LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Neural Networks to Consumer Networks: EEG in Research and Marketing

Introduction to ERP Analysis using EEGLAB

PART I

Dr. Artyom Zinchenko

MUNICH-ÇANAKKALE 2026

15.04.2026

Why EEG?

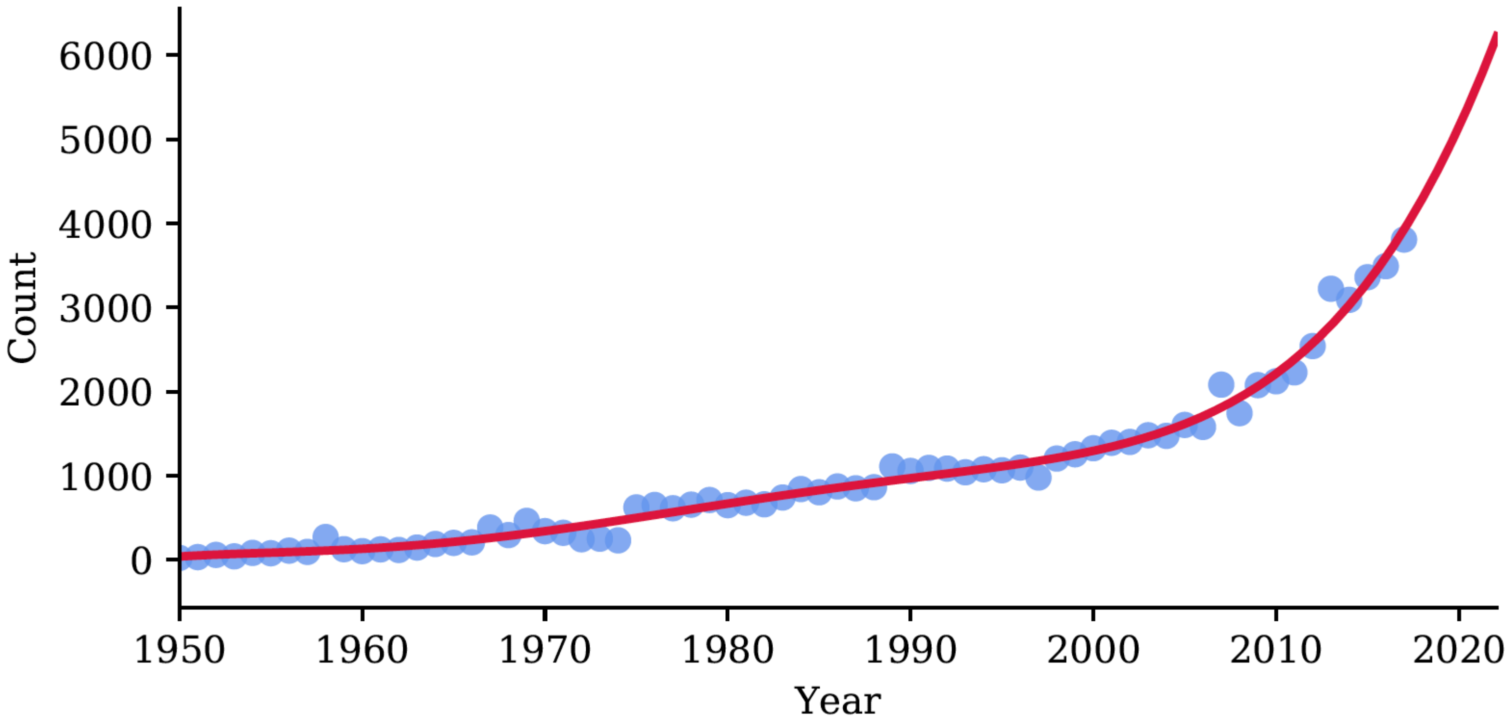


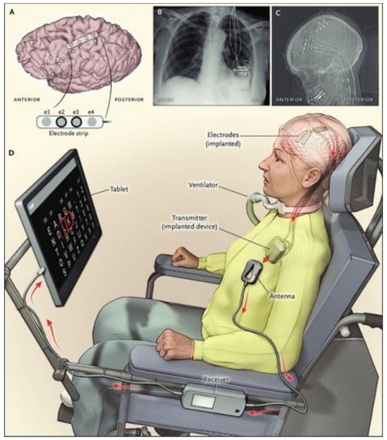
Figure 1: Number of publications per year since 1950 with EEG in the title or abstract as obtained from PubMed. See the code at https://zenodo.org/record/1490630 to reproduce the figure.

Why EEG?

Neuromarketing

Social interactions

Brain computer interfaces (BCI)



Clinical psychiatric studies

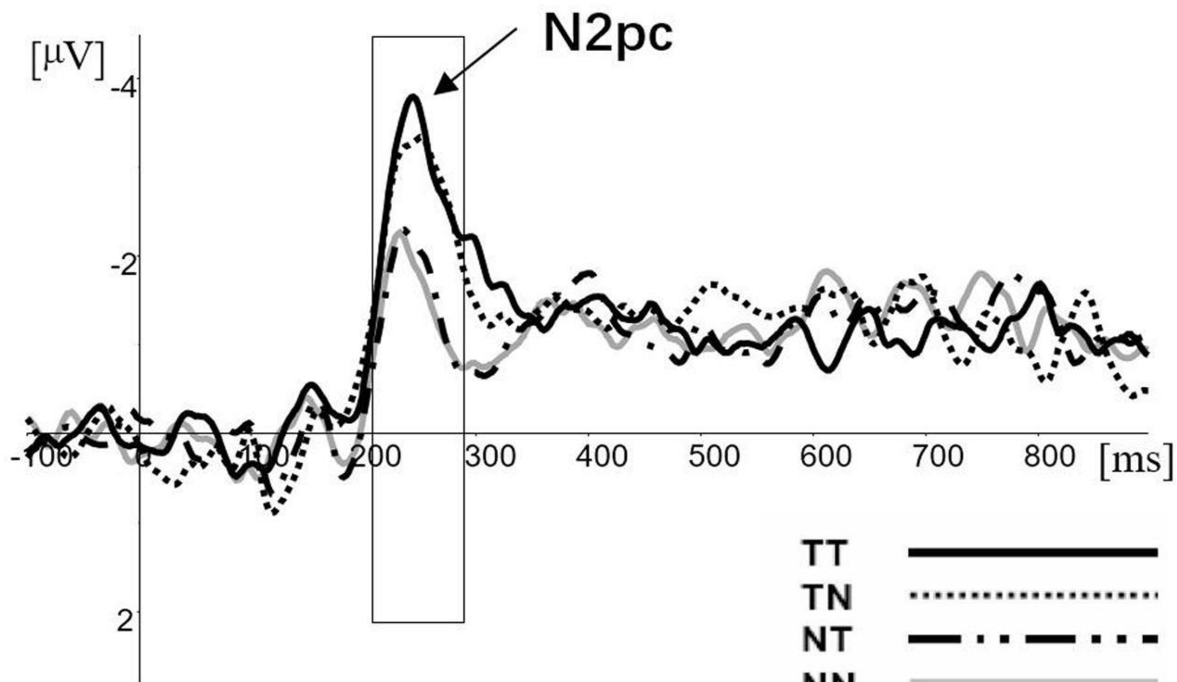
https://www.youtube.com/watch?v=3OVtRCKegfQ

https://pubmed.ncbi.nlm.nih.gov/27959736/

https://imotions.com/blog/top-6-common-applications-human-eeg-research/

Why EEG?

Experimental Psychology



https://www.frontiersin.org/articles/10.3389/fpsyg.2017.02275/full

Overview

The Neural Origins of ERPs

a) Basic Electrical Concepts
b) Signal Transmission Within and Across Neurons
c) Scalp-recorded Potentials, Topographies, and the Inverse Problem

Basic Principles 2 of ERP Recording

a) The Importance of Clean Data
b) Electrodes, Cap Application, and Head Preparation
c) The Data Acquisition System

1a

Basic Electrical Concepts

Ohm‘s Law

Voltage(E) = Current(I) x Resistance(R)

Ohm‘s Law: E = IxR

Voltage(E) = Current(I) x Resistance(R)

Voltage (E, Electromotive Force; Volts)

- is not the actual flow of electricity!
- is the pressure that pushes the electrical current through the conductor
- … it reflects the potential for charges to flow from one place to another

- analogy: water tank at the top of a hill // water pressure
- i.e., potential for water to flow downhill is present even if no water is actually flowing

Ohm‘s Law: $E = I \times R$

Voltage(E) = Current(I) x Resistance(R)

Current (I, Intensity; Amperes)

- … is the actual flow of electricity through a conductor (e.g., brain)

- measures the amount of charged units (electrons or protons) that move across space

- analogy: flow of water through a pipe or hose

Ohm‘s Law: E = IxR

Voltage(E) = Current(I) x Resistance(R)




Resistance (R, measured in ohms (Ω) **):**

•Resistance, often denoted as R, is a fundamental property of materials and components in electrical circuits that opposes the flow of electric current.

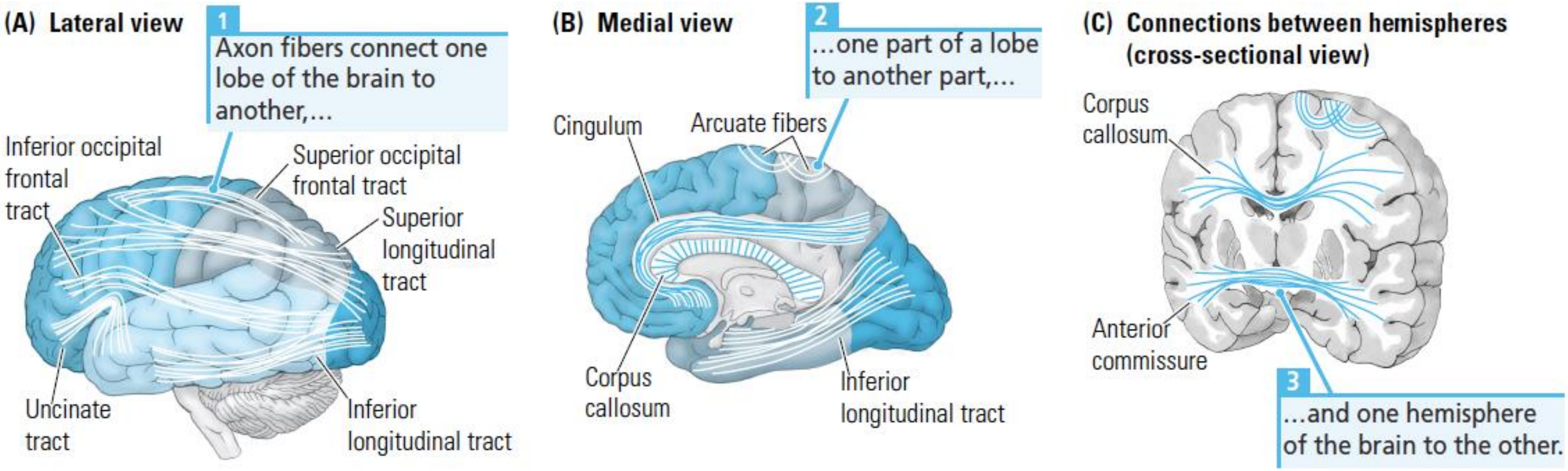
•It is named after the German physicist Georg Simon Ohm, and one ohm represents the resistance that allows one ampere of current to flow when one volt of voltage is applied across it.

- analogy: flow of water through a wide vs. narrow pipe

1b

Signal Transmission Within and Across Neurons

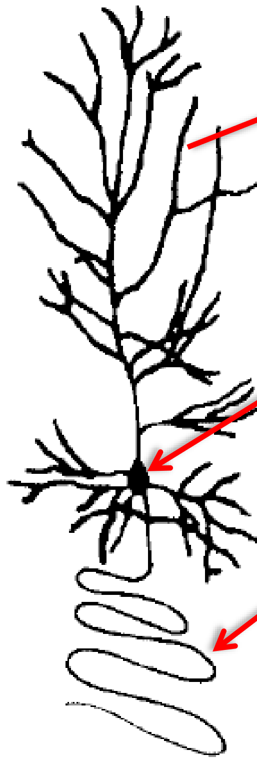
Connections Between Cortical Areas



Signal Transmission

- chemical between neurons (at the synapse)
- electrical within a neuron

Information Flow in a Neuron



Neuron
(pyramidal cell)

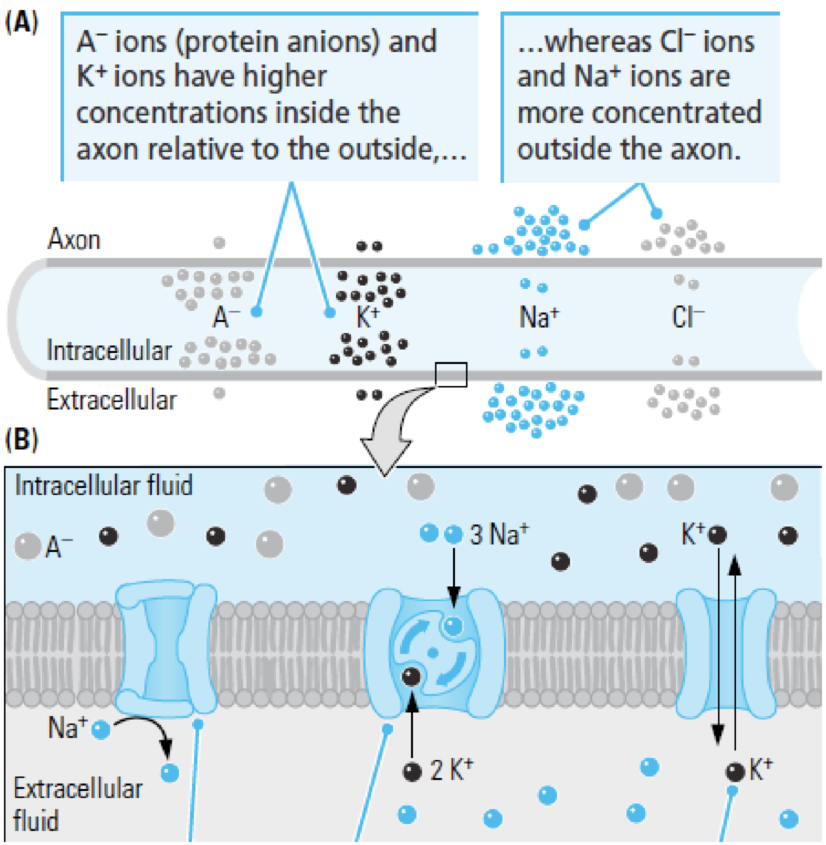
...Information from other neurons is **collected** at dendrites.

... **processed/integrated** in the cell body (soma)

... and then **sent** to the axon, where it is passed on to a target neuron

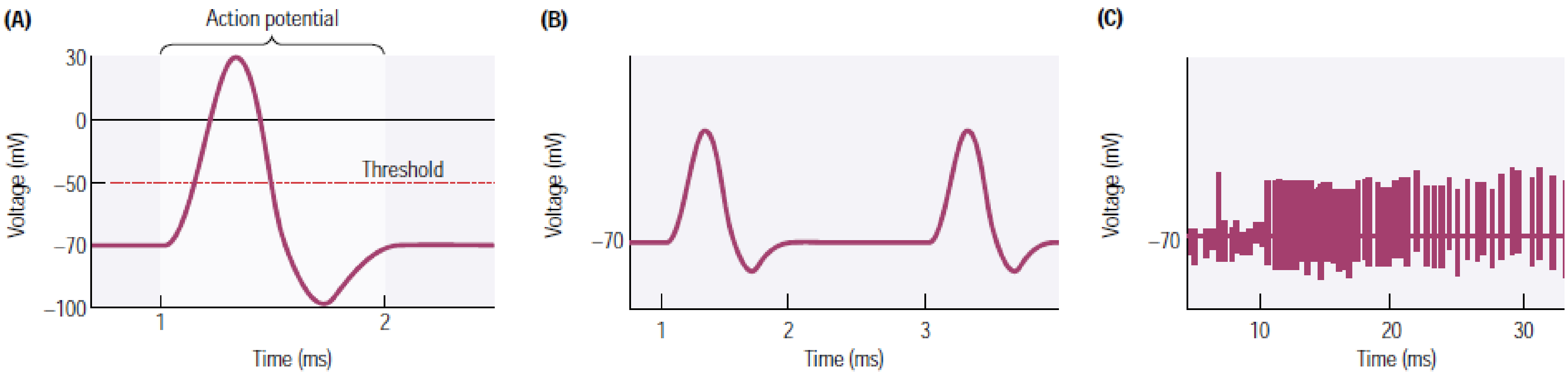
1. The Resting Potential: - 70 mV

(inside relative to the outside)



- produced by 4 kinds of ions: - sodium (Na^+), chlorid (Cl^-), potassium (K^+), protein anions (A^-)
- Na^+ channels are ordinarily closed, while K^+ ions are free to enter and leave the cell
- high extracellular Na^+ concentration due to Na^+ K^+ pump, exchanges 3 Na^+ for 2 K^+ ions

2. The Action Potential

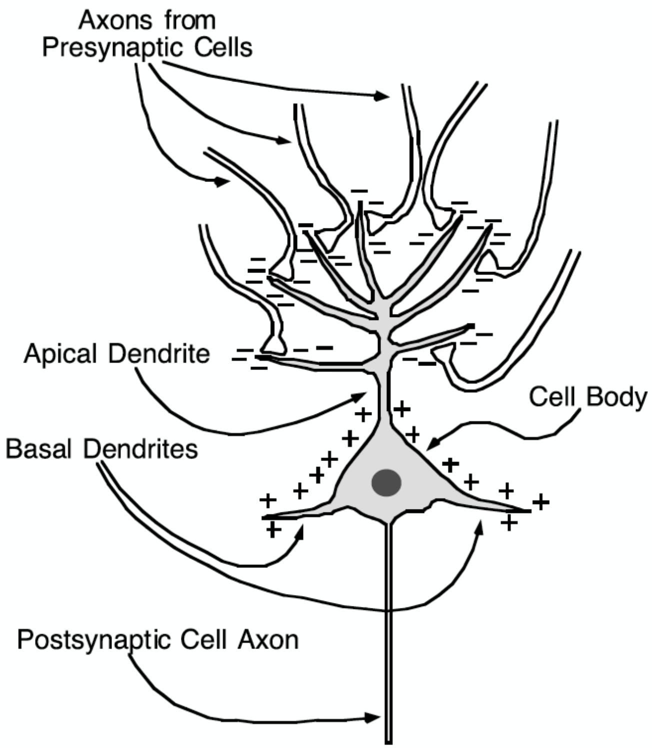


= brief but large change in polarity of an axon‘s membrane

... making the inside positive relative to the outside, and then abruptly reverses again

... information coding via spike rate

3. The Postsynaptic Potential



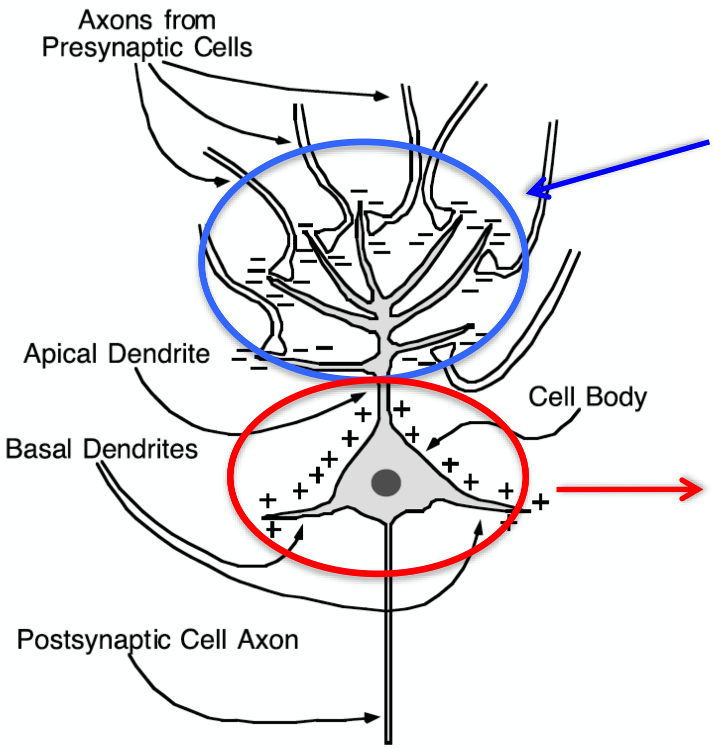
Cortical pyramidal cell

voltages that **arise** when the neurotransmitters bind to the receptors on the postsynaptic cell membrane

... can **last** hundreds of milliseconds

... are **largely** confined to the dendrites and cell body

3. The Postsynaptic Potential



Cortical pyramidal cell

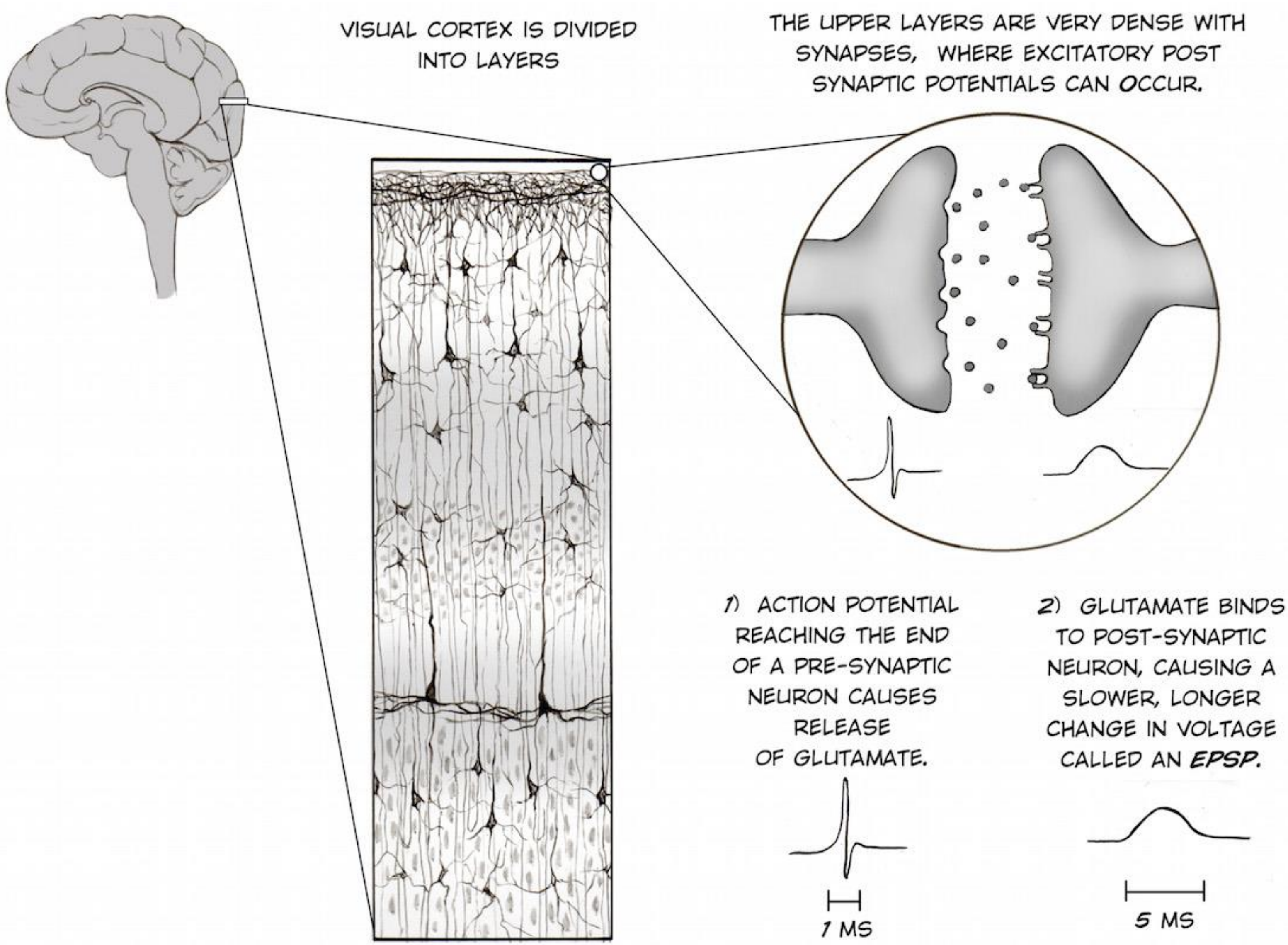
excitatory transmitter released on apical dendrites causes positive charges to flow into the cell >> yielding a net negativity outside of the cell

… to complete the circuit, current will also flow out of the soma and basal dendrites >> yielding a net positivity

This negativity (at the apical dendrites) and positivity (at the soma) create a **dipole**

> Polarity reverses with inhibitory transmitter!

From Single Neurons to Scalp-recorded Potentials



https://docs.backyardbrains.com/retired/experiments/eeg/

Action vs. Postsynaptic Potentials

	Action Potentials	Postsynaptic Potentials
Definition	discrete voltage spikes that travel from the soma to the axon terminals	graded changes in the membrane potential of the post-synaptic terminal
Duration	~ 1 msec	can last up to several hundred msec
Summation between Neurons	highly unlikely	possible
Measures	single-cell recordings	surface electrode recordings

ERPs reflect Postsynaptic Potentials rather than Action Potentials

1c

Scalp-recorded Potentials, Topographies, and the Inverse Problem

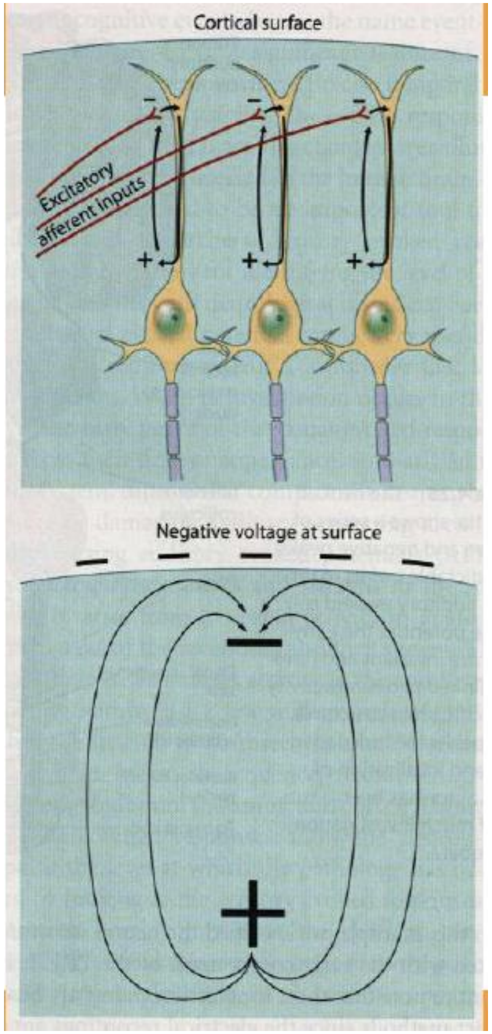
From Single Neurons to Scalp-recorded Potentials

a single neuronal dipole is too small to be detected
... but, dipoles from many neurons may summate,
IF:

- they occur at approximately the same time across large numbers of neurons (i.e., they fire in a synchronized manner)

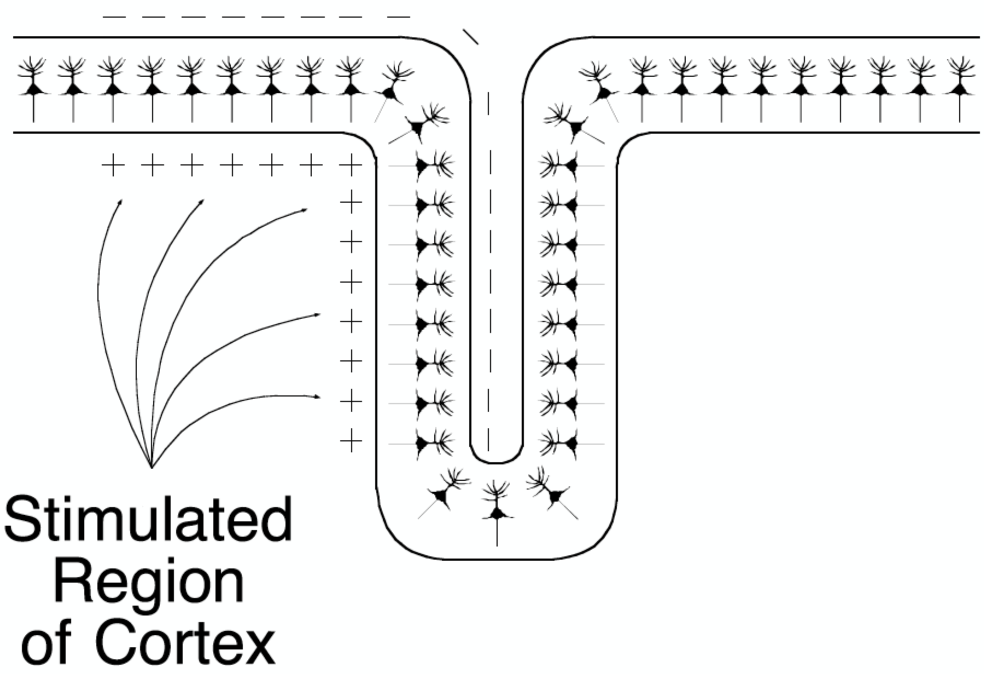
- they receive the same kind of input (excitatory vs. inhibitory)

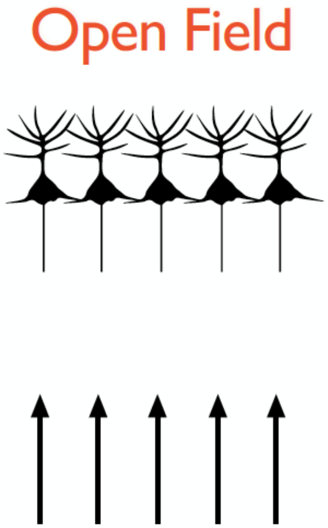
- they are spatially aligned (i.e., similar oriented dipoles → open electrical field)



From Single Neurons to Scalp-recorded Potentials

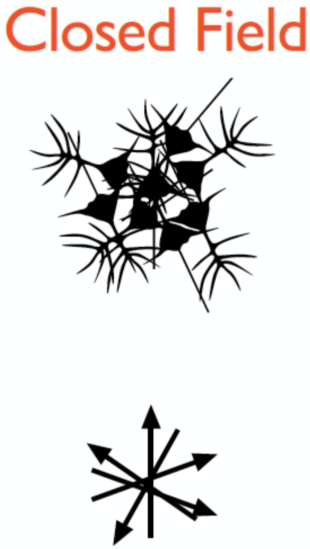
most likely cortical pyramidal cells, which are aligned perpendicular to the surface of the cortex

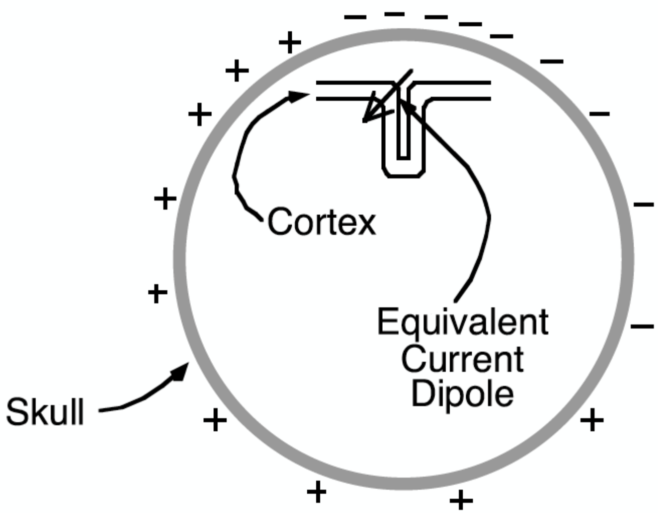




From Single Neurons to Scalp-recorded Potentials

most unlikely cerebellar cells (and glial and sub-cortical cells), as cortical surface is so highly folded **that the dipoles between nearby cortical patches will cancel**





Electricity does not run directly between two poles of a dipole, but instead:

‣ spreads through the brain by „volume conduction; nearly at the speed of light

‣ follows the path of least resistance: Ohm‘s law: V=IR

‣ spreads laterally when encountered with resistance of the skull

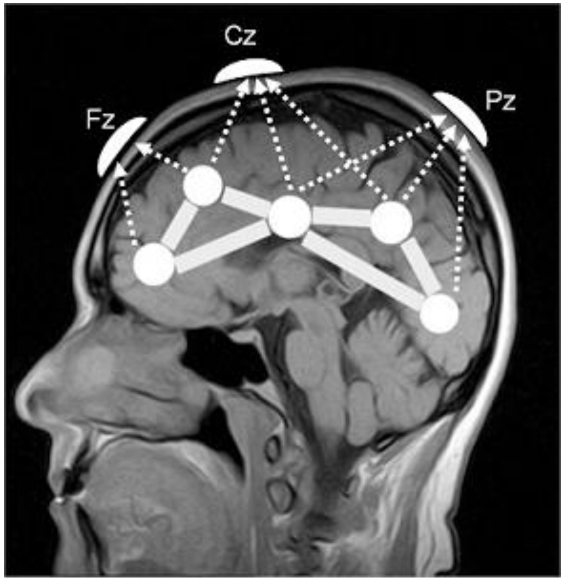
Blurring of scalp distribution of ERPs >> Inverse problem of source localization!

ERP Source localization

Inverse (or superposition) **problem**:

- ... to compute the location and orientation for one or more dipoles underlying a given scalp distribution

- ... is an „ill-posed“ problem since any scalp distribution can be explained by an infinite number of different dipole configurations



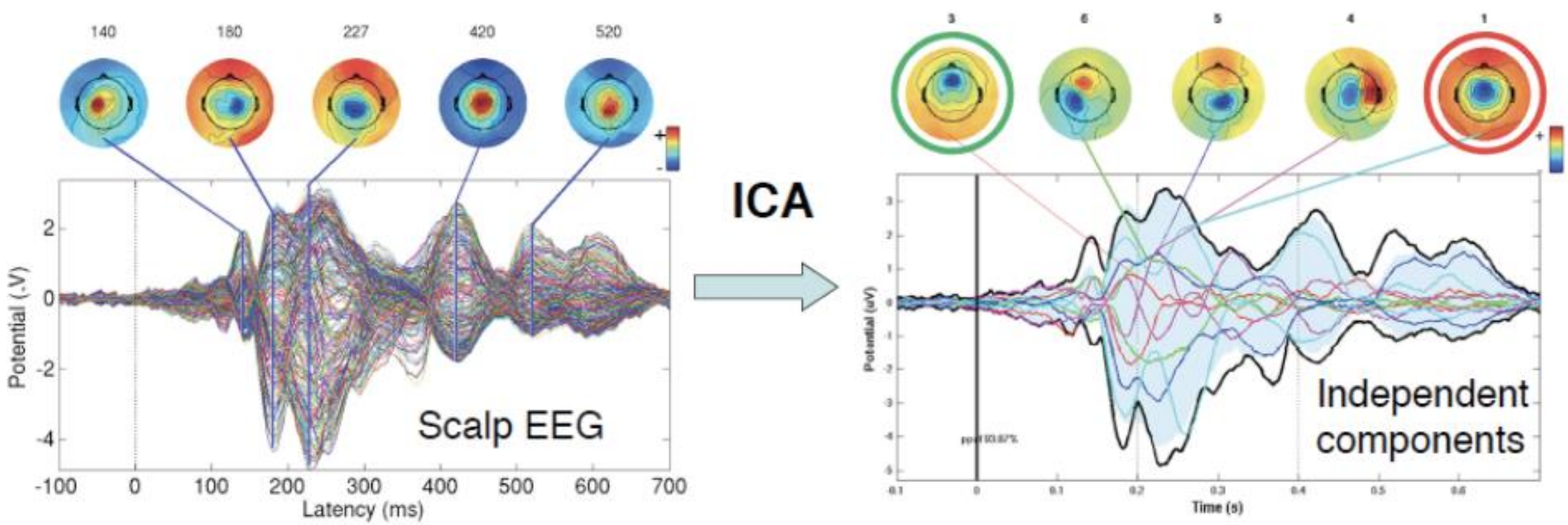
Forward problem:

- ... to compute the distribution of voltage observed for one or more dipoles with a known location (→ relatively easy to solve)

Topography vs. sources

Be careful to infer EEG sources from EEG topographies!

One (debatable) strategy: Try to minimize solutions by limiting the number of possible dipoles to „one“; for example, by running ICA first ...



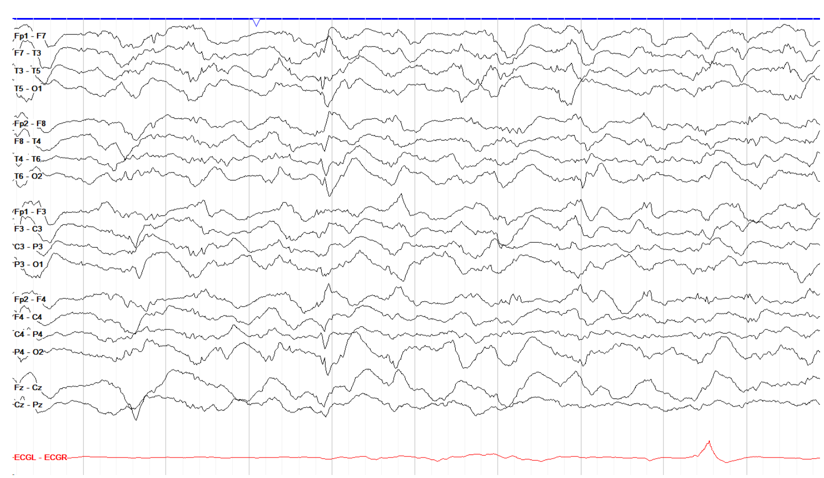
From Single Neurons to Scalp-recorded Potentials

Voltage depends on:

- magnitude of current flowing through the postsynaptic membrane
- resistance and shape of various components of the head
- number of synchronously firing, spatially aligned cortical neurons
- location and orientation of the generator dipole

Polarity depends on:

- type of transmitters: excitatory vs. inhibitory
- location and orientation of postsynaptic activity
- orientation of the cortical surface
- location of reference electrode



Interim Summary

EEG is sensitive to:

‣ excitatory and inhibitory postsynaptic potentials at apical dendrites of massively synchronized cortical neurons

EEG is not very sensitive to:

‣ action potentials
‣ single neurons and/or asynchronous activity
‣ glial and subcortical cell‘s activity

EEG source localization techniques are still very poor:

‣ better change method if interested in high spatial resolutions

2a

The Importance of Clean Data

Trial Number & Signal-to-Noise Ratio

trial number = one of the most important parameters to be set!

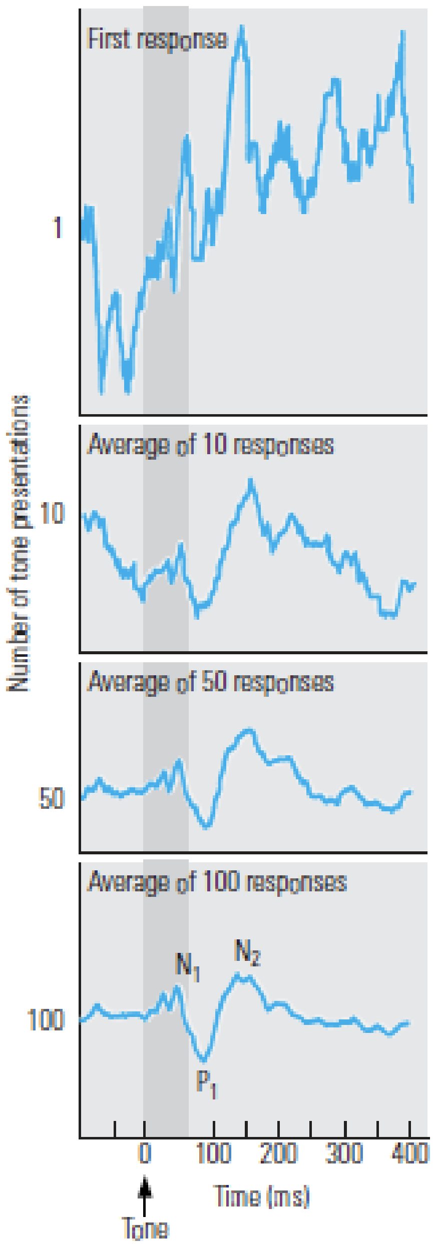
SNR increases with number of trials!!!

Luck's rule of thumb:

- small components (P1) >> 400-800 trials
- medium-sized components (N2) >> 150-200 trials
- large components (P3) >> 30-60 trials
- needs to be doubled for children/psychiatric patients

BUT, noise decreases as a function of the square root of the trial number:

➡doubling the trial number reduces noise about 30%
➡doubling the SNR requires 4 times as many trials!!!



Hansen‘s Axiom

„There is no substitute for good data.“

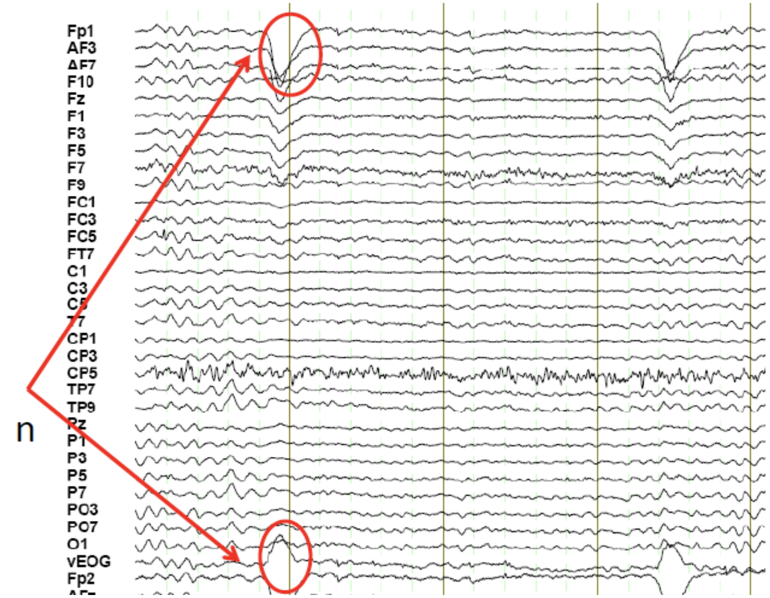
4 Main Sources of Noise

I. Environmental electrical activity

- Line frequency noise from video monitors, and other electrical devices

II. Artifactual bioelectric activity

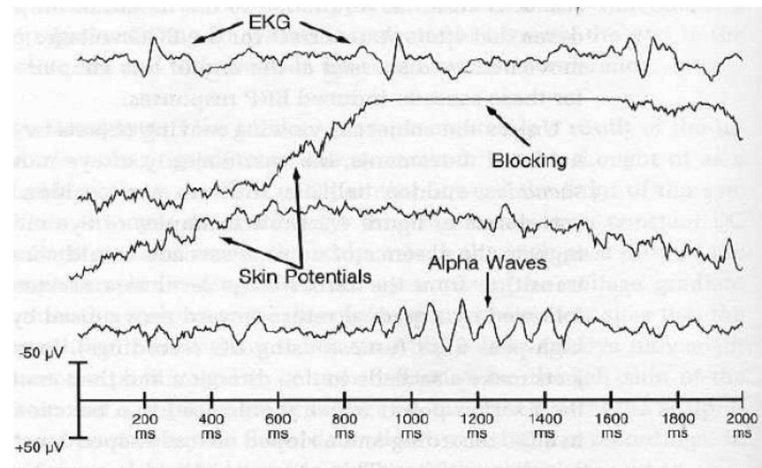
- Blinks & eye movements
- Muscle (EMG) & heart activity (EKG)
- Skin potentials (=slow voltage shifts)



III.EEG activity not elicited by the stimuli

- Alpha waves

IV.EEG trial-to-trial variability due to variations in neural/cognitive activity



Recommendations for Noise Minimization

- **Line frequency noise** (e.g., video monitors)

(1) electrically shielded cabin

(2) placing the video monitor outside the cabin

(3) placing the monitor inside a Faraday cage

(4) shielded AC power cord

(5) replacing AC lights with DC lights

(6) 30 Hz low-pass filter or notch filter

Recommendations for Noise Minimization

- **Blinks**

(7) don‘t instruct to blink during intertrial interval!

(8) subjects should wear glasses instead of contact lenses

(9) supply of eye drops

(10) use blocks of 5 minutes with a minimum break of 20-30s

(11) let subject know about blinks

(12) use VEOG and Fp1 electrodes

Recommendations for Noise Minimization

- **Slow voltage shifts**

(13) maintain the recording chamber at a cool temperature

(14) low humidity level

(15) run a fan between trial blocks

(16) make sure that the subject doesn‘t move

(17) don‘t use a head rest

(18) use 0.1 Hz high-pass filter to reduce shifts

Recommendations for Noise Minimization

- **Alpha waves**

  (19) use well-rested subjects

  (20) use intertrial interval-jitter of +/- 50 msec

  (21) keep subjects happy (e.g., drinks, snacks, etc.)

  (22) avoid late afternoon hours

Eliminating all these sources of noise can save up to 30-50 % trials!

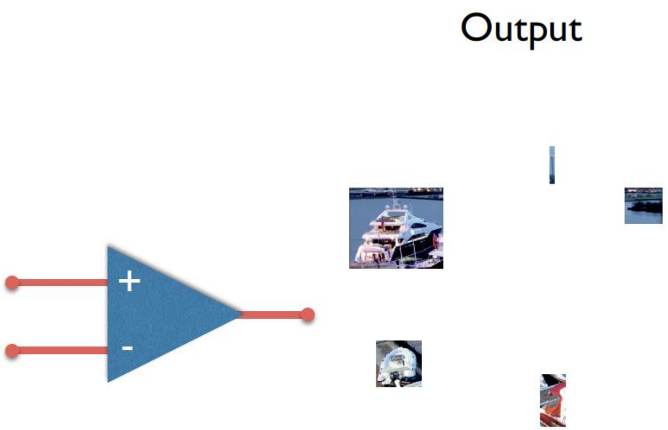
2b

Electrodes, Cap Application, and Head Preparation

How is EEG recorded?

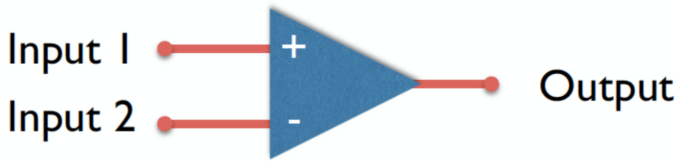
Differential Amplifier System

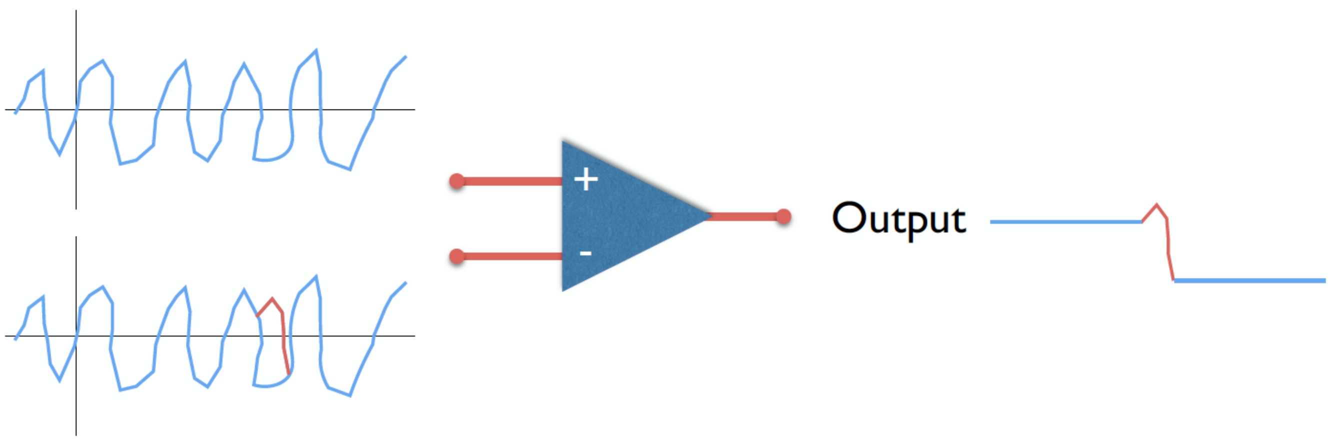
Differential Amplifier System



… displays the output as the difference between the inputs

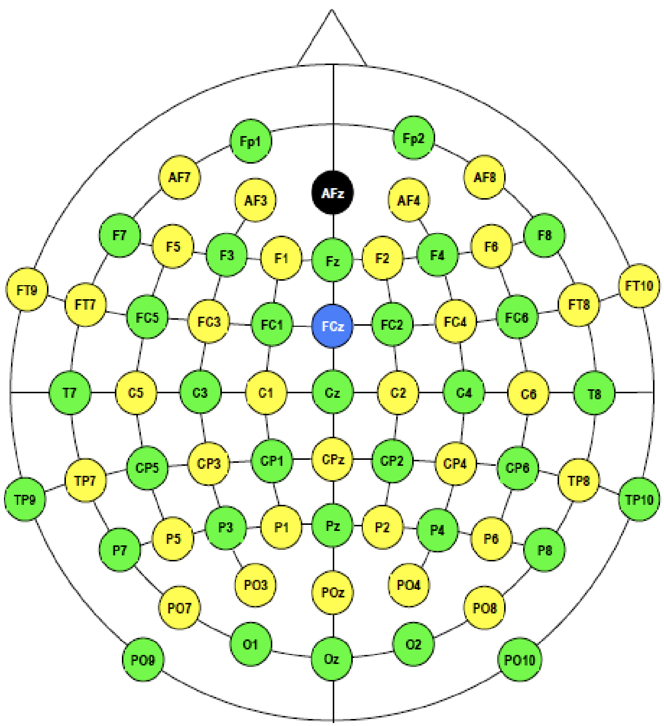
Differential Amplifier System





EEG is always relative

Differential Amplifier System



uses 3 different electrode types

- ACTIVE (A), REFERENCE (R), & GROUND (G)
- Voltage is measured between ACTIVE and GROUND
- Voltage is measured between REFERENCE and GROUND
- Output is difference between these voltages!
- Observed Voltage = (A-G) minus (R-G)

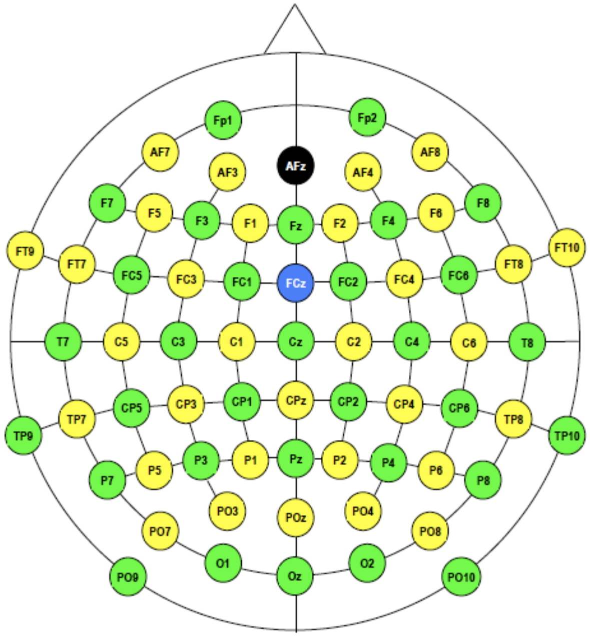
Any signals that are common to A and R will be eliminated!

ERPs reflect the Difference in Activity between Two Sites, Not the Activity at a Single Electrode.

Choosing a Reference Site

Consider …

- as neutral as possible
- convenient and comfortable
- not be biased to one hemisphere
- avoid electrodes prone to noise
- common to other investigators/labs



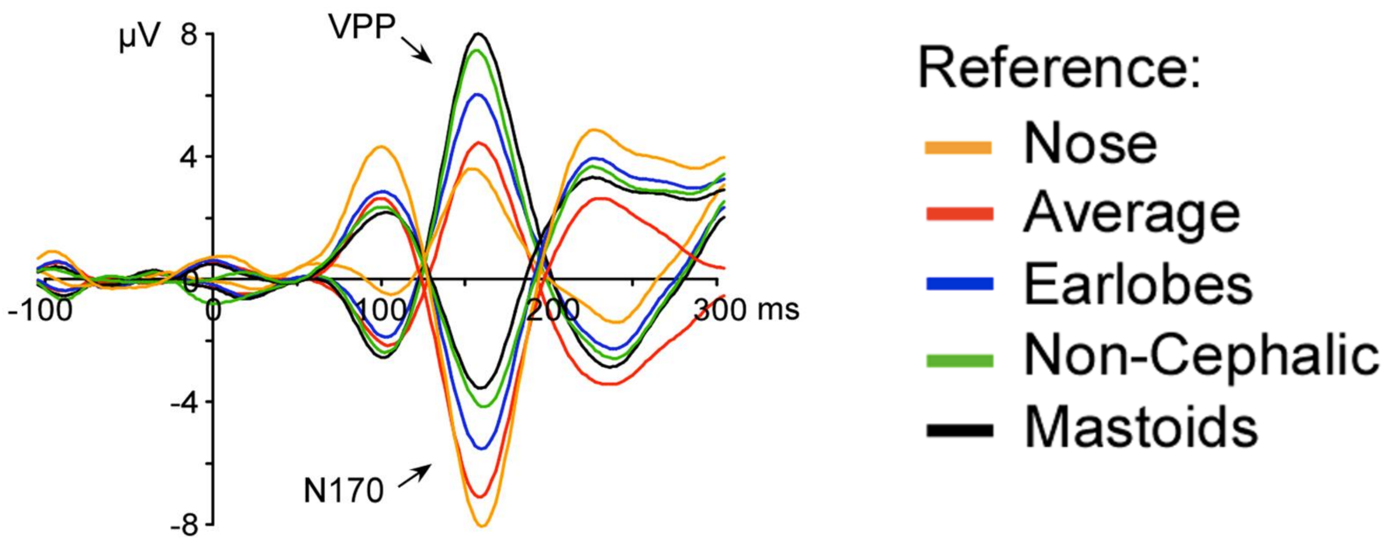
Most common (offline) reference sites are the earlobes & averaged mastoids

Be careful with common avergage reference! Might reverse polarity!

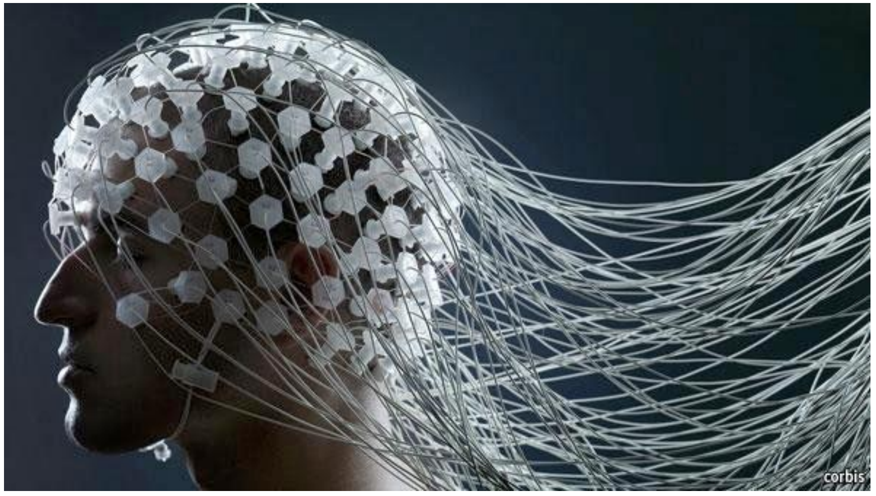
Choosing a Reference Site

➡ Ideal: Active electrodes placed near the active neural tissue; reference electrode placed at distant, neutral site (e.g., earlobes)

➡ Reality: There is no electrically neutral site!

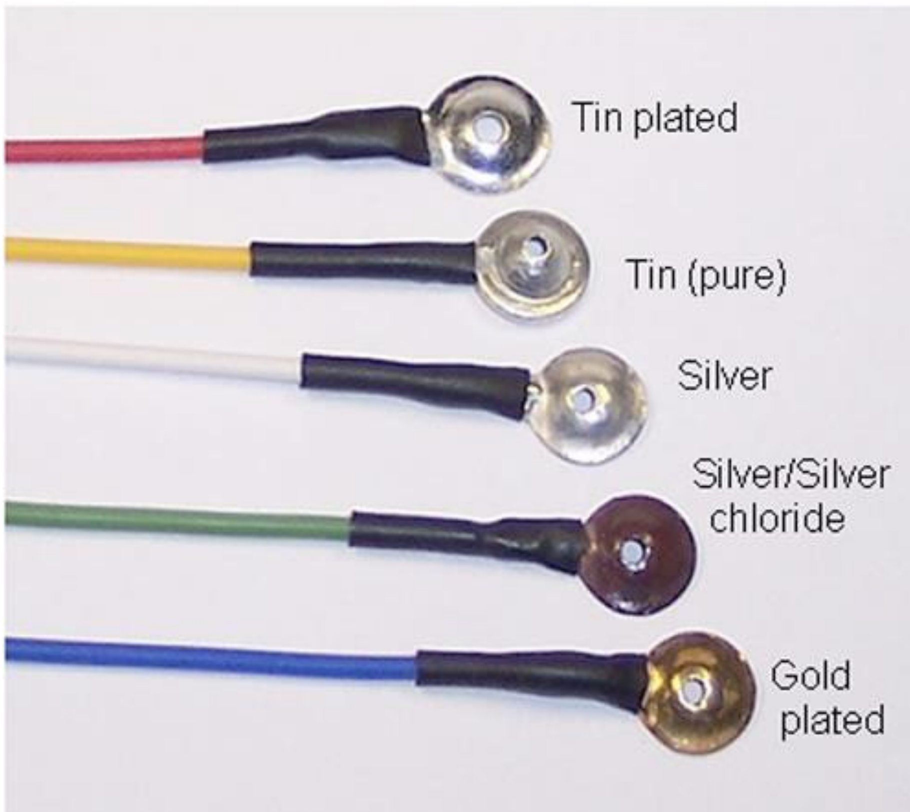


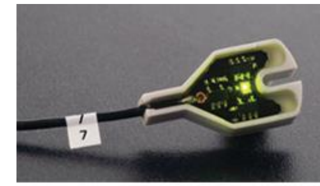
ERPs can change polarity with different references!



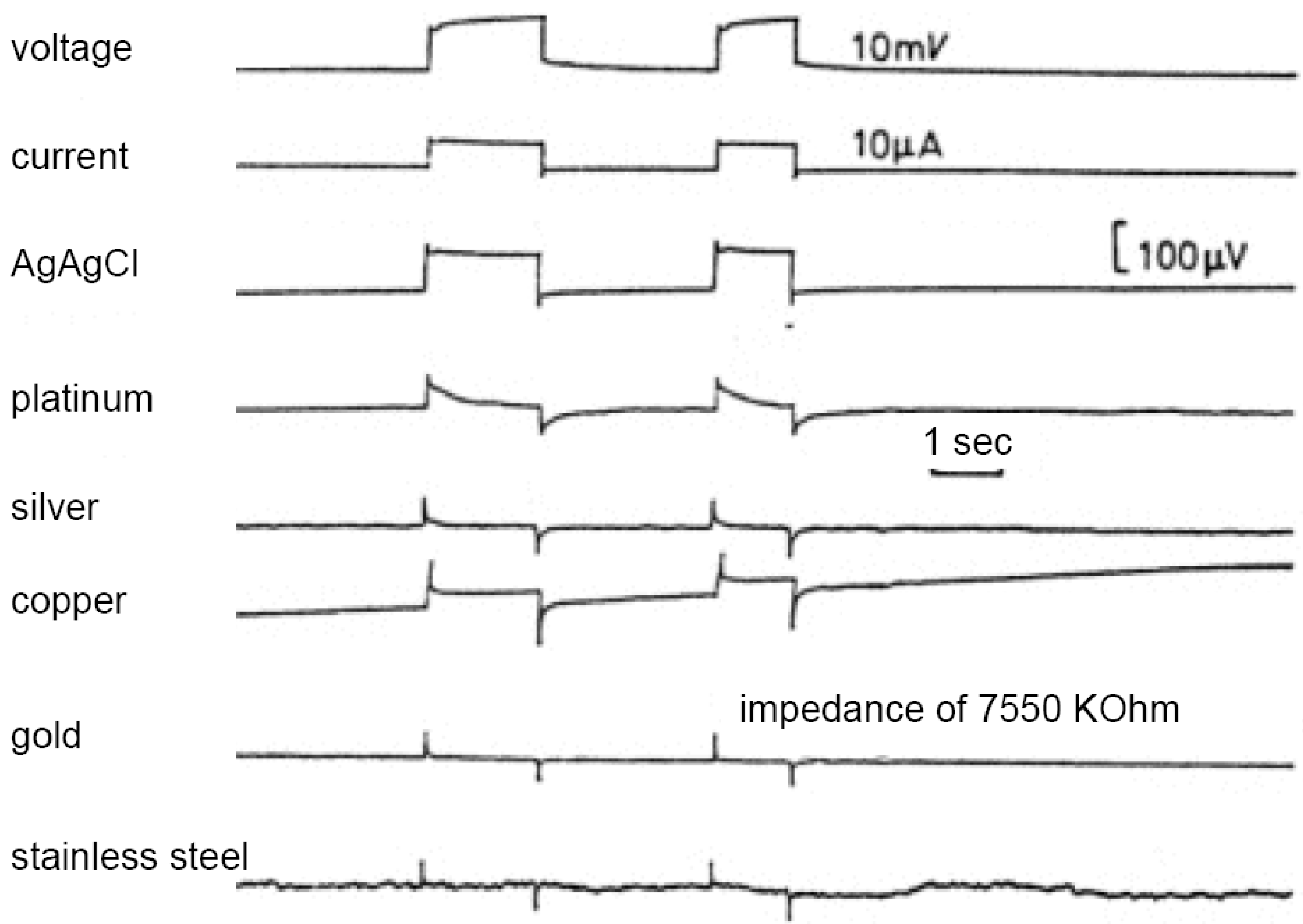
- Electrode types
- Electrode placement
- Cap Application
- Head Preparation

Various Electrode Types

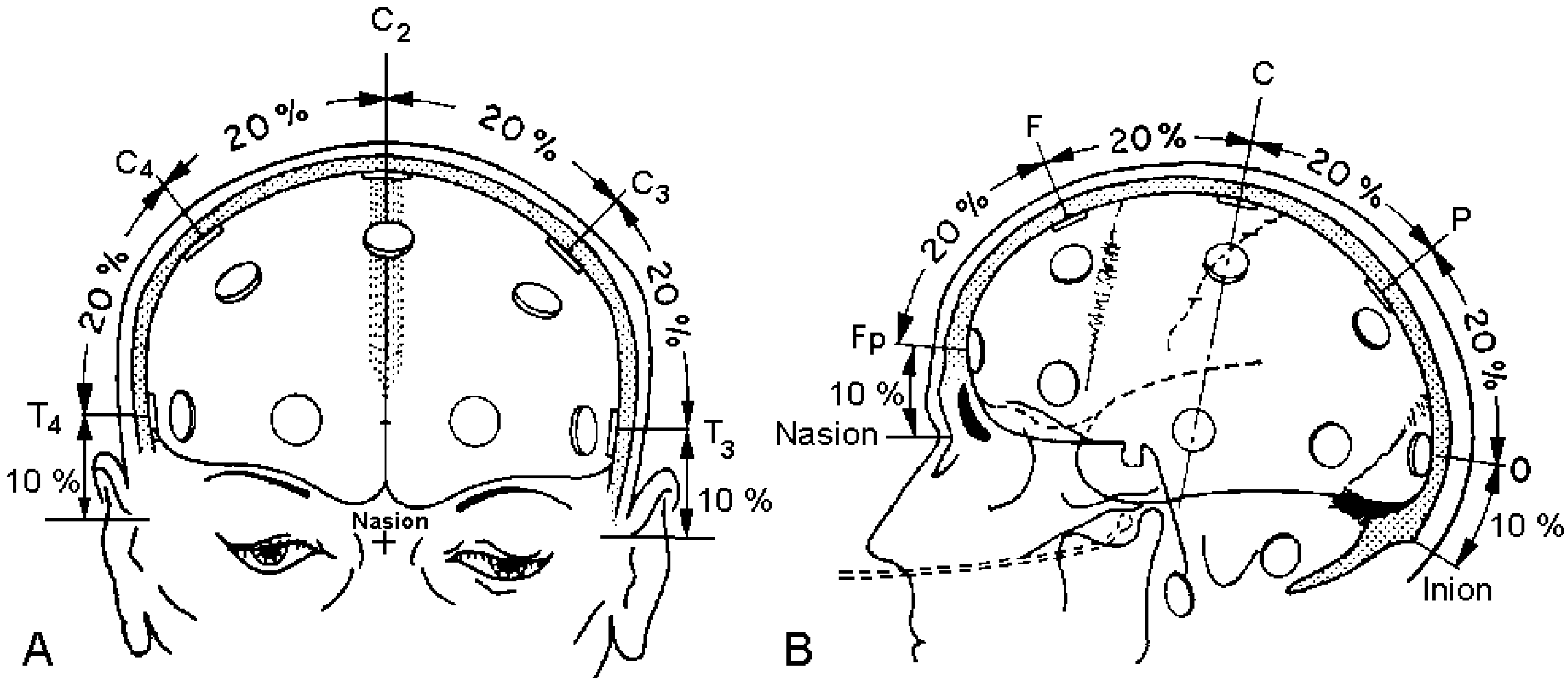




Various Electrode Types

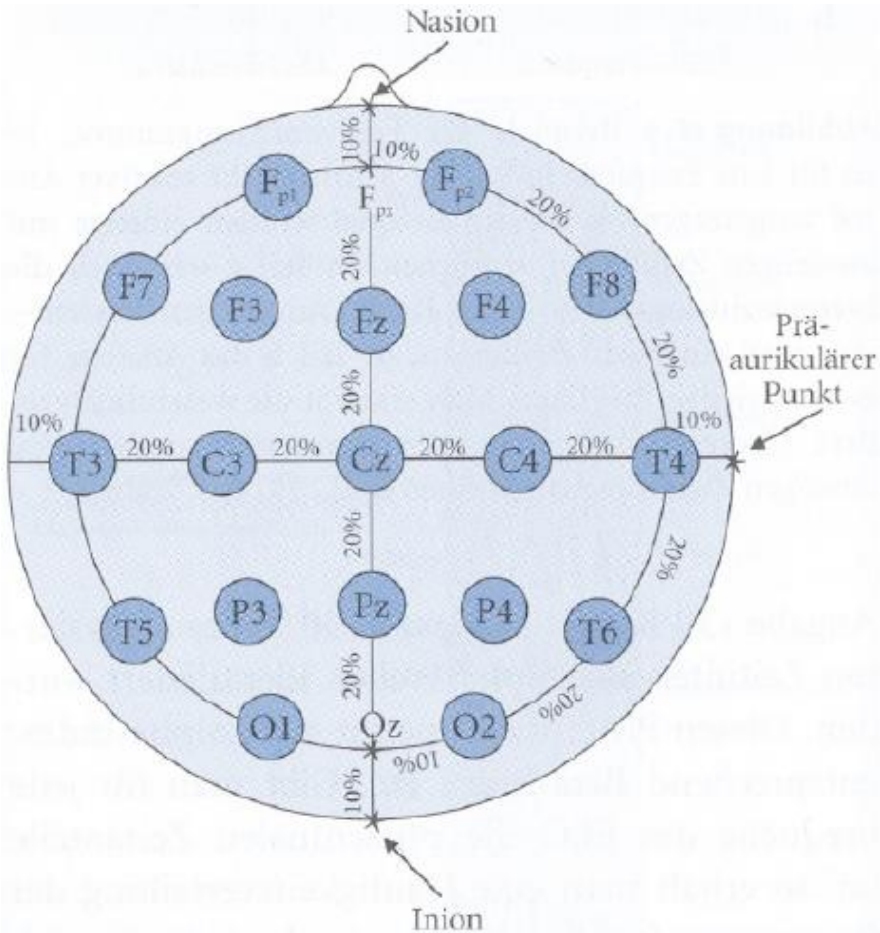


EEG Electrode Placement



The original figure introducing the 10-20 system (Jasper, 1958), with the 19 electrodes erroneously located inside the skull on the surface of the cortex

3 Advantages of Standardized EEG Electrode Placement



- placement independent of head size
- comparison of results across individuals and paradigms
- communication/comparison across different laboratories

EEG Electrode Labeling

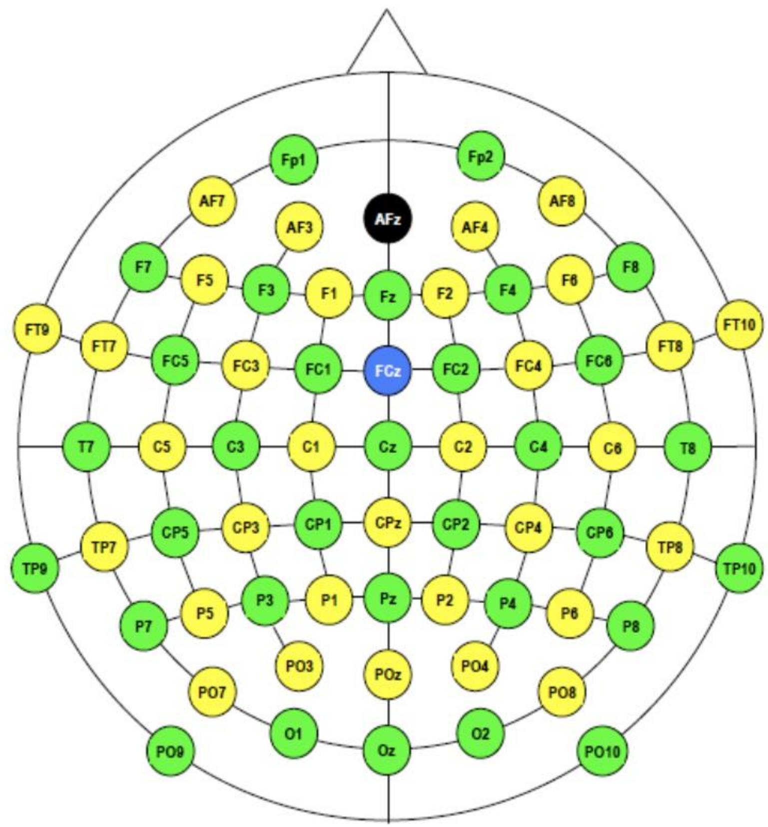
F = Frontal

C = Central

T = Temporal

P = Parietal

O = Occipital



Fp = Fronto-polar

AF = Anterior-Frontal

FC = Fronto-Central

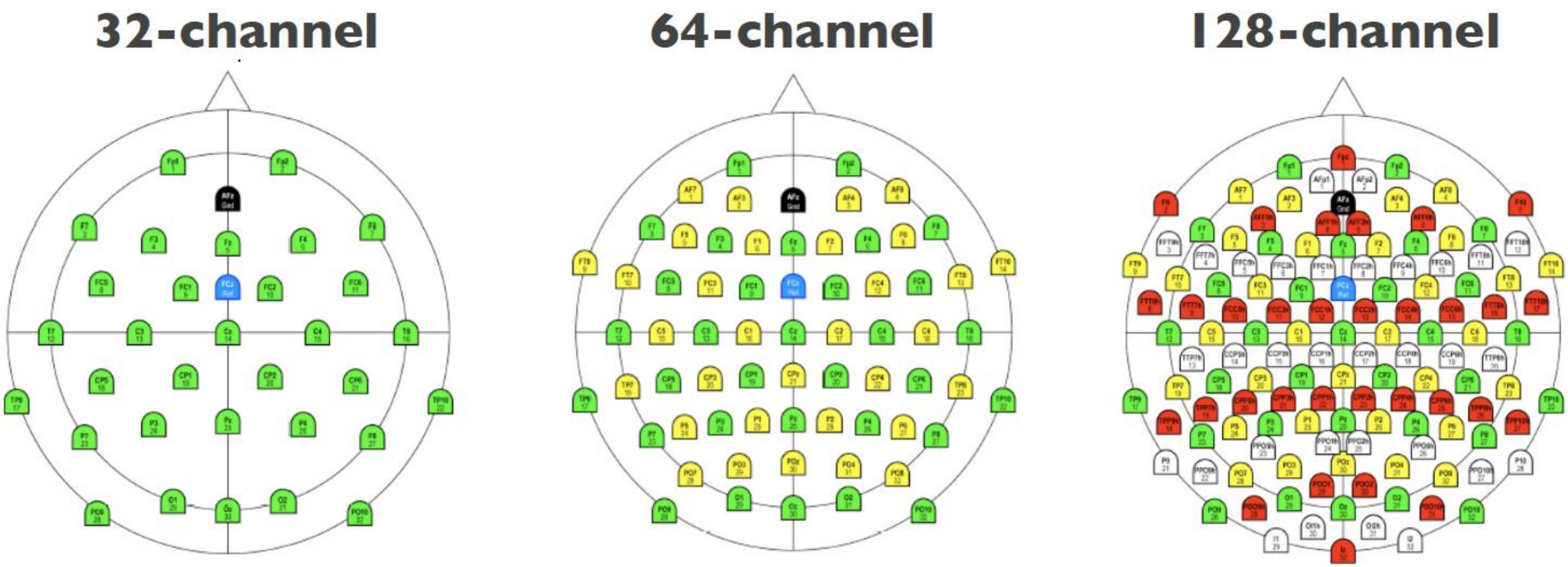
CP = Centro-Parietal

PO = Parieto-Occipital

Odd Numbers = Left Hemisphere

Even Numbers = Right Hemisphere

EEG Channels Montages

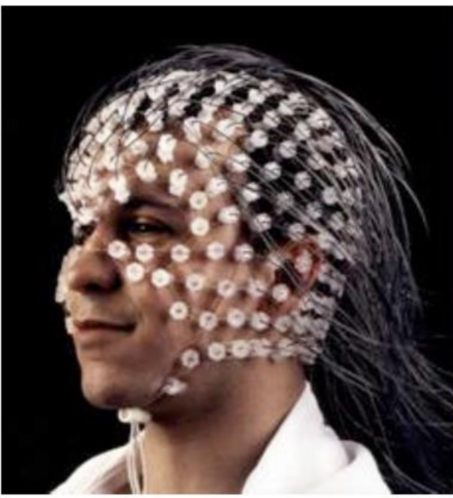


But ... do you really need 128 channels?

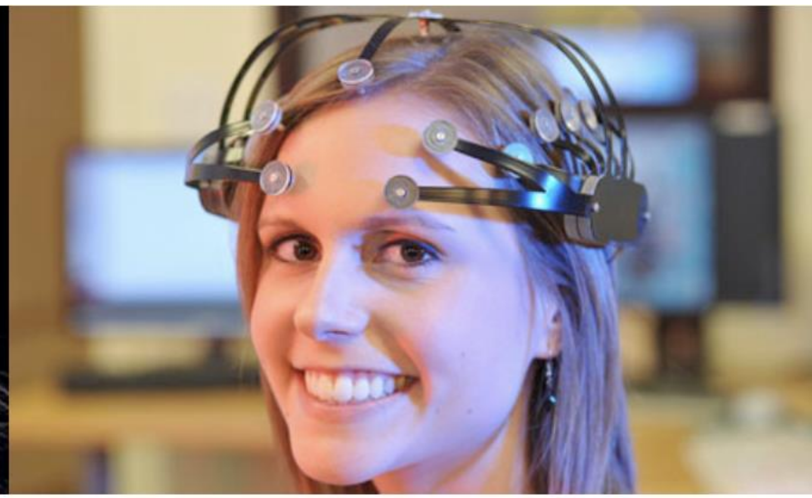
Potential Issues: Bridging, more electrodes > more chances for problems

<u>Dilution Rule</u>: Don‘t dilute good data by adding bad data!

Various Attachments of Electrode



Geodesic net
up to 512 channels



Wireless EEG
(currently) only a few

Elastic cap
up to 256 channels

Elastic Cap Application

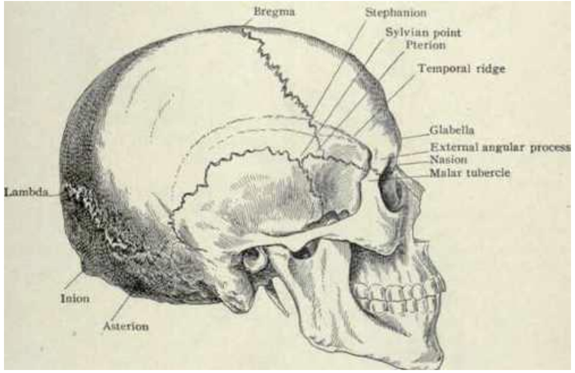
Two Measures:

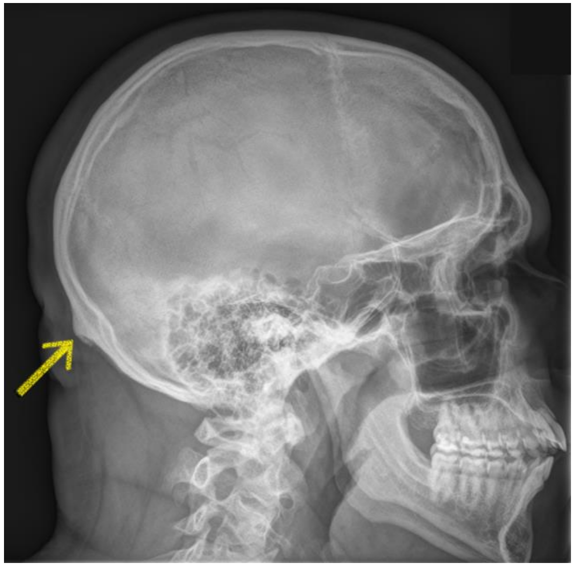
1. Circumference of the head = cap size
2. Distance between nasion (intersection of the frontal bone and the two nasal bones) and inion (most prominent projection of the occipital bone)

Correct Placement of Cap

1. according to standardized positions >>
Cz at 50%, and Fpz at10%, of the distance between nasion and inion

2. Additional Fixation of the cap via strips
>> to prevent from displacement/movements





Electrode Wires

Be always very careful when ...

- placing the cap
- carrying the cap
- preparing the head
- removing the cap
- washing the cap
- plugging the electrodes to the amplifier

Electrode wires break easily and are expensive!

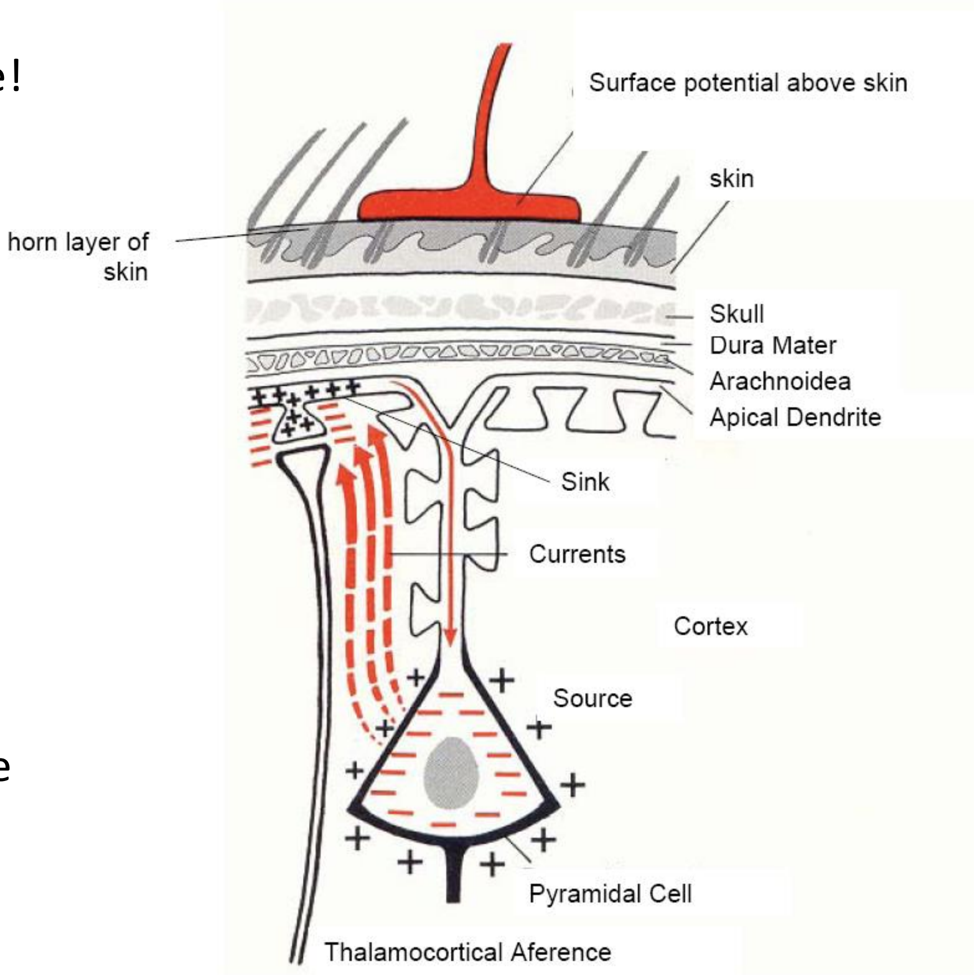
Why Actually Preparing the Head?

To achieve and maintain low impedance!

- for proper differential amplification
- reducing skin potentials

Ohm‘s Law: V=IxR

- Voltage=Current x Resistance
- Make sure you have similar impedance on all channels - as current flows the path of least resistance!

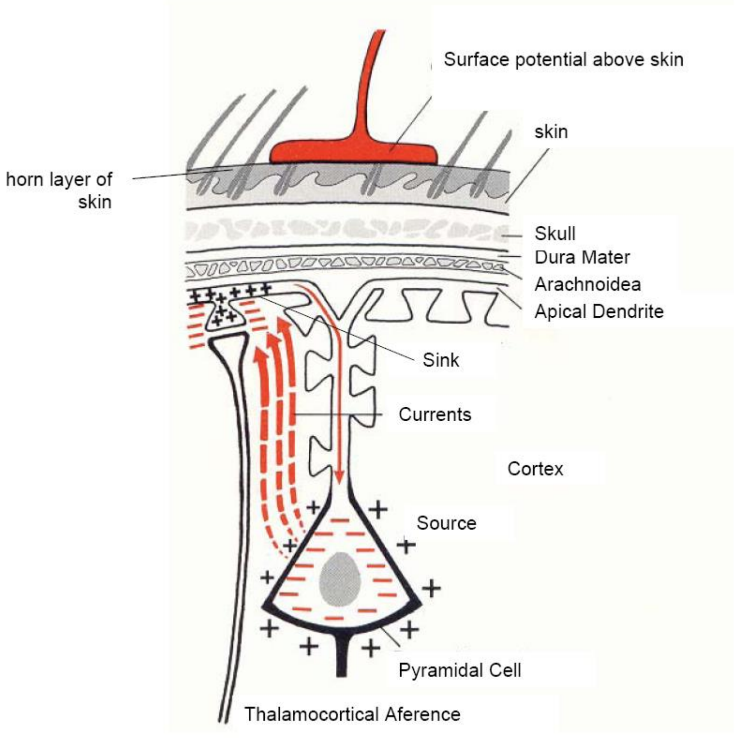


Functions of Electrodes and Gel

Electrodes ...

‣ make the contact between the tissue from which activity is recorded (skin) to the input of the recording system (amplifier)

- Electrolyte (gel) ...
- Creates a stable conductive medium for better volume conduction
- Reduces electrode-skin impedance
- Allows for better transmission of the electrical potential differences
- Improves signal quality by providing a stable electrical interface



Note: too much electrolyte can harm!
→ can produce bridges between electrodes

Head Preparation and Impedance

3-Stage Procedure when using (standard) ring electrodes:

1. Scrubbing the skin with alcohol
using a Q-tip ... to clean the skin

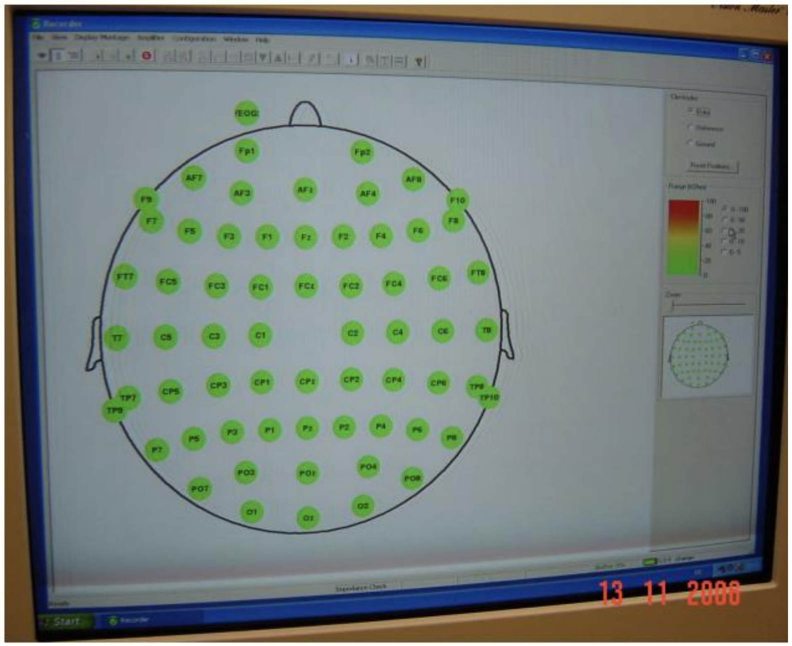
2. Scrubbing the skin with electrolyte
using another Q-tip ... to remove the
outer layer of dead skin cells which cause
high skin impedance

3. Filling-up the electrode channels
with electrolyte using a syringe ... to
build an „elastic bridge“ between skin and
electrode

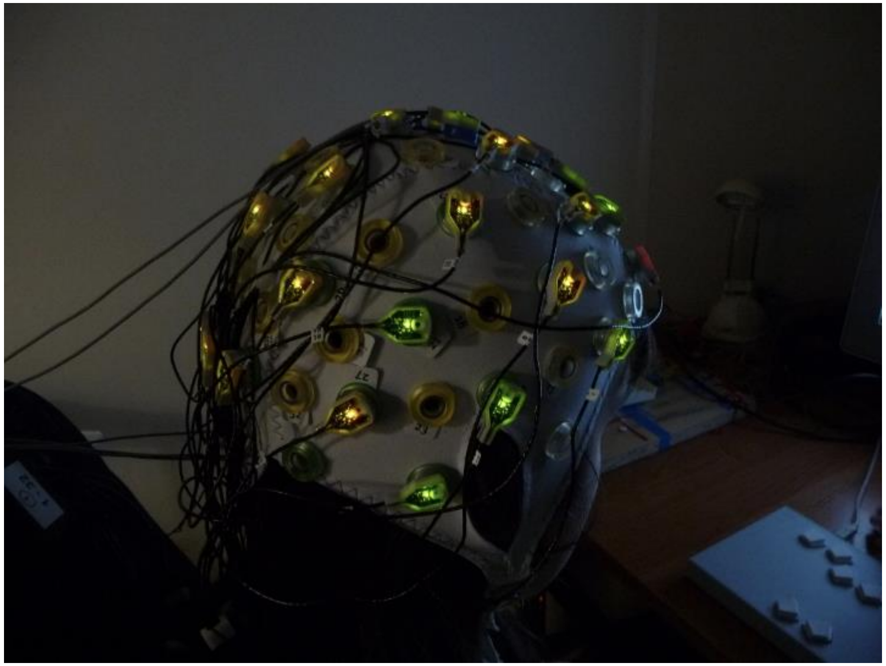
Head Preparation and Impedance

All-in-one Procedure when using (newer) active electrodes

Finally ... Impedance Check



@computer

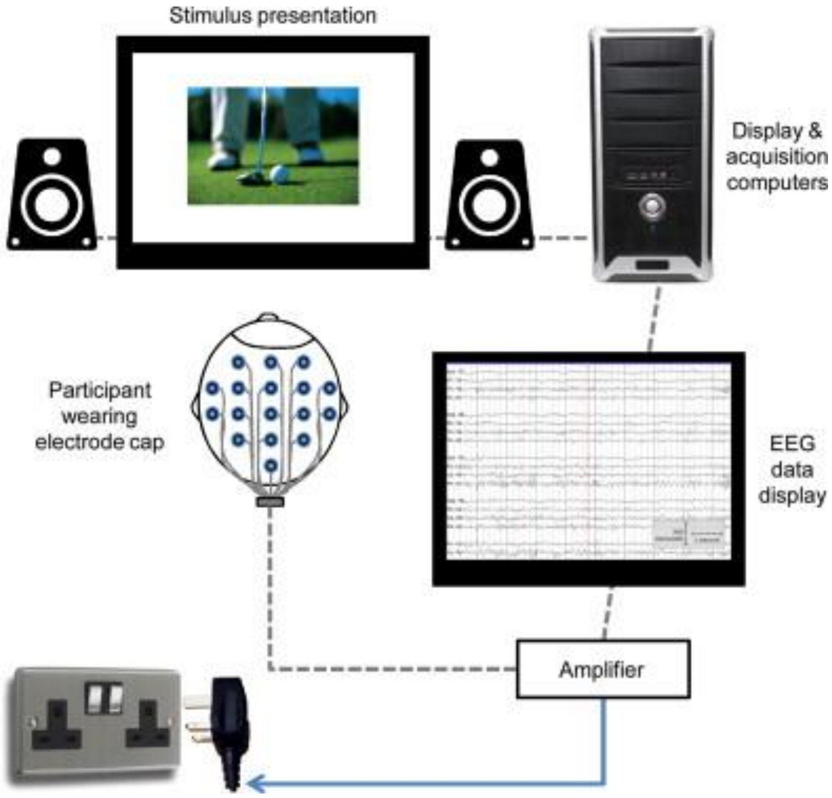


directly@participant‘s head

2c

The Data Acquisition System

(Desirable) Major Components of an ERP Lab



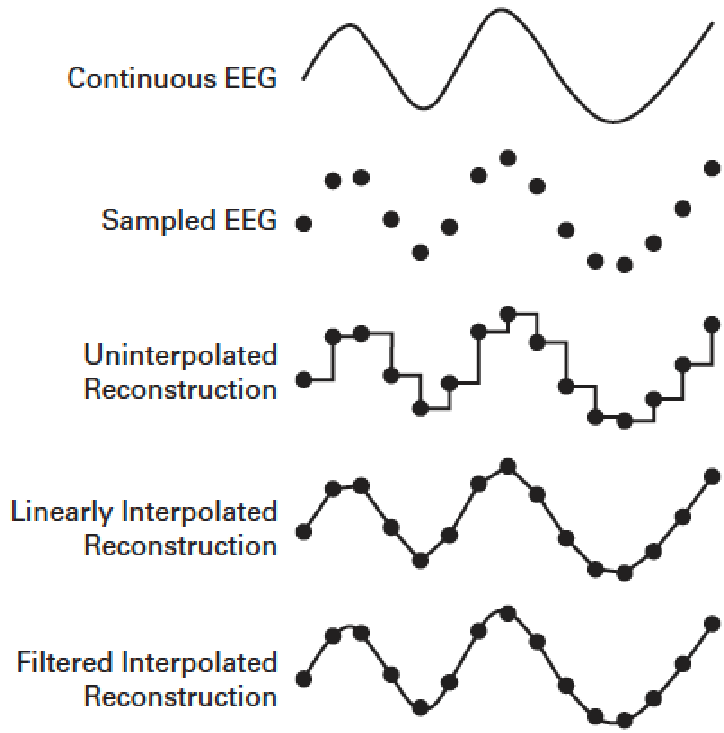
electrically shielded and sound attenuated **chamber**

2 monitors (stimulus presentation, digitization)

2 computers (separately controlling behavior and EEG) outside the chamber

amplifier (typically inside the chamber) so that less noise can be picked up by the wires

What Sampling Rate Should be Used?

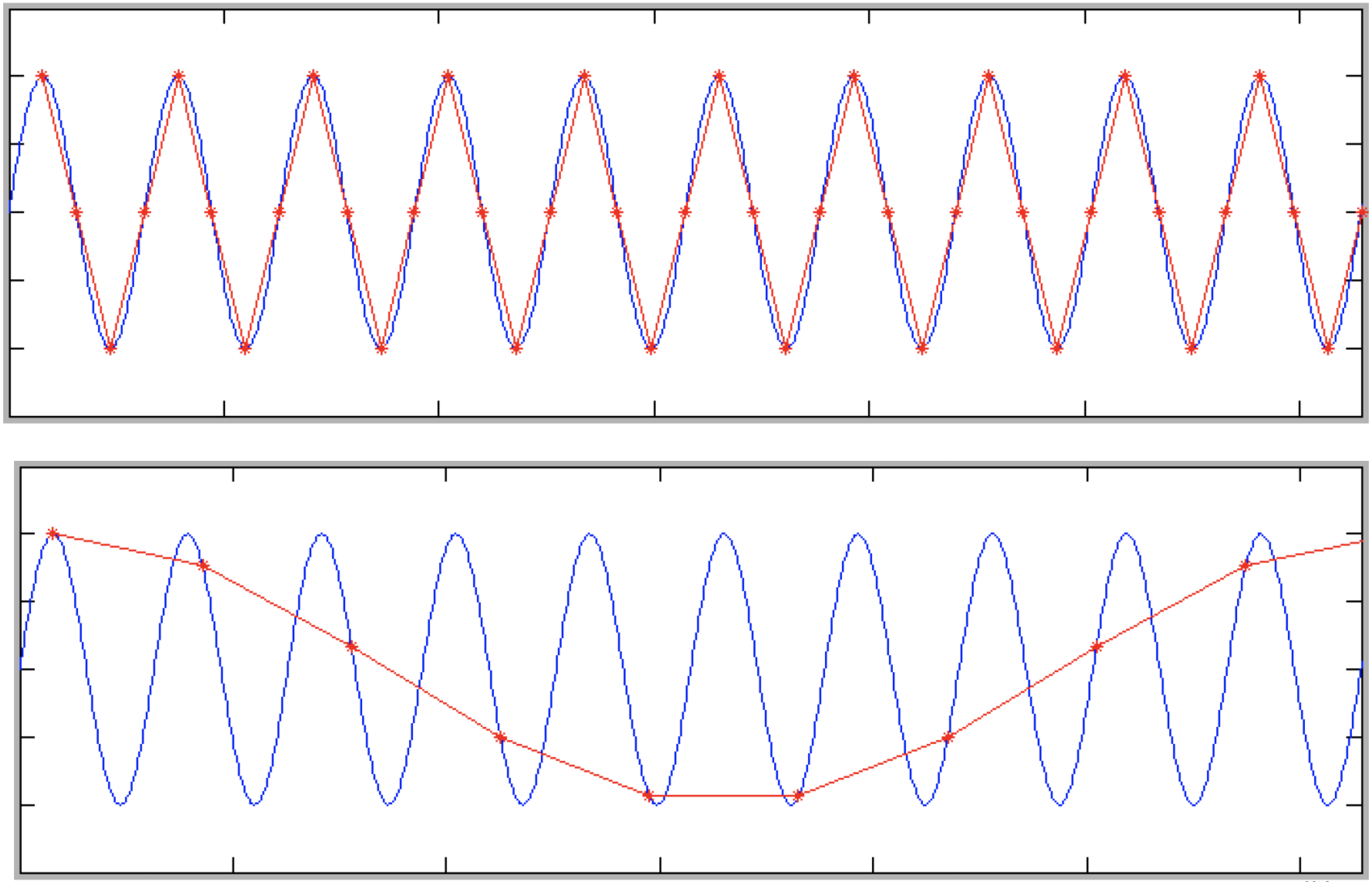


During EEG digitization, an analog EEG signal is converted to a digital signal at discrete time points

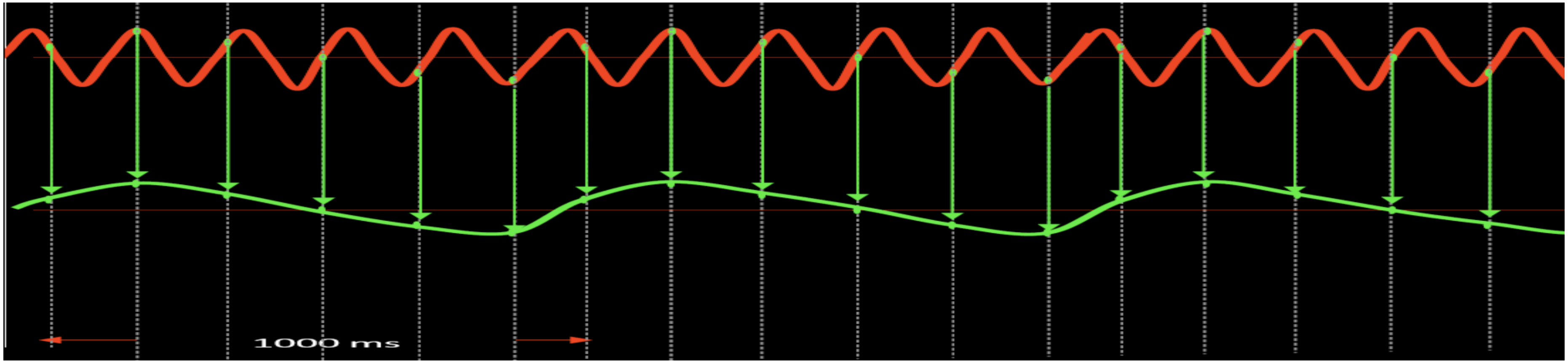
- Sampling Rate: number of samples taken per second
(e.g., 200 Hz, 500 Hz, 1kHz)

- Sampling period: time between 2 samples (ms)

If Sampling Rate Too Low: Aliasing



Solution to Aliasing: Nyquist Theorem



Nyquist Theorem: Sampling rate has to be twice as large as the highest frequency in the signal you are interested in!

- Nyquist frequency (or limit) ... is the highest frequency that can be represented in a digitized signal.

- If frequencies higher than the Nyquist frequency are digitized, they end up with an (lower) aliased frequency!

What Filters Should be Used?

Two major types of filters:

High-pass Filter

- determines the lower cutoff frequency
- high frequencies can pass

Low-pass Filter

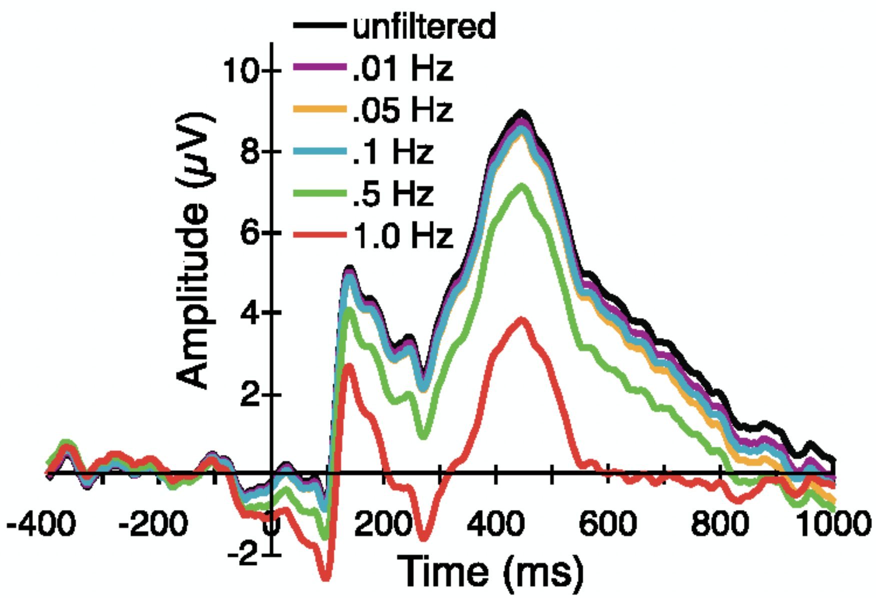
- determines the upper cutoff frequency
- low frequencies can pass

- They are used to get rid of frequencies we are not interested in.
- BUT ... they can severely distort the data!

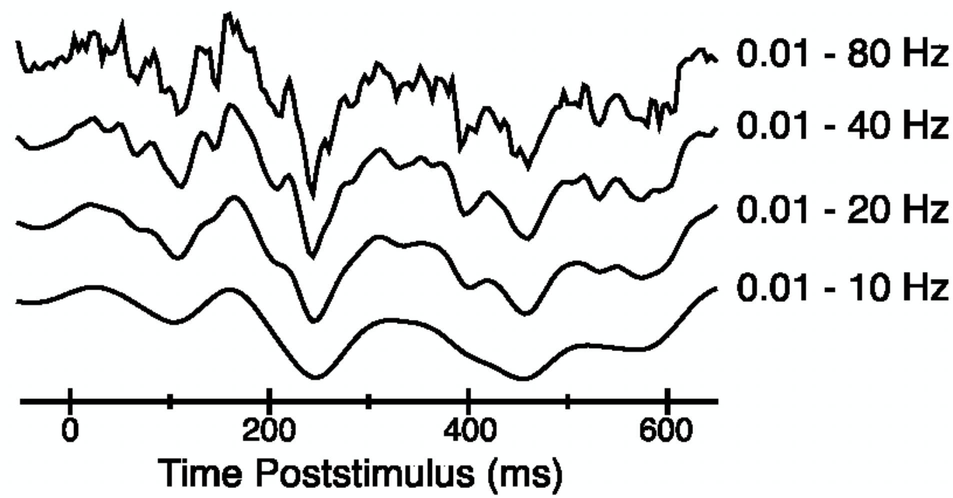
What Filters Should be Used?

Two major types of filters:

High-pass Filter



Low-pass Filter



High-pass filters cause significant amplitude reduction in slow components!!!

Filters Distort Your Data … so
They Should Be Used Sparingly!

Why Are Filters Necessary?

Nyquist Theorem

- make sure you have frequencies 1/2 the sampling rate

Noise reduction

- low-pass filters for muscle noise
- high-pass filters for skin potentials

Luck‘s advice:

- low-pass filter: ~ three times smaller than sampling rate
- high-pass filter: 0.1 Hz (eventually 0.5 - 1.0 Hz for patients/children)

What have we reviewed today

- Basic Electrical Concepts // Ohm's Law
- Signal Transmission Within and Across Neurons
- Scalp-recorded Potentials, Topographies, and the Inverse Problem
- Hansen's Axiom, Artifacts, Recommendations for Minimization of noise
- Electrode Types, Montages, and Labeling
- Sampling Rate, Filters, Aliasing, and the Nyquist Theorem

References

Kolb, B., & Whishaw, I.Q. (2003). Fundamentals in Neuropsychology. Worth Publishers; Fifth Edition.

Luck, S. (2005). Introduction to the Event-related potential technique. MIT Press, Cambridge, MA.

Luck, S. (2011). The ERP Boot Camp: What Are ERPs and What Are They Good For? [PowerPoint slides]. Retrieved from University of Davis website: http://erpinfo.org/the-erp-bootcamp