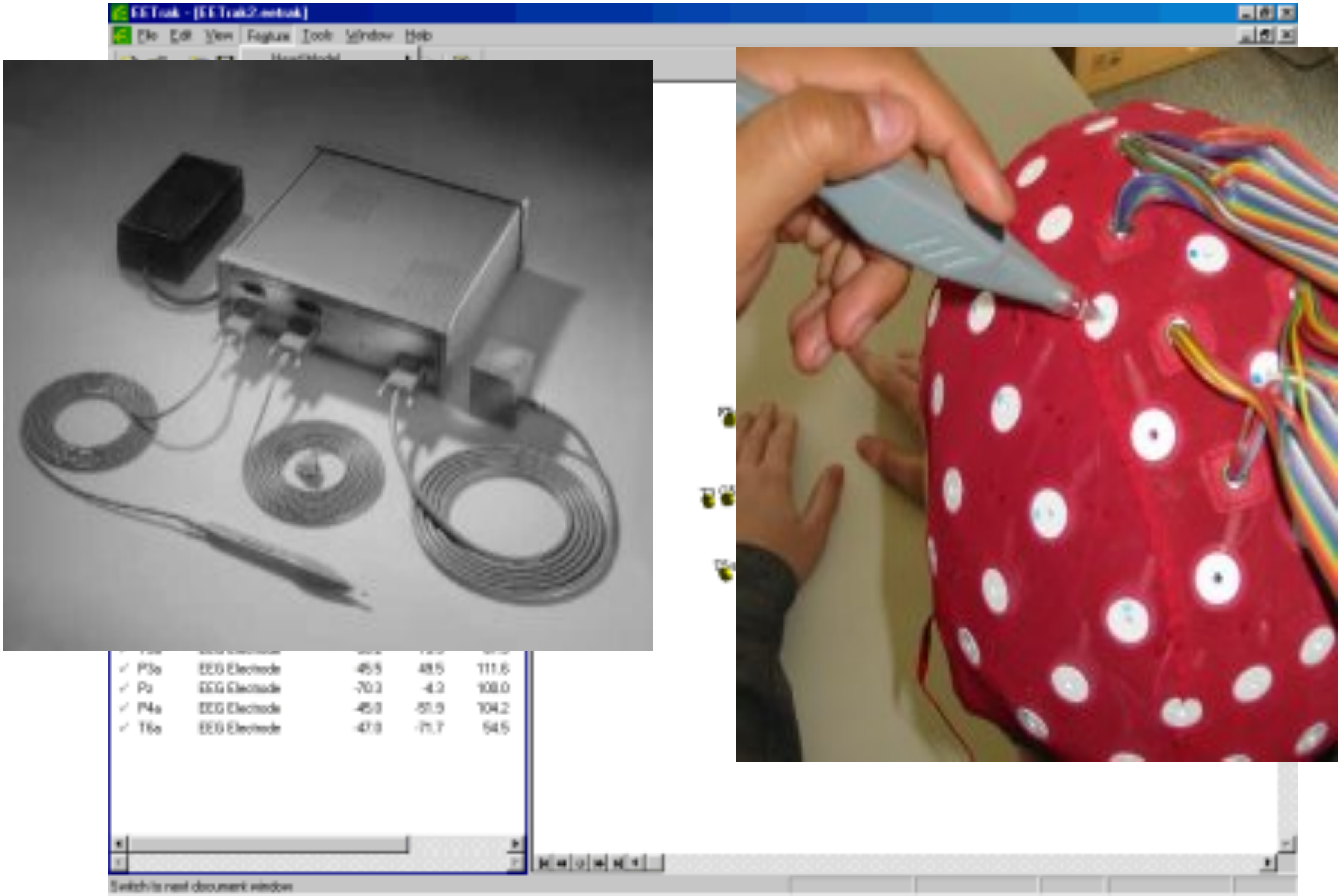
Visual stimulus presentation



Fixed chin rest

Keypress response pad

Electrode Position/orientation Measuring



What EEG/ERPs Can and Cannot Tell Us About Brain Functions

CAN

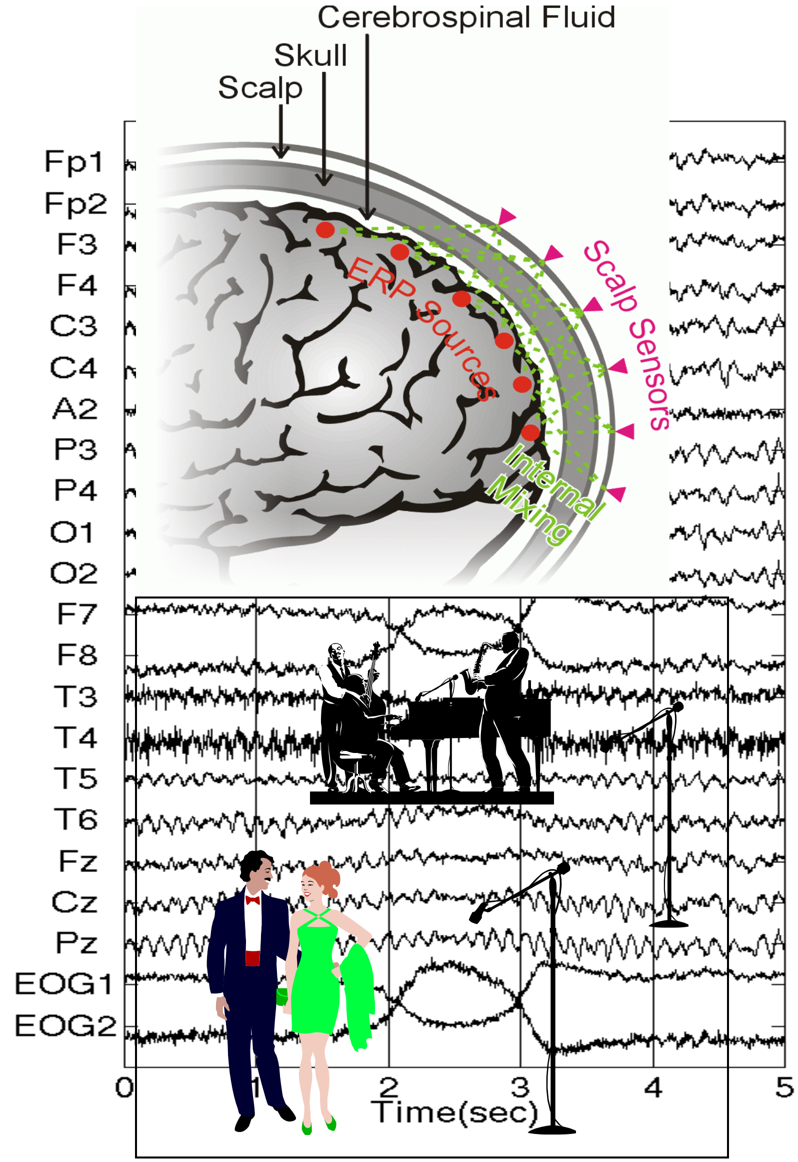
- Precise timing of neural activity
- Sequence of mental operations

CANNOT

- Precise brain location of neural activity

Challenges of EEG Analysis

- Pervasive artifacts
- EEG recordings are mixtures of all brain activities arising from different networks
- Response variability
- Inverse problem
- others



Human Electrophysiology

Event-related Potentials (ERPs)

Time-domain average of EEG signals both time- and phase-locked to stimulus presentation or subject response.

On-going (spontaneous) EEG

Time-frequency dynamics

- Event-related synchronization or de-synchronization
- Event-related spectral perturbation (ERSP)

What is ERP?

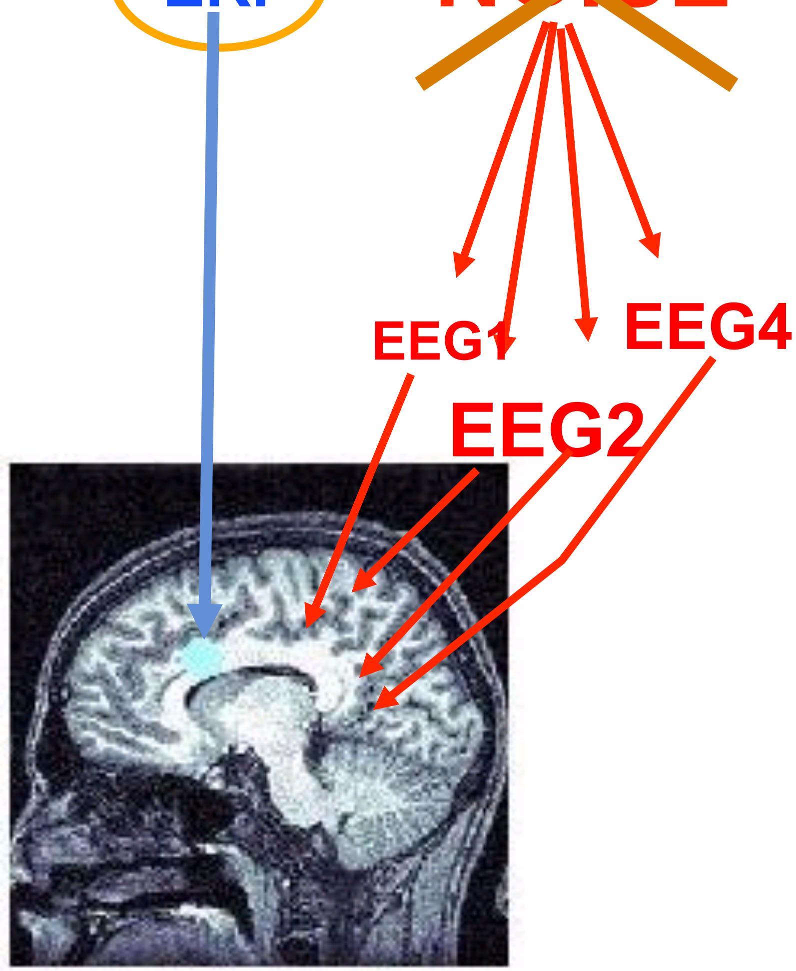
ERPs (Dawson, 1937) are changes in the electrical activity of the brain which occur time-synchronized

- In response to physical stimuli
- In association with mental activity
- In preparation of actions

(Picton, 1980)

ERP Model

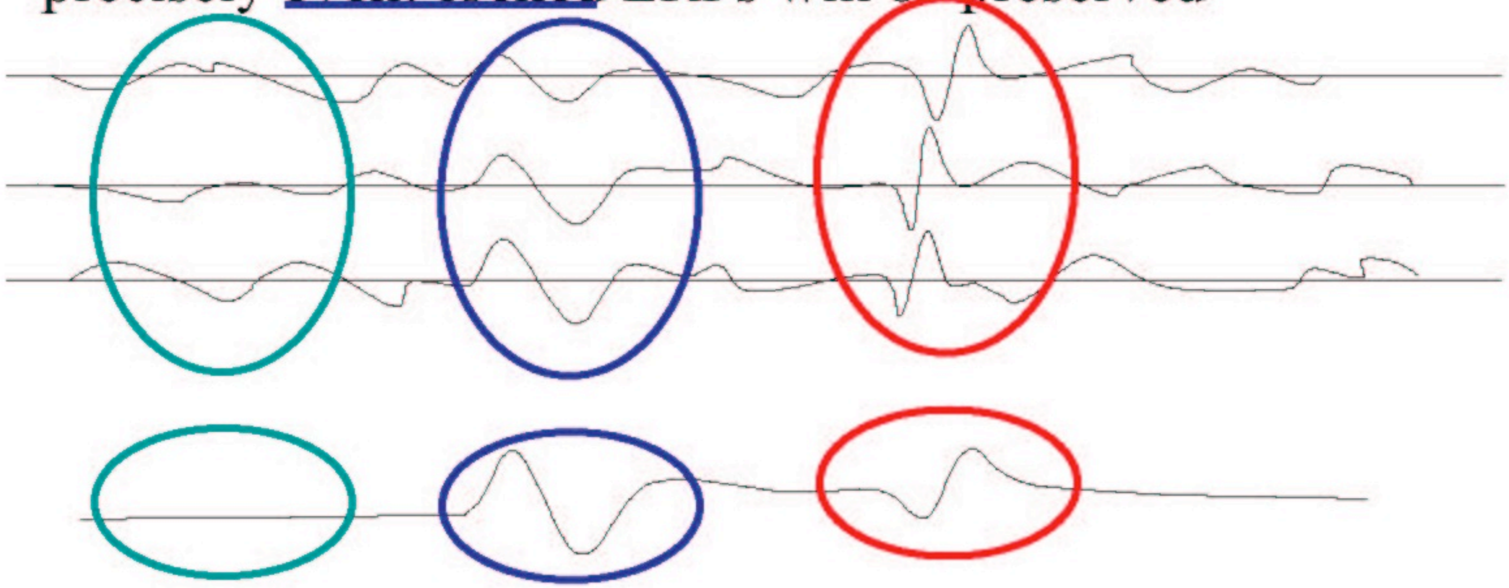
$EEG_{data} = ERP + NOISE$



Effects of Transforming Raw Data

Averaging event-locked segments will have the effect that *anything* not precisely time-locked to the event will be flattened out in averaging

- noise
- 'jittered' ERPs (I.e. occuring at variable latencies)
- precisely event-locked ERPs will be preserved



Theorem of Signal Averaging

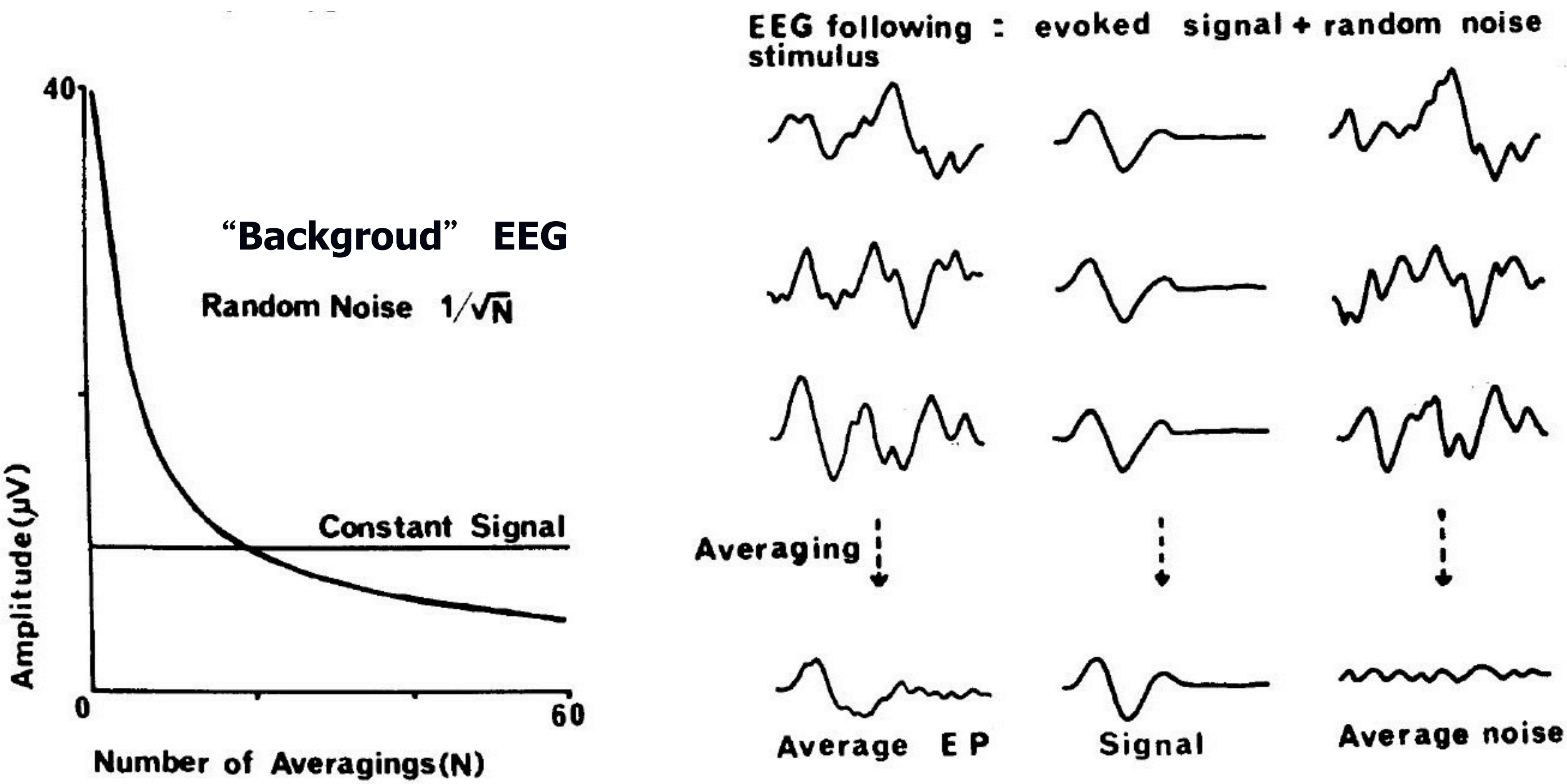
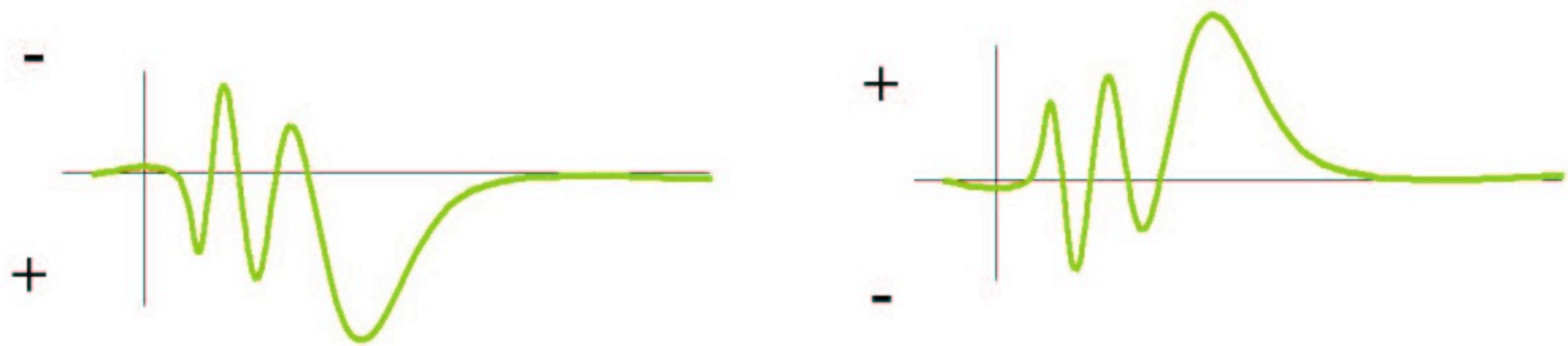


Figure 7
Theory of Signal Averaging

BIOE 280A

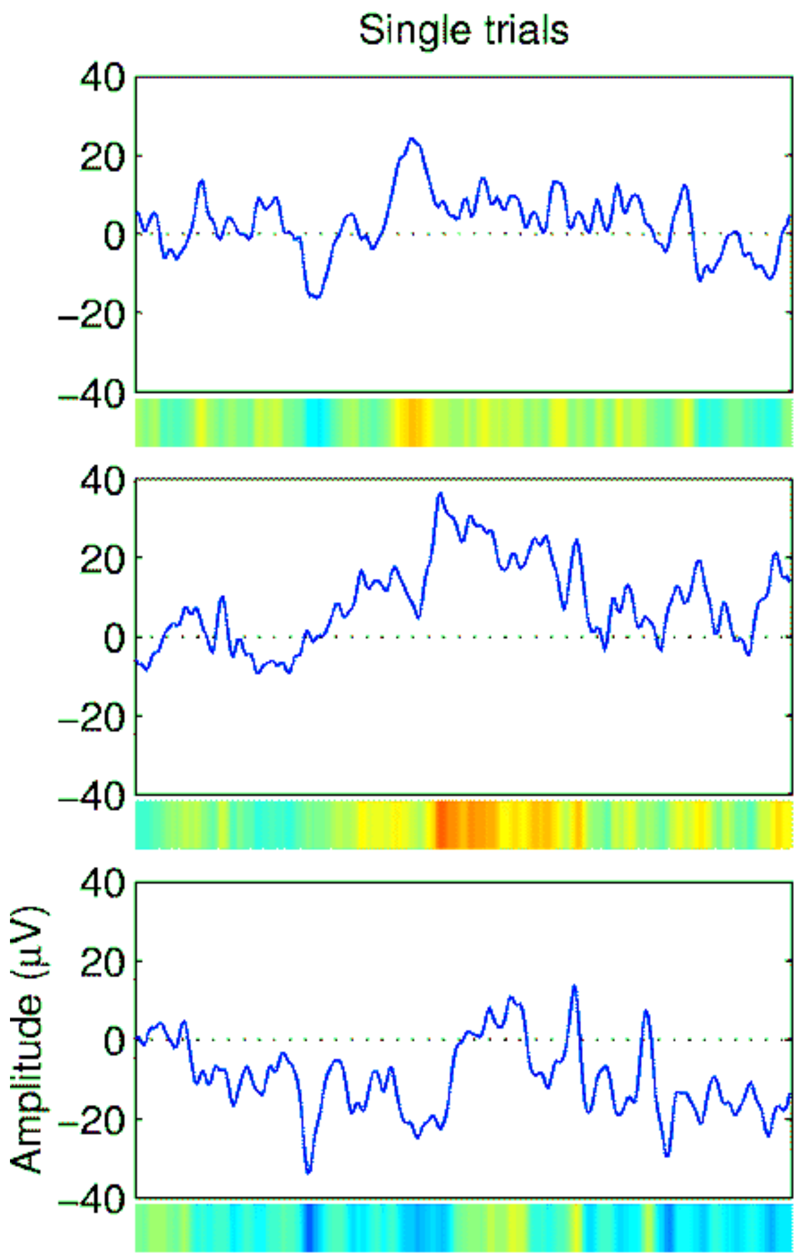
Naming of ERP Components

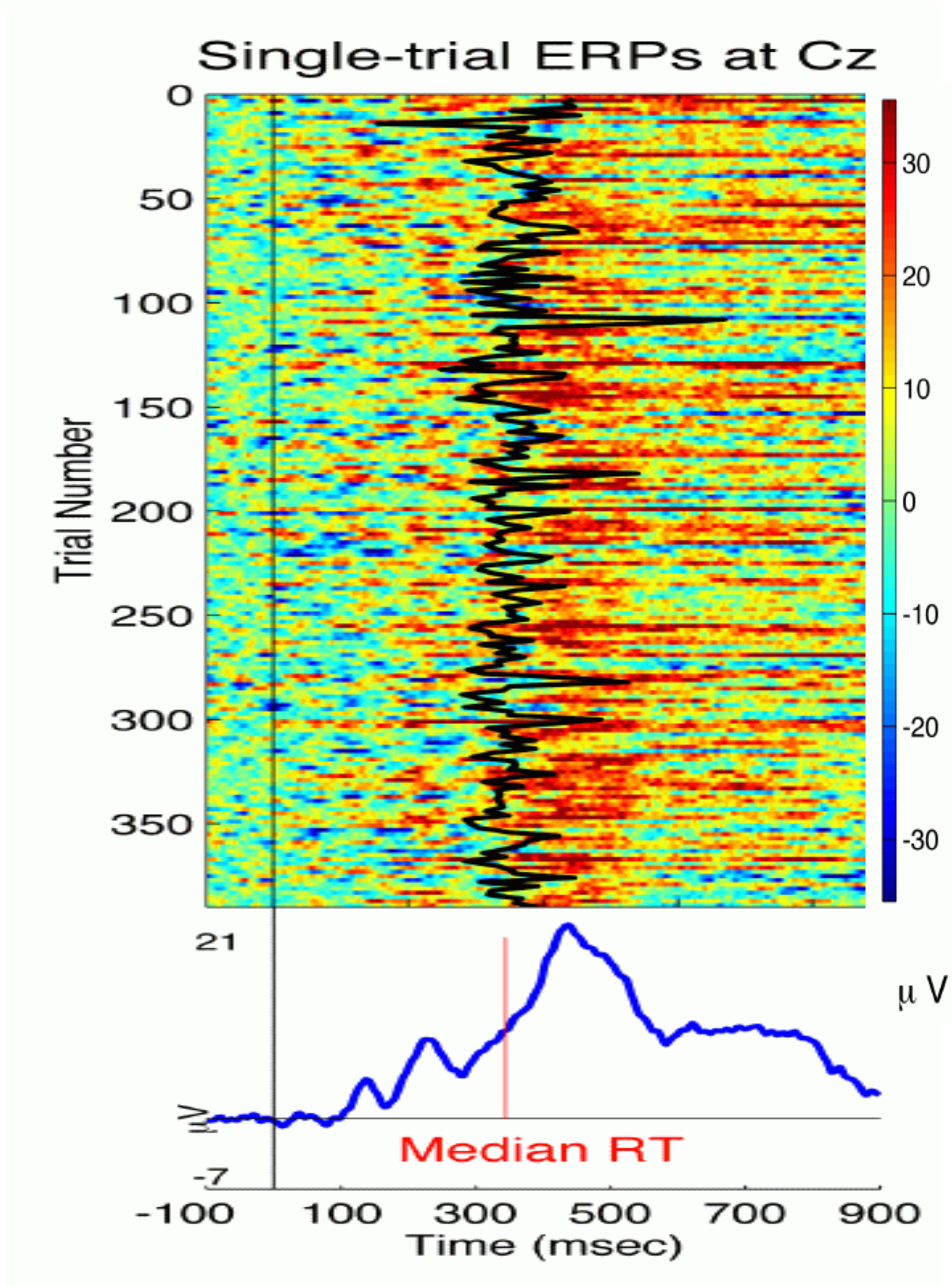
- Positive ⇒ ‘P’
- Negative ⇒ ‘N’
  - NB Is Negative plotted up or down?



- 1st, 2nd, 3rd : ‘P1’, ‘P2’, ‘P3’
- Precise latency : ‘P300’
  - latency of *peak* or of *onset*
- >1 name can refer to same component
  - e.g. P3 ~= P300
- Topography is important : frontal N2, occipital N2

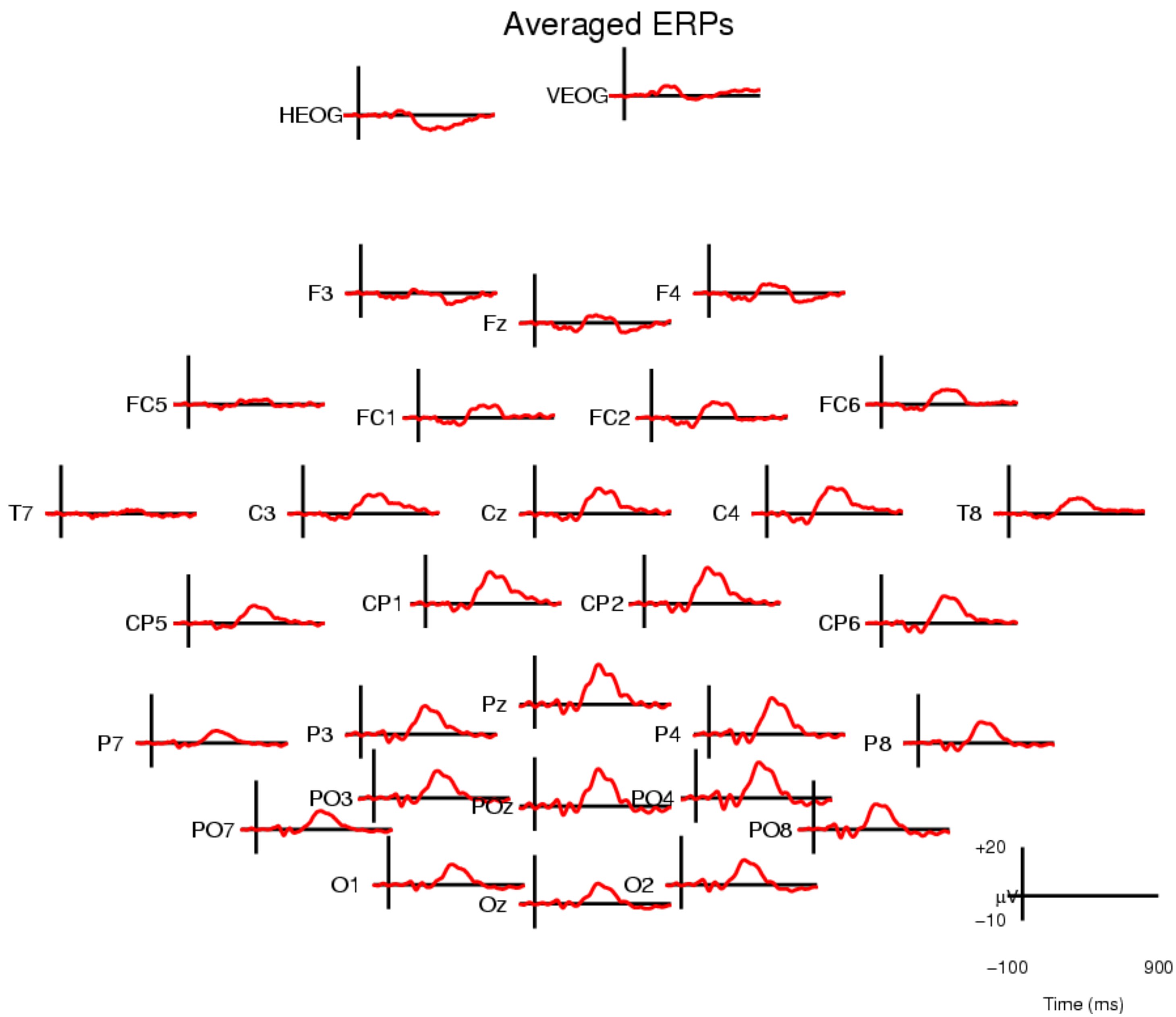
ERP Image


Single trials
40
20
0
−20
−40
Amplitude (μV)


Single-trial ERPs at Cz
Trial Number
0
50
100
150
200
250
300
350
30
20
10
0
-10
-20
-30
21
μ V
Median RT
-7
-100
100
300
500
700
900
Time (msec)

BIOE 280A

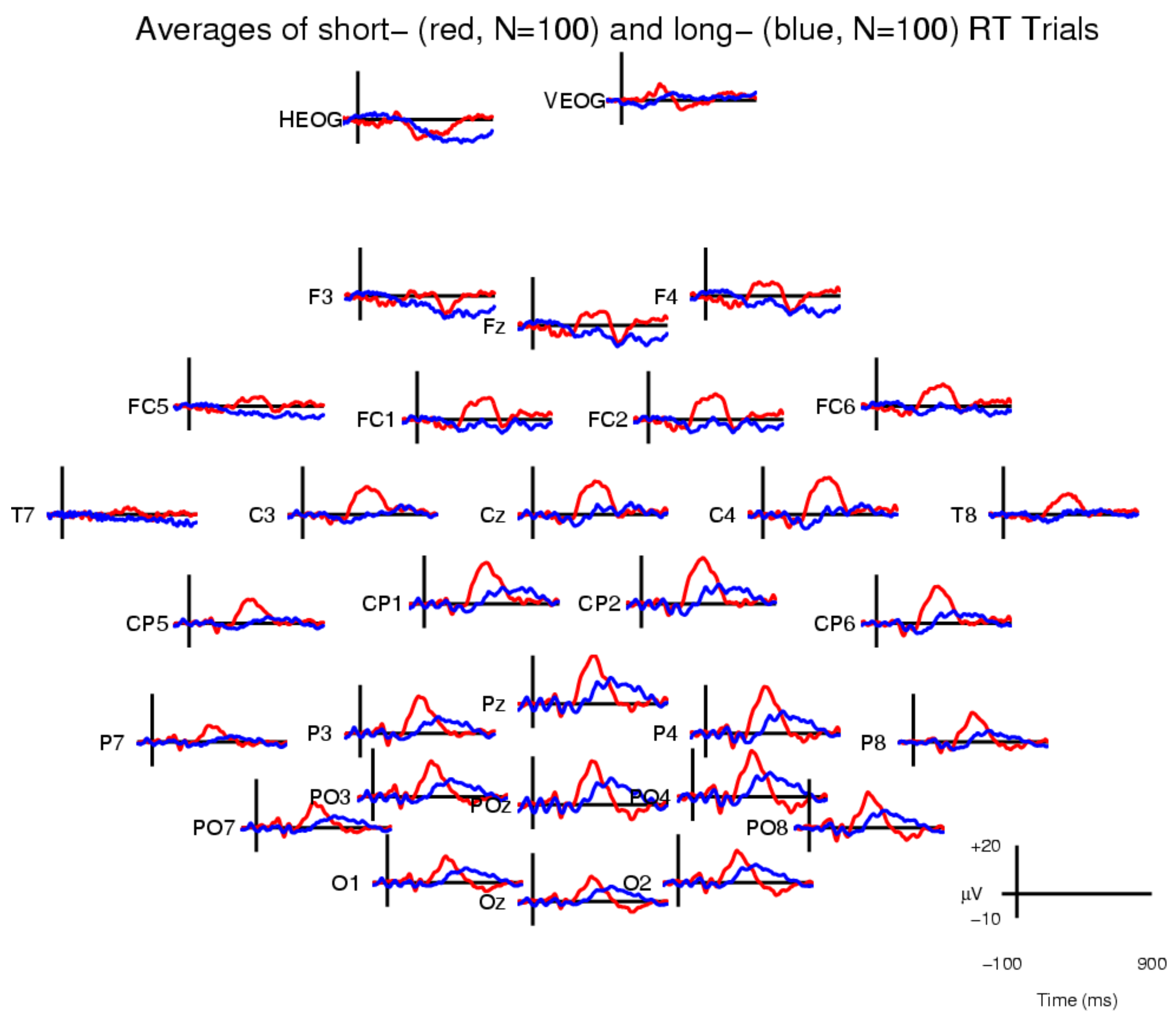
Averaged ERP across Trials



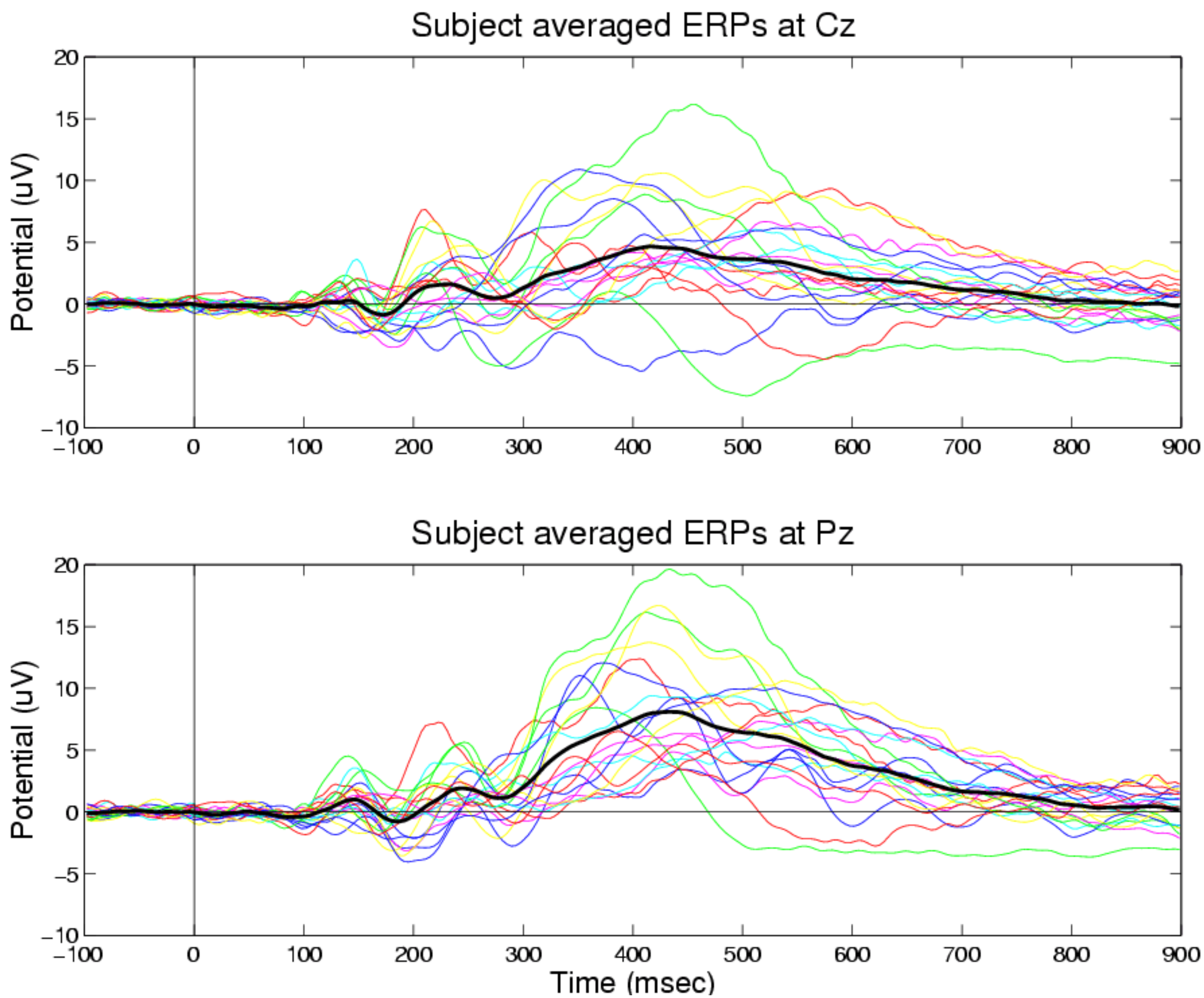
UCSD

BIOE 280A

Averaged ERP across Trials



Averaged ERP across Subjects



EEG Analysis

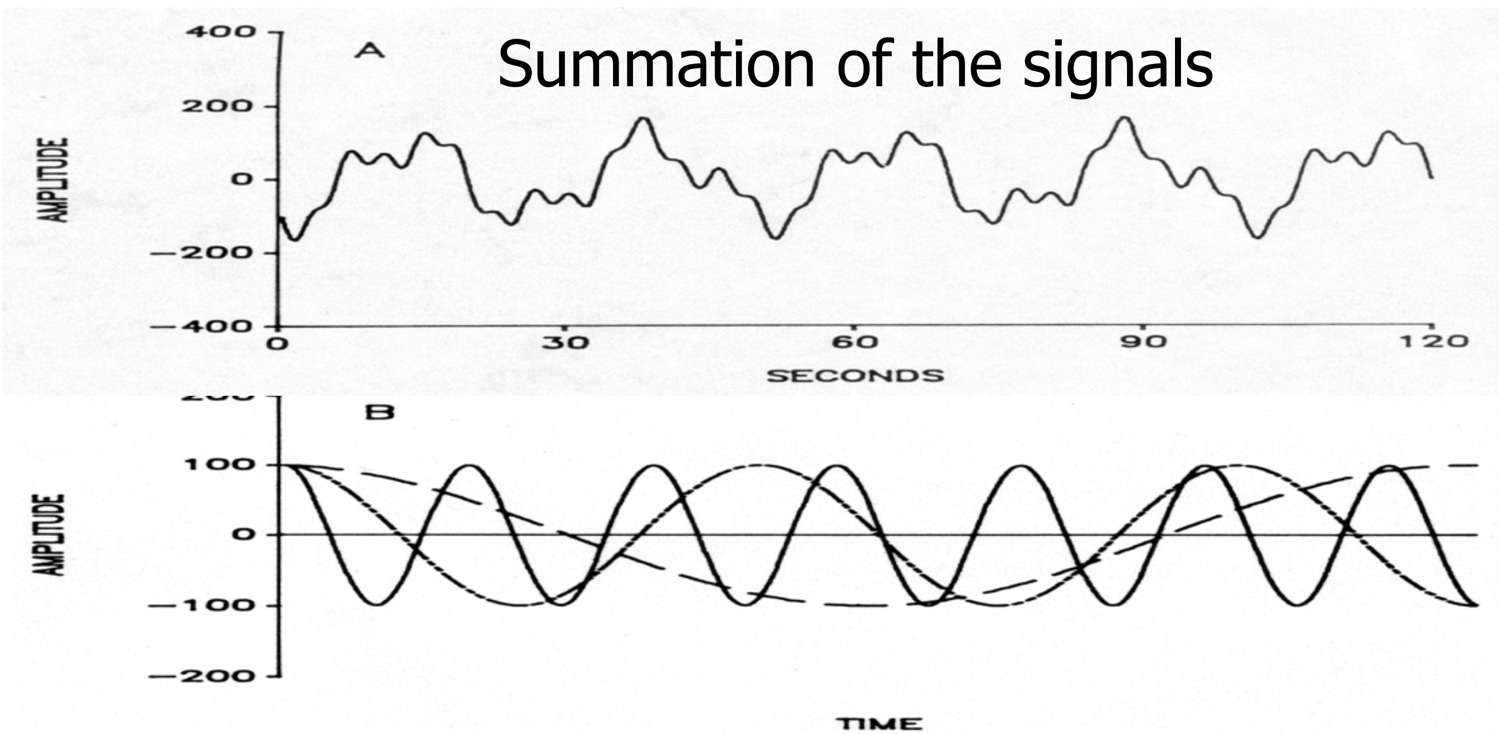
- Time- & Phase-locked Potentials
  - Evoked Potentials (EPs, *exogenous* / sensory)
  - Event-Related Potentials (ERPs, *endogenous/* cognitive)
    - Contingent Negative Variation (CNV), 'Here it comes…!', Walter et al., 1964)
    - P300 ('Oh, there's one!')
    - N400 ('Huh?')
    - ERN ('Oops!')
- On-going (spontaneous) EEG
  - Frequency-domain analysis
  - Time-frequency analysis (Event-related spectral perturbation)
  - Event-related (de-) synchronization (Pfurtscheller et al., 1979)

BIOE 280A

Frequency-domain Analysis of the EEG

UCSD

- Joseph Fourier (1768-1830)
- Any complex time series can be broken down into a series of superimposed sinusoids with different frequencies.



Fourier Analysis

Fourier-Transformation:

$$H(f) = \int_{-\infty}^{\infty} h(t) e^{2\pi i f t} dt \; ; \quad h(t) = \int_{-\infty}^{\infty} H(f) e^{-2\pi i f t}$$

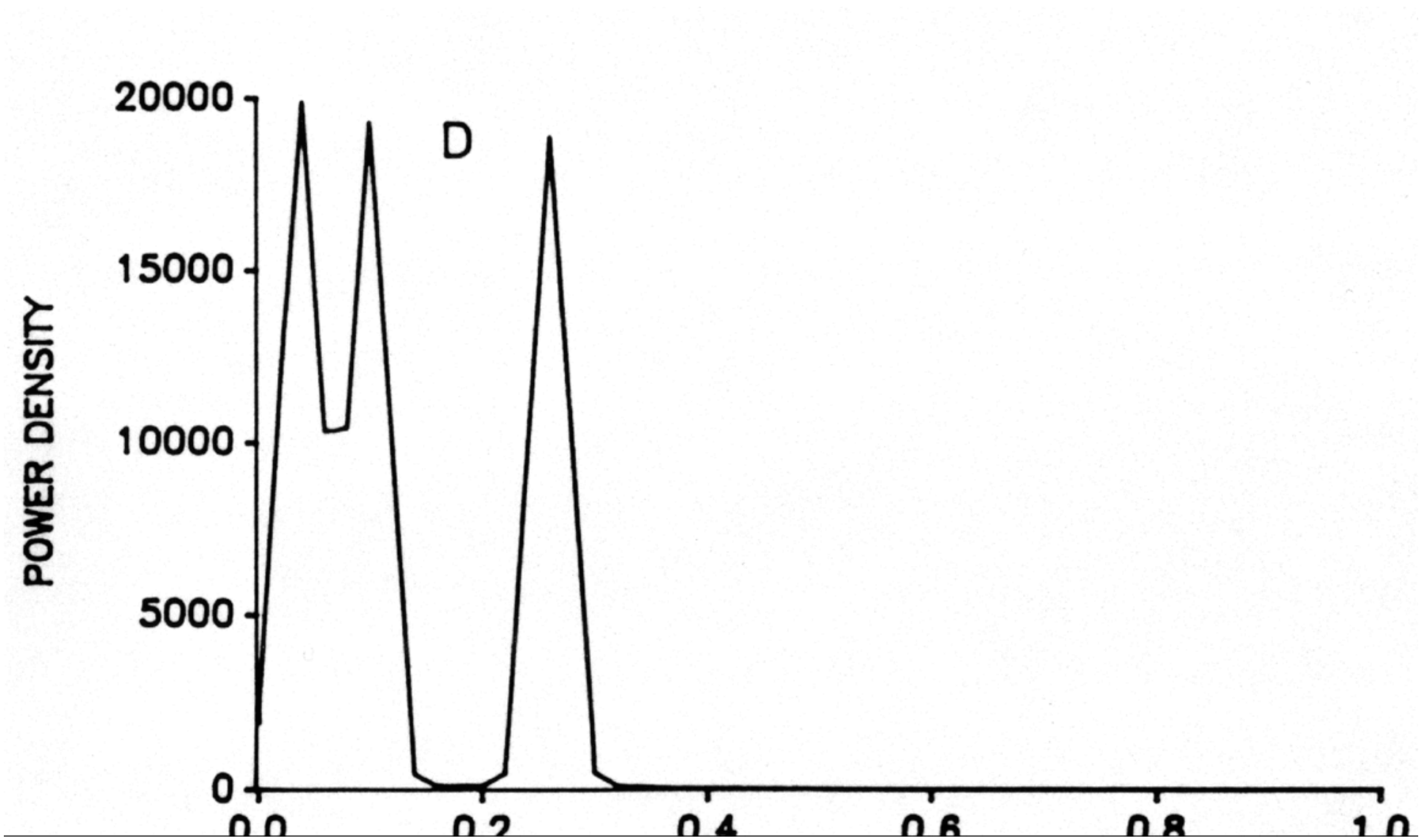
Diskrete Fourier-Transformation (O(N²)):

$$X(k) = \frac{1}{N} \sum_{n=0}^{N-1} x[n] e^{-ik(2\pi/N)n} \qquad k = 0,1,..,N-1$$

$$x[n] = \sum_{k=0}^{N-1} X(k) e^{ik(2\pi/N)n} \qquad n = 0,1,..,N-1$$

Fast Fourier Transform (FFT), Cooley und Tukey (1965)

Fourier Analysis



FREQUENCY (Hz)

Fourier Transform

- Advantage:

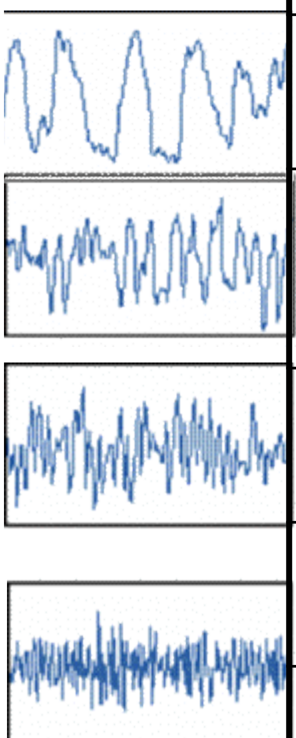
For many signals, Fourier analysis is extremely useful because the signal's frequency content is of great importance.

- Disadvantage:

Fourier analysis has a serious drawback.

In transforming to the frequency domain, time information is lost.

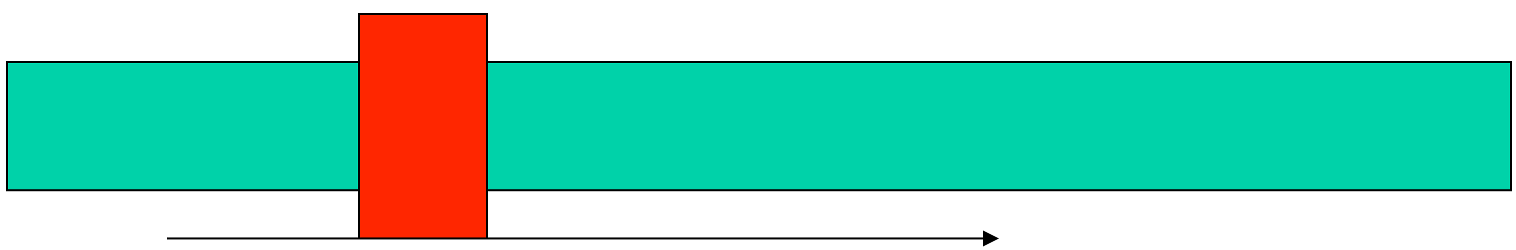
Frequency-domain Analysis of the EEG



EEG Bands (Hz)	Distribution	Subjective feeling	Associated tasks & behaviors	Physiological correlates
Delta 0.1-3	Distribution: generally broad or diffused	deep, dreamless sleep, non-REM sleep, unconscious	lethargic, not moving, not attentive	not moving, low-level of arousal
Theta 4-8	usually regional, may involve many lobes	intuitive, creative, recall, fantasy, imagery, creative, dreamlike, drowsy	creative, intuitive; distracted, unfocused	healing, integration of mind/body
Alpha 8-12	regional, usually involves entire lobe	relaxed, not agitated, but not drowsy	meditation, no action	relaxed, healing
Beta 12-30	localized	alertness, agitation	mental activity, e.g. math	alert, active
Gamma >30	very localized	Focused arousal	high-level information processing, "binding"	information-rich task processing

Time-Frequency Analysis of the EEG

- We often apply a ‘window’ to the data.
- This simply means taking the amount we want from the data stream
- ie

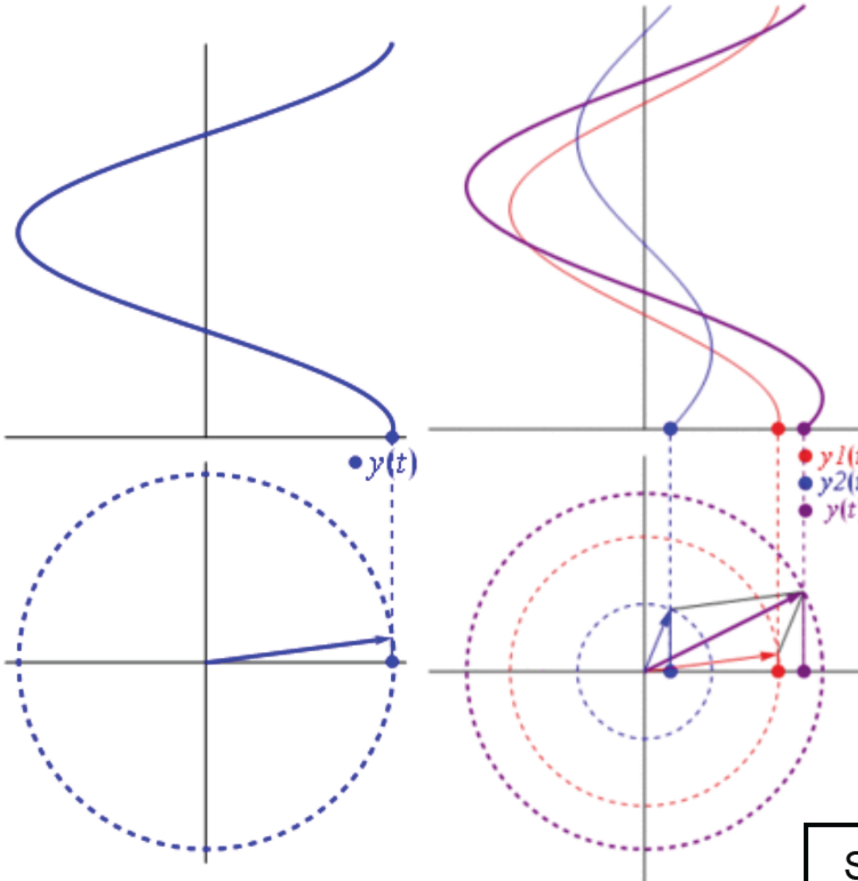


The window is moved along the data; we perform the FFT on this windowed data

Phasor

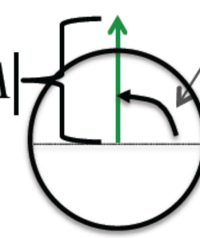
Phasors

Rotation velocity (Rad/S; Hz)
= (angular) frequency (*w*; *f*)



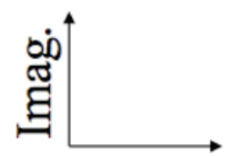
$$A \cdot \cos(\omega t + \theta) = \mathrm{Re}\{Ae^{i(\omega t + \theta)}\}$$
$$= \mathrm{Re}\{S(\omega, t)\}$$

$$|S(\omega,t)| = |A|$$



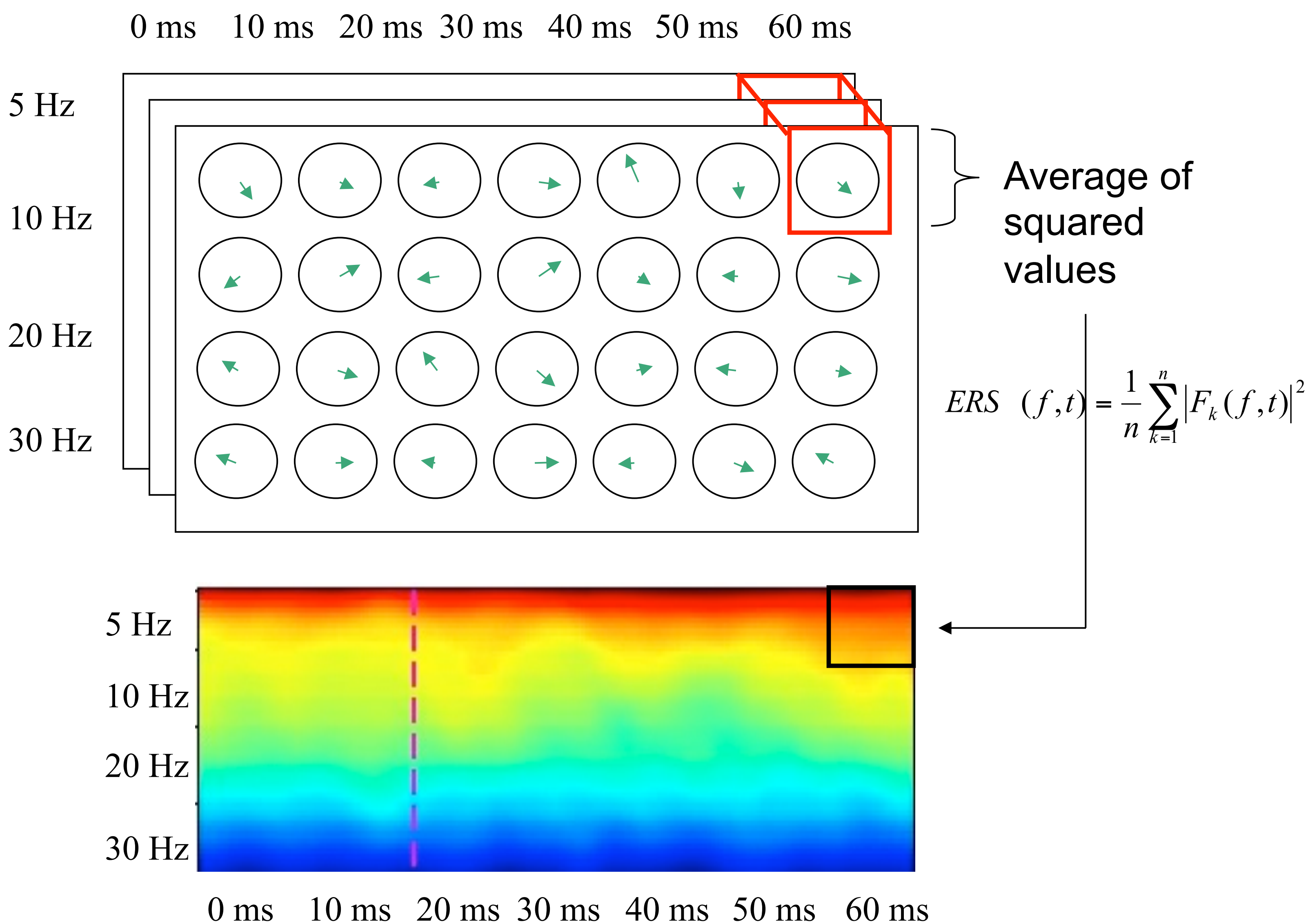
$$\theta = \frac{\pi}{2}$$

Shorthand phasor notation: $Ae^{i\phi}$



Polar animations courtesy Wikipedia

Spectrogram

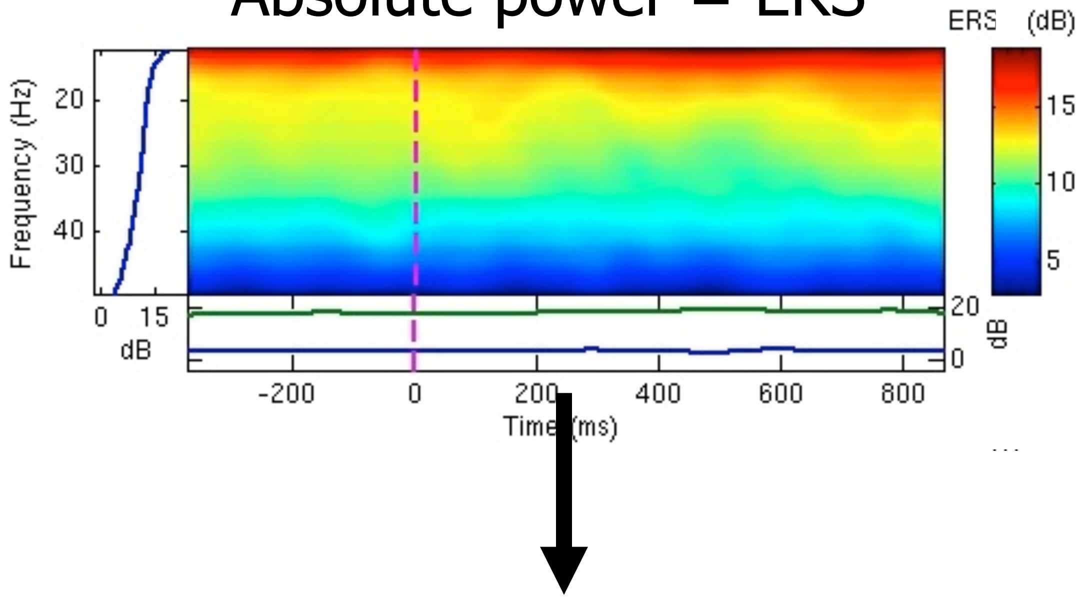


BIOE 280A

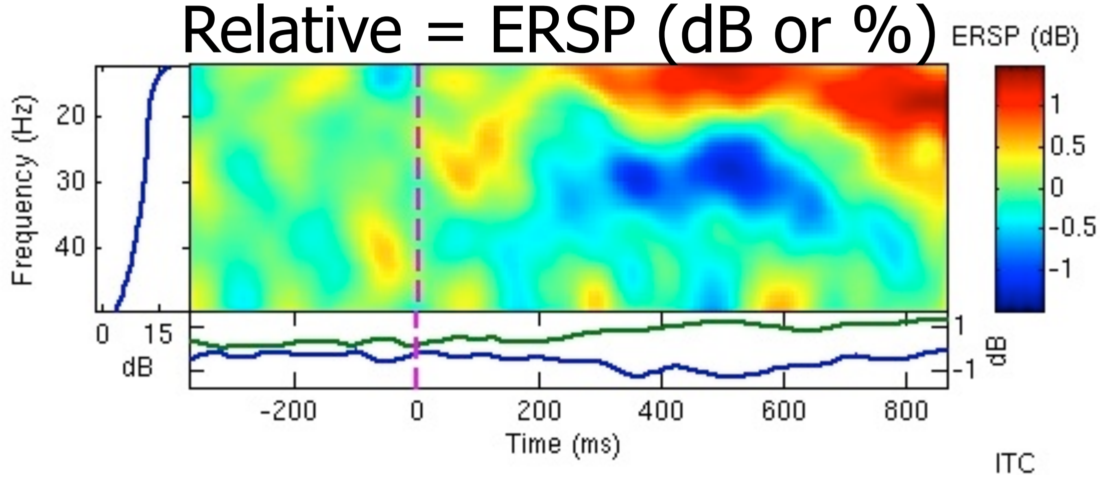
Absolute versus Relative Power

UCSD

Absolute power = ERS

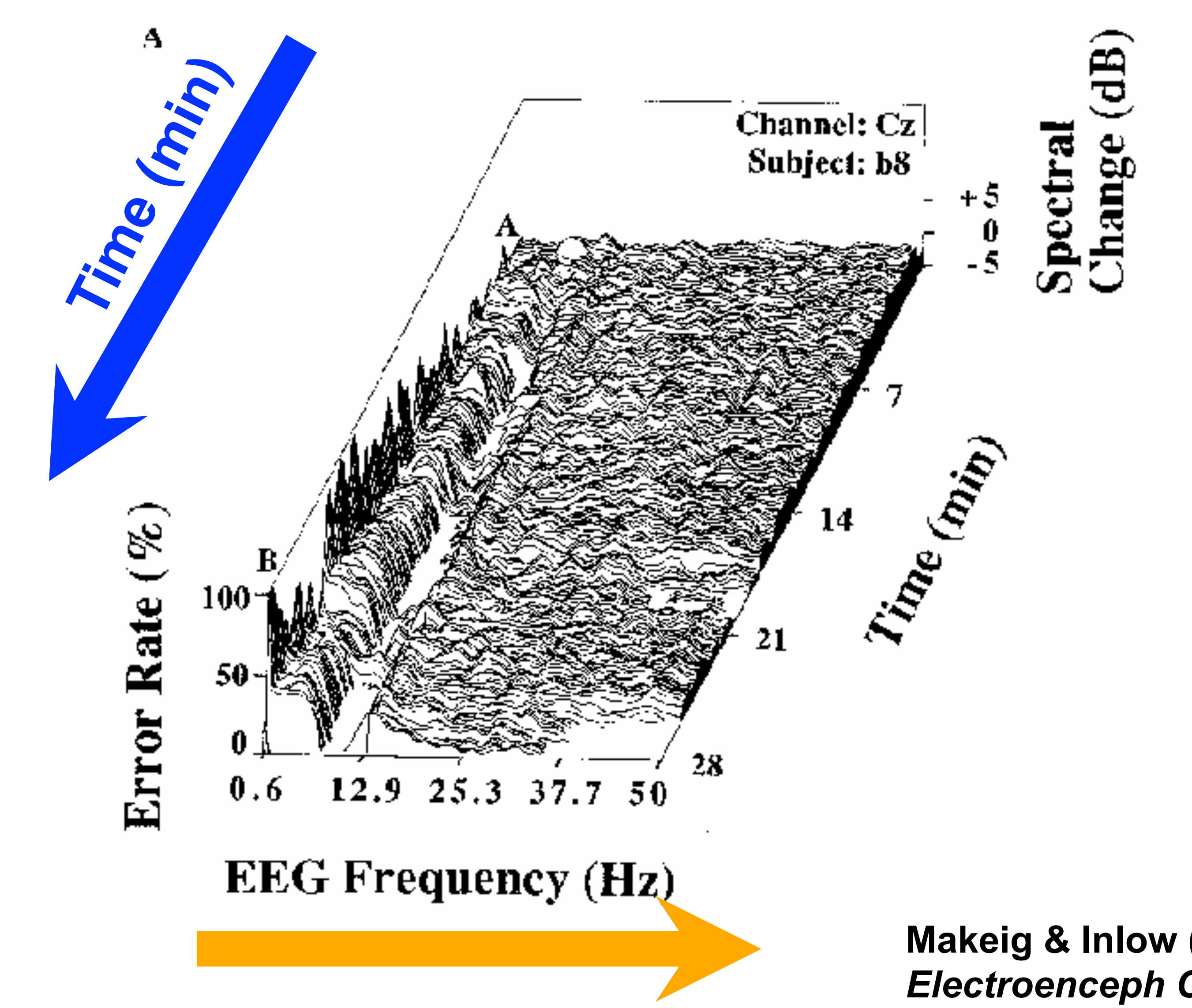


Relative = ERSP (dB or %)



Makeig, *Clinical Neurophysiology,* 1993.

Time-Frequency Analysis of the EEG



Makeig & Inlow (1993)
Electroenceph Clin Neuro

Event-related (De-)Synchronization

- Time- but NOT phase-lock signals
- Highly frequency-specific
- ERD/ERS are location-dependent

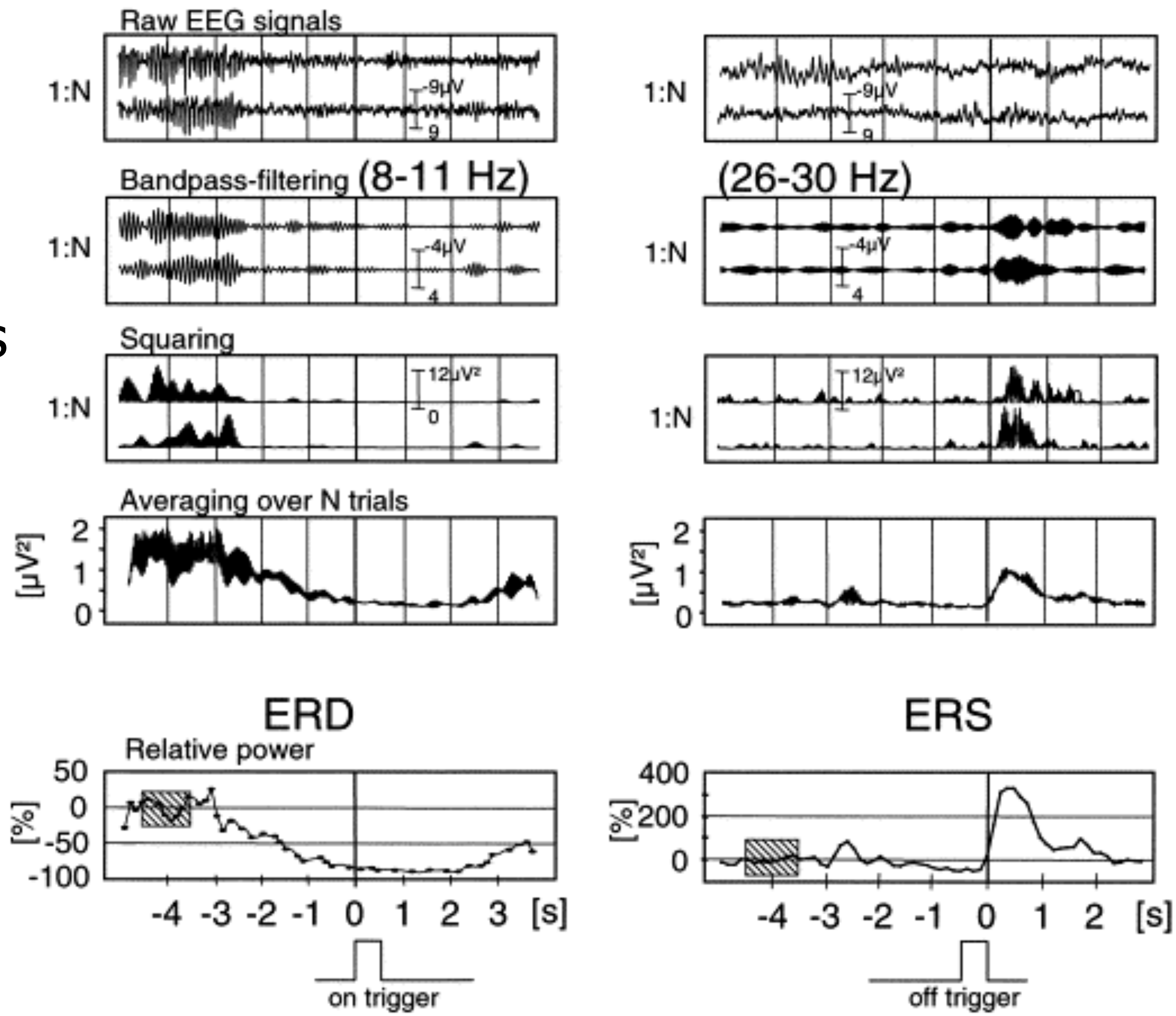
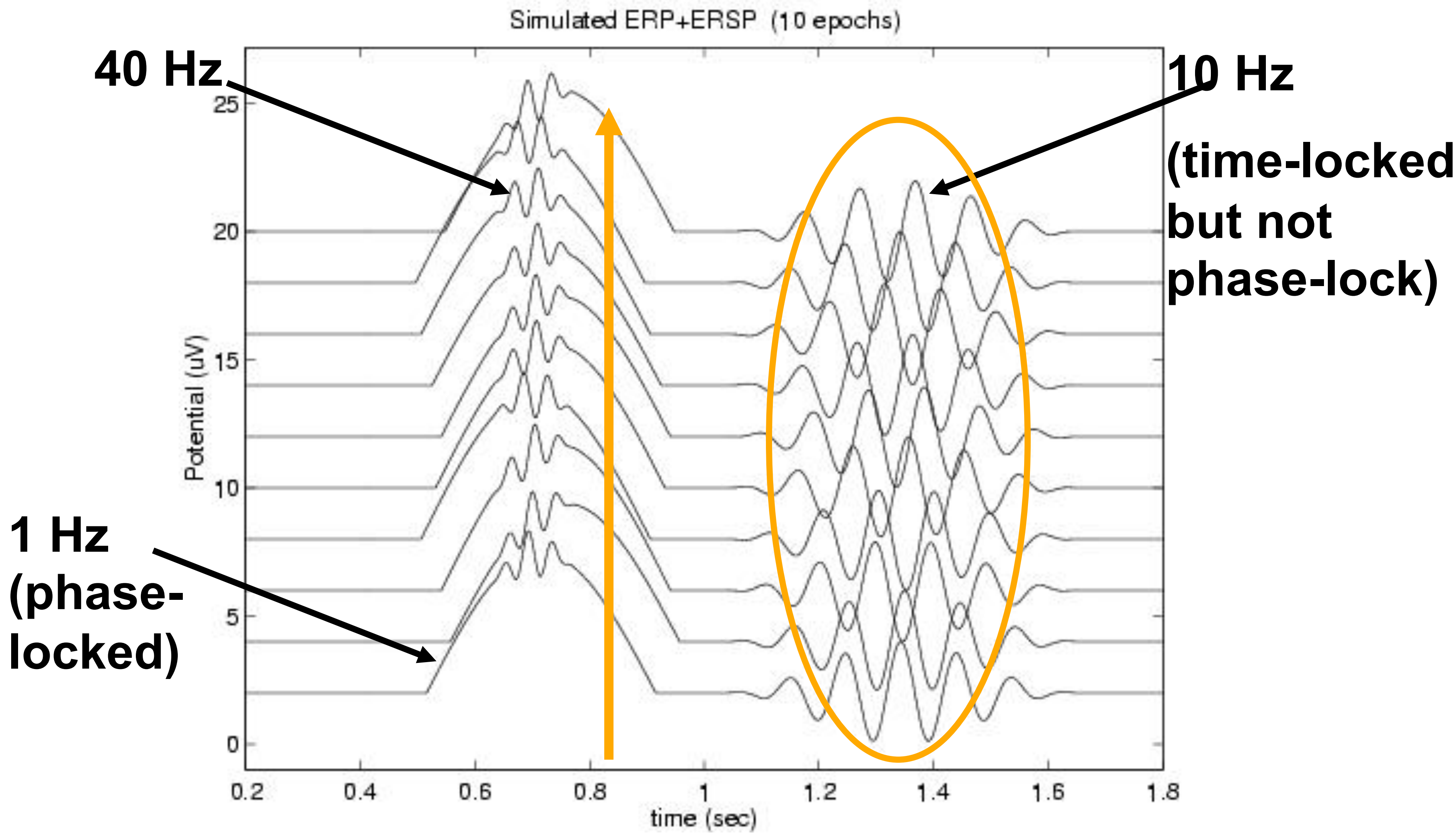
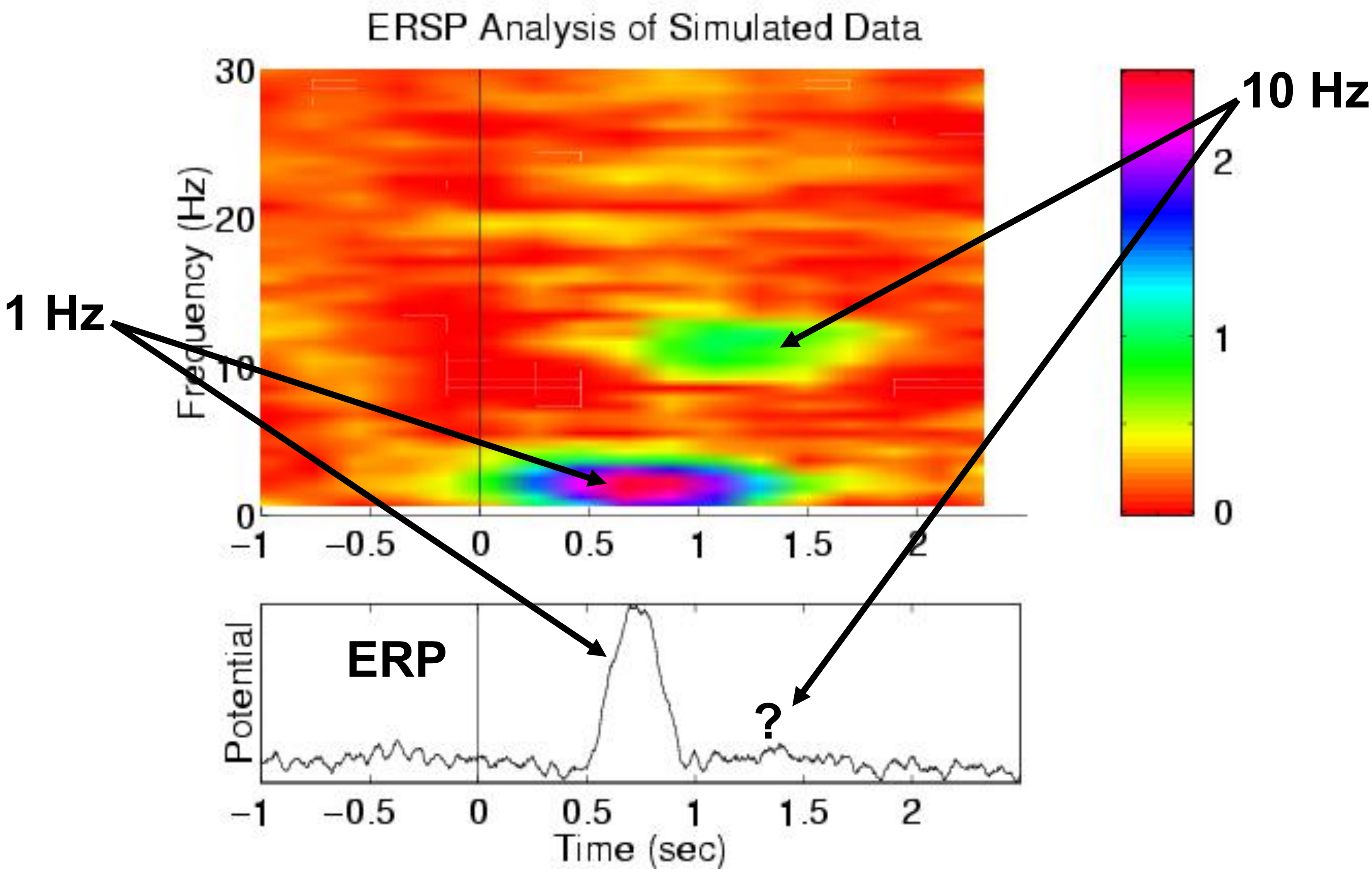


Figure is from Pfurtschellera & Lopes da Silvab, *Clinical Neurophys.*, 1999.

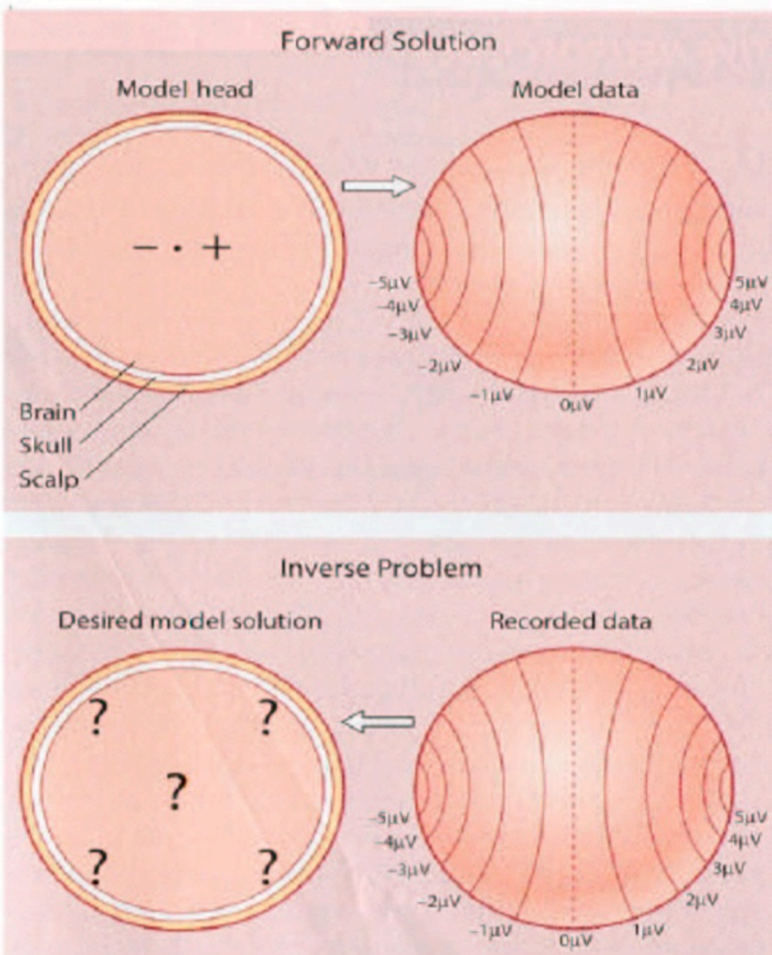
Time-locked Spectral Changes ≠ Time- & phase-locked ERP



ERSP vs ERP


ERSP Analysis of Simulated Data
Frequency (Hz)
30
20
10
0
−1
−0.5
0
0.5
1
1.5
2
0
1
2
10 Hz
1 Hz
ERP
?
Potential
Time (sec)

Forward Solution and Inverse Problem

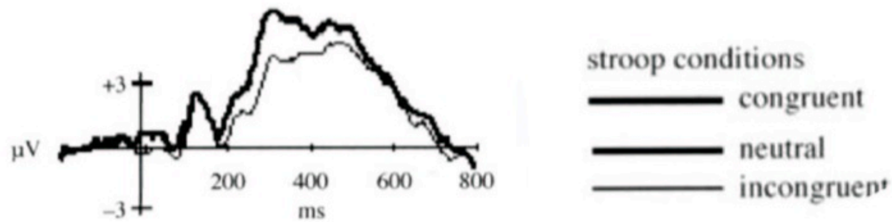


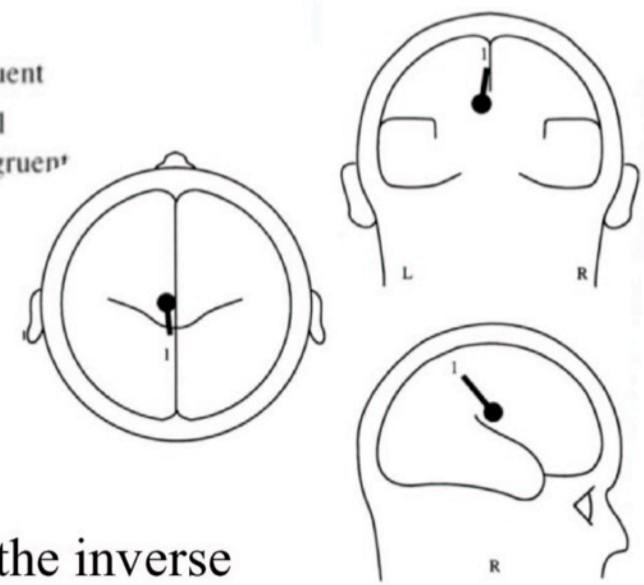
A single pattern of neural activity will produce a unique scalp map

BUT …A single scalp map could have been produced by an infinite number of patterns of neural activity

Figure is copied from Gazzaniga et al., *Cognitive Neuroscience: The biology of the mind Norton and Company,* 2009.

Source Localization with ERP Data





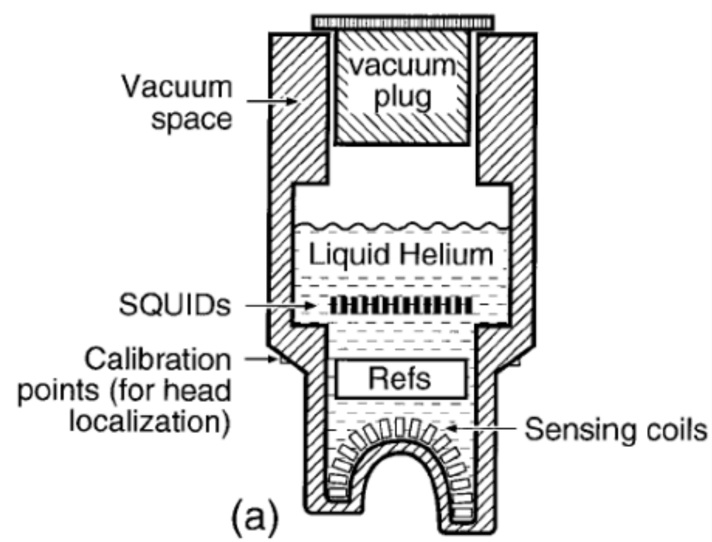
BESA Brain electrical sources analysis procedure.

- Knowing *likely* sources will reduce the inverse problem
- fMRI / PET / patient neuropsychology can indicate likely sources
- Realistic head models / subject's own MRI can improve estimation of potential sources

Magnetoencephalogram (MEG)

Birth of MEG: David Cohen, 1968.

- SQUID Sensors to detect magnetic Flux of 10th of fT
- Shielded rooms made of successive layers of mu-metal, copper and aluminum.



From Vrba & Robinson, 2001

Slide is modified from Houches and Hipp, 2007.

Source Localization EEG vs MEG