Introduction to EEG

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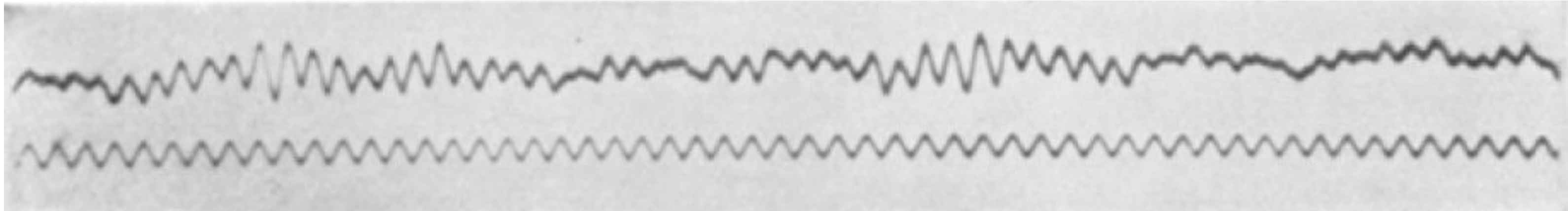
Electroencephalography (EEG)

- records **electrical activity** from the brain
- used in medicine to diagnose epilepsy, sleeping disorders, etc.
- first human EEG recorded in 1924 by Hans Berger
- first ERP experiments in the 1960s



upper panel: EEG recorded from a young boy; lower panel: 10 Hz frequency reference

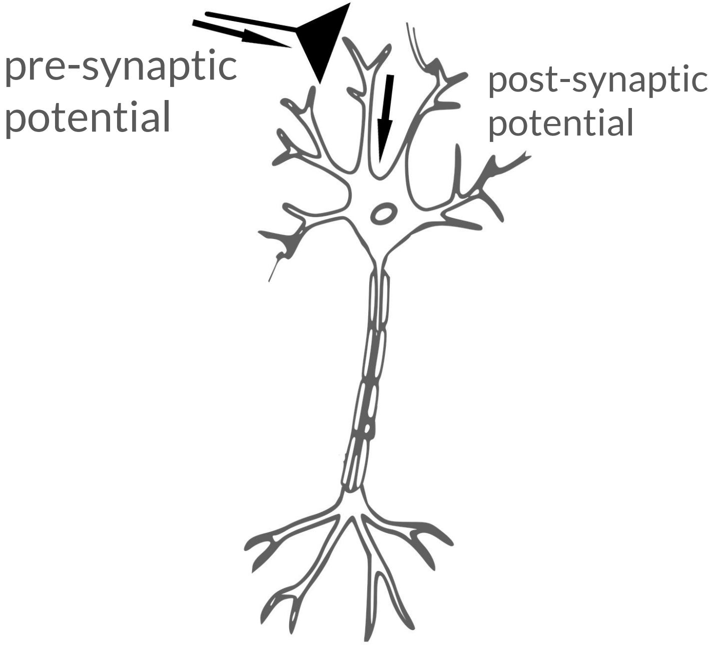
Berger H.(1929) *Archives für Psychiatrie.*

Why use EEG?

- high temporal resolution
  (on the order of 1-2 milliseconds)
- non-invasive
- relatively inexpensive
- usable with different populations

What does EEG measure?

- scalp potentials (computed as active scalp site minus reference)
- generated by **post-synaptic potentials (PSPs)** of large numbers of **synchronized**, parallel pyramidal cells
- PSPs represent the excitatory and inhibitory signals that these neurons receive



Why post-synaptic potentials?

- pre-synaptic potentials
  - brief and biphasic
  - easily cancel out during summation
- post-synaptic potentials
  - slow and monophasic
  - can be summed up more easily

Stephen Whitmarsh
https://www.youtube.com/watch?v=15Qs4fuPpes

Summation and open fields

- **sum of inhibitory and excitatory** PSPs of pyramidal cells organized in an **open field**
- simultaneous excitatory PSPs sum up to a greater excitatory PSP (same for IPSPs)
- simultaneous excitatory and inhibitory PSPs cancel each other out

What does EEG *not* measure?

- pyramidal cells organized in a closed field
- deeper brain regions not well measured, e.g. basal ganglia
- interneurons in cortex generate little to no scalp ERP activity
- i.e. **only a fraction** of brain activity leads to measurable ERP activity on the scalp

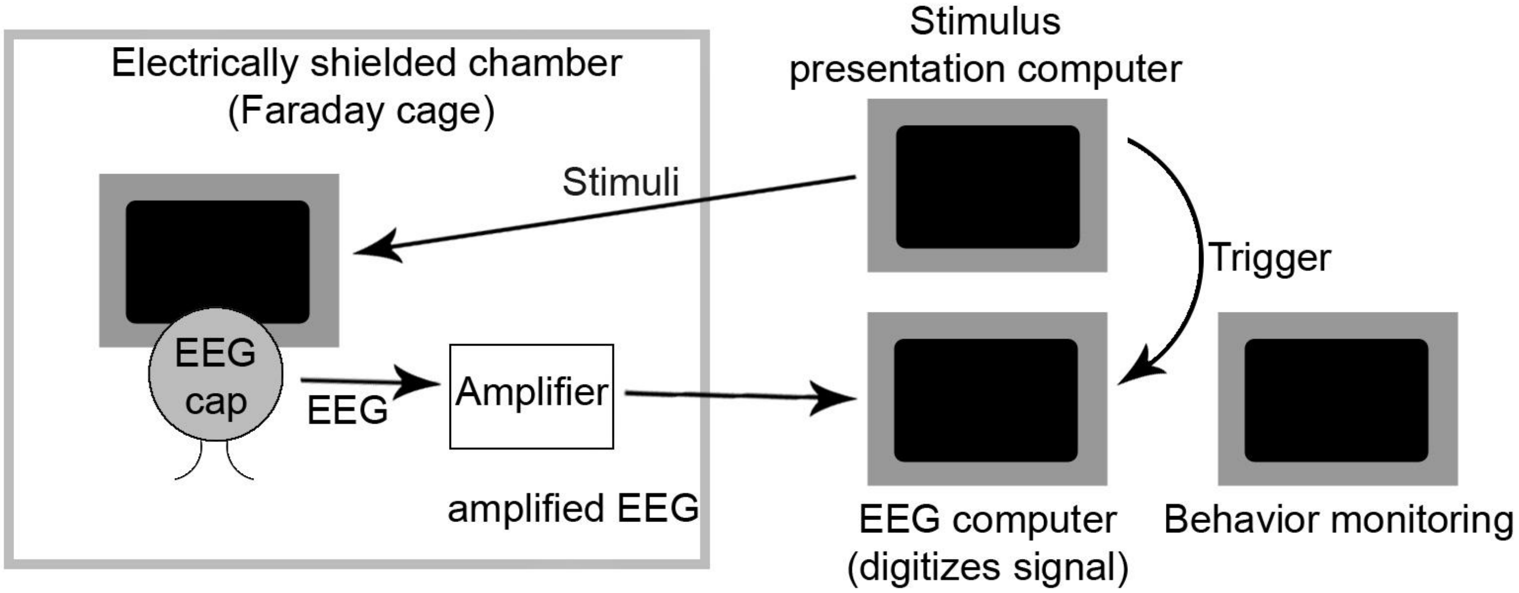
What does EEG *also* measure?

- low **signal-to-noise ratio (SNR)**
- sources of noise (**artifacts**)
    - eye blinks and movements (saccades)
    - motor activity (muscle movements)
    - sweating (drifts)
    - technical artifacts, e.g. jumps
    - high impedances of electrodes

Amplification

- raw EEG signal is relatively weak and needs to be amplified
- simple amplification leads to amplified noise as well as signal
- thus, amplification works **differentially** (active electrode - reference)
    - logic: differential amplification should mainly amplify the signal, less so the noise

A look into an EEG-lab



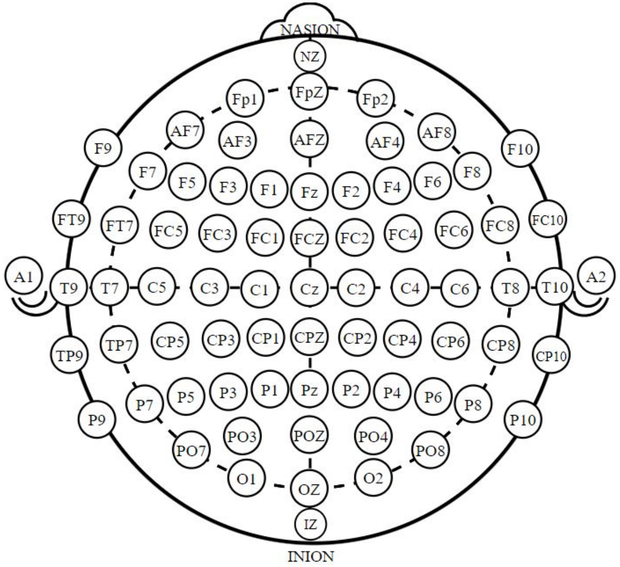
EEG setup

https://www.youtube.com/watch?v=I3j2VrhqTAA (2:12 - 4:43)

EEG caps

Electrodes are named according to position on the head

- F- frontal, C - central, P - parietal, O - occipital, T - temporal, M - mastoids, Fp - frontal polar
- odd numbers - left, even numbers - right, z - center (midline electrodes)
- e.g. Cz is in the very middle (C: in the middle of nasion and inion, z: in the middle of the ears)



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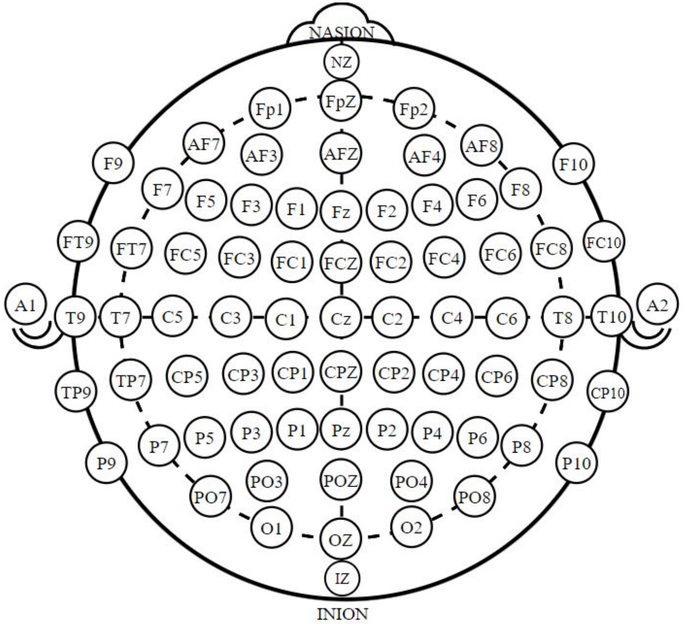
International 10-20 system

- international system for electrode placement
- electrodes are placed in relation to nasion and inion (Cz is 50% from nasion, inion, and both tragi; Oz is 10% from inion)
- adjacent electrodes are placed in 10 or 20% of total distance



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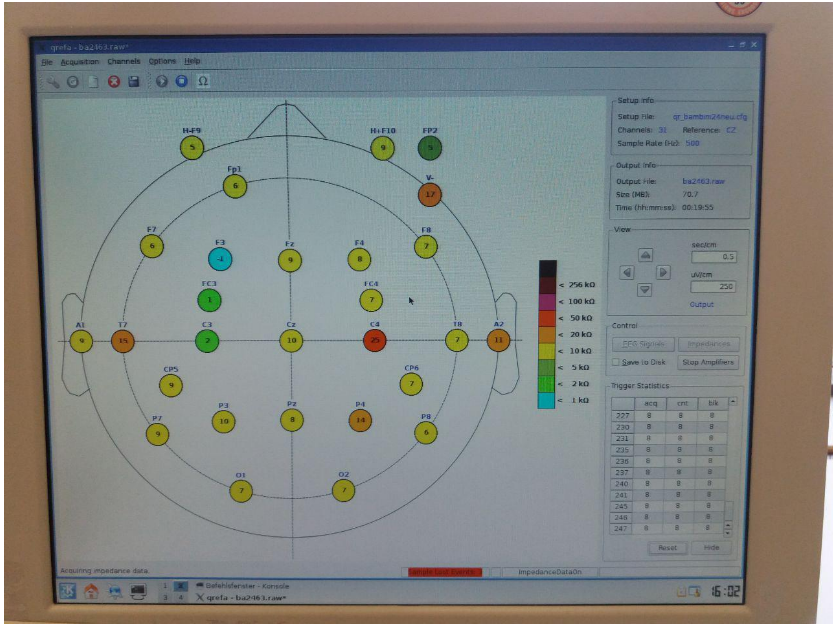
Impedances

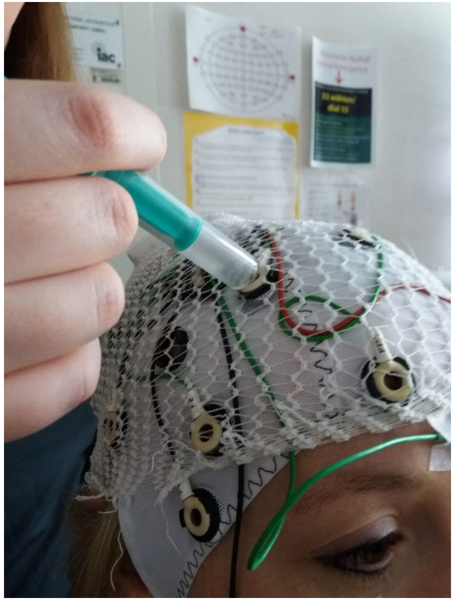
- each electrode has an **impedance**, the resistance between the electrode and the head
- factors influencing impedances
  - electrode gel
  - hair
  - skin conductance



Passive vs active electrodes

- active electrodes have built-in amplifiers in each electrode, while passive don’t
- active electrodes are less susceptible to power line noise
- most “modern” EEG systems are active
- careful: active/passive is also sometimes used to refer to electrodes that measure brain activity (active) as opposed to the reference and ground electrode

Exercise: active or passive electrodes?



“Special” electrodes: Ground

- used for common mode rejection, i.e. rejecting signals that appear on all electrodes (noise)
- primarily rejects power line noise (60 Hz in the Americas and parts of Asia, 50 Hz everywhere else)
- often placed on forehead, but location is generally irrelevant

“Special” electrodes: Reference

- subtracted from active electrodes, getting rid of noise
- typical placements
  - mastoids (bone behind the ear)
  - Cz
  - average reference
- online vs offline reference
  - EEG is referenced online, dependent on reference electrode
  - usually re-referenced offline, “cancels” online referencing

Electrooculogram (EOG)

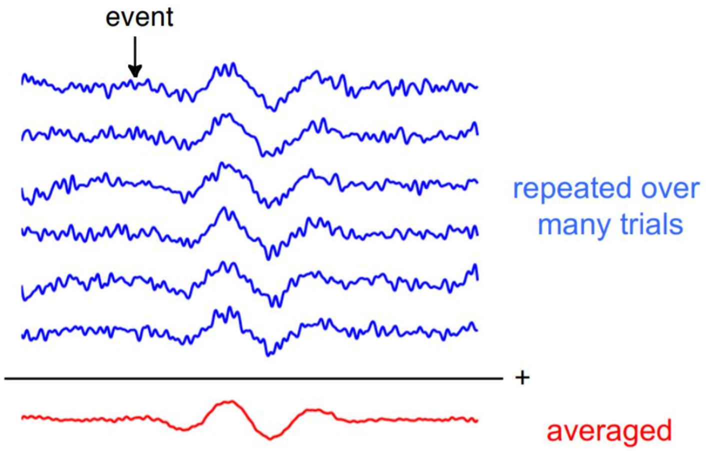
- horizontal and vertical eye movements are often measured by dedicated electrodes
- horizontal EOG (HEOG): e.g. saccades
- vertical EOG (VEOG): e.g. blinks
- measuring the EOG separately helps recognizing artifacts caused by the eyes and removing them from the EEG

Sampling rate

- EEG is most commonly sampled at 1024 or 512 Hz, i.e. once every one or two milliseconds
- oftentimes it’s enough to have a lower sampling rate (e.g. 256 Hz)
- the sampling rate can be changed offline to save working memory

Event-related Potentials (ERPs)

- **timelocked** to an experimental event, usually your experimental manipulation
- calculated by **averaging** over trials and subjects
- logic: only activity elicited by the event (experimental stimulus) will be timelocked to the stimulus, noise will not and will there be averaged out



http://www.fieldtriptoolbox.org/assets/pdf/workshop/toolkit2018/introduction.pdf

Possible ERP research questions

- time course of processing
- which process / stage of process is influenced by this experimental manipulation?
- how many processes are involved in a task?
- implicit processes

Research questions not (well) suited for ERPs

- where in the brain does a process take place?
- isolated processes (superposition of components)
- ERPs need to be timelocked to an event
- movement studies are difficult because of artifacts (but possible)

Designing an ERP study

- have a research question / hypothesis suited for ERPs
- ERP analyses are based on **comparisons of conditions**
- usually, you'll want to have a control condition and a condition of interest
- decide beforehand what you're going to timelock your signal to: stimulus (which part?) or response?
- if at all possible, include a behavioral correlate
- build in **baseline** period, ideally without stimulation
- include lots of trials (low SNR)

Baseline periods

- before the stimulus that you're going to timelock your signal to, you should have a baseline period
- this period should be the same across conditions
- baselines are used to show that your ERPs are elicited by your experimental manipulation and not by something that happened irrespective of that
- ideally, there should be no stimulation in the baseline period, but this isn't always possible (e.g. in many language experiments)

Signal-to-noise ratio (SNR)

- EEG has a low signal-to-noise ratio, i.e. single trials contain more noise than the signal of interest

$$\text{SNR} = \frac{\text{size of signal}}{\text{size of noise}}$$

example:

- assumption: signal of interest is an ERP component with 20 µV amplitude and the noise of a typical trial is 50 µV
- SNR: 20:50, or 0.4

Increasing the SNR

- if we assume that the **noise is random**, i.e. not timelocked to the experimental manipulation, but the signal of interest is, then **averaging increases the SNR**
- however, the SNR doesn't increase linearly in proportion to the number of trials, but in proportion to the *square root of the number of trials*

$SNR(average) = (S/N)\sqrt{T}$ S - signal, N - noise, T - number of trials

- thus, doubling the number of trials only increases the SNR by 40%
- to double the SNR, you have to quadruple the number of trials

Instructing your participants

- participants should sit as still as possible and not clench e.g. their jaw, since muscle movements also cause large artifacts
- include breaks in your experiment, so that participants can move around
- you can instruct participants to only blink during specific time windows of your experiment, which don’t contain an experimental manipulation
    - this is sometimes done because blinking causes large artifacts
    - however, it also introduces a dual task for participants: your experimental task and not blinking at certain times

Counterbalancing

- counterbalancing helps avoiding confounds in your experiments
- for example, you should counterbalance the following factors in your experiments
  - response hand. e.g. for button presses
  - target stimuli, e.g. in the visual oddball paradigm, targets should be “X”s for some participants and “O”s for other participants
  - if you have within-subject conditions, you should counterbalance the order of these conditions

ERP components

ERP components are usually described by their

- polarity (positive or negative deflection)
- latency
- amplitude
- topography

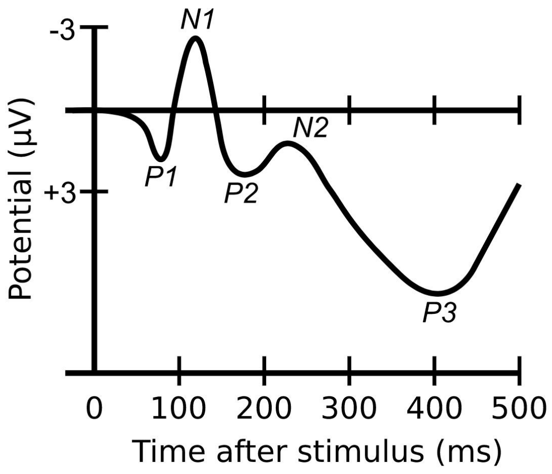
ERP naming conventions

- polarity + peak position (N1, P2)
- polarity + peak latency (e.g. N400, P600)
- topography (e.g. left anterior negativity)
- function (e.g. mismatch negativity, error-related negativity)

Sensory ERP components

P1 - first major positivity following sensory stimulation (peak around 100 ms): processing of sensory stimulation, sensitive to attention; different sources depending on the type of input, e.g. visual P1 is largest over occipital sites

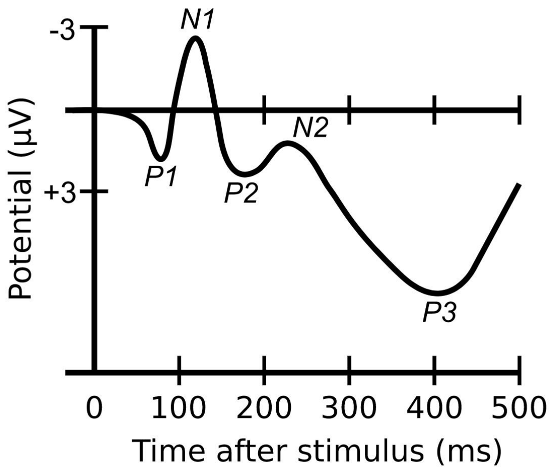
N1 - first major negativity (peak around 100-150 ms): capture of attended stimulus, stimulus discrimination; reduced for repeated attended stimuli



Sensory ERP components

P2 - follows N1 wave (N1-P2 complex): larger for target features and infrequent stimuli if they are defined by relatively simple features; often observed over anterior and central sites

N2: - detection of infrequent, “oddball” stimuli: larger for infrequent than for frequent stimuli; also responds to conflict: larger for conflict trials, e.g. in Stroop task (200 - 400 ms, maximal over frontocentral sites)



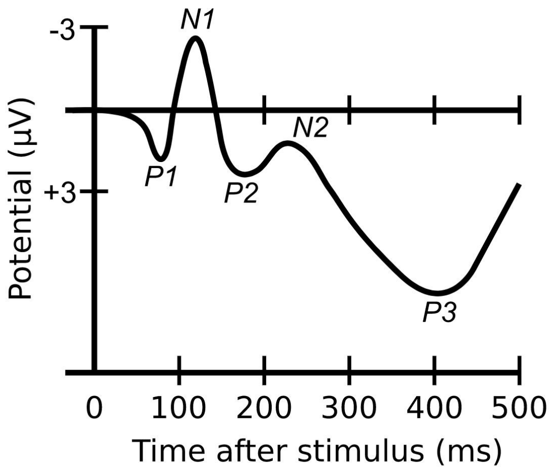
By Mononomic (talk) 16:12, 21 December 2008 (UTC) [CC BY-SA 3.0] via Wikimedia Commons

P300 family

P3a - maximal over frontal electrodes

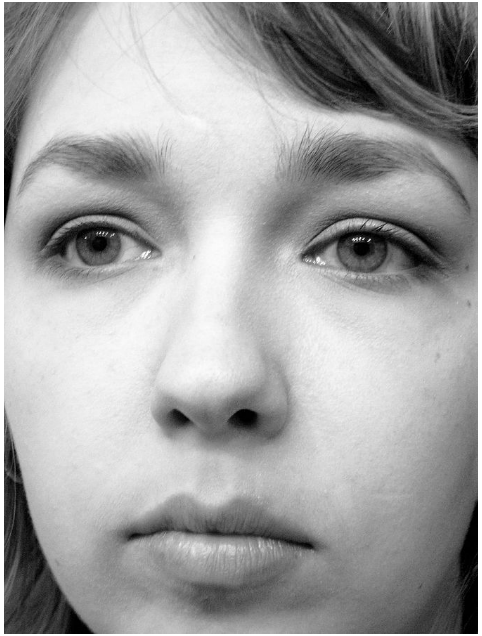
P3b - maximal over parietal electrodes

- both are elicited by infrequent stimuli
- respond to indefinitely complex stimulus features
- but P3b is only elicited if changes in stimuli are task-relevant, larger if target probability is smaller



Face-related ERP components

N170 - elicited for face stimuli compared to non-face stimuli;
also elicited for stimuli that you are an expert in, e.g. elicited by bird stimuli for bird experts



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Auditory ERP components

MMN - mismatch negativity (160 - 220 ms): indexes processing of stimuli that differ from preceding stimuli, e.g. in amplitude or length; often elicited in auditory oddball paradigm can be used to investigate whether participants can distinguish two stimuli

MMR - mismatch response: this term is often used to refer to the MMN in infant studies, because infants sometimes have a positive-going MMR

Language-related ERP components

N400 - indexes semantic violations or semantic unexpectedness (e.g. “she smeared the bread with shoe”), centro-parietal distribution

P600 - indexes syntactic violations and syntactic reanalysis processes (e.g. “the horse raced around the barn fell”), frontal distribution

LAN - left anterior negativity (300 - 500 ms) indexes violation of morphosyntactic agreement (e.g. “die Tisch”, *the_f table_m*)

ELAN - early left anterior negativity (100 - 200 ms) indexes violation of word categories (e.g. “the pizza was in the eaten”)

Response-related ERP components

LRP - lateralized readiness potential, appears shortly before response and indexes response preparation; larger over contralateral than ipsilateral sides with regard to response hand; amplitude of LRP is related with latency of behavioral response

ERN - error-related negativity (80 - 150 ms after erroneous response), indexes incorrect responses, even when participants have little to no awareness of the error

Exercise

Which ERP components could be elicited in the following experiments?

Exercise

Experiment 1: participants hear the following types of sentences:

condition 1: “*Berlin underground trains are yellow.*”
condition 2: “*Berlin underground trains are white.*”
condition 3: “*Berlin underground trains are sour.*”

Exercise

Experiment 2: participants listen to a stream of syllables

80% of the syllables are “*bit*”
20% of the syllables are “*beat*”

Exercise

Experiment 3: participants are presented with the following types of sentences

condition 1: “*The cook hoped to master the recipe.*”
condition 2: “*The cook persuaded to master the recipe.*”

Exercise

Experiment 4: participants are asked to classify names as male (frequent) or female (infrequent)

Stimulus stream: *Thomas Michael Paul Lucas Wendy Philipp*

Example: difficulties in interpreting ERPs

- N400 was originally reported as a language-specific component, elicited by semantic violations
- however, Nieuwland and van Berkum (2006) showed that it’s not specific to semantics
- and Daltrozzo and Schön (2009) found evidence that it’s also not specific to language

"Mr. Peanut Hot Air Balloon" by Bobcatnorth [CC BY-NC-SA 4.0]

Kutas & Hillyard (1984) *Nature*
Nieuwland & Van Berkum (2006) *J Cogn Neurosci*
Daltrozzo & Schön (2009) *J Cogn Neurosci*

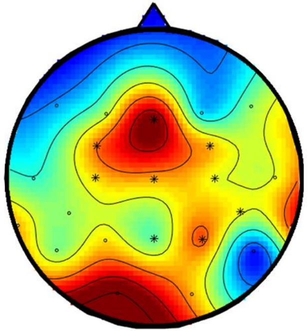
Exercise

Design an experiment with the hypothesis of finding an N400

- example item for each condition
- what would your signal be timelocked to?
- what would be your baseline period?

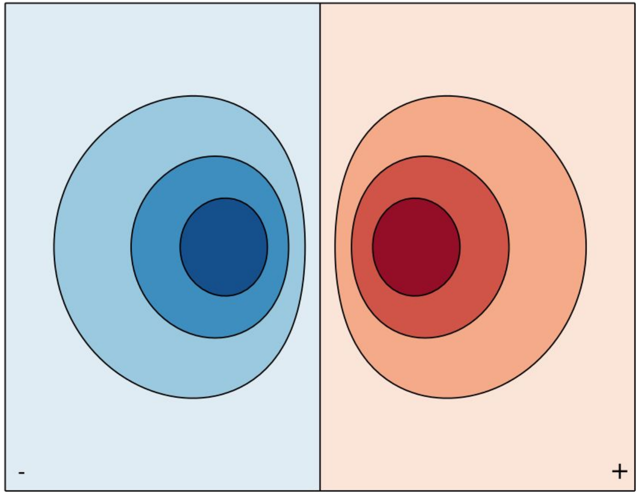
Topographies

- ERP studies often report the topography of an effect, which may be useful for identifying ERP components
- e.g. “found over frontal electrodes”
- however this **does NOT mean that the source of the effect are frontal brain regions**
- for example, the N400 is typically found over centro-parietal electrodes and is often larger over the right than the left hemisphere, but it is generated in the left temporal lobe



Dipoles

- a dipole is a separation of positive and negative electric charges
- dipoles emerge on the surface of the skull as a result of dipoles of pyramidal cells



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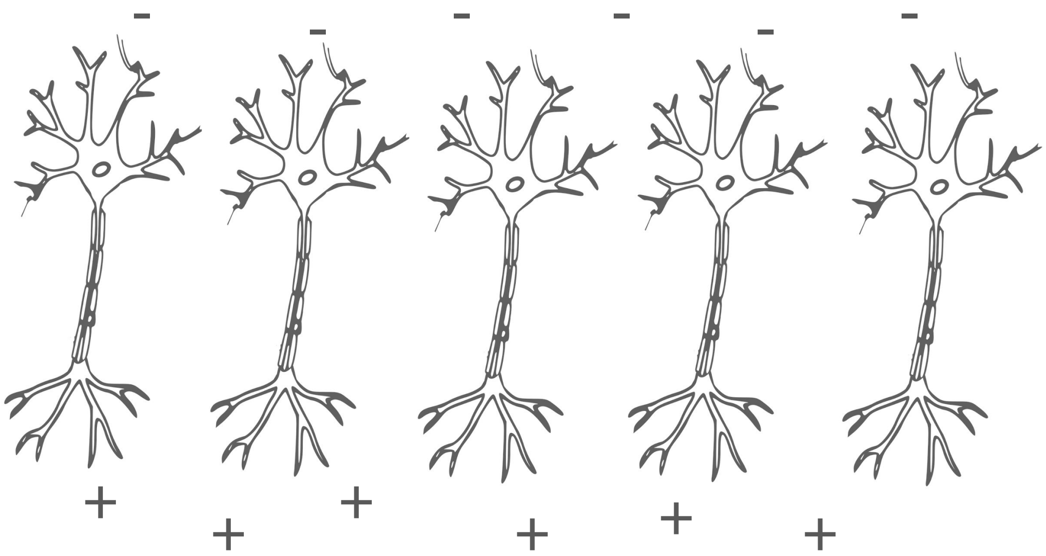
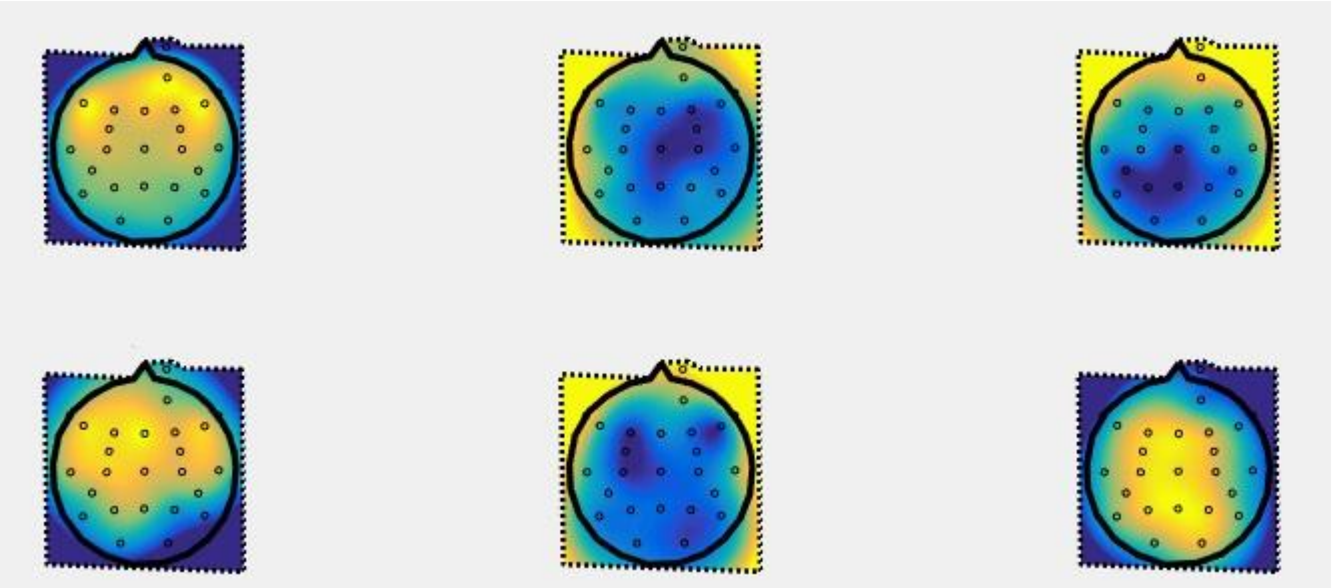
Pyramidal cells as dipoles



Dipoles picked up by EEG

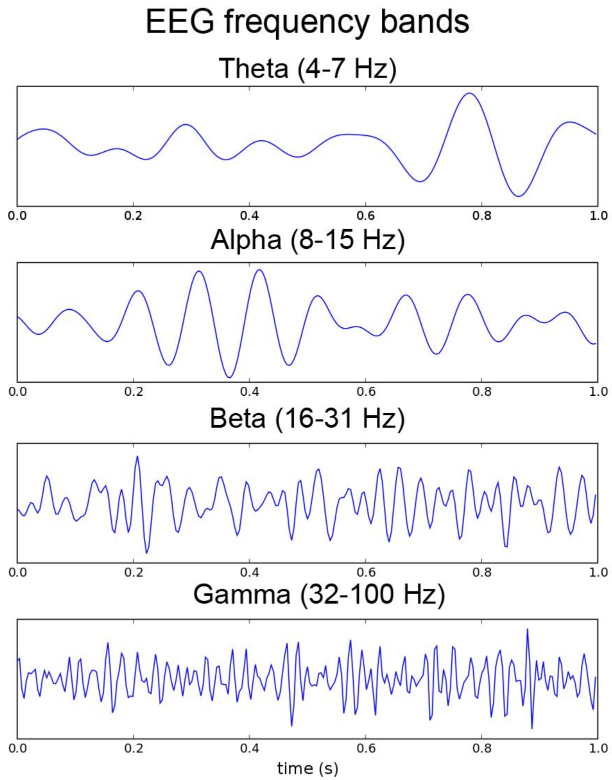


The inverse problem

- given a dipole (i.e. source of an EEG signal), it is possible to unequivocally model the voltage distribution on the scalp (**forward model**)
- however, the **inverse problem**, i.e. unequivocally finding the source of a given voltage distribution (given the topography) is impossible
- one can still model the source, but not with absolute certainty

Outlook: oscillations

- oscillations can be seen in the EEG online (e.g. for diagnoses)
- they can also be computed offline; these are useful for cognitive neuroscience
- the **interpretation** for online and offline oscillations **differs**!



By Hugo Gamboa (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0], via Wikimedia Commons

Outlook: oscillations

- neurons are oscillating at different frequencies
- neurons in the same functional network fire synchronously at a given frequency
- cognitive events induce amplitude increases in specific frequency bands
- most general dynamics in the brain are governed by oscillations in these frequency bands (Basar et al., 2001)
- oscillations may provide links to brain functions

Application examples: different age groups

- EEG can be used with any age group: from newborns to elderly populations
- some populations can't respond explicitly
- EEG can tap into implicit knowledge

Child lab at MPI-CBS in Leipzig (2:20 - 4:55)

Application examples: movement

- with some extra effort, EEG can be used while people move
- mobile EEG: active electrodes that connect to the amplifier via bluetooth
- benefits: “in the wild” studies
- limitations: movement artifacts

BeMoBIL lab at TU Berlin

Application examples: combination of methods

- EEG has relatively poor spatial resolution
- combining it with other methods, such as near-infrared spectroscopy or fMRI can add spatial resolution
- NIRS optodes and EEG electrodes can be combined in the same cap

Application examples: “hyperscanning”

- EEG can be measured from two or more participants at the same time
- during interaction, people’s brain waves synchronize; the extent of synchronization can be measured with EEG

Dikker et al. (2017) Curr. Biol.
https://doi.org/10.1016/j.cub.2017.04.002

Early social cognition at MPI-CBS

Acknowledgement

These slides, like the rest of this course, are in part based on slides by PD Dr. Ulla Martens as well as Steven J. Luck (2014) An Introduction to the Event-Related Potential Technique, second edition, *MIT Press*