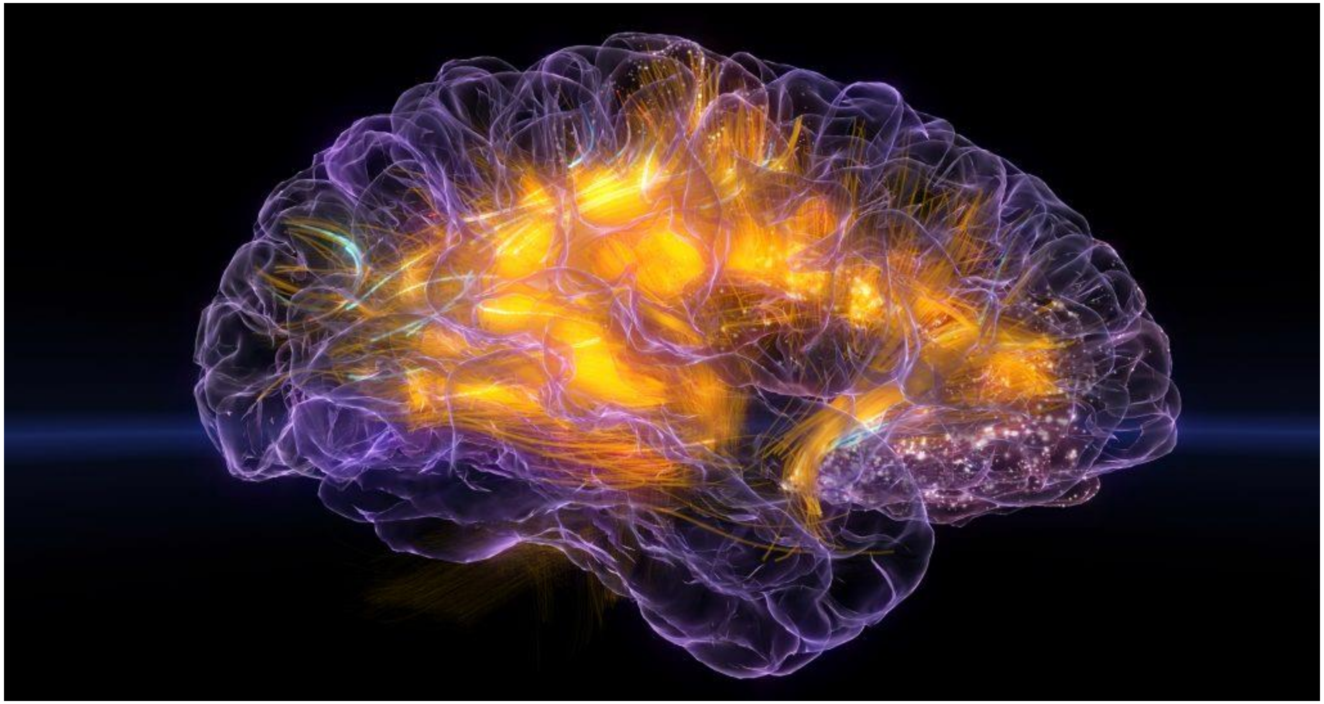
Interfaces Cerveau Machine

Introduction aux neurosciences et à l’électroencéphalographie (EEG)



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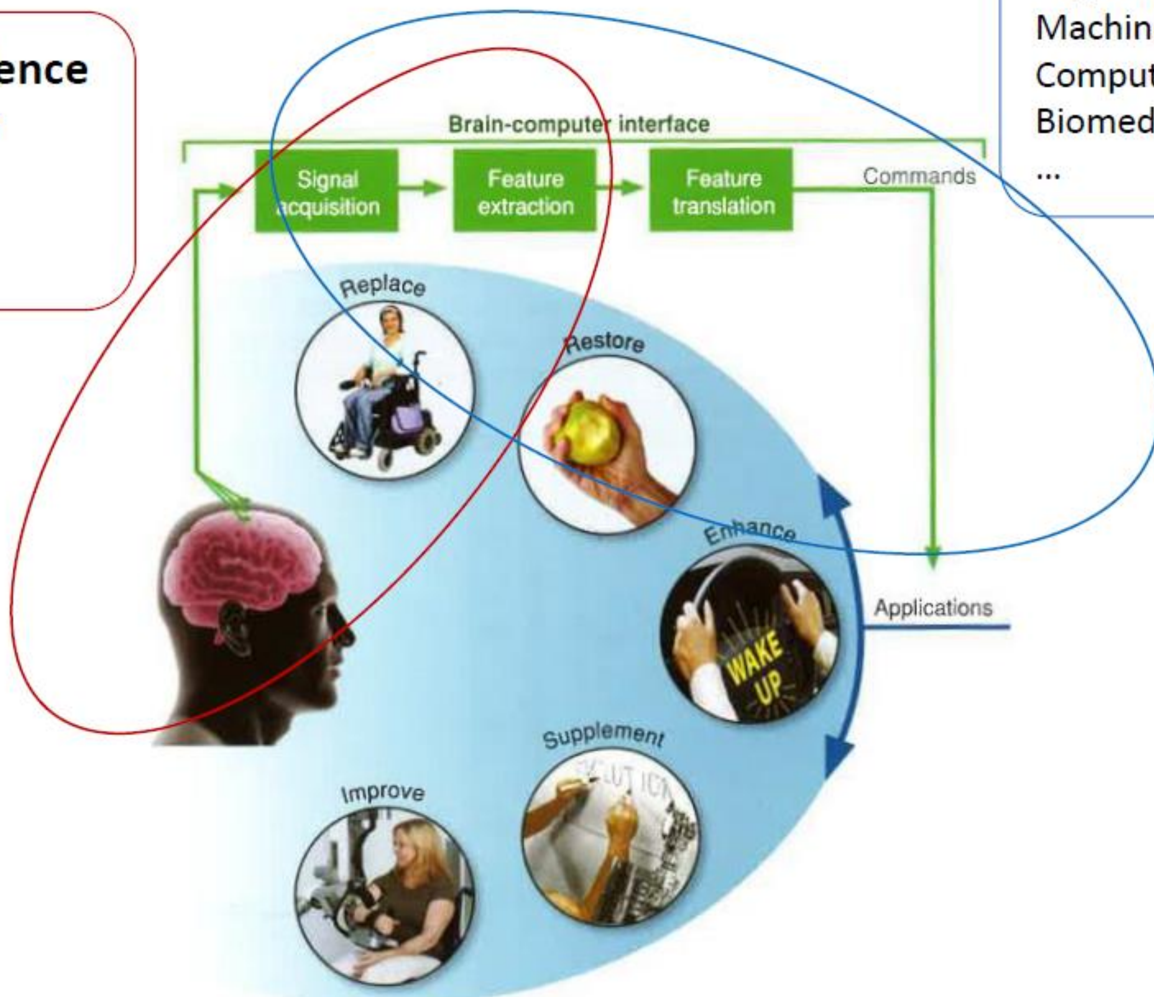
Toulouse

The brain part of Brain-Computer Interfaces

Cognitive Neuroscience
Experimental Psychology
Neuropsychology
Neuro-ergonomics
...

Signal processing
Machine learning
Computer science
Biomedical engineering
...



Roadmap

- What is cognition, what do we know about it?
- Neuroimaging: a window into the human mind
- EEG as a non-invasive and online measure of cognitive processes and mental states
- EEG-based Brain-Computer Interfaces: paradigms and neural signals
- Challenges of EEG: extracting neural signatures of interest from other noisy sources

What is cognition?

The mind is a system that creates representations of the world so that we can act within it to achieve our goals (Goldstein, 2011).

Cognition refers to the mental processes of the mind:

- Perception
- Attention
- Consciousness
- Memory
- Semantics
- Visualization and simulations
- Understanding and production of language
- Reasoning and decision making
- Spatial orientation and navigation
- Motor planning
- …

Early days of cognitive science

Donders (1868) paradigms:

- Reaction Time (RT) experiments: measures of the interval between stimulus presentation and response to it
- Perception: respond as fast as possible when a light flashes
- Decision making: Choice task: press one button if left light flashes, another one if the right one flashes
- Inhibition: only press a button when the right light flashes, do nothing when the left light flashes
- Motor planning: Laterality effect: respond to right light with right hand and left light with left hand (congruent) versus incongruent
- …

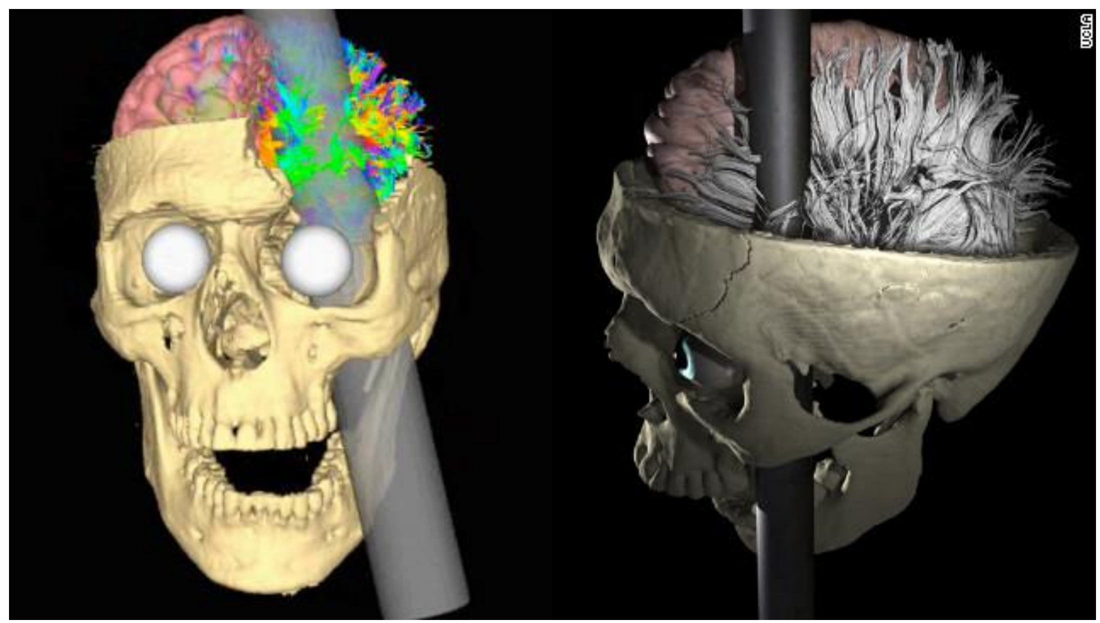
Issues of early cognitive science studies

- Extremely variable results from person to person
- Findings are difficult to verify: invisible inner mental processes
- Subjective reports from participants and patients

Need for objective measures of mental abilities that would be consistent (to some degrees) across individuals

Insights from brain lesions: Neuropsychology

- Phineas Gage
- Famous case of a 19th-century railroad worker who survived an accident where a metal rod went through his brain
- Frontal lobe was heavily damaged
- Changes in behaviour, social relationships, impulsivity, perseverance

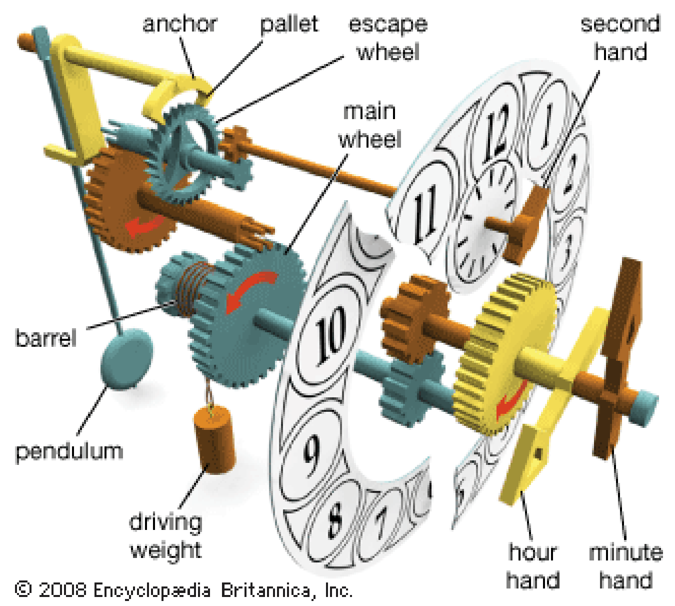


Cognitive Neuropsychology: when things go wrong

- Focus: behavior of patients with brain injury
- Explain patterns of impaired/intact cognitive performance in brain-injured patients in terms of damage to one or more components of a theory or model of normal cognitive functioning
- Draw conclusions about normal, intact cognitive processes from the patterns of impaired/intact capabilities seen in brain-injured patients.

Single case reports: limitations

- What are the component processes required to perform a given cognitive test?
- Issues in choosing patients
- Single case vs. Group Studies
- Selection on the basis of lesion site or functional deficit
- Time of test: acute vs. chronic stages
- Site of injury: focal vs. diffuse
- Distance effects: disconnection and diaschisis
- What is the appropriate control group?
- How do you define “normal” performance?



Overcoming limitations

- Strong theories of brain-behavior relationships require converging evidence from complementary techniques
- EEG, fMRI (neuroimaging)
- Virtual lesions (TMS)
- With fMRI, regions other than those critical for process may become activated (e.g., due to feedback connections, strategies)
- Can do extensive testing without time limit or methodological constraints
- With TMS, “lesion” effects are brief, although “patients” can serve as their own controls

➡ Cognitive Neuroscience

Cognitive Neuroscience: Research Methods

Brain Imaging Methods:

- fNIRS: functional Near-Infrared Spectroscopy
- MEG: Magnetoencephalography
- fMRI: functional Magnetic Resonance Imaging
- EEG: Electroencephalography
- …

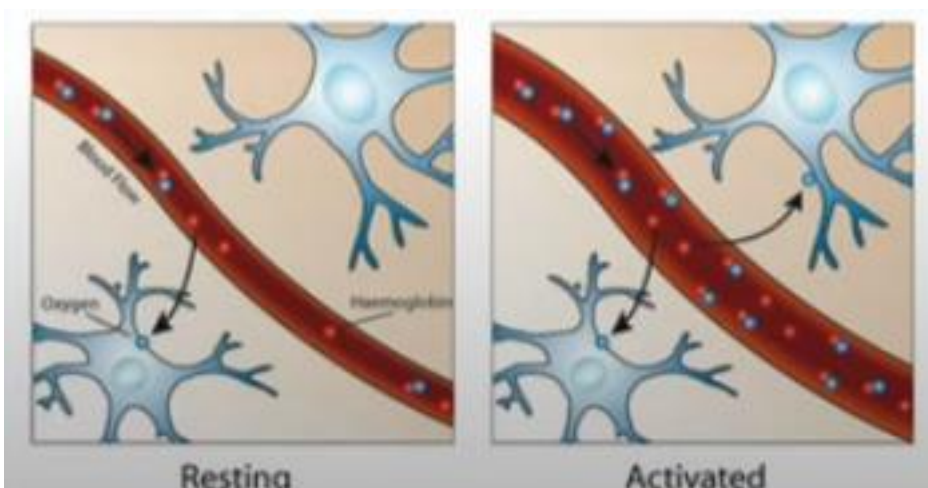
Stimulation methods:

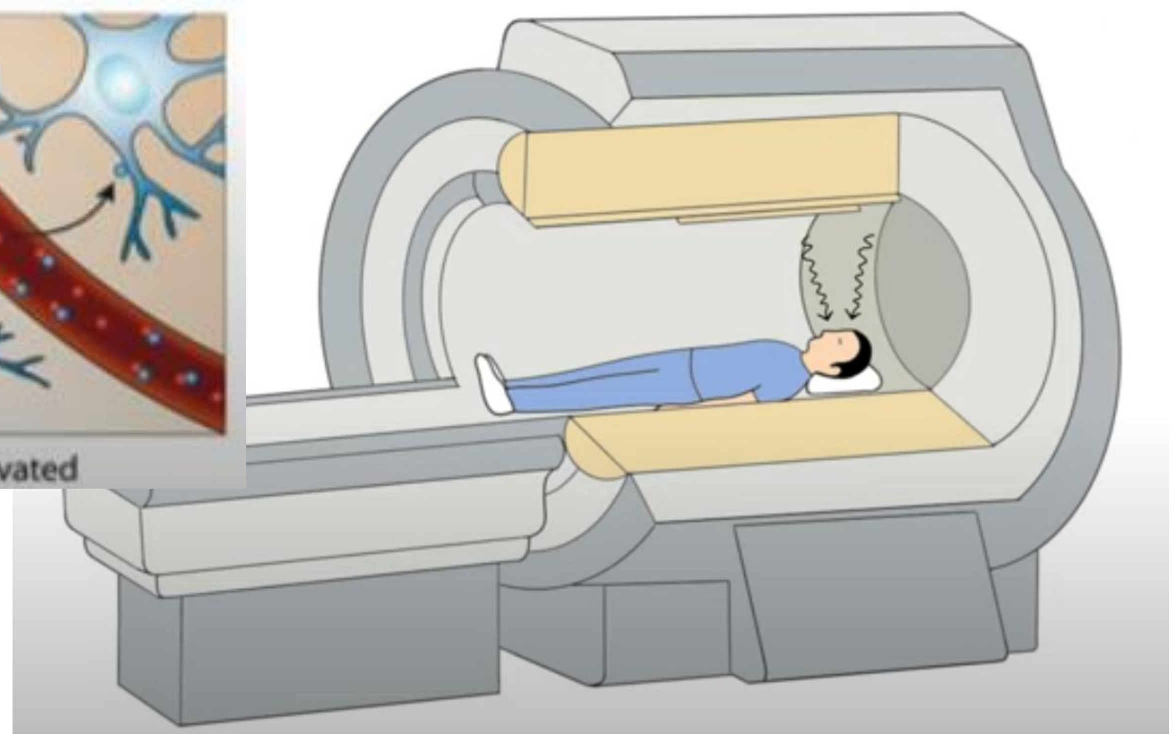
- TMS: Transcranial Magnetic Stimulation
- tDCS: transcranial Direct Current Stimulation

…and various physiological and behavioural measures: EOG, ECG, EMG, EGG, …

Functional Magnetic Resonance Imaging (fMRI)

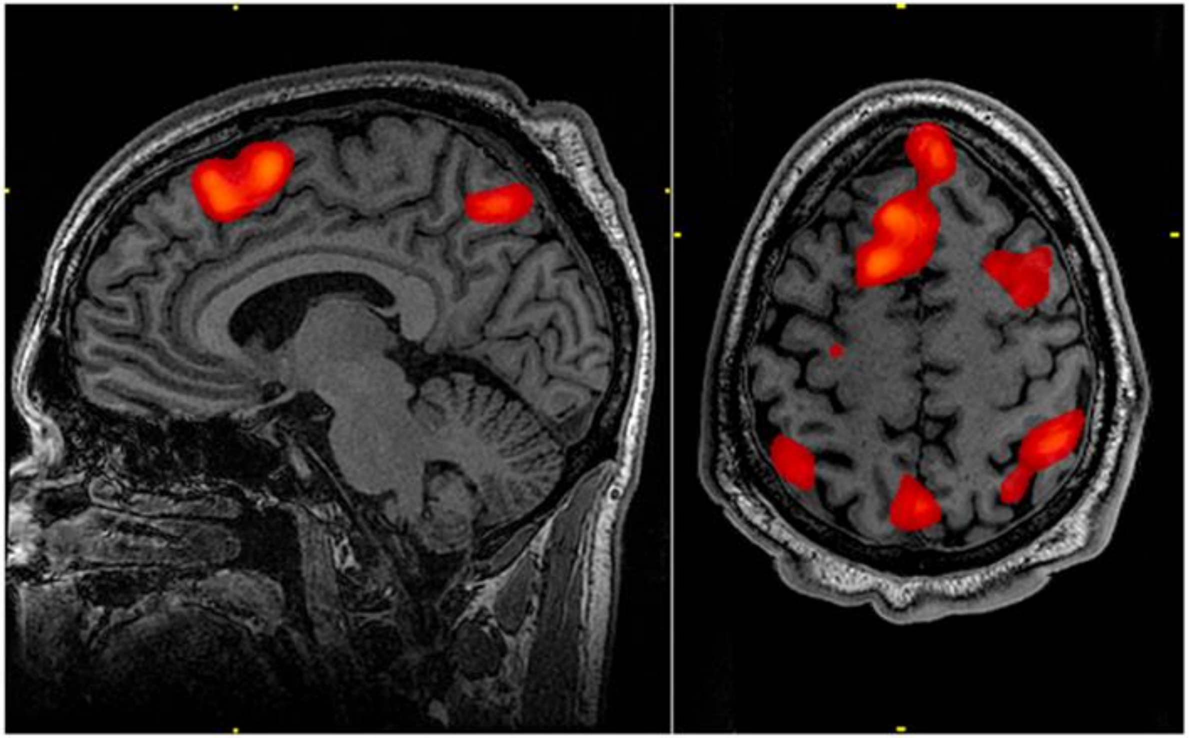
- Areas of the brain that are more active require higher levels of oxygenated blood
- Hydrogen protons respond through emission of an electromagnetic signal
- Scanner records BOLD (Blood Oxygenation Level Dependent) signal and create high spatial resolution image of the brain





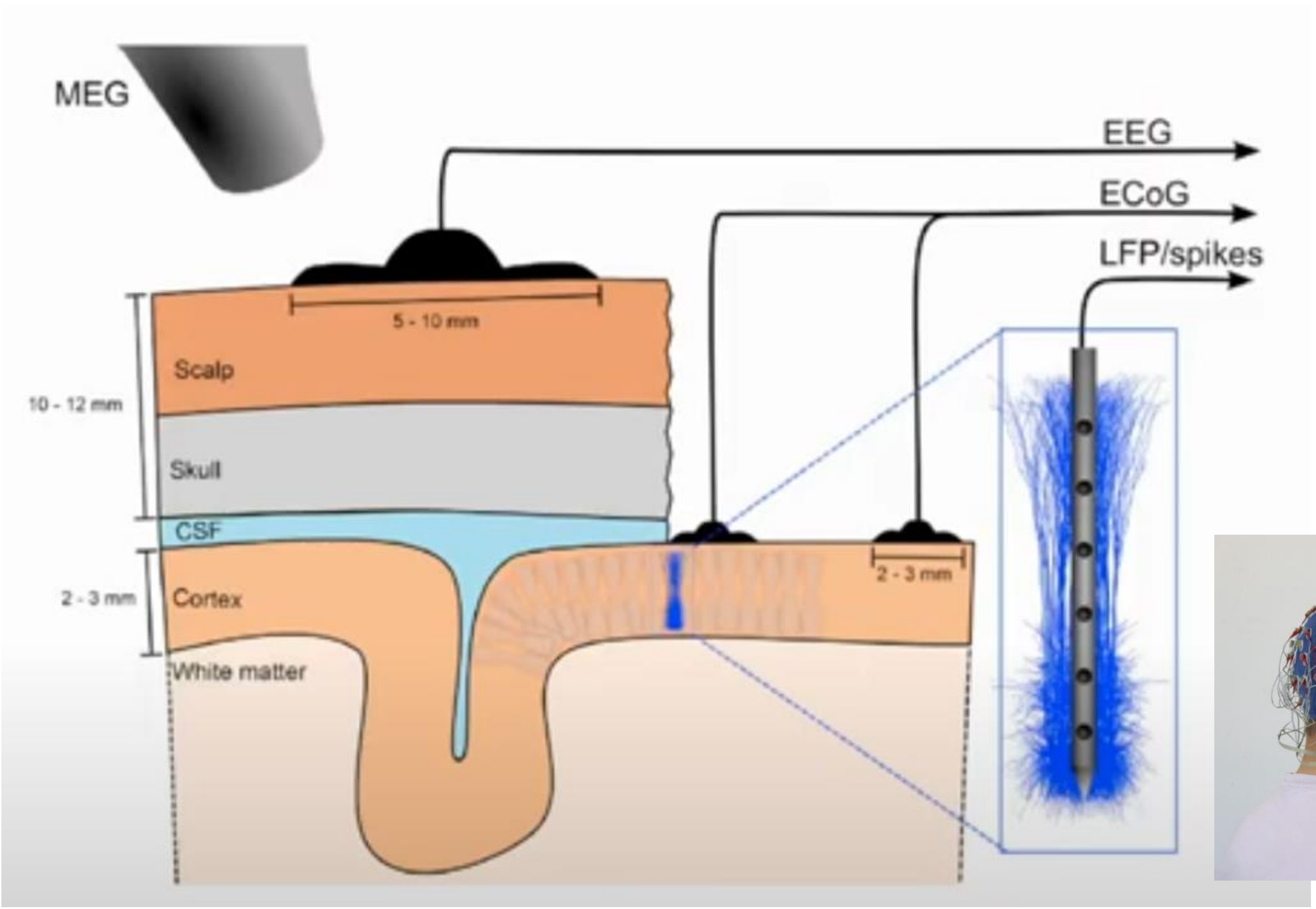
Functional Magnetic Resonance Imaging (fMRI)

- Difference between experimental conditions reveal areas related to specific cognitive processes (baseline resting period versus working memory task)

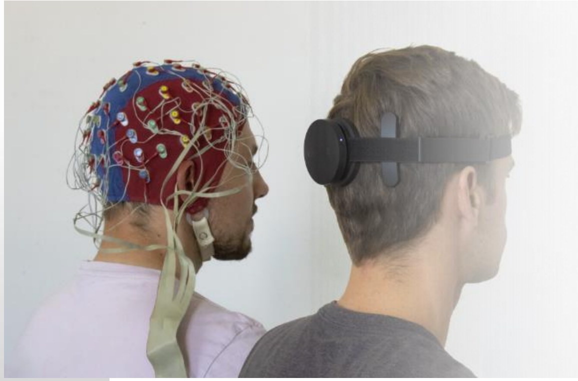


- fMRI measures a vascular response to brain activity (**blood-oxygen-level-dependent or** BOLD signal), indirect measure of cognitive processes

Electrical recordings of the brain



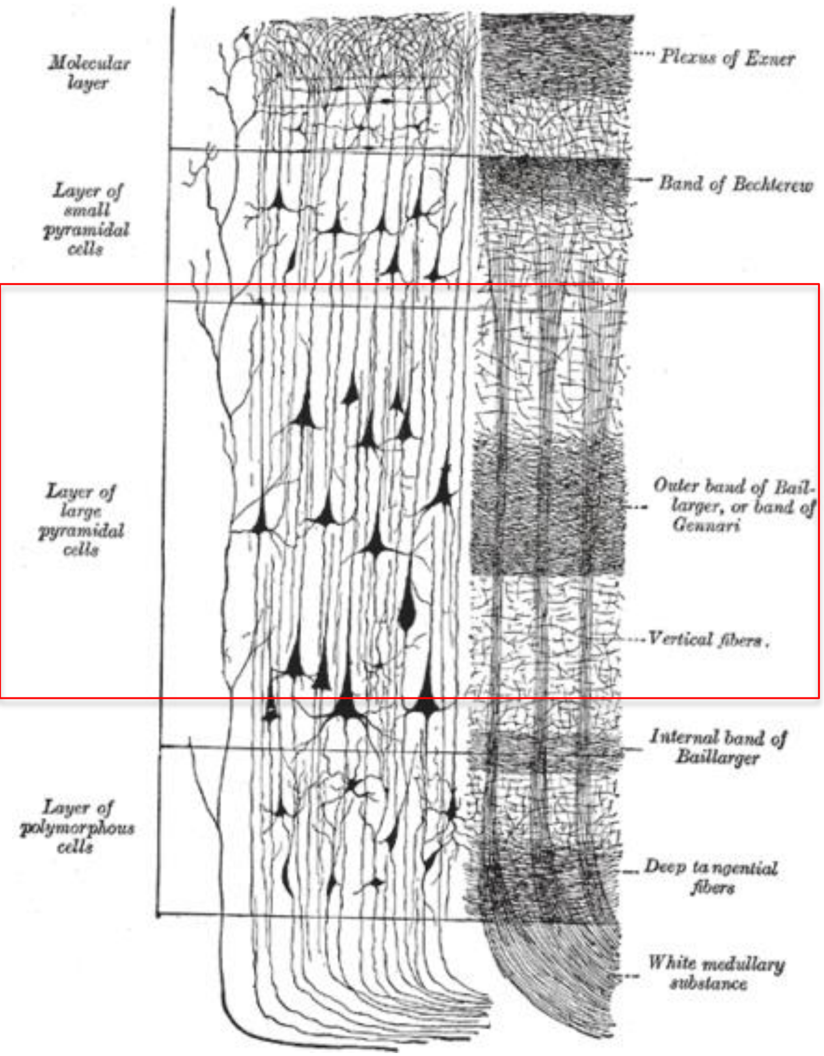
MEG

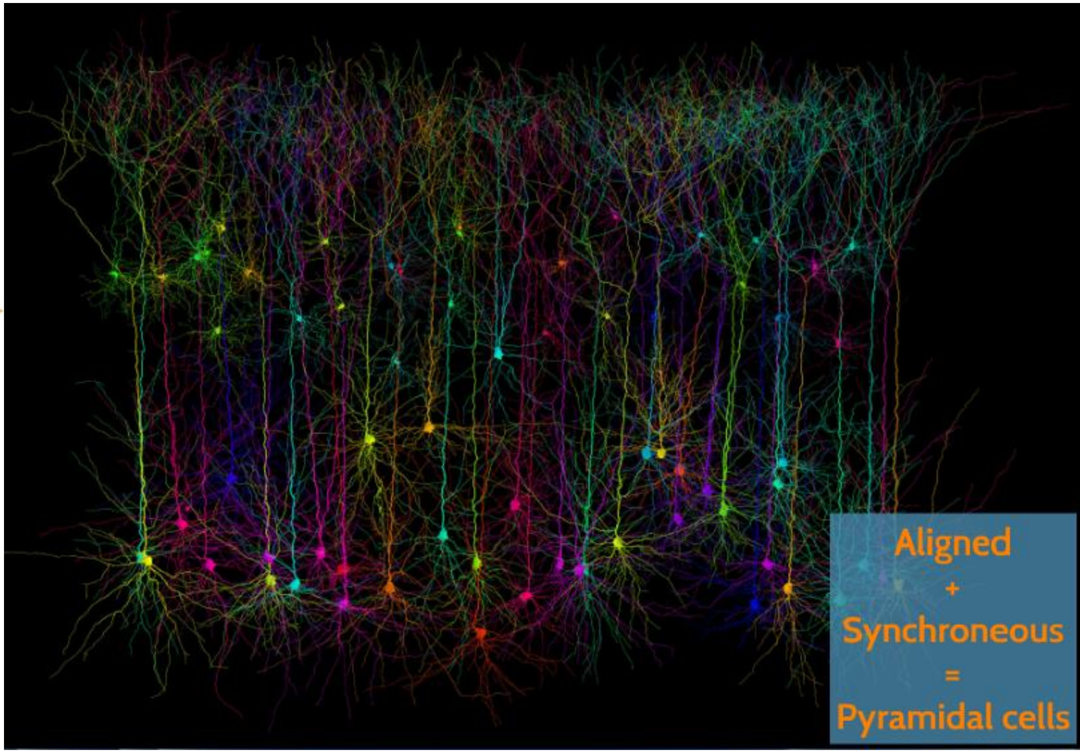


EEG

ElectroEncephaloGraphy (EEG)

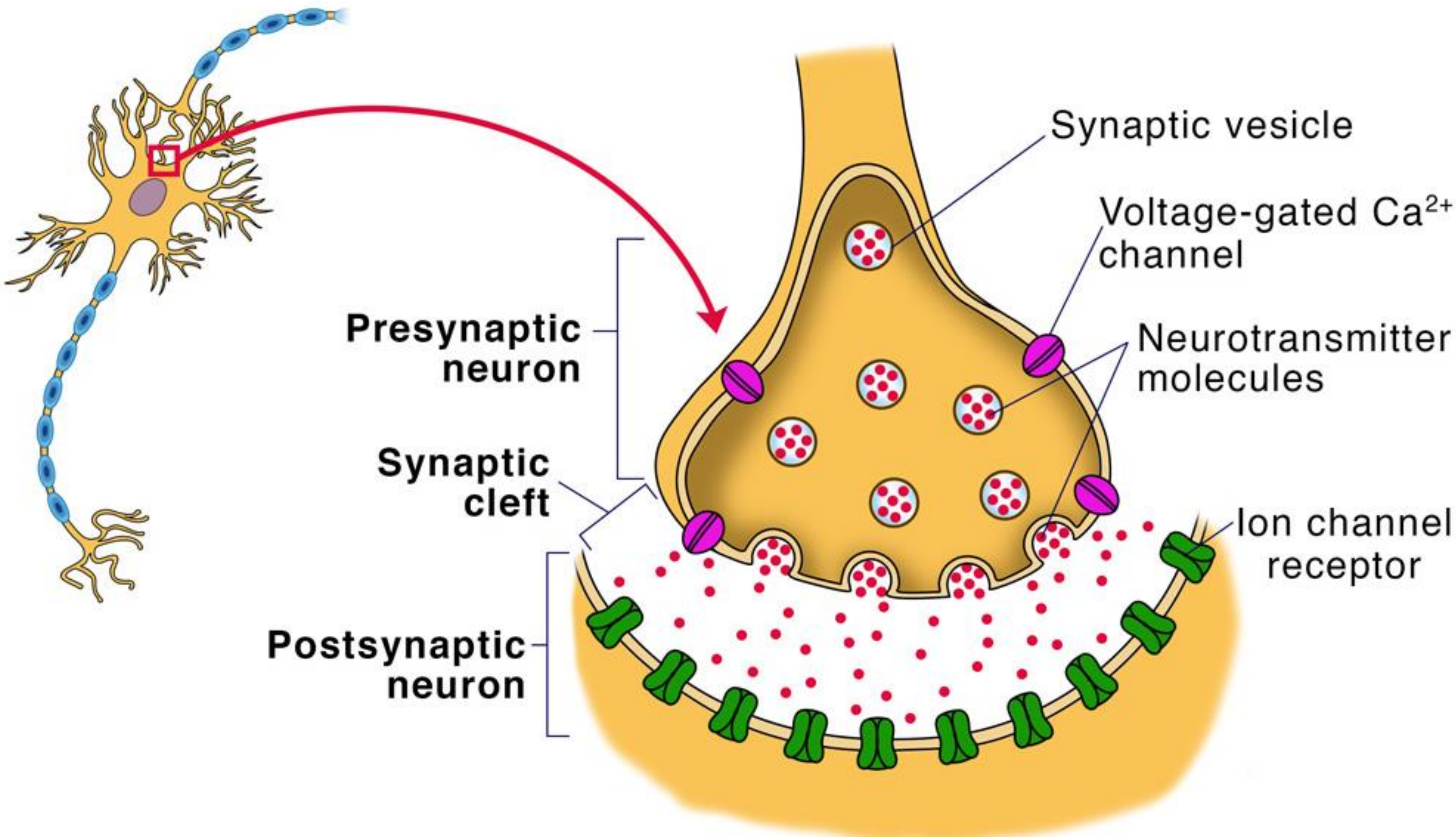
- Global field electrical signals arising from post-synaptic activity of neuronal populations firing
- Clinical use: anesthesia depth assessment, detection of epileptic seizures and estimation of their location, sleep disorders, used for differential diagnosis of coma, encephalopathies, cerebral hypoxia and brain death.
- Research: Frequency decomposition of continuous signals, extraction of signals time-locked to experimental events (presentation of stimuli, motor responses,…)
- Main advantages: high temporal resolution, non invasive, easy to use, relatively cheap
- Pitfalls: Poor three dimensional spatial localization (volumetric localization based on data outside scalp, inverse problem difficult to solve without a clear model of volume conduction)





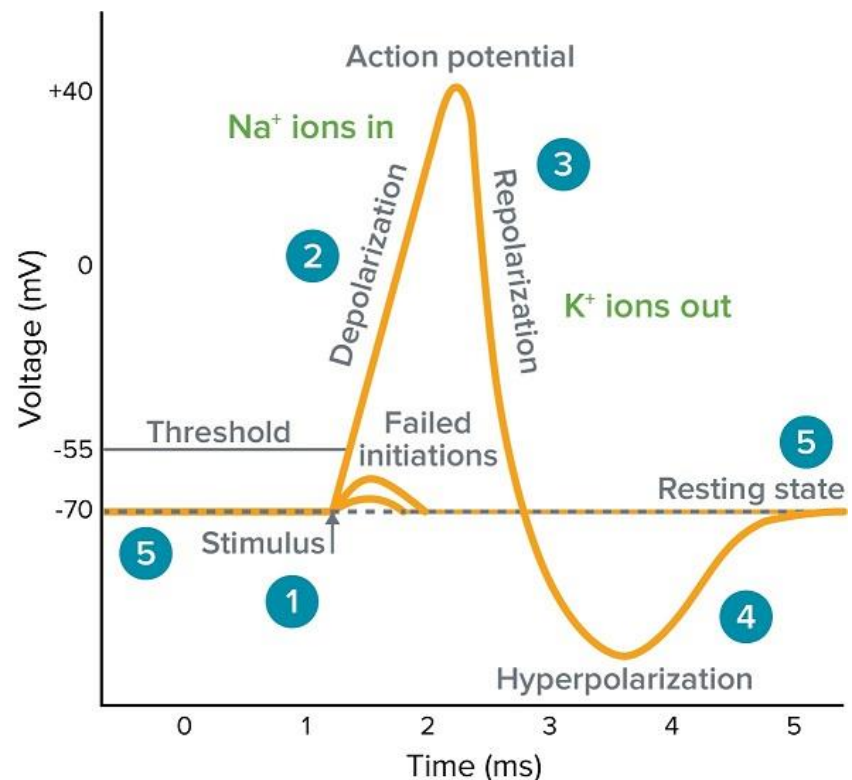
Electric field on one single neuron is too weak to be measured by surface EEG: only equivalent dipoles generate enough current

Action potentials

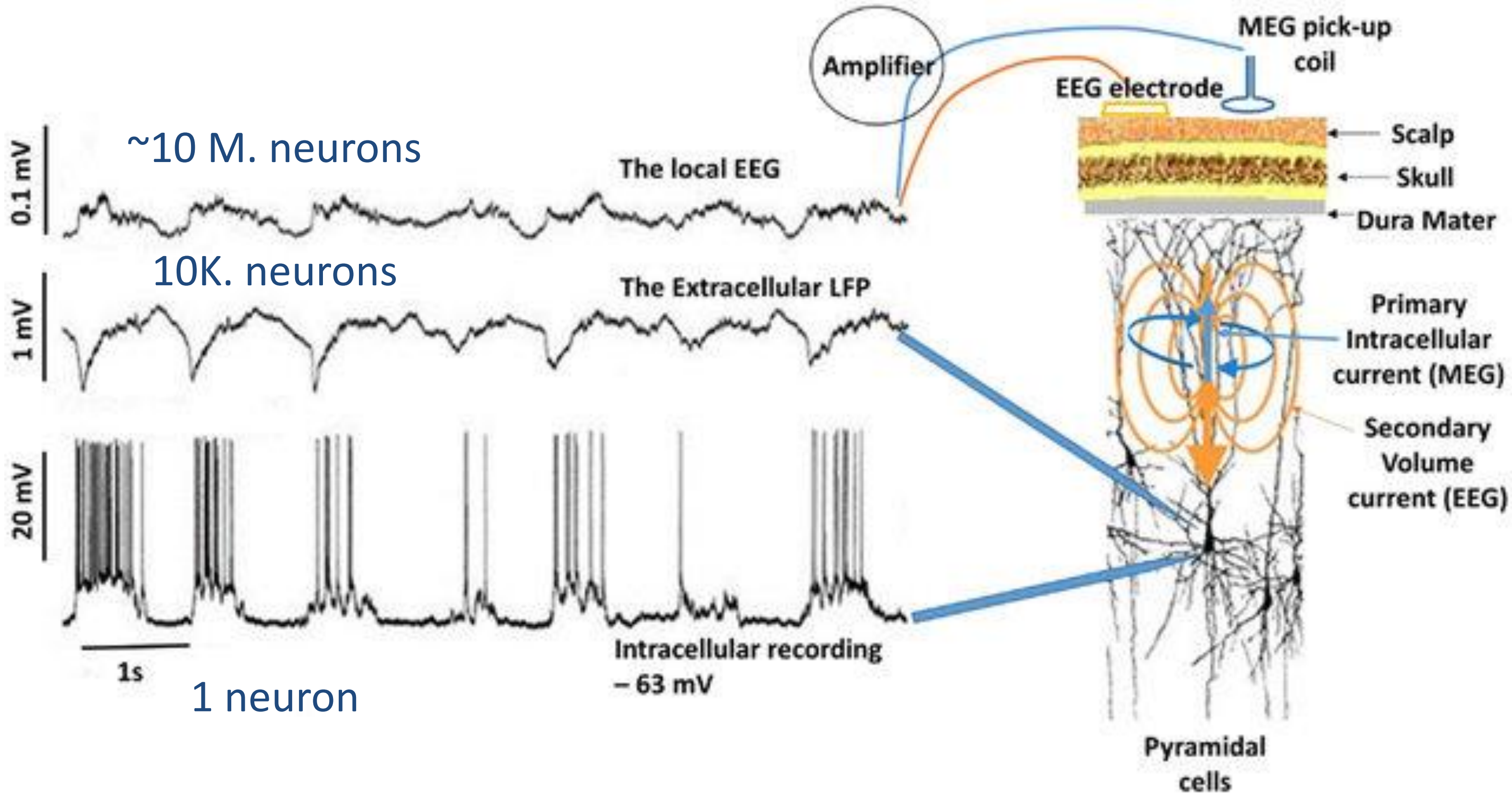


Action potentials

- Action potentials: rapid changes in polarity of membrane potentials
- Differential distribution of ions on either side of the membrane creates a membrane potential
- Influx of Na+ ions and efflux of K+ ions underlie action potentials
- All or nothing
- Set amplitude, duration and refractory period

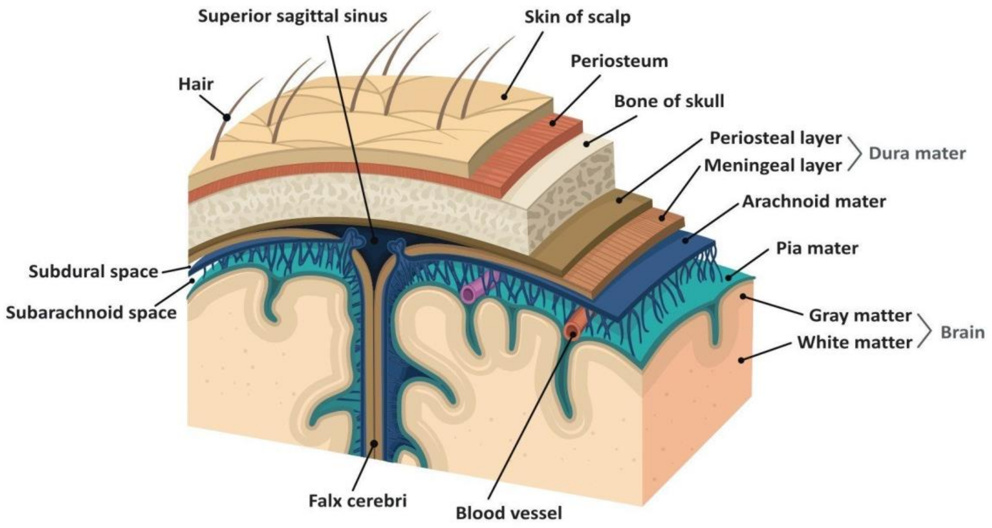


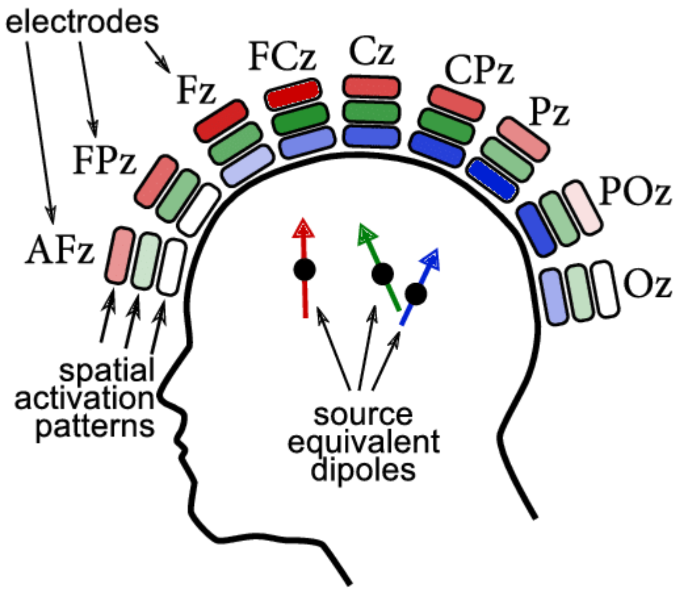
EEG: Principles and limitations



EEG: Principles and limitations

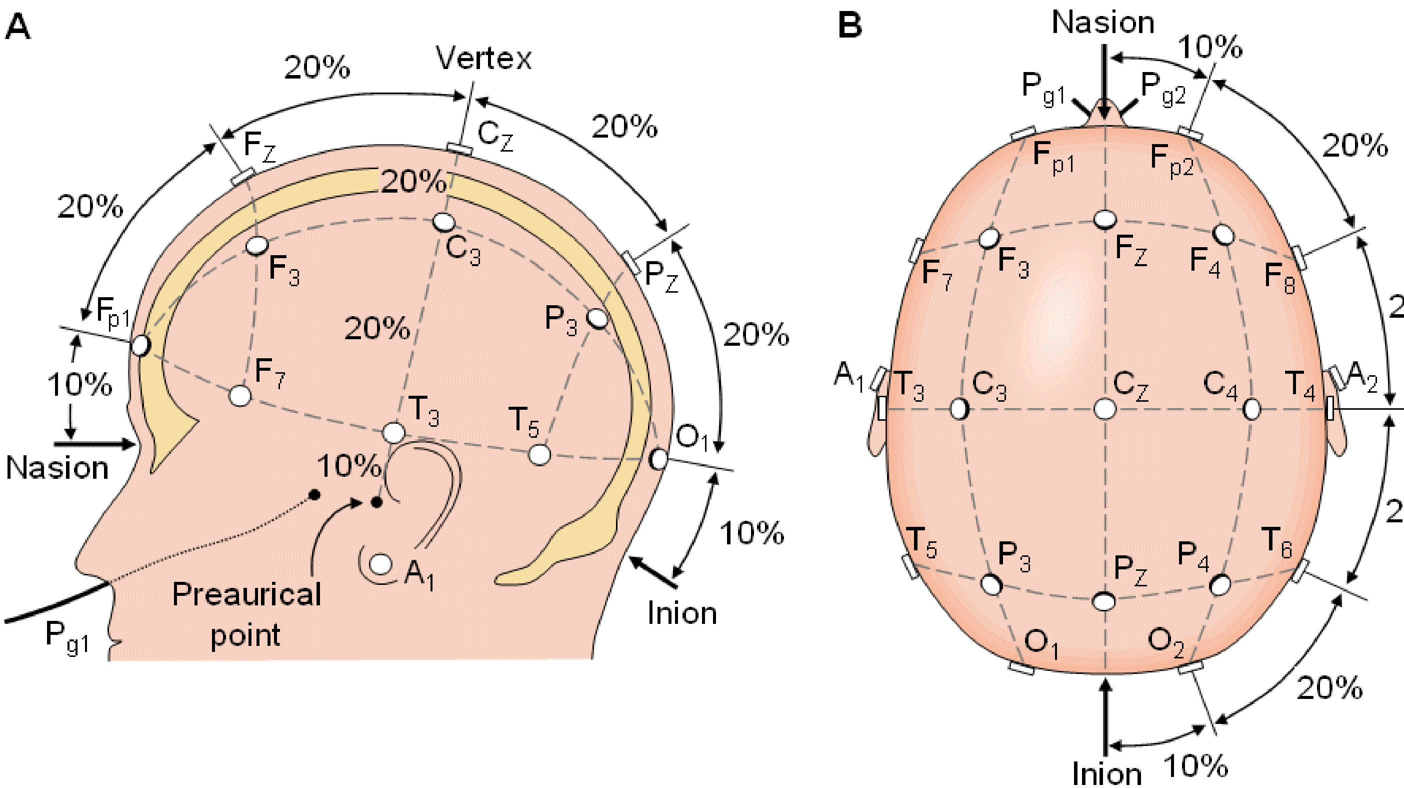
Volume conduction issue: neural activity is conducted through brain tissue to the scalp & sensors





Each electrode measure a weighted sum of the the cerebral sources

EEG: Principles and limitations

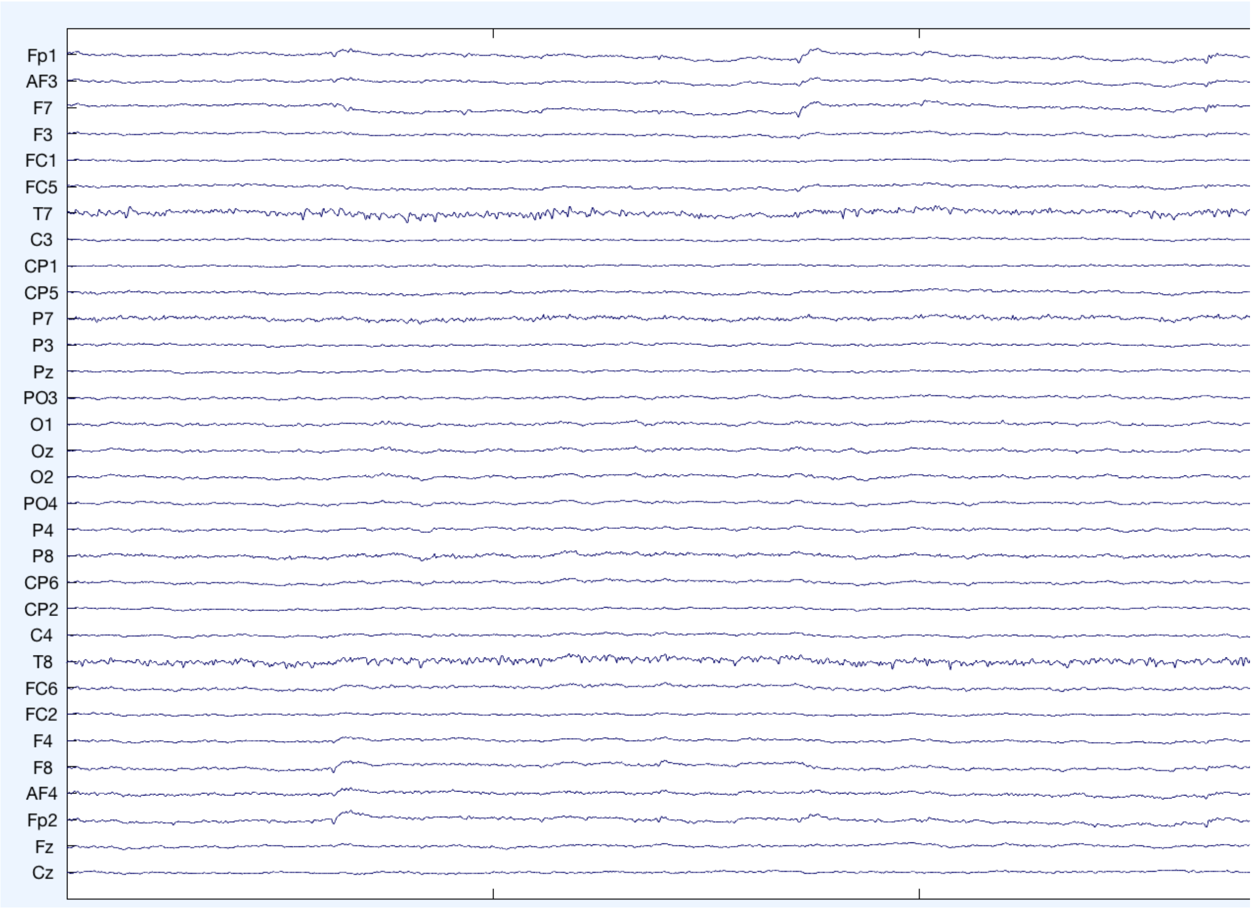


Cap:

- choose the best size for each participant (eg. Small, medium…)
- Place Cz carefully!

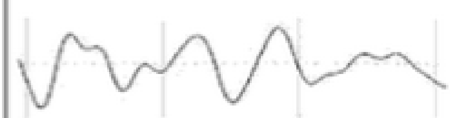
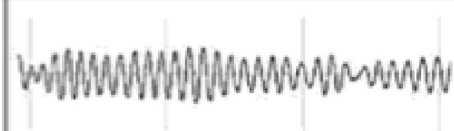
EEG: Principles and limitations

EEG Signal (oscillation) reflects voltage deflection coming from the activity assembly of pyramidal neurons



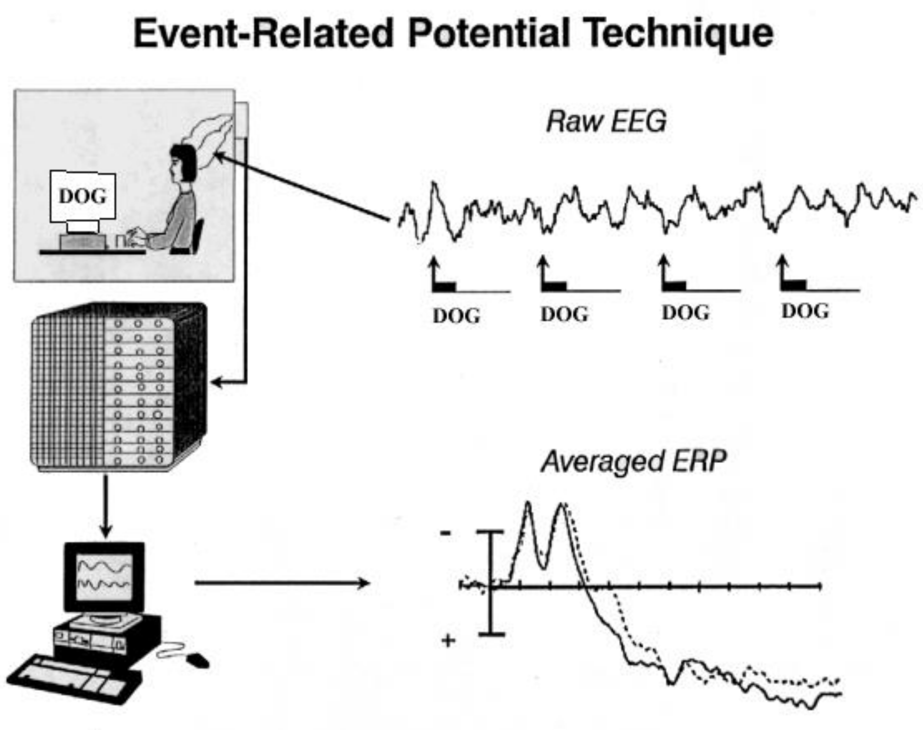
EEG

EEG rhythmic activity frequency bands

Frequency Band Name	Frequency Bandwidth	State Associated with Bandwidth	Example of Filtered Bandwidth
Raw EEG	0–45 Hz	Awake	
Delta	0.5–3.5 Hz	Deep Sleep	
Theta	4–7.5 Hz	Drowsy	
Alpha	8–12 Hz	Relaxed	
Beta	13–35 Hz	Engaged	

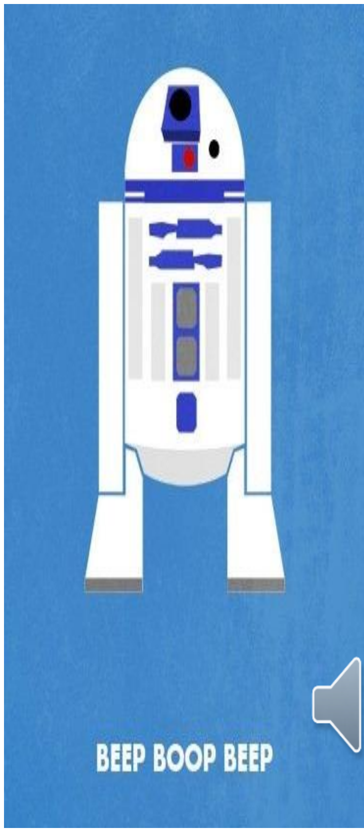
Event-Related Potentials

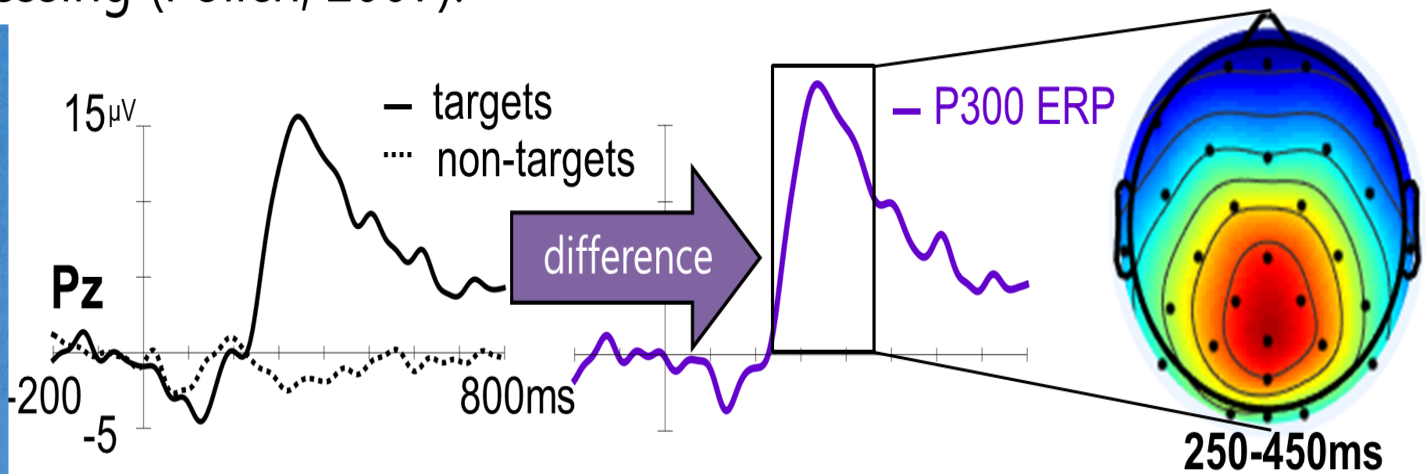
- Time-locked average of EEG from many trials involving same event
- Signal/Noise Ratio reduction; what is left is related to the event



P300 Event-Related Potentials (ERPs) are typical positive deflections in the EEG trace elicited 250-450ms after presentation of target stimuli and are most prominent at centroparietal electrode sites.

P300 ERPs amplitude and peak latency have been linked to attentional and memory processing (Polich, 2007).





P300 elicitation through an auditory oddball paradigm

2 tones: 20% targets, 80% non-targets, pseudo-randomized. Participants were asked to count the number of target stimuli over a period of 5 minutes (300 trials).

EEG-based
Brain-Computer Interfaces

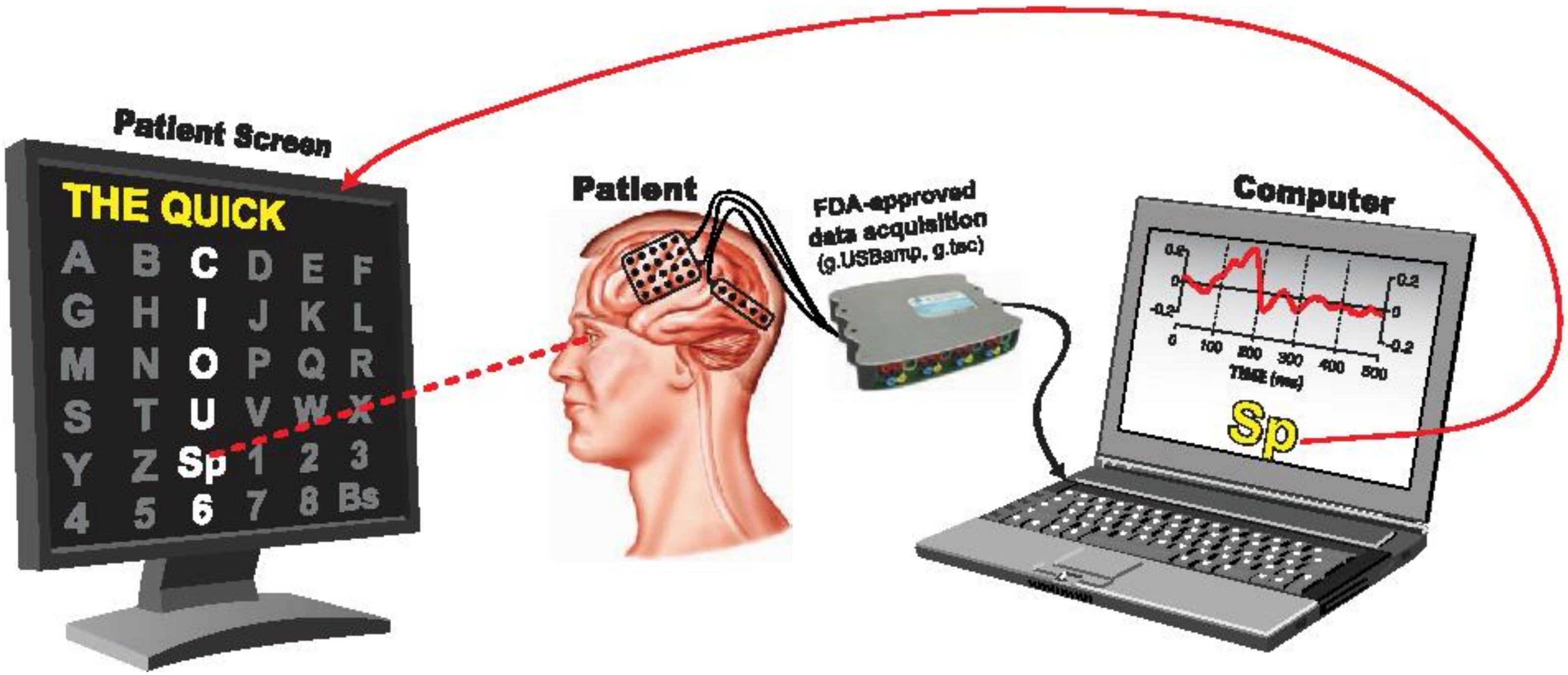
Direct (second-scale) communication between the brain and external devices

Without requiring muscular engagement

Spellers for locked-in patients have been an influential application for the development of EEG-based BCI

- Active, Passive and reactive BCI: endogenous and exogenous stimuli
- Requires knowledge about neural dynamics related to targeted functions
- Challenges in terms of online signal processing to allow for seamless user experience

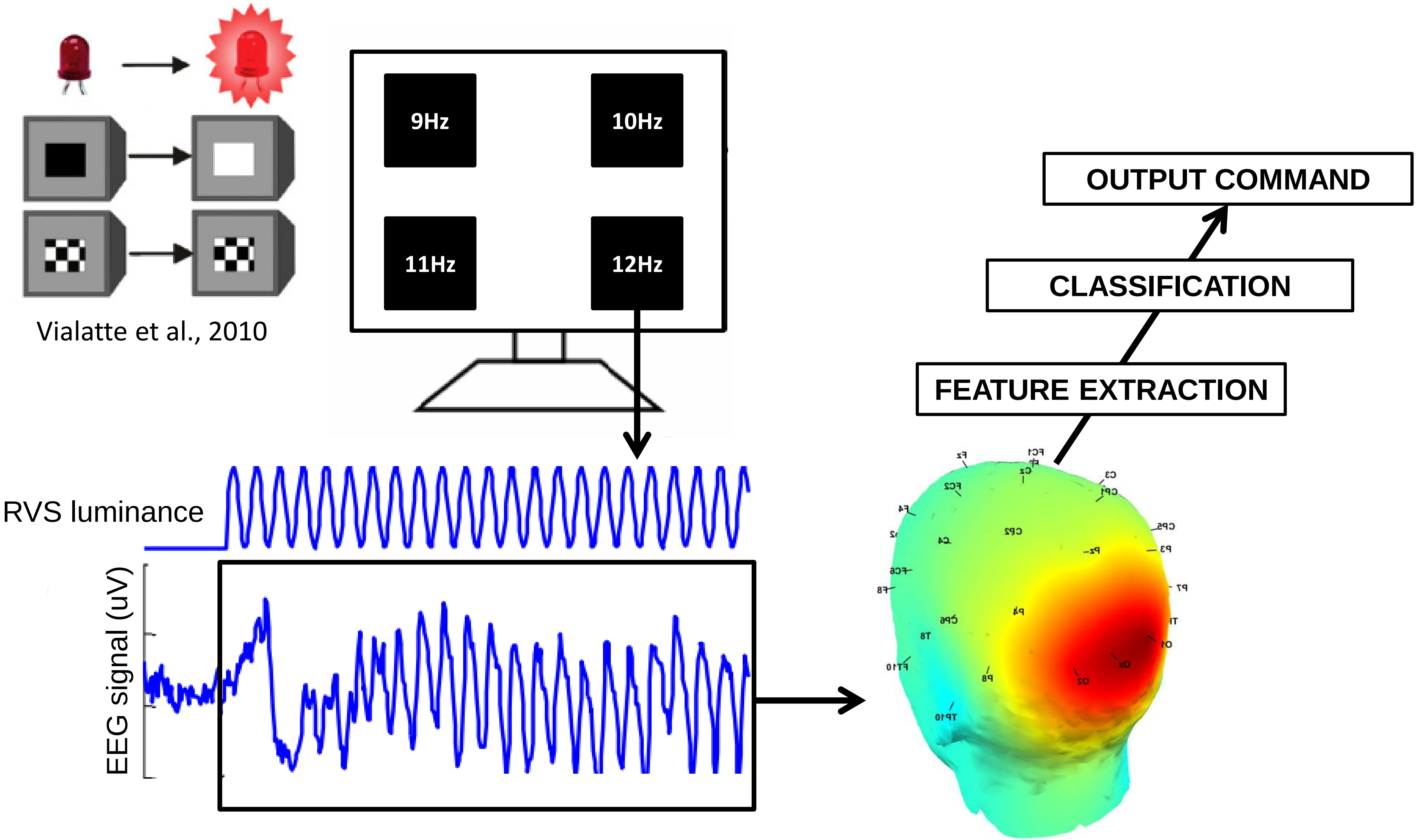
P300 ERP-based BCI



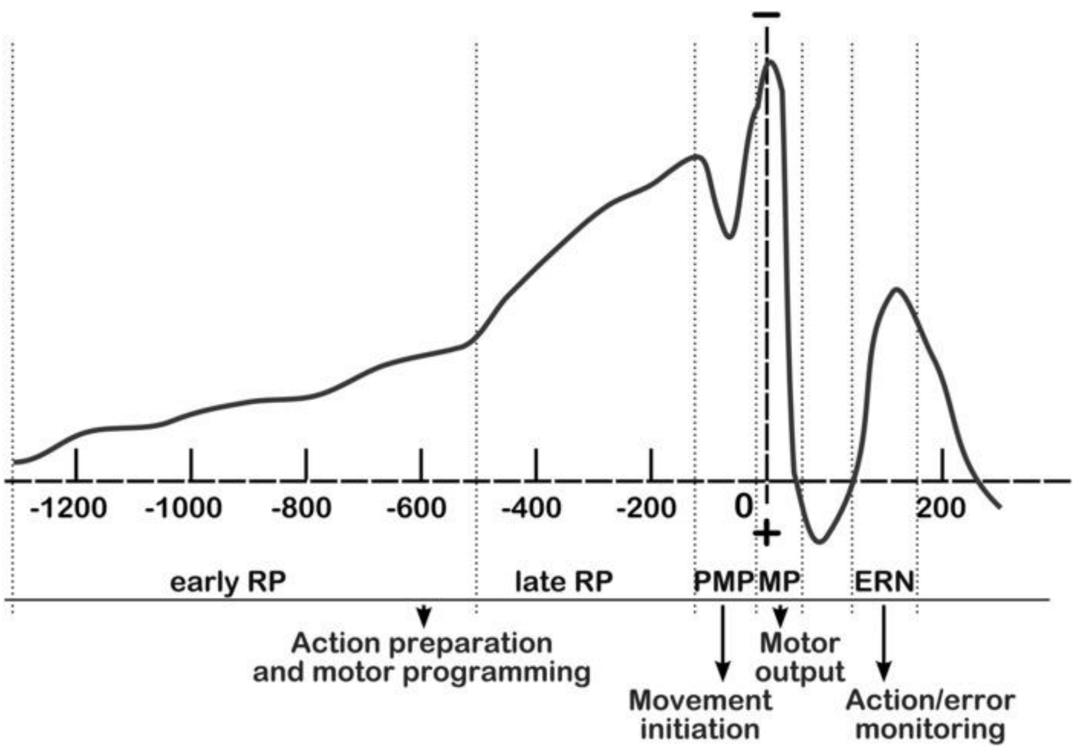
SSVEP-based BCI

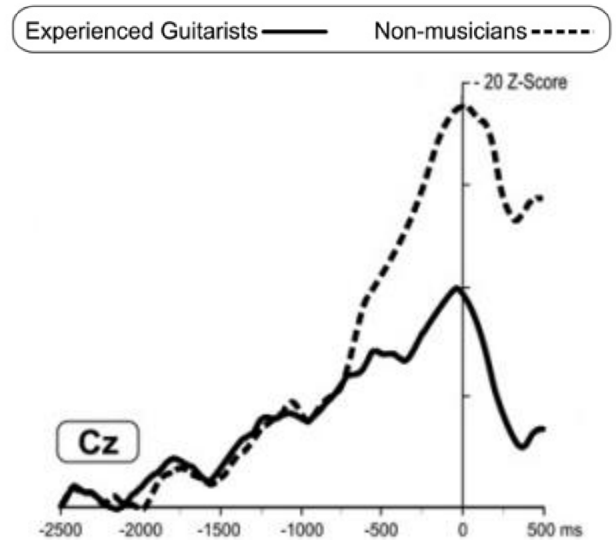
Presentation of Repeated Visual Stimuli (RVS)

Synchronization of neural populations to the RVS frequency

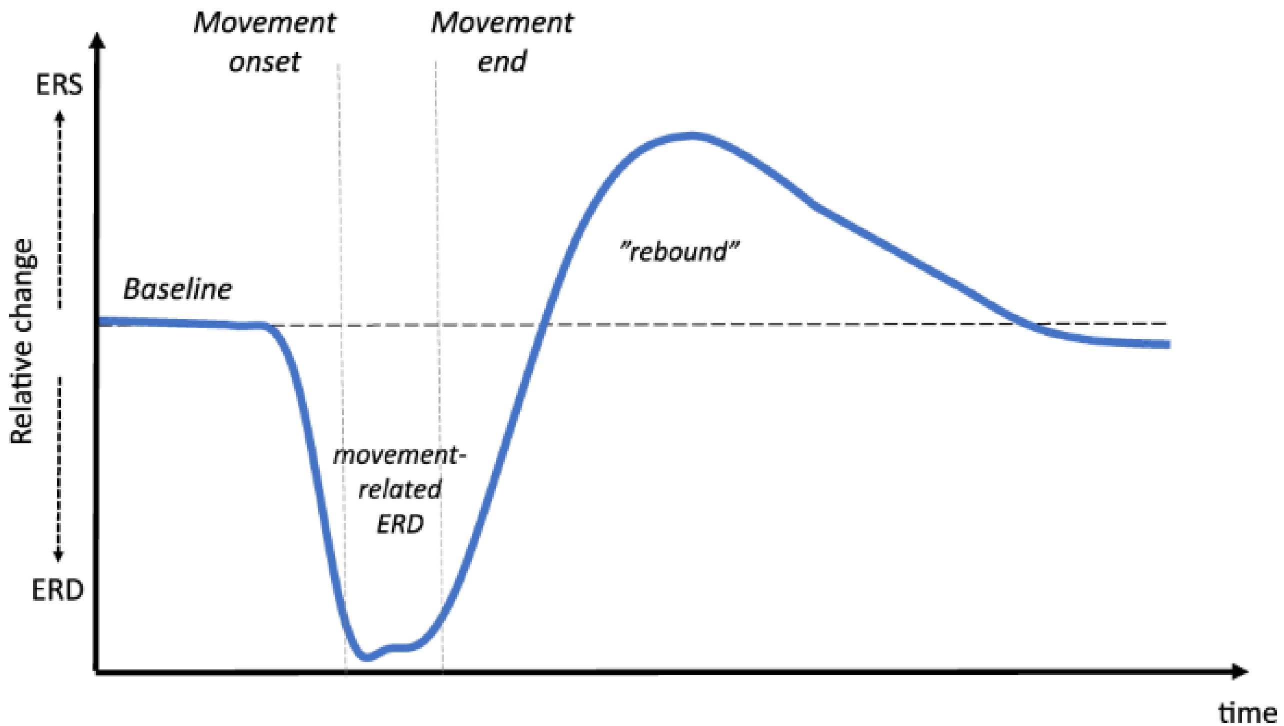


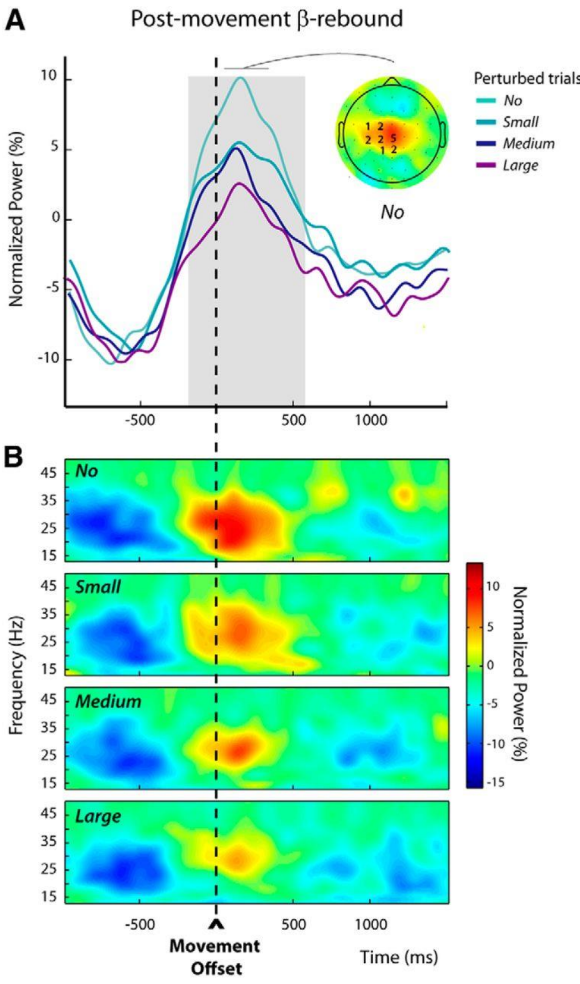
Motor planning: Readiness potential



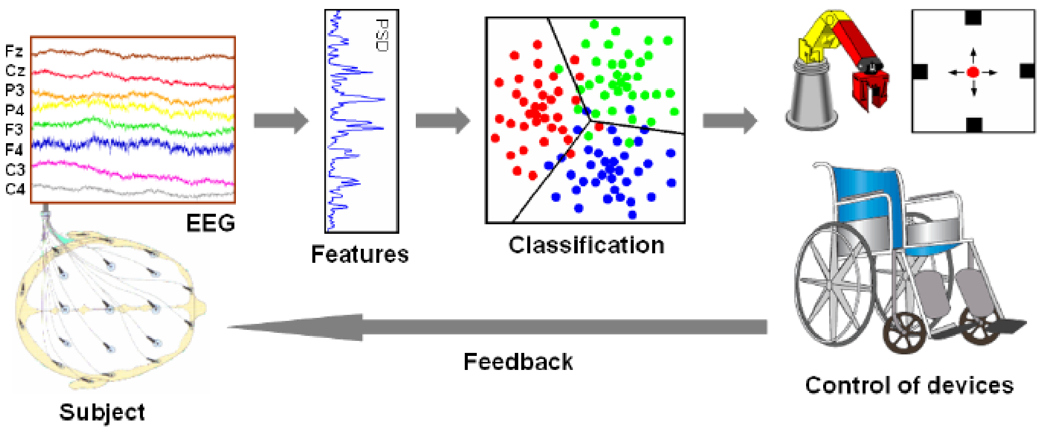


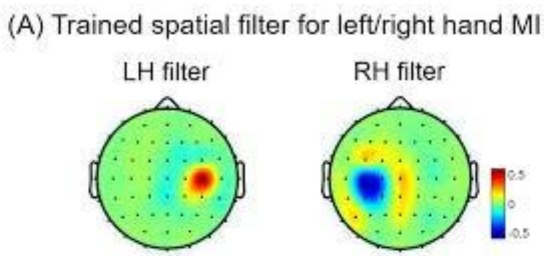
Motor planning: Beta rebound



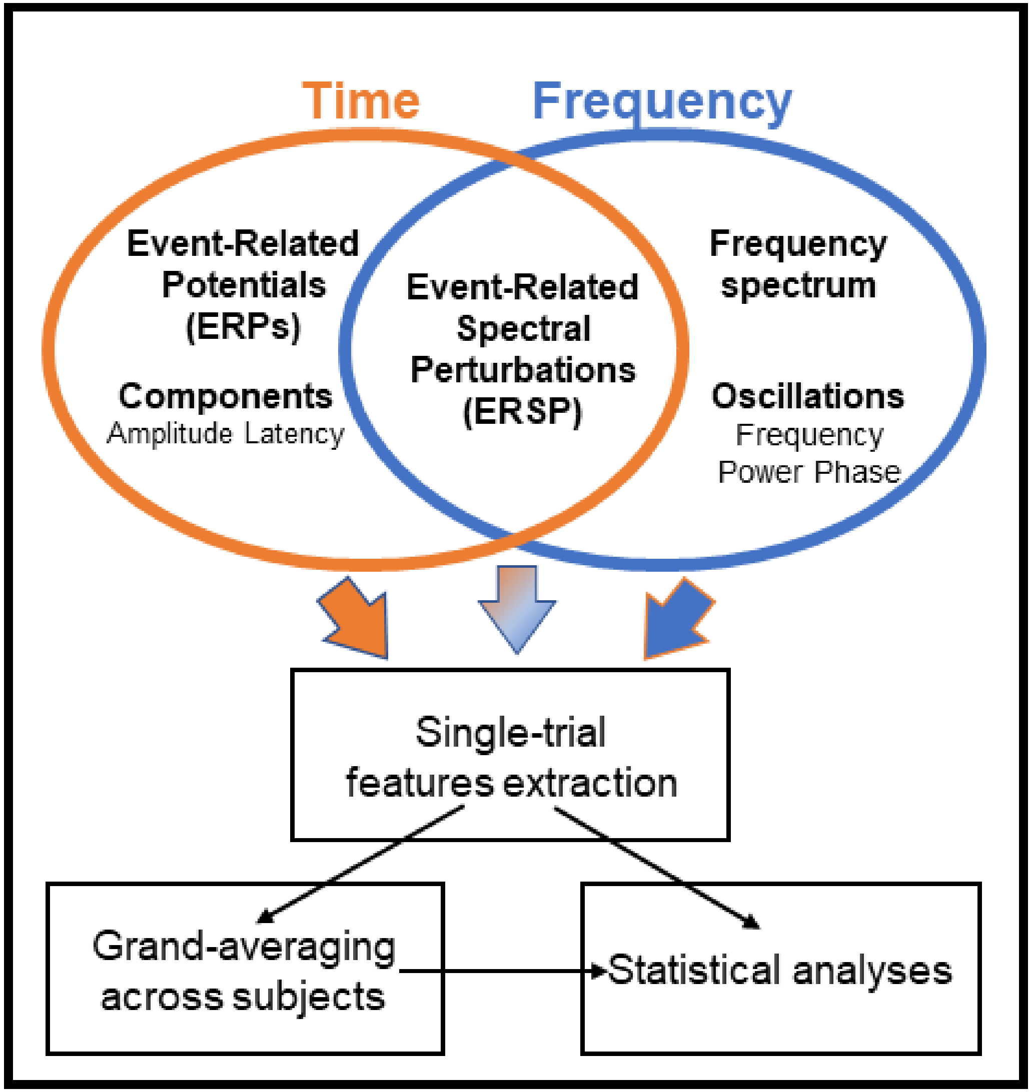


Motor imagery

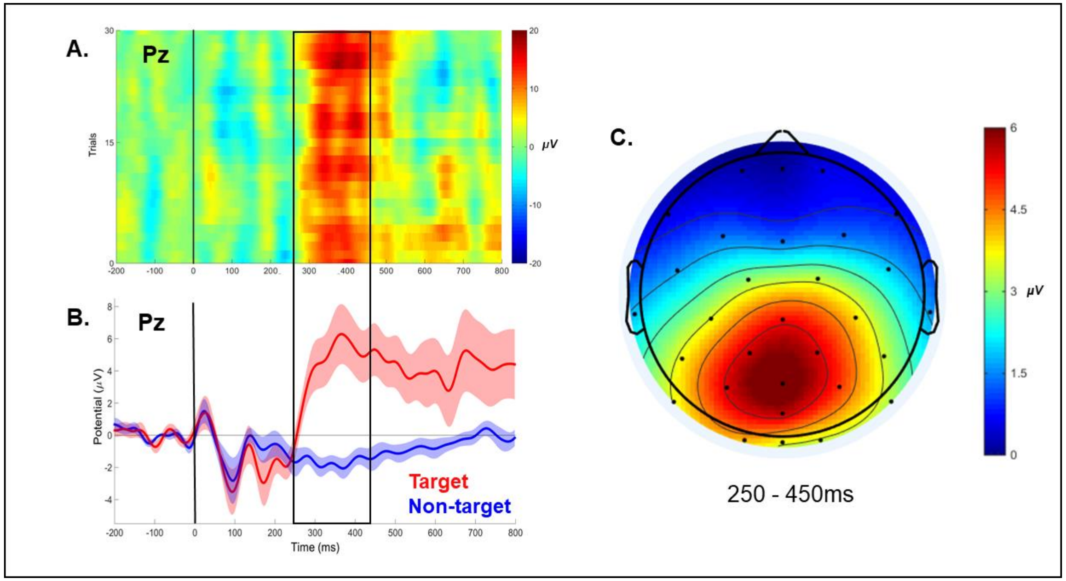




EEG Data analysis



EEG measures:
Event-Related Potentials (ERP)



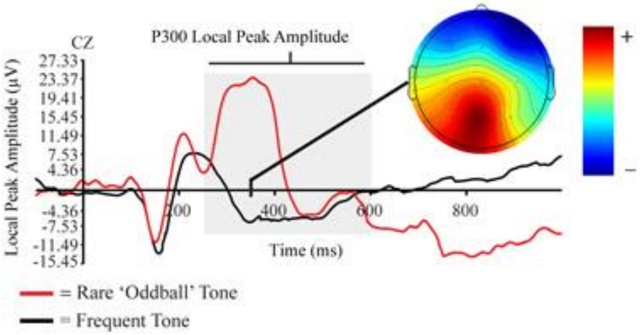
Time-domain analysis

Response locked Event Related Potential (ERP)

Oddball paradigm

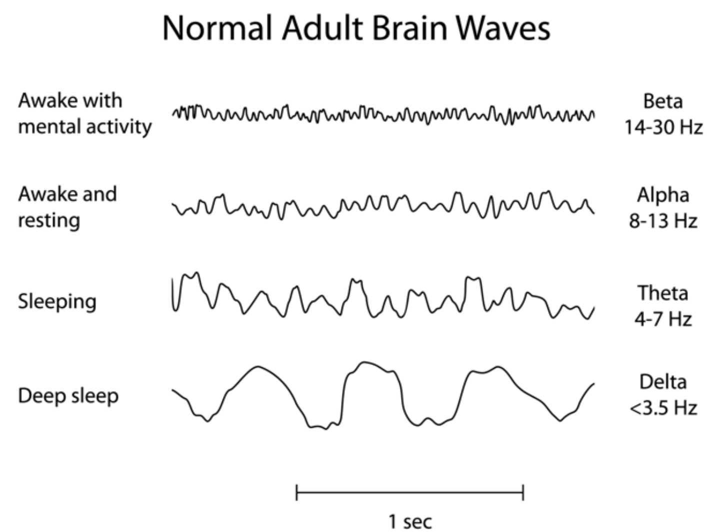
Frequent
Tone (75%)

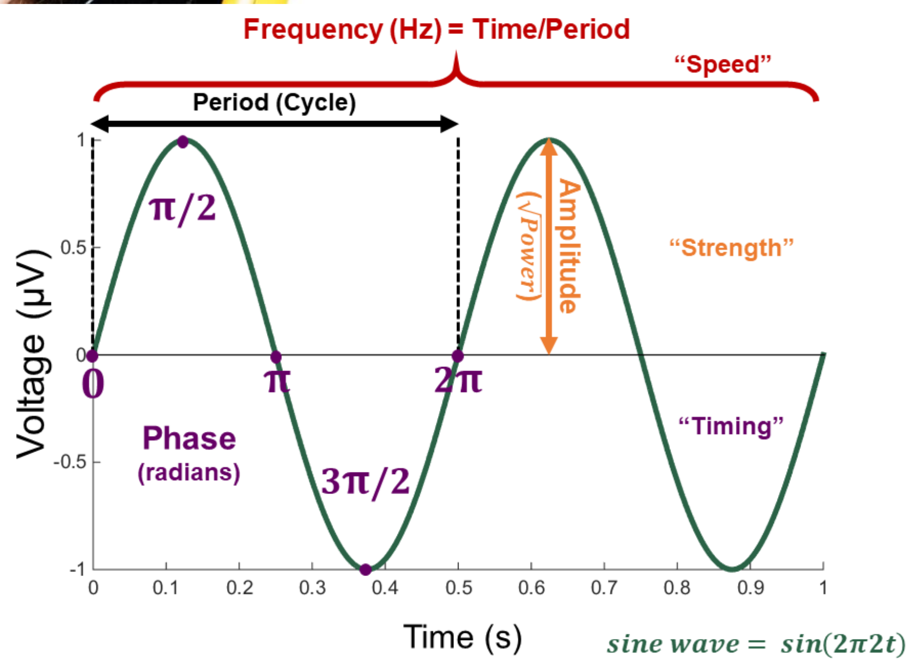
Rare
Tone (25%)



EEG: Measures
Power spectral analyses

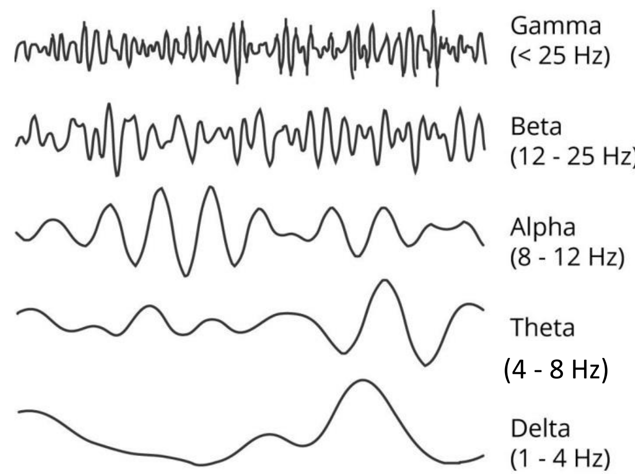
Frequency domain analysis



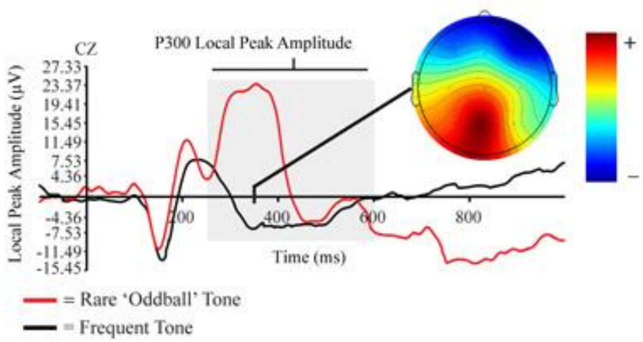


EEG measures: Time-frequency decompositions

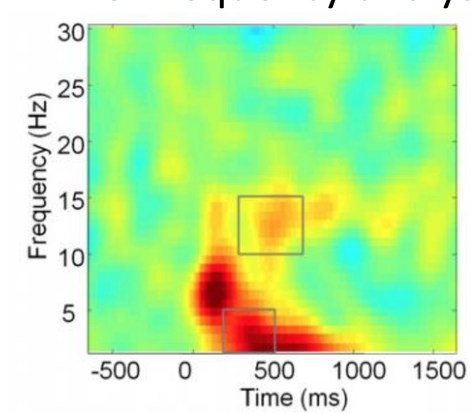
Frequency domain analysis



Time-domain analysis

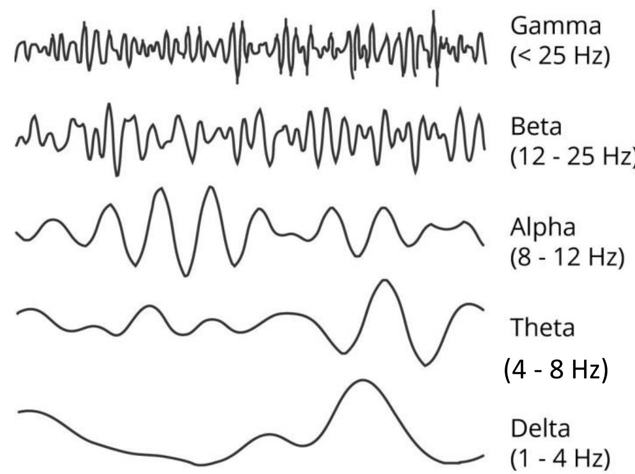


Time-Frequency analysis

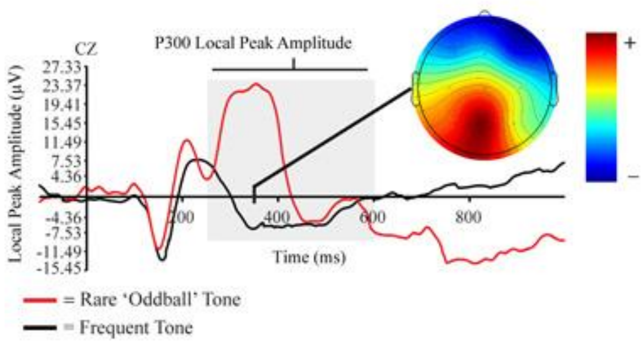


EEG measures: Phase-locking and coherence

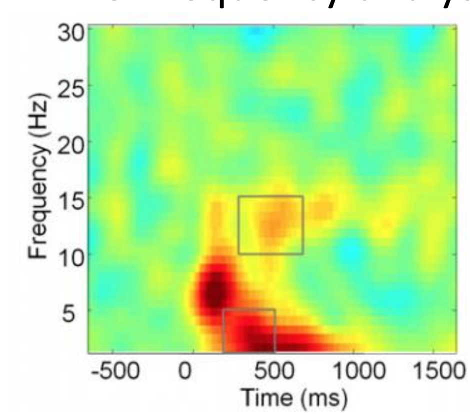
Frequency domain analysis



Time-domain analysis



Time-Frequency analysis



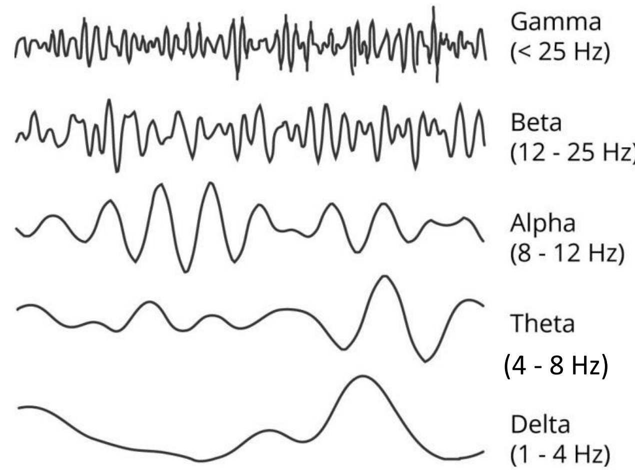
Phase based analysis

Sync!

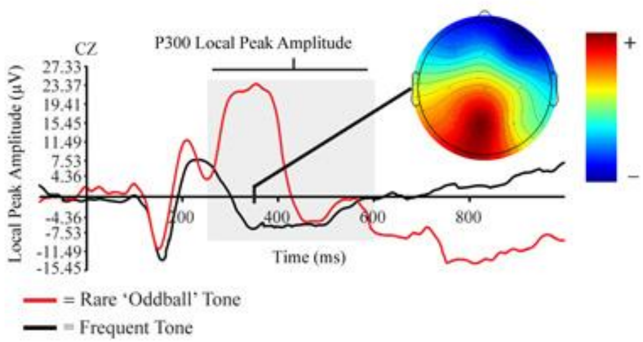
No sync!

EEG measures: Phase-locking and coherence

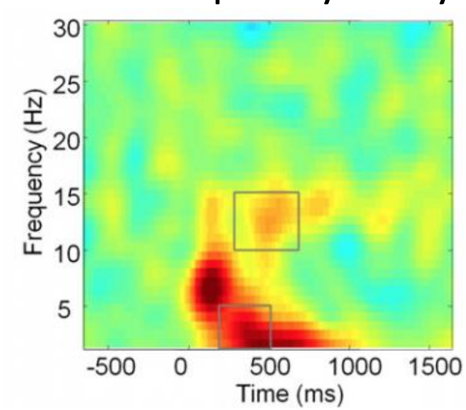
Frequency domain analysis



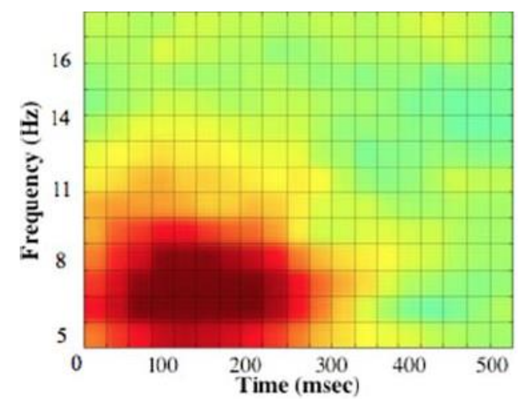
Time-domain analysis



Time-Frequency analysis



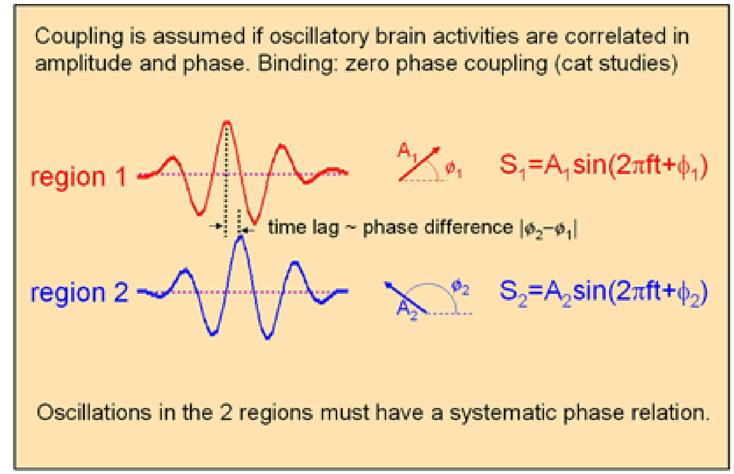
Phase based analysis



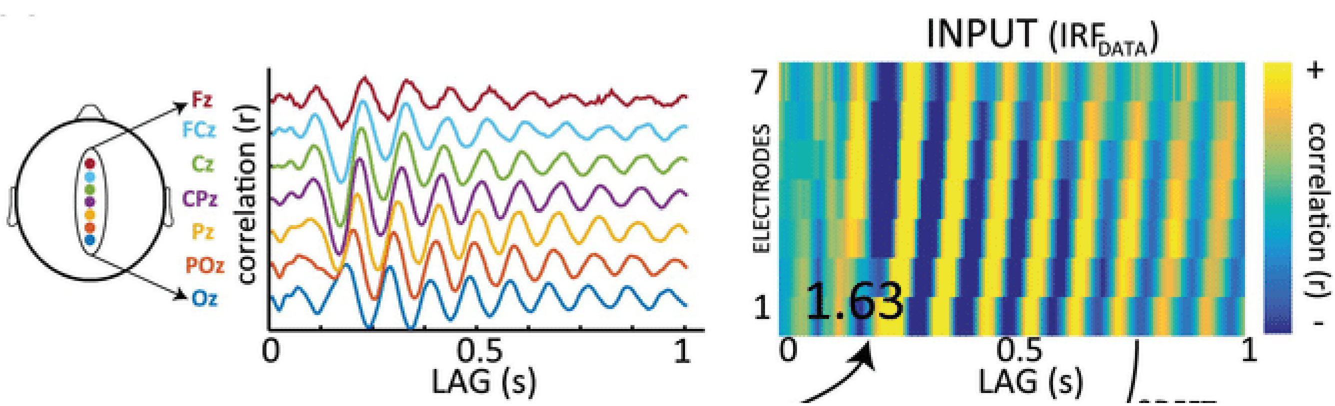
Electro-encephalography: measures

Spatial analyses

Oscillatory coupling between 2 brain regions

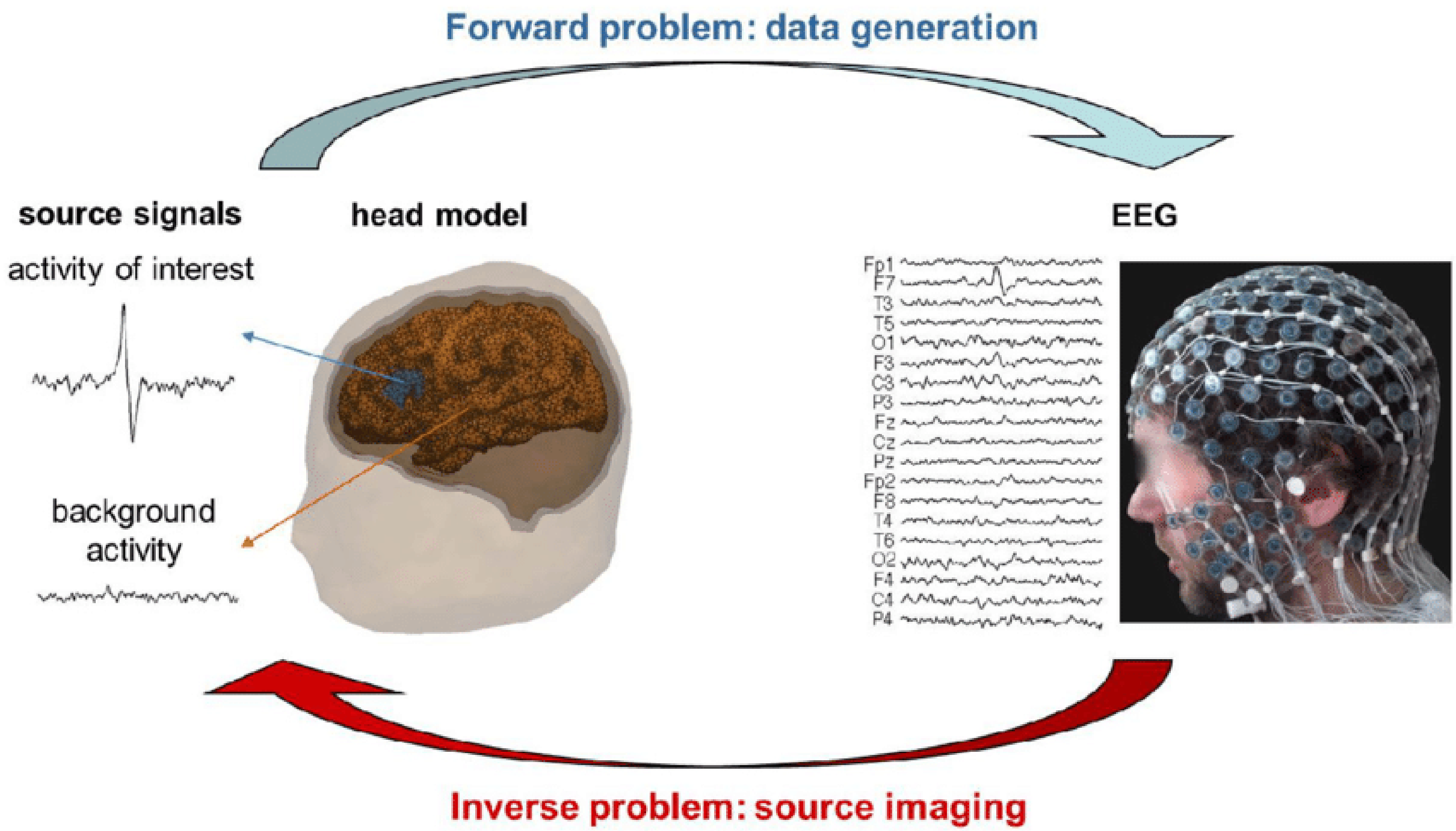


Travelling waves

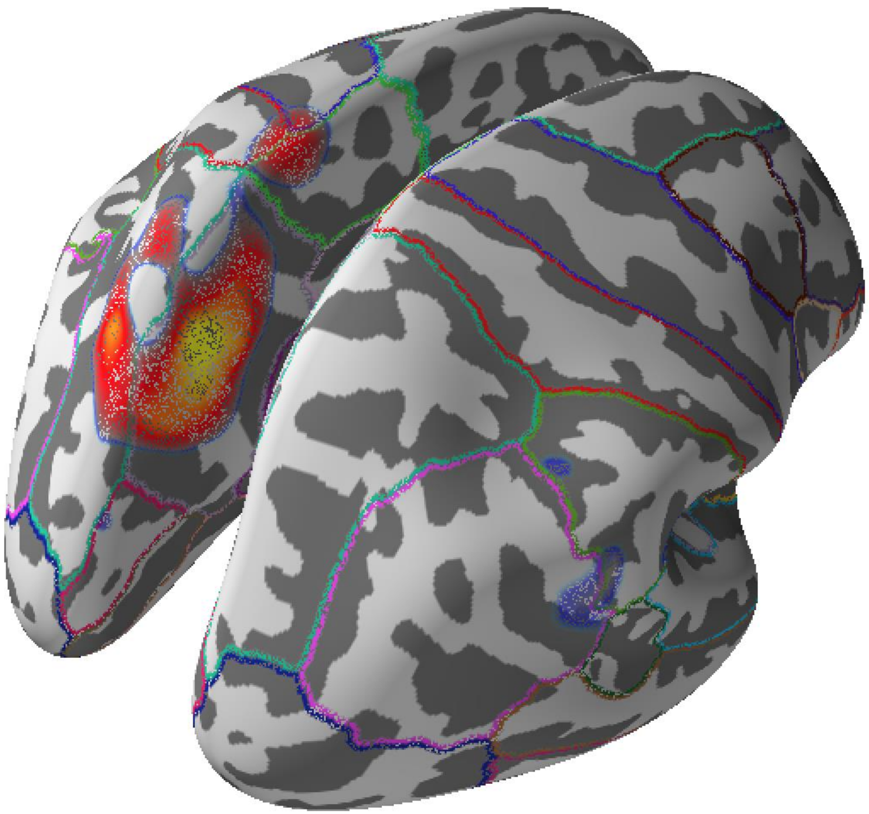


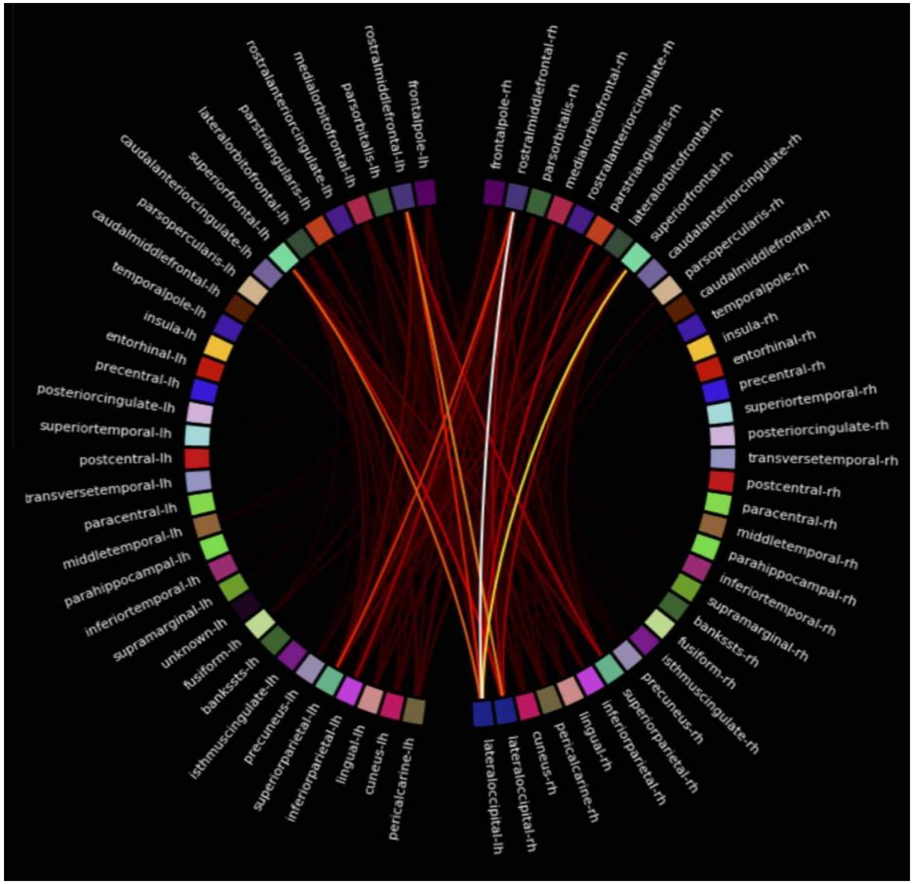
Electro-encephalography: measures

Source localization and inverse problem



Source localization and inverse problem

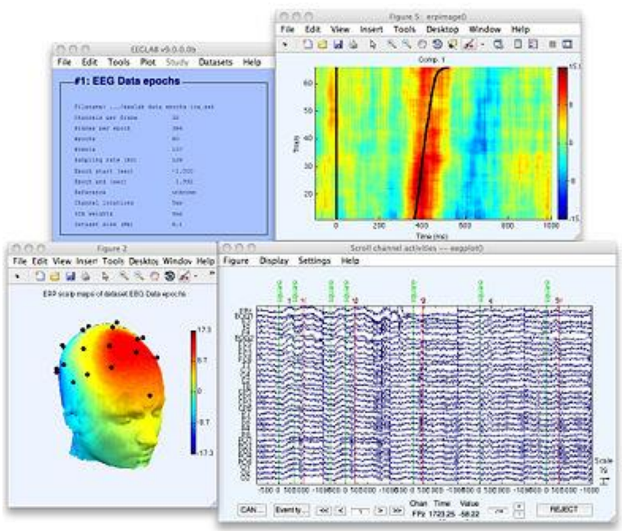




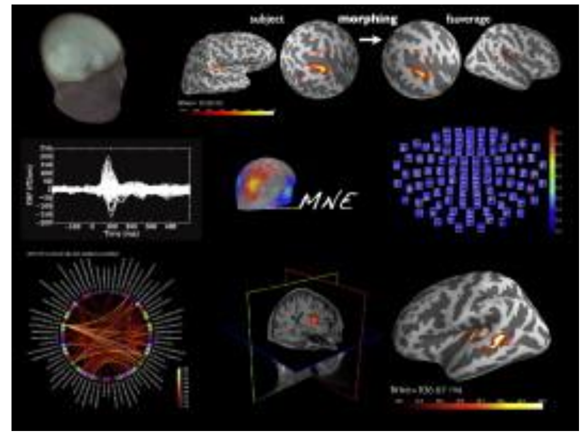
BUT BEFORE GETTING TO THESE FANCY ANALYSES

YOU'LL HAVE TO PRE-PROCESS YOUR SIGNAL!

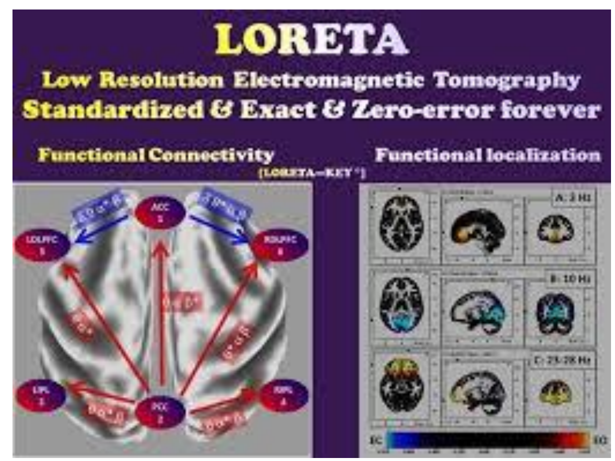
Software



EEGlab (Matlab toolbox)

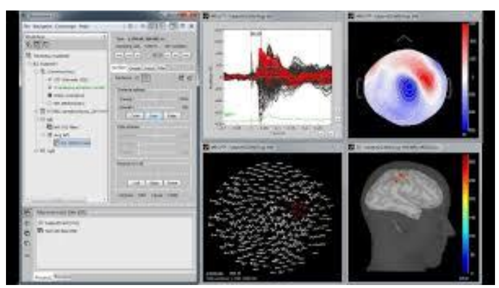


MNE (Python)



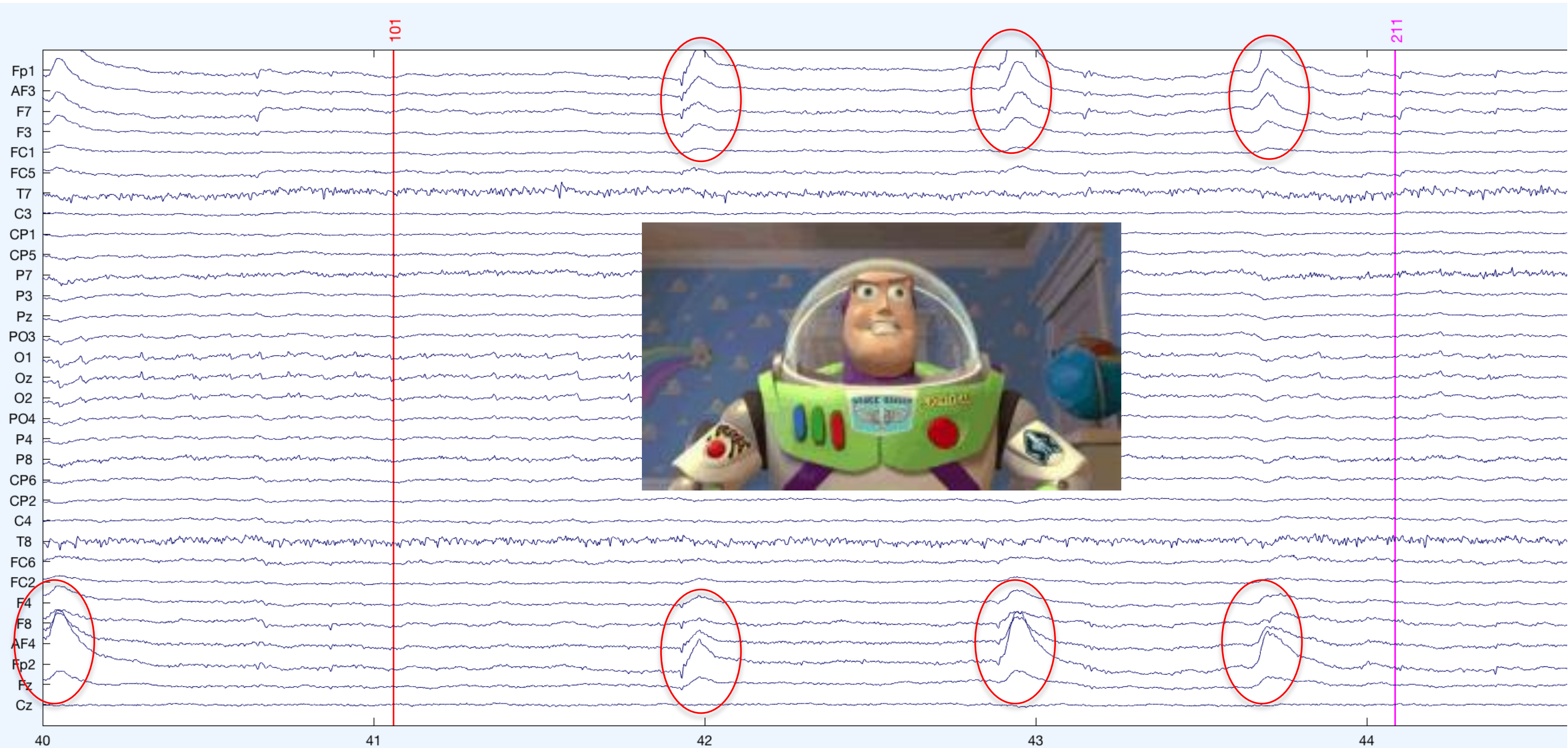
Sloreta (Stand alone)

Fieldtrip (Matlab toolbox)



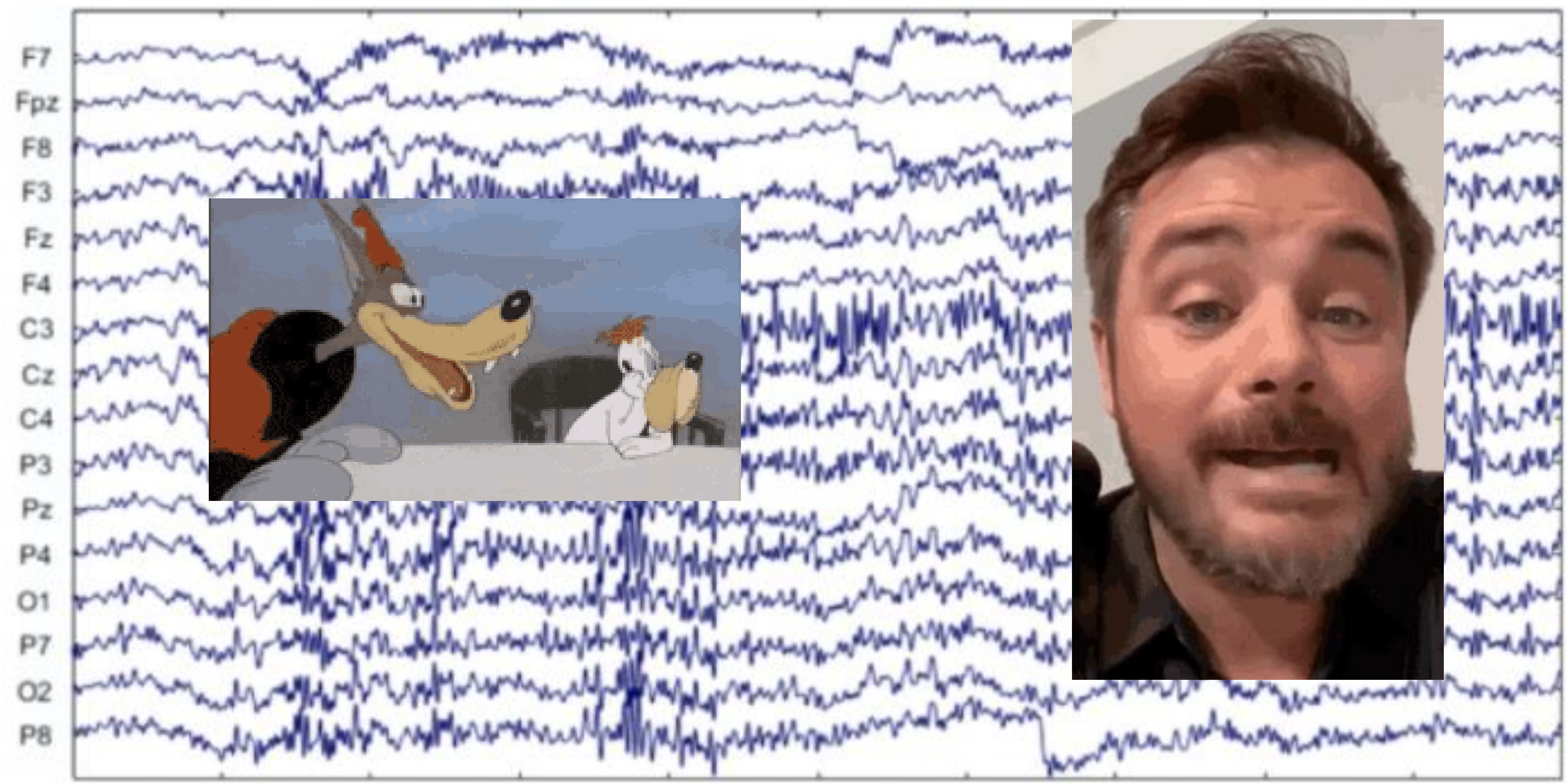
Brainstorm (Stand alone)

NOISE!



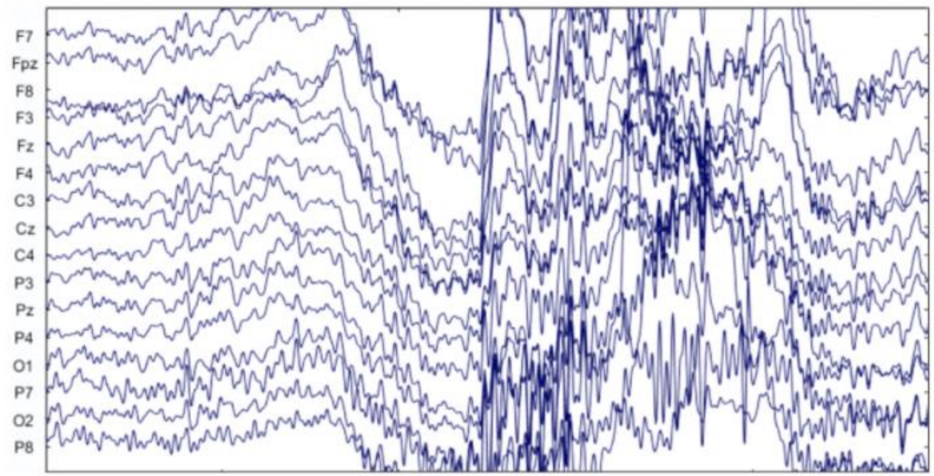
Blinks / Eye movement : <4 Hz – mostly frontal electrodes

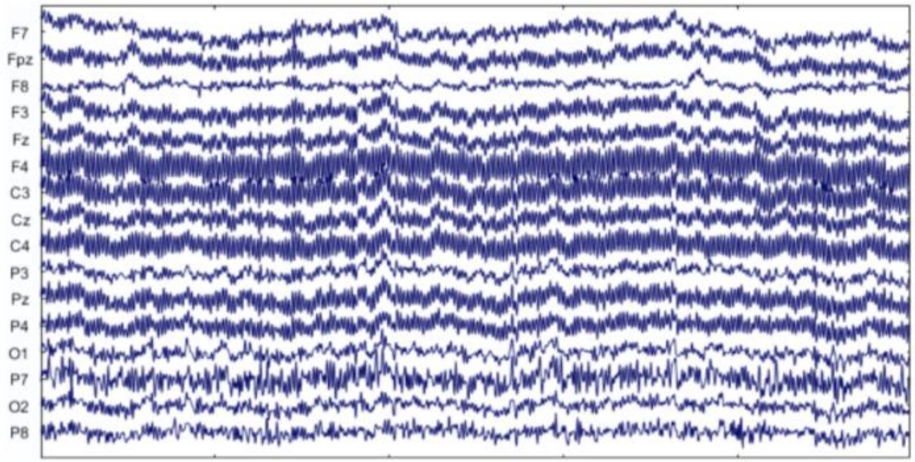
NOISE!



Affect all electrodes – increasing from 10 Hz with a plateau from 60 to 80 Hz – until 128 Hz

NOISE!





Line noise : 50 Hz or 60 Hz

- **Avoid artifacts:**

  - Optimize the experimental environment : eg. no cell phone, use fixation cross

  - Give appropriate and clear instruction: “Do not move”, do not clinch, do not speak, “avoid swallowing saliva..”

WHAT CAN BE DONE?

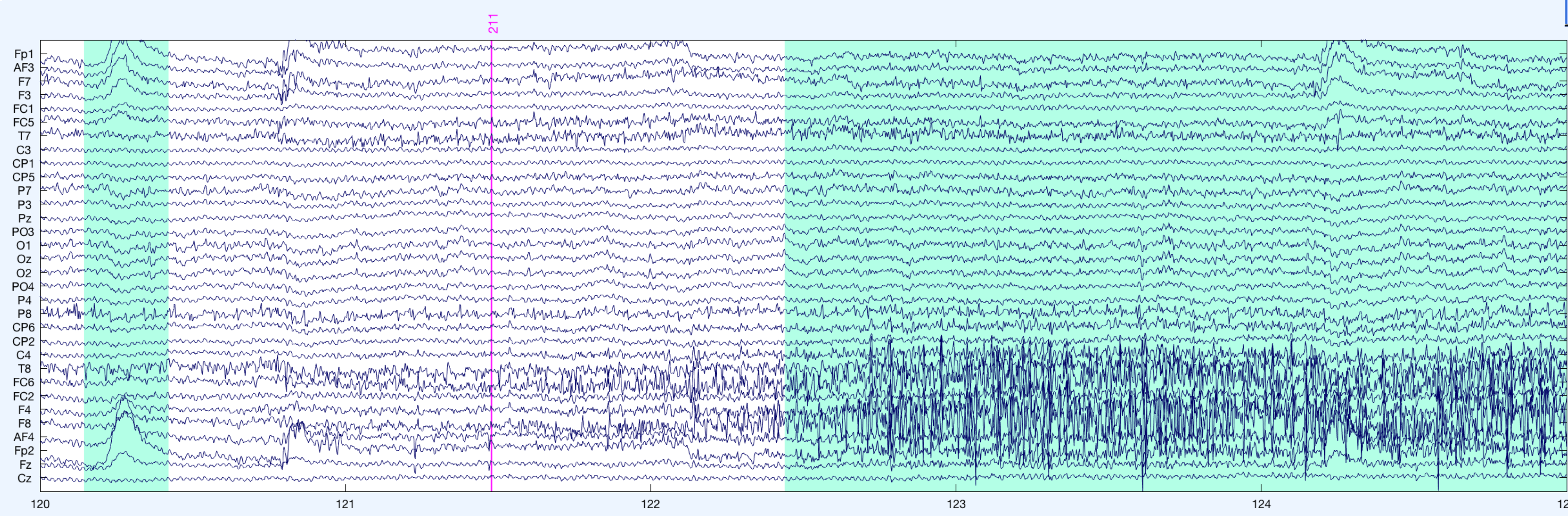
Avoid artifacts:

- Optimize the experimental environment : eg. no cell phone, use fixation cross
- Give appropriate and clear instruction: "Do not move", do not clinch, do not speak, "avoid swallowing saliva.."

NOT RELEVANT AT ALL FOR NEUROERGONOMICS RESEARCH AND BCI APPLICATIONS!!!

WHAT CAN BE DONE?

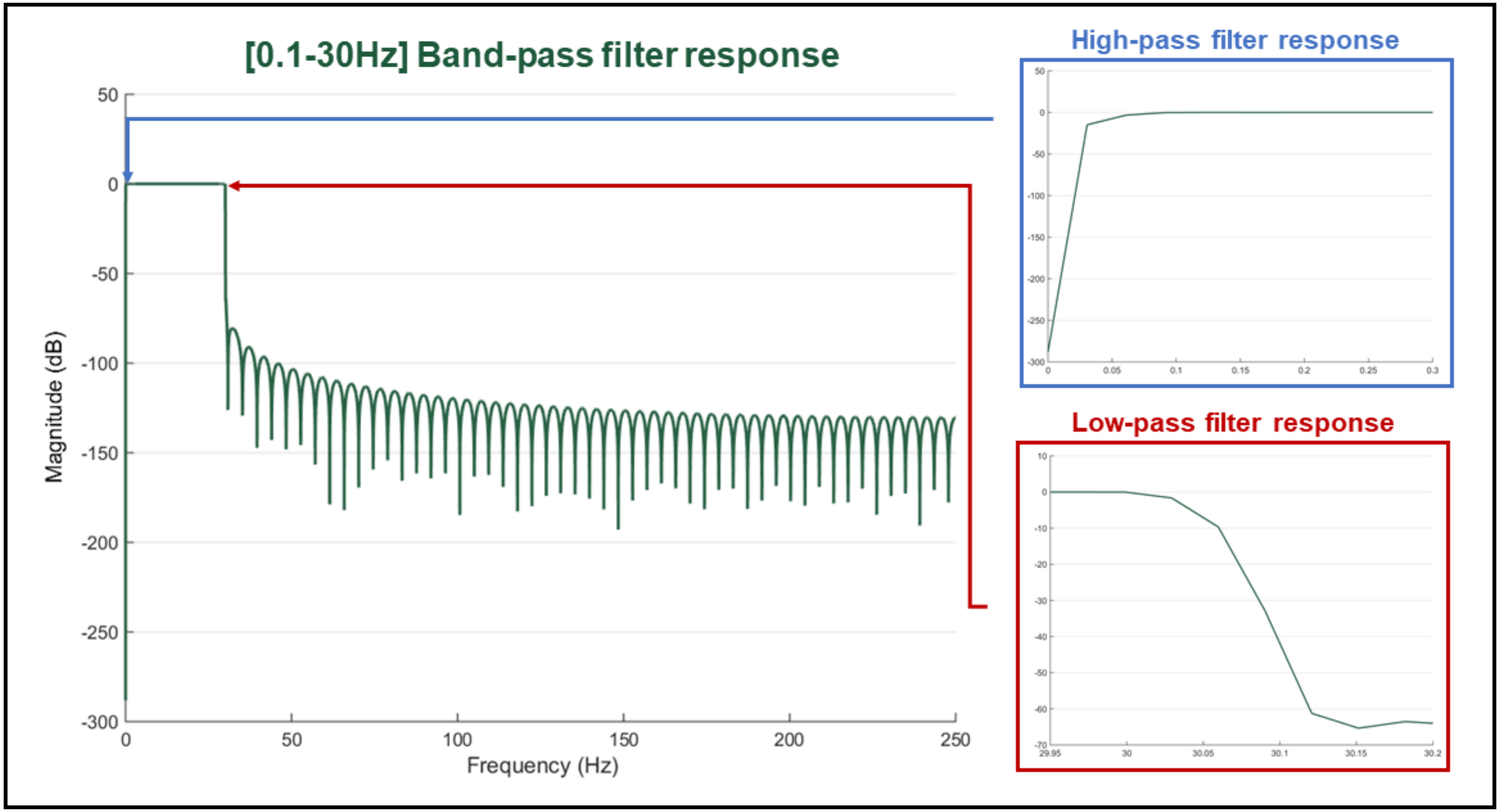
Manually remove artifacts:



Pro	Cons
• Visual inspection of data (mandatory)	• Time consuming and too much signal loss • Relies on your own skill and may be subject to bias • Not adapted for on-line processing (BCI)

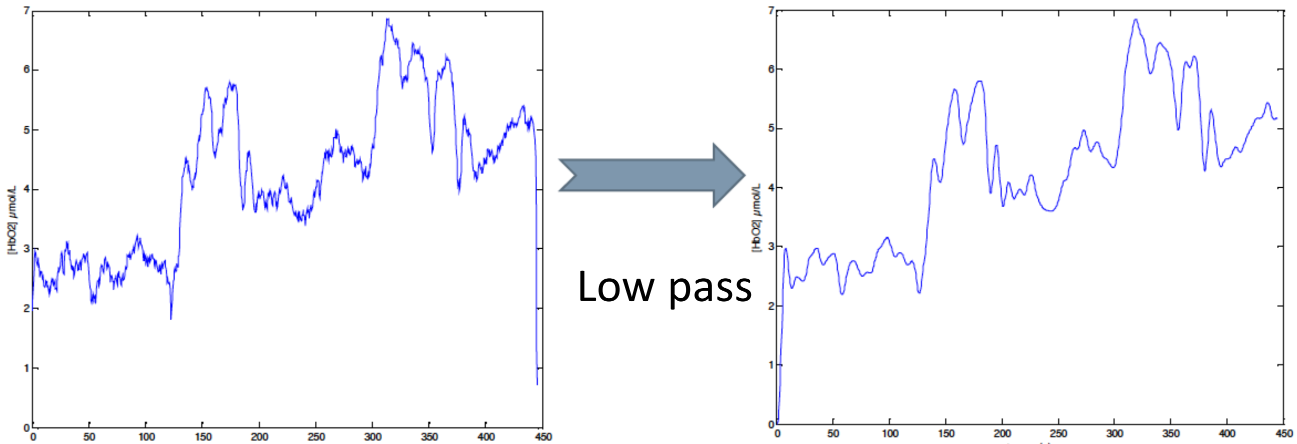
WHAT CAN BE DONE?

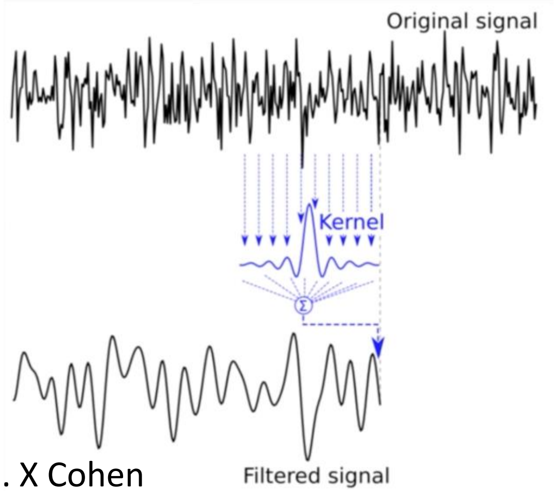
Use linear filtering: Low pass, High Pass, Band Pass, Notch filer



WHAT CAN BE DONE?

Use linear filtering: Low pass, High Pass, Band Pass, Notch filer





From M. X Cohen

WHAT CAN BE DONE?

Use linear filtering: Low pass, High Pass, Band Pass, Notch filer

Filtering: Goals, intuition, and types (FIR/IIR)

	FIR	IIR
Name	Finite impulse response	Infinite impulse response
Kernel length	Long	Short
Speed	Slower	Fast
Stability	High	Data-dependent
Mechanism	Multiply data with kernel	Multiply data with data

From M. X Cohen

WHAT CAN BE DONE?

Use linear filtering:

- Eye blink<4Hz, Line noise = 50Hz
- Band pass: [4,50]Hz???

Pro	Cons
• Easy to implement (one line of code) • On-line processing	• A priori knowledge about artifacts • Remove brain signal (i.e.. overlapping issue)

WHAT CAN BE DONE?

Use linear filtering:

- Eye blink<4Hz, Line noise = 50Hz
- Band pass: [4,50]Hz???

Pro	Cons
• Easy to implement (one line of code) • On-line processing	• A priori knowledge about artifacts • Remove brain signal (i.e.. overlapping issue)

Recommendation

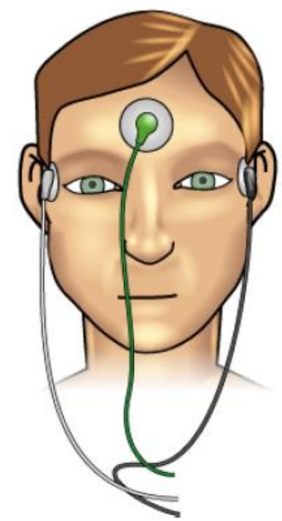
- High pass> 1Hz
- Notch filter: 50 Hz

https://sccn.ucsd.edu/wiki/Makoto's_preprocessing_pipeline + EEGlab list

WHAT CAN BE DONE?

Use linear regression with “reference” channels:

- EOG, EMG, ECG…

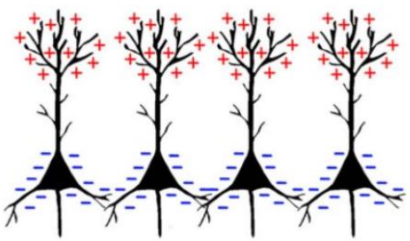


$$EEG_{NC}{}^{i}(t) = EEG_{C}{}^{i}(t) - \mathrm{K.EOG(t)}$$

Pro	Cons
• Easy to implement • On-line processing	• Need to have “reference” channels • Vicious circle: reference channels are contaminated by “brain signal”

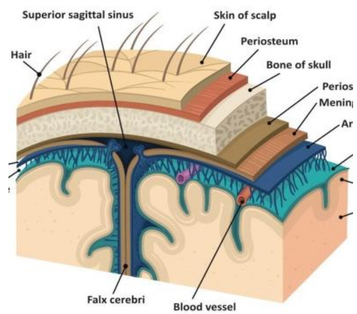
Spatial filtering

S



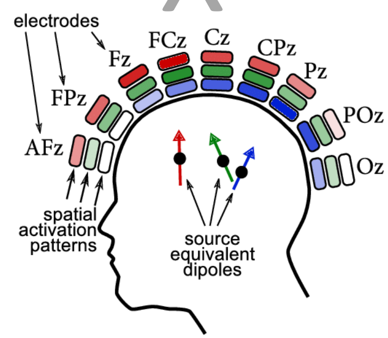
Cerebral source

A

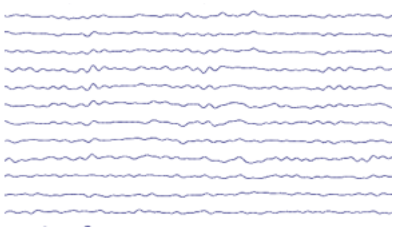


Volume conduction:
Mixing the « source »

X



$$X = A \times S$$



Electrodes:
Weighted sum of sources

What we want to estimate: <u>Sources</u> (S)

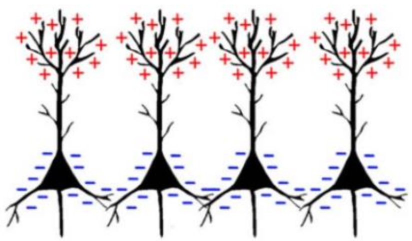
$$\sim S = \sim A^{-1} \times X$$

Variance and orthogonality: *Principal Component Analys*
Independance : *Independent Component analysis*
And many others…

WHAT CAN BE DONE?

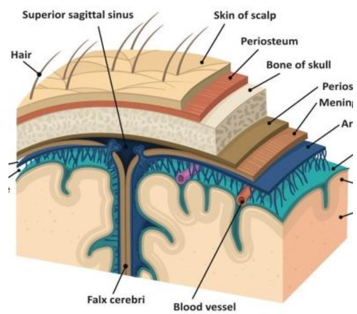
Spatial filtering

S



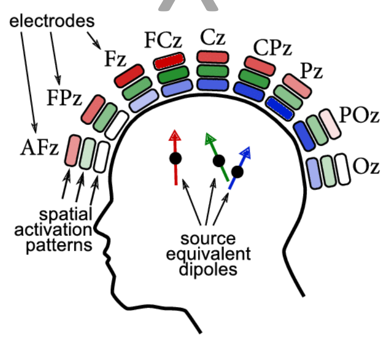
Cerebral source

A

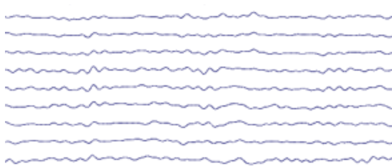


Volume conduction:
Mixing the « source »

X

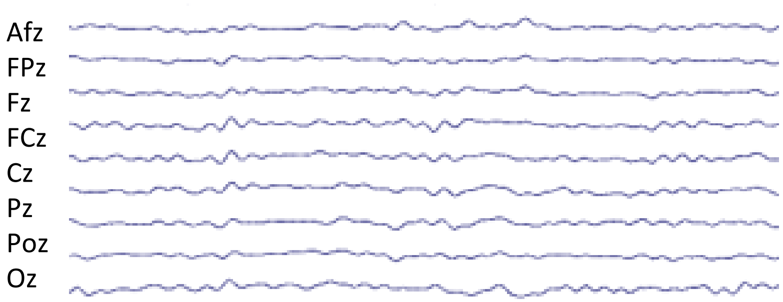


$$X = A \times S$$



Electrodes:
Weighted sum of sources

<u>Sources</u> (S) -> Components



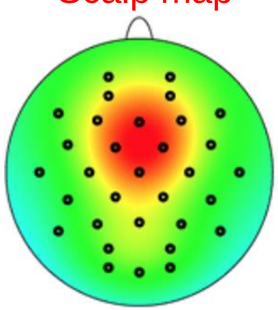
x

$$\begin{bmatrix} 0.0001 \\ 0.0002 \\ 0.2 \\ 0.5 \\ 0.2 \\ 0.01 \\ 0.0002 \\ 0.000 \end{bmatrix}$$

=

Component

Scalp map



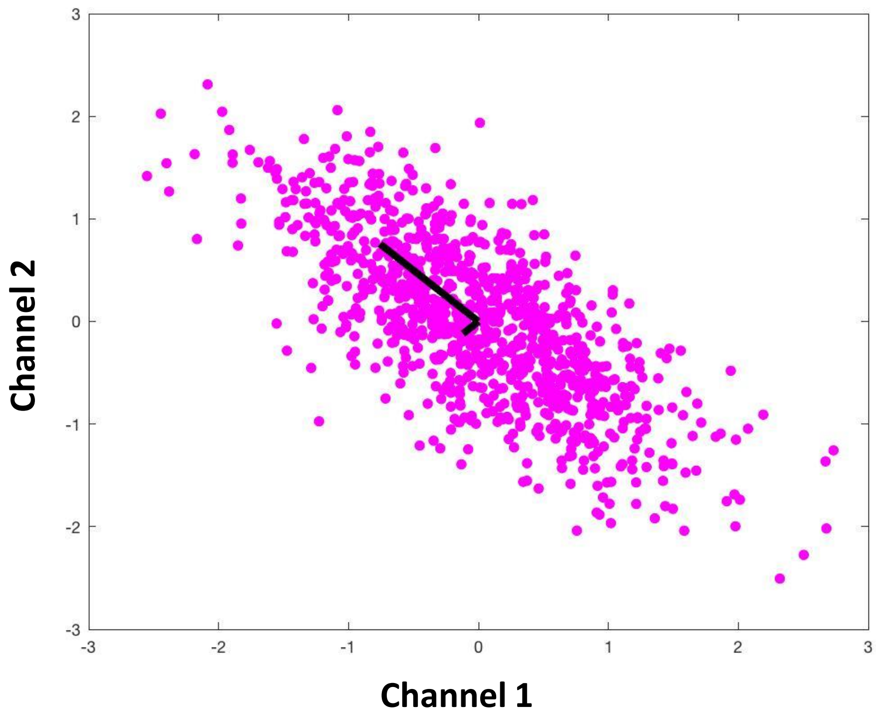
PRINCIPAL COMPONENT ANALYSIS (PCA)

PCA finds:

- The directions(*components*)of maximum variance
- Direction/*components* are orthogonal to each other

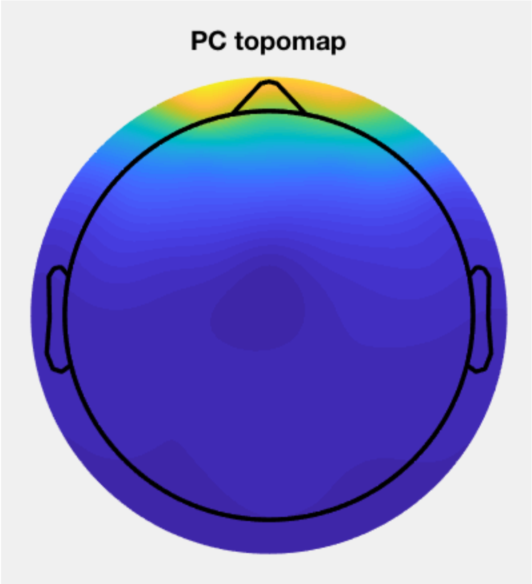
Eigen vectors are « scaled »/sorted by Eigen values

PRINCIPAL COMPONENT ANALYSIS (PCA)

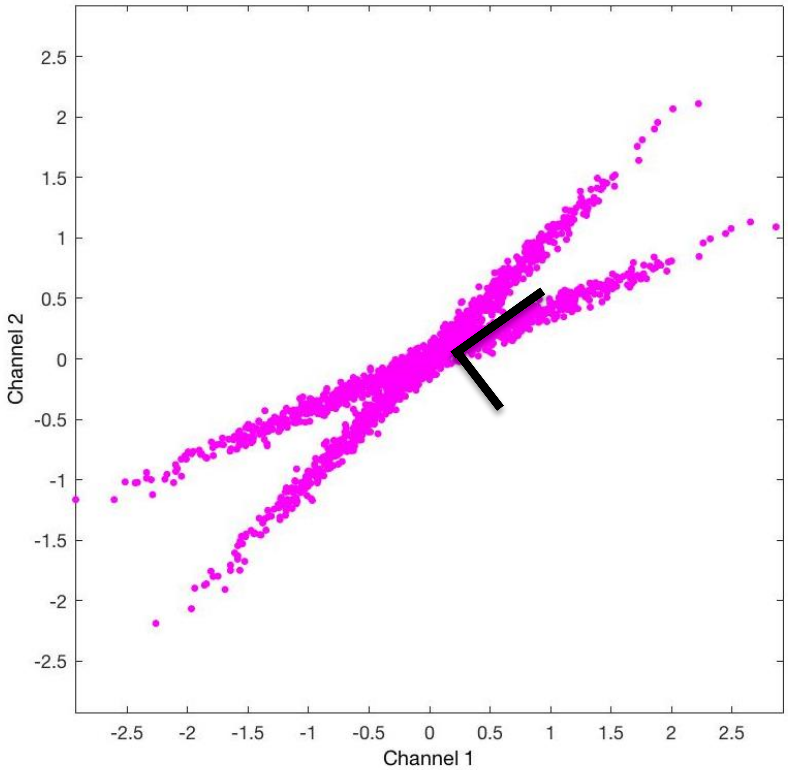


PCA finds:

- The directions(*components*)of maximum variance
- Direction/*components* are orthogonal to each other



PRINCIPAL COMPONENT ANALYSIS (PCA)

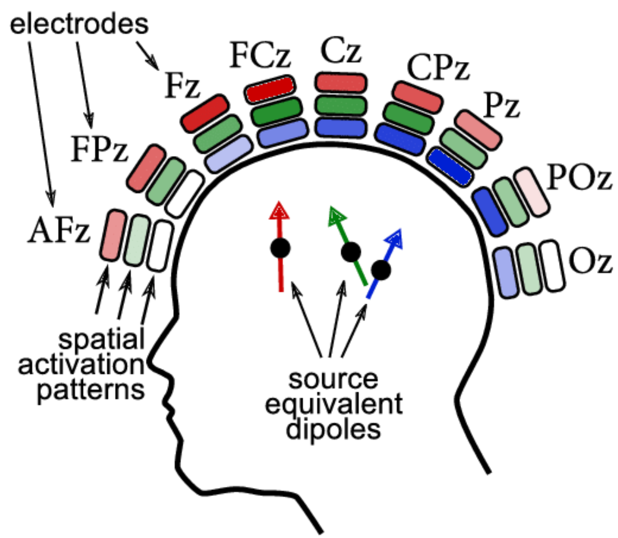


PCA finds:

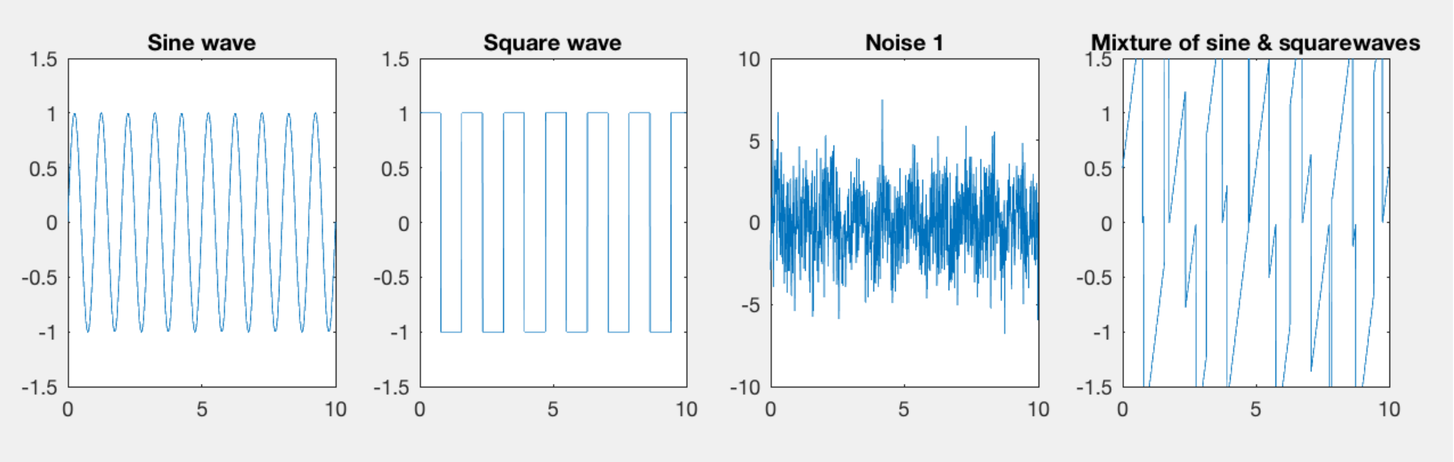
- The directions(*components*)of maximum variance
- Direction/*components* are orthogonal to each other

Pro	Cons
• Easy to implement • On line! • Data reduction technique	• Physiological data are not orthogonal

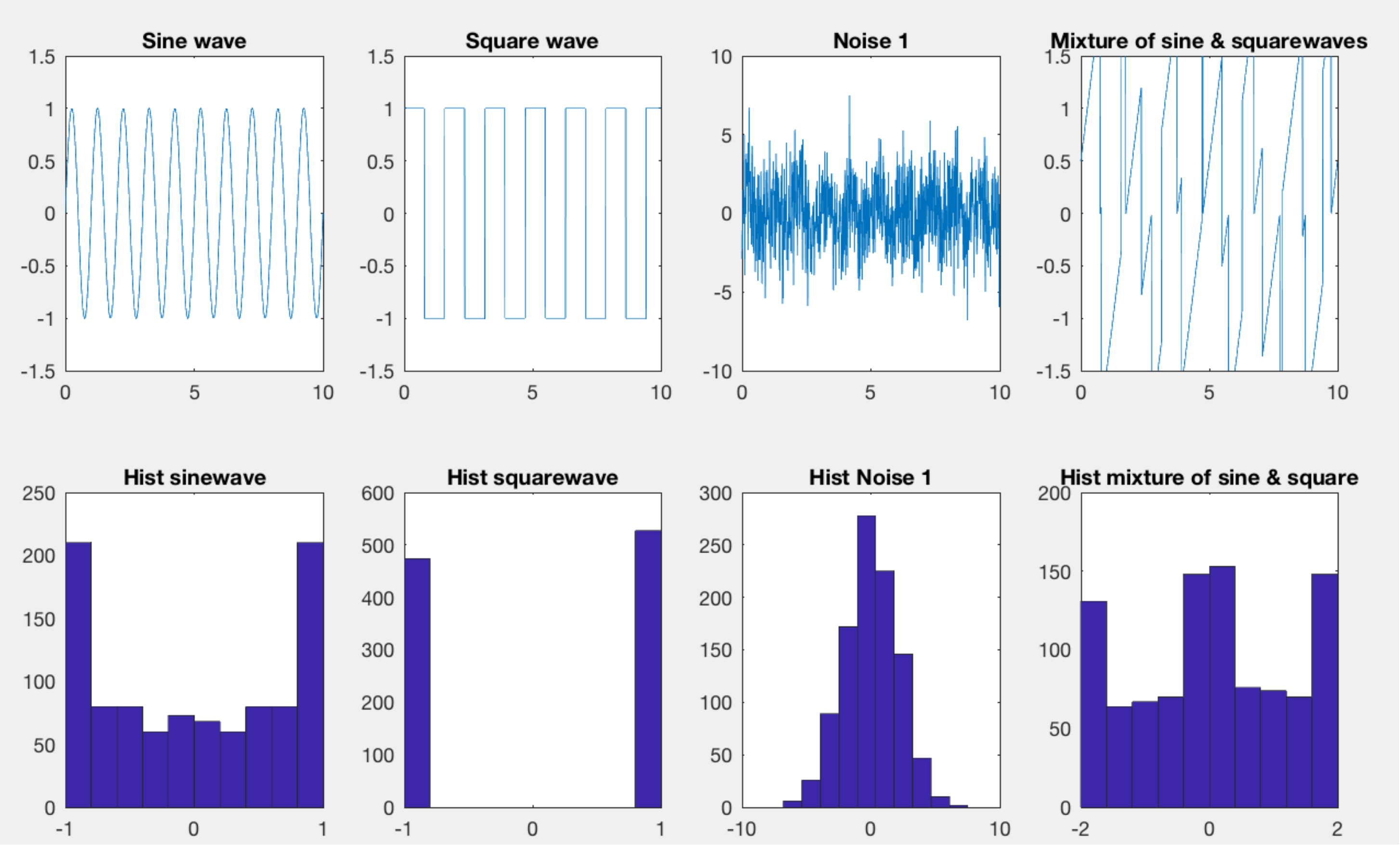
INDEPENDENT COMPONENT ANALYSIS (ICA)



INDEPENDENT COMPONENT ANALYSIS (ICA)

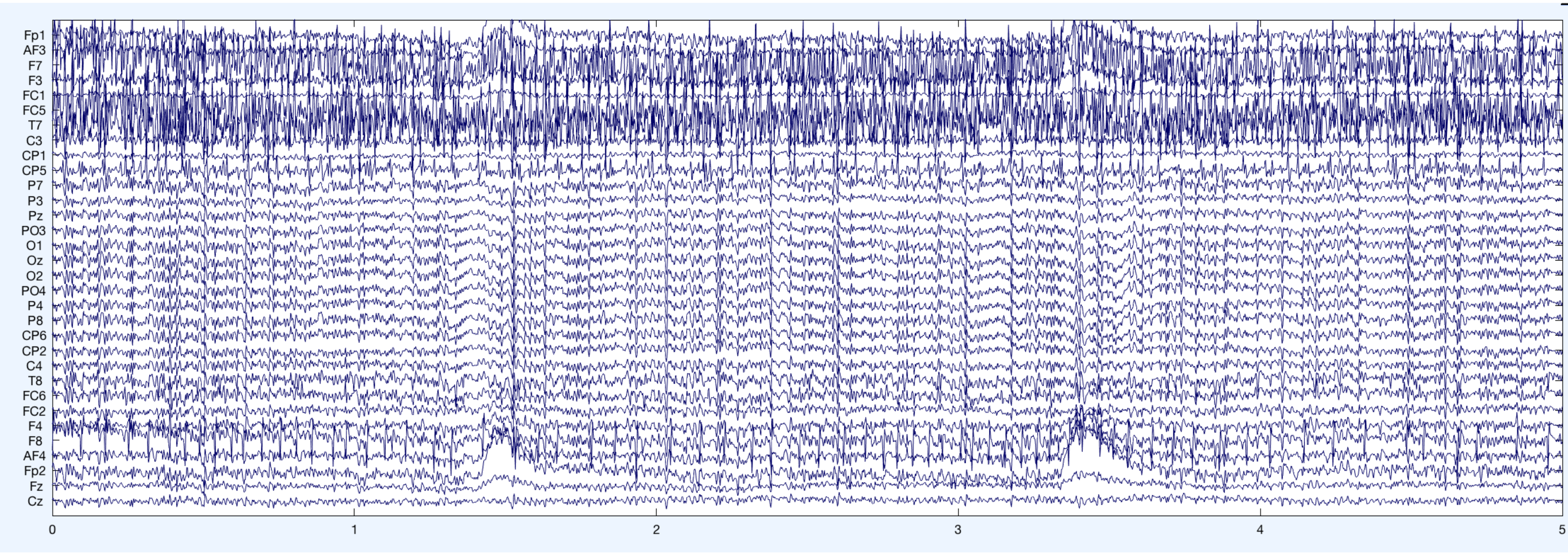


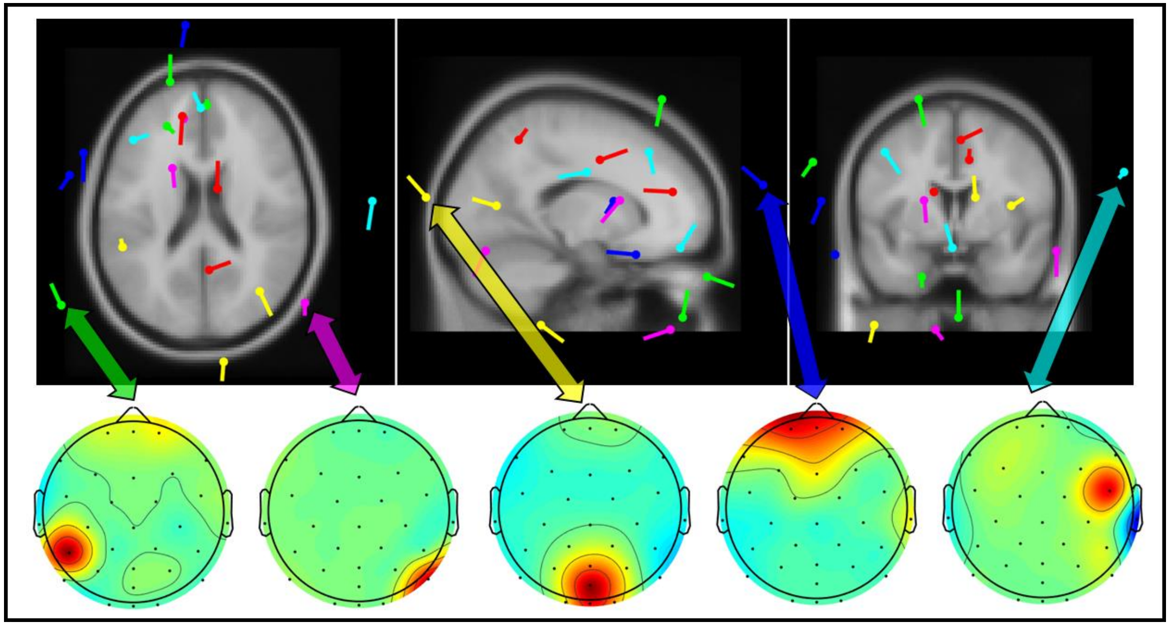
INDEPENDENT COMPONENT ANALYSIS (ICA)

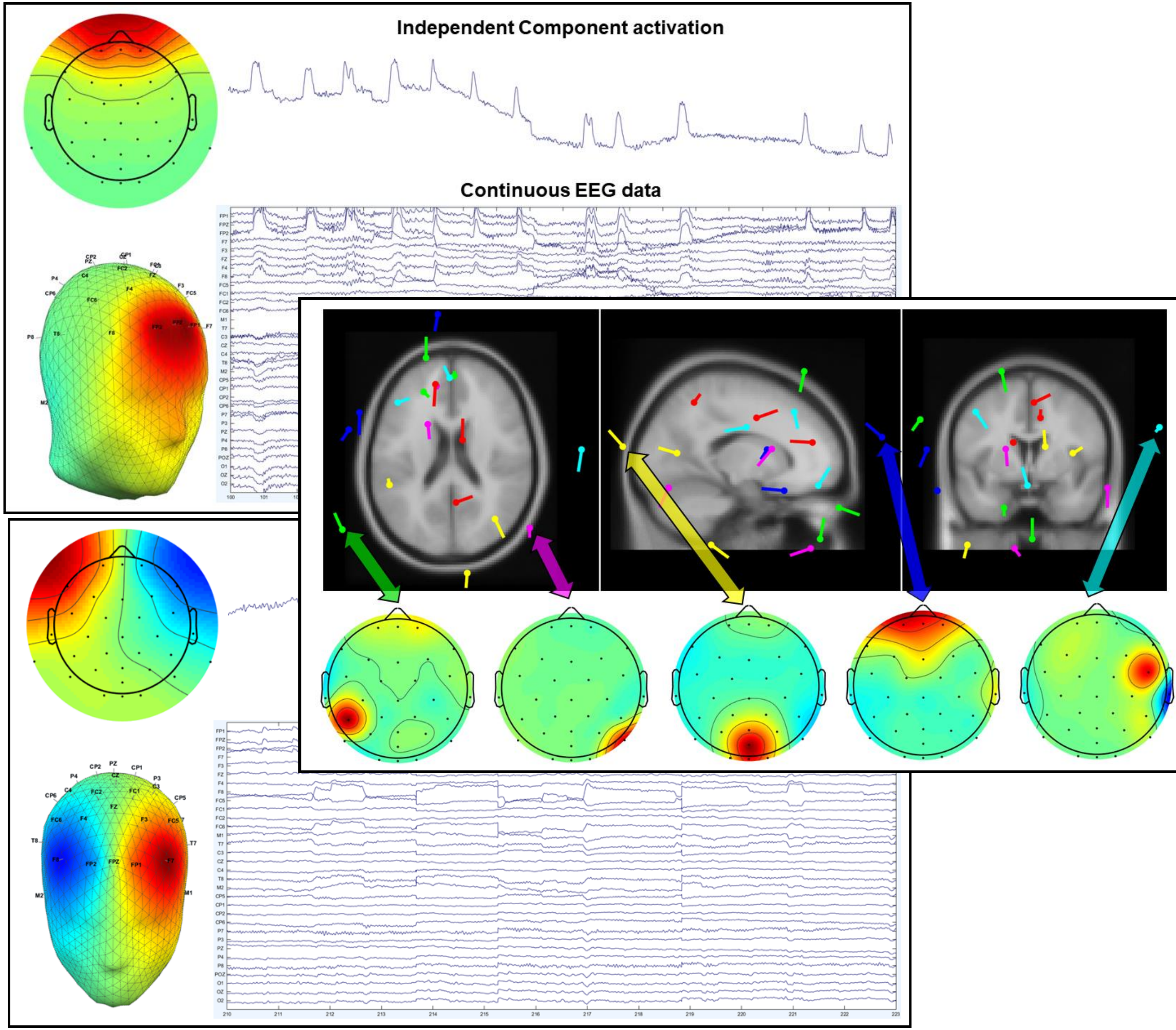


Noise = gaussian distribution
Pure signal : non gaussian distribution
Mixture of « pure » signal ~gaussian distribution

INDEPENDENT COMPONENT ANALYSIS (ICA)

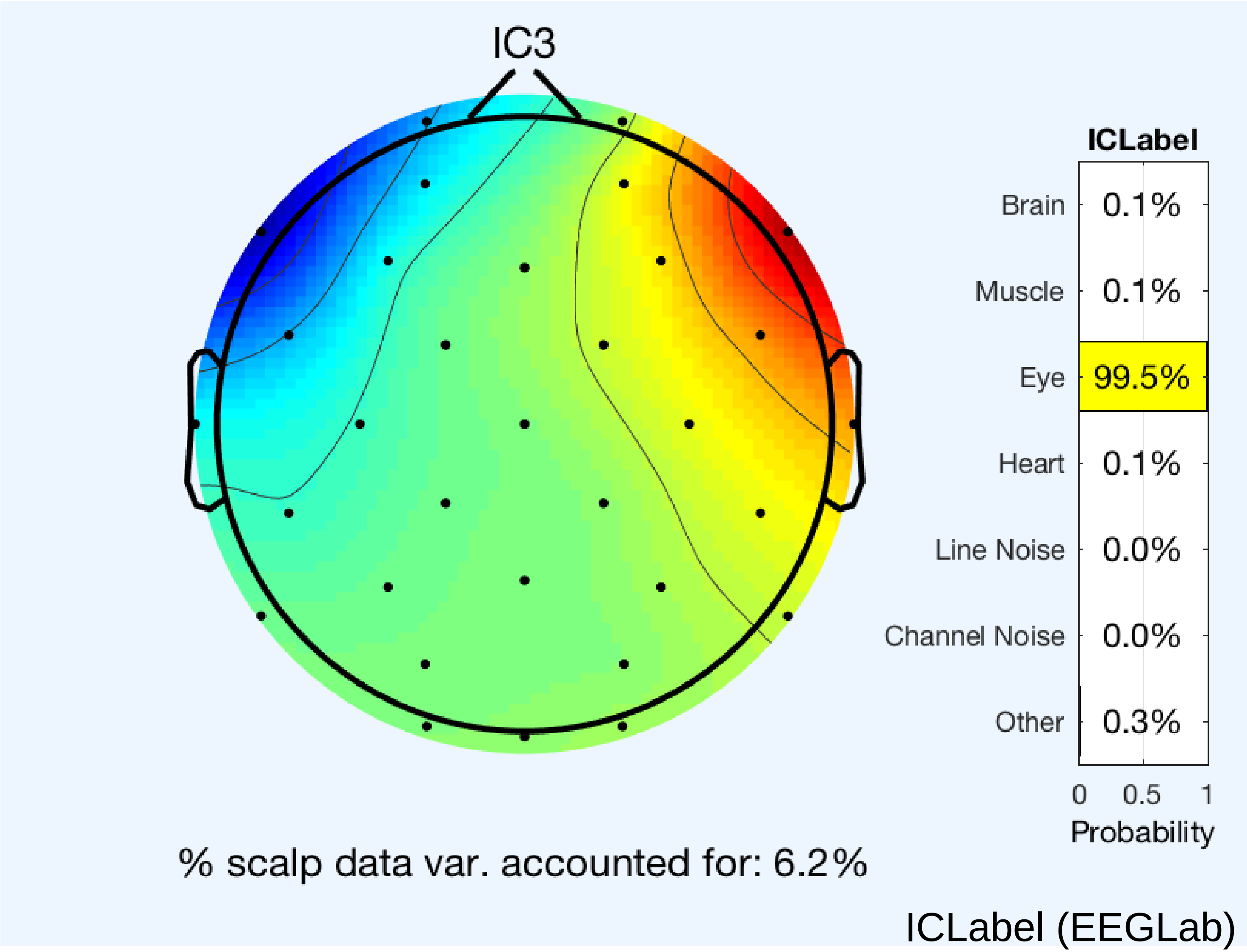




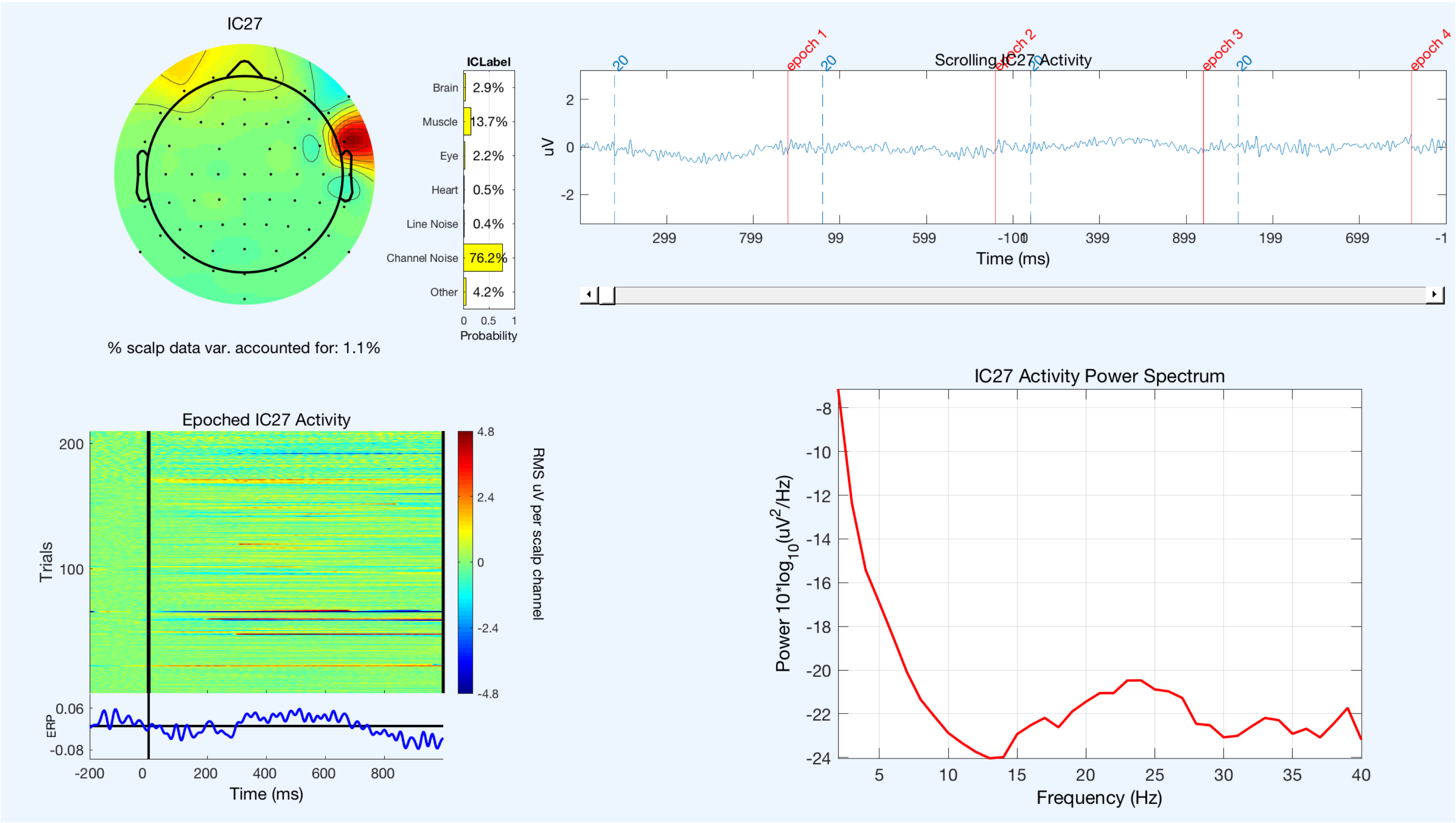


Independent Component activation
Continuous EEG data

INDEPENDENT COMPONENT ANALYSIS (ICA)



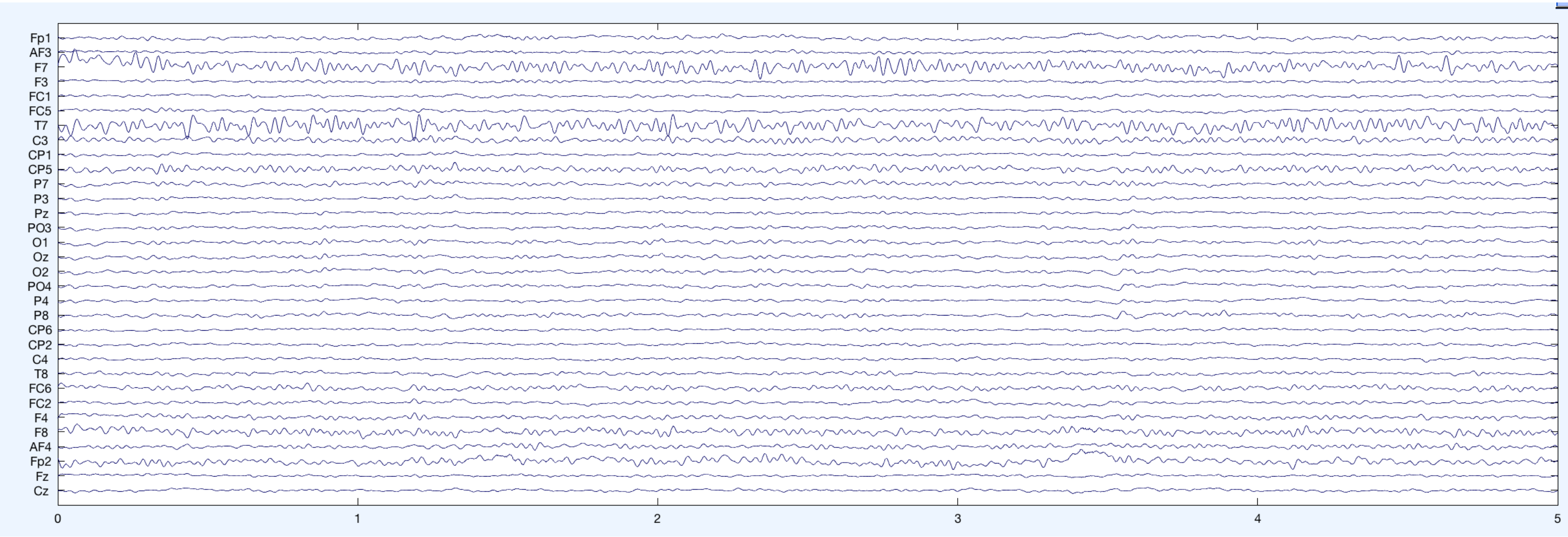
INDEPENDENT COMPONENT ANALYSIS (ICA)



https://labeling.ucsd.edu/tutorial

INDEPENDENT COMPONENT ANALYSIS (ICA)

AFTER ICA



Pro	Cons
• Super efficient method to identify and remove artifacts • **Can be automatized!**	• High computation time! • Nb electrodes > ~16 • Are sources really « independent »?

Neuroergonomics: measuring the brain in ecological conditions

-

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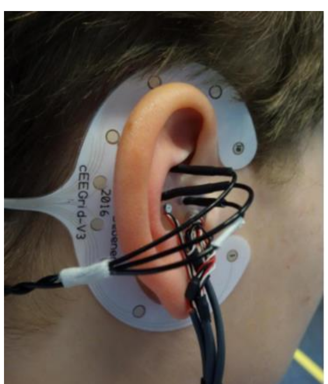
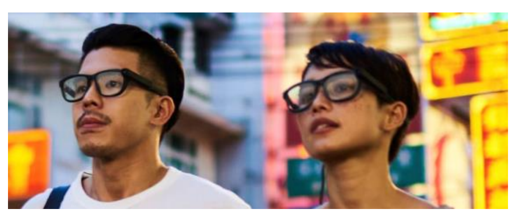




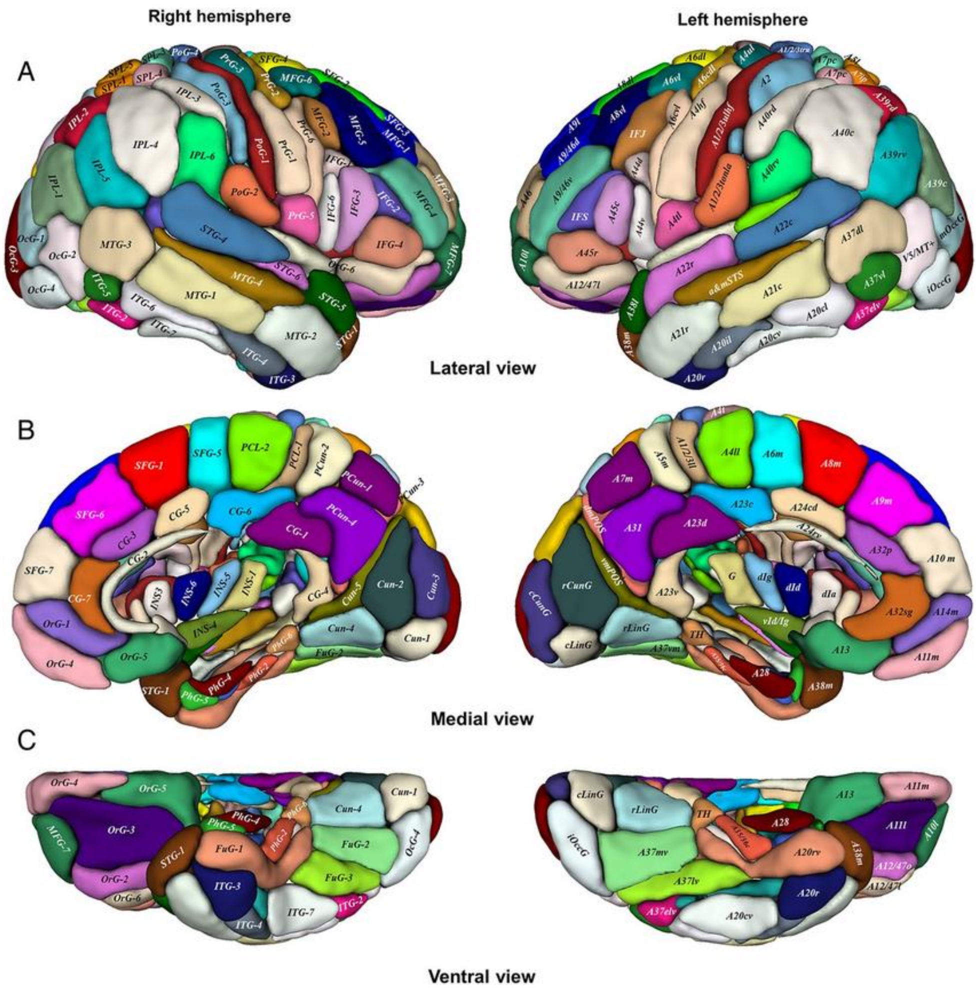

Functional Magnetic Resonance Imaging (fMRI)

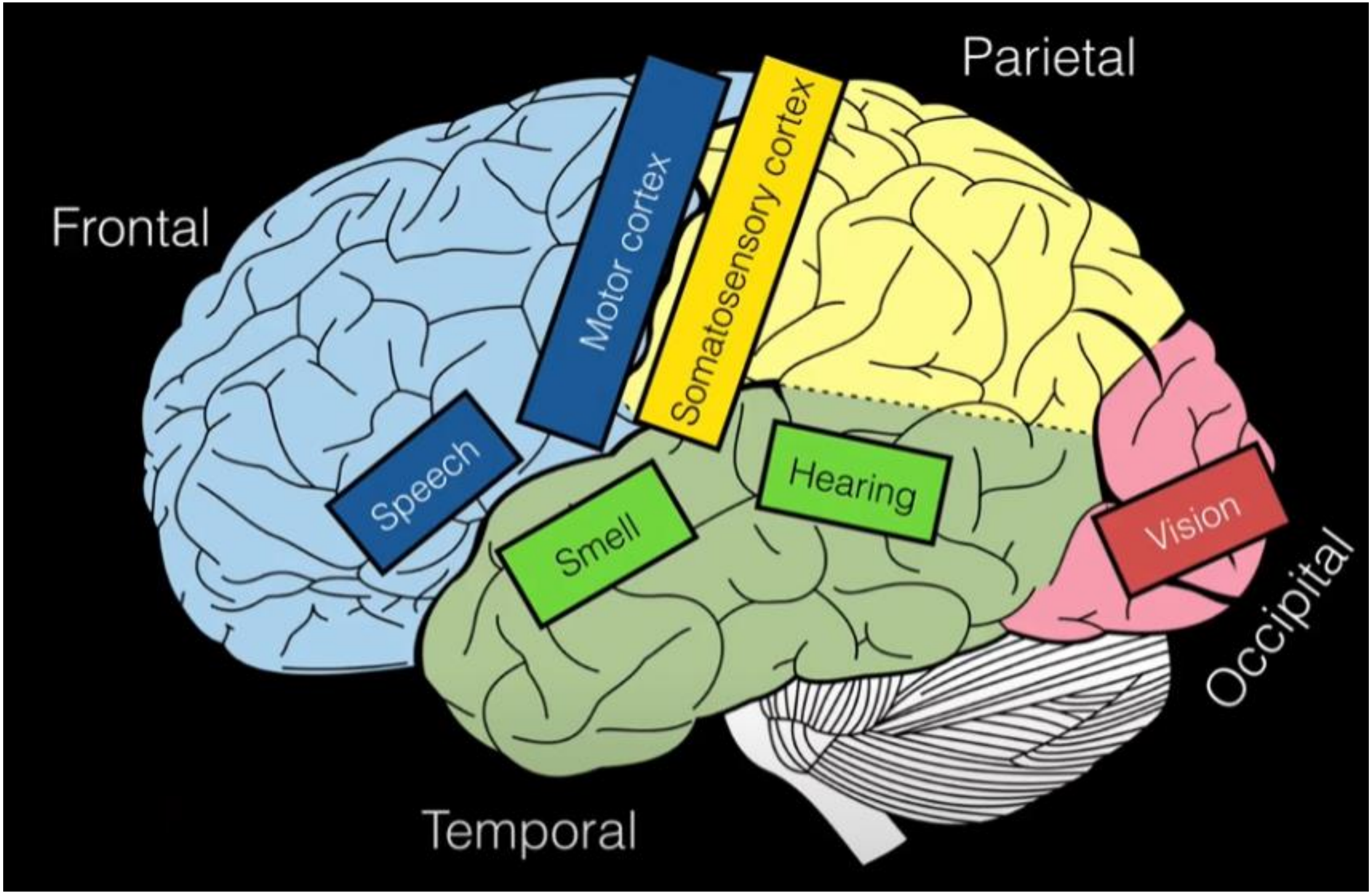
- Best non-invasive approach to locate neural underpinnings of cognition (high spatial resolution at deeper layers of the brain: sub-cortical structures)
- Can be used to evaluate spatial connectivity between brain structures: diffusion tensor imaging tractography

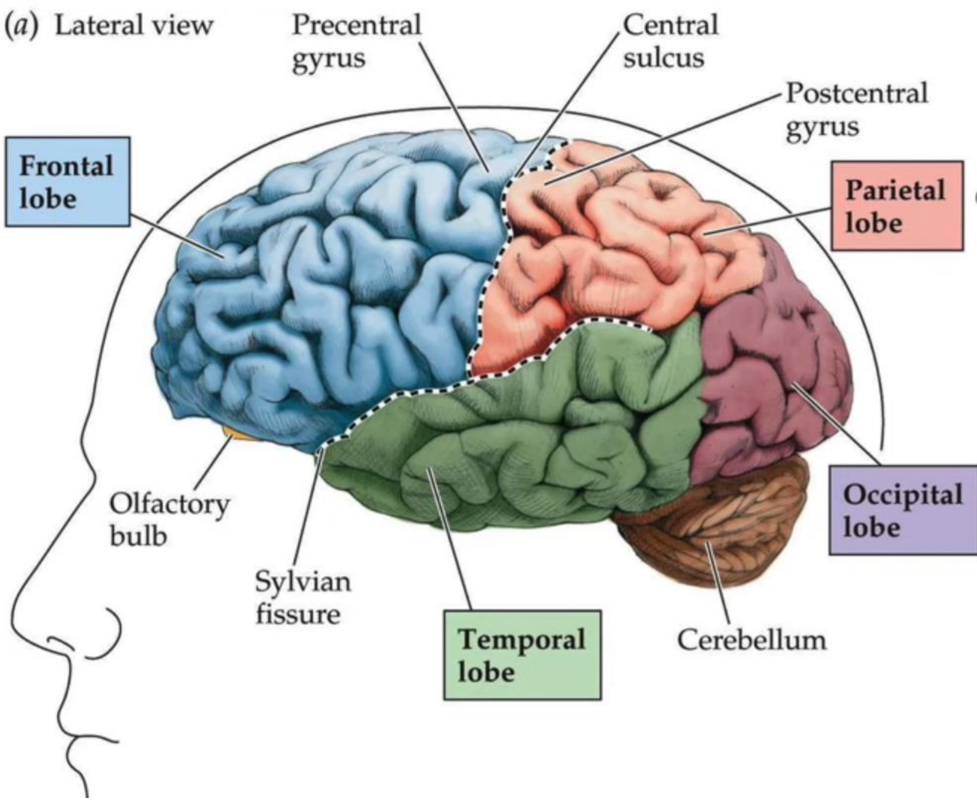
- Poor temporal resolution
- Costly
- Subjects have to be laying in a big noisy scanner

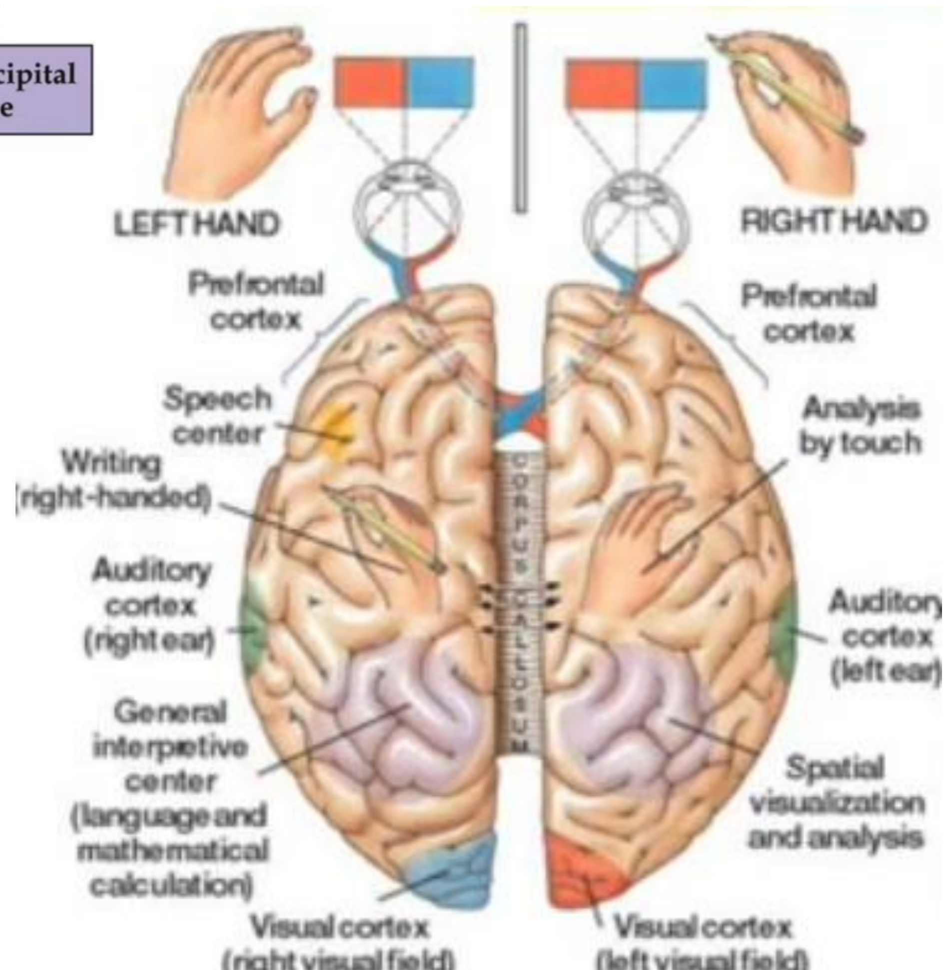
Mapping cognitive functions on brain anatomy

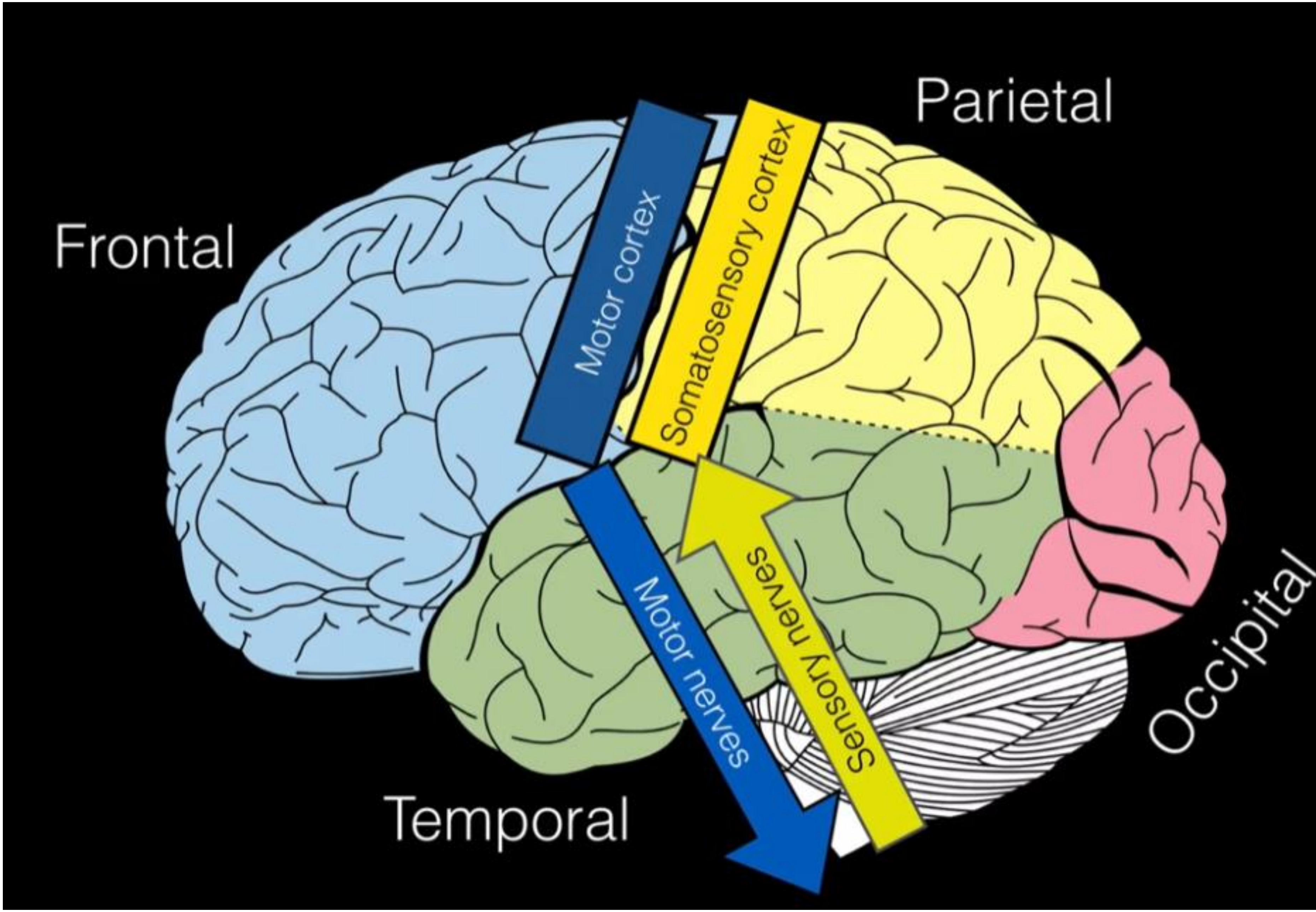
- Atlases of structural and functional brain anatomy
- Building an understanding on the properties of brain structures and organization of its architecture
- In patients but also healthy subjects!



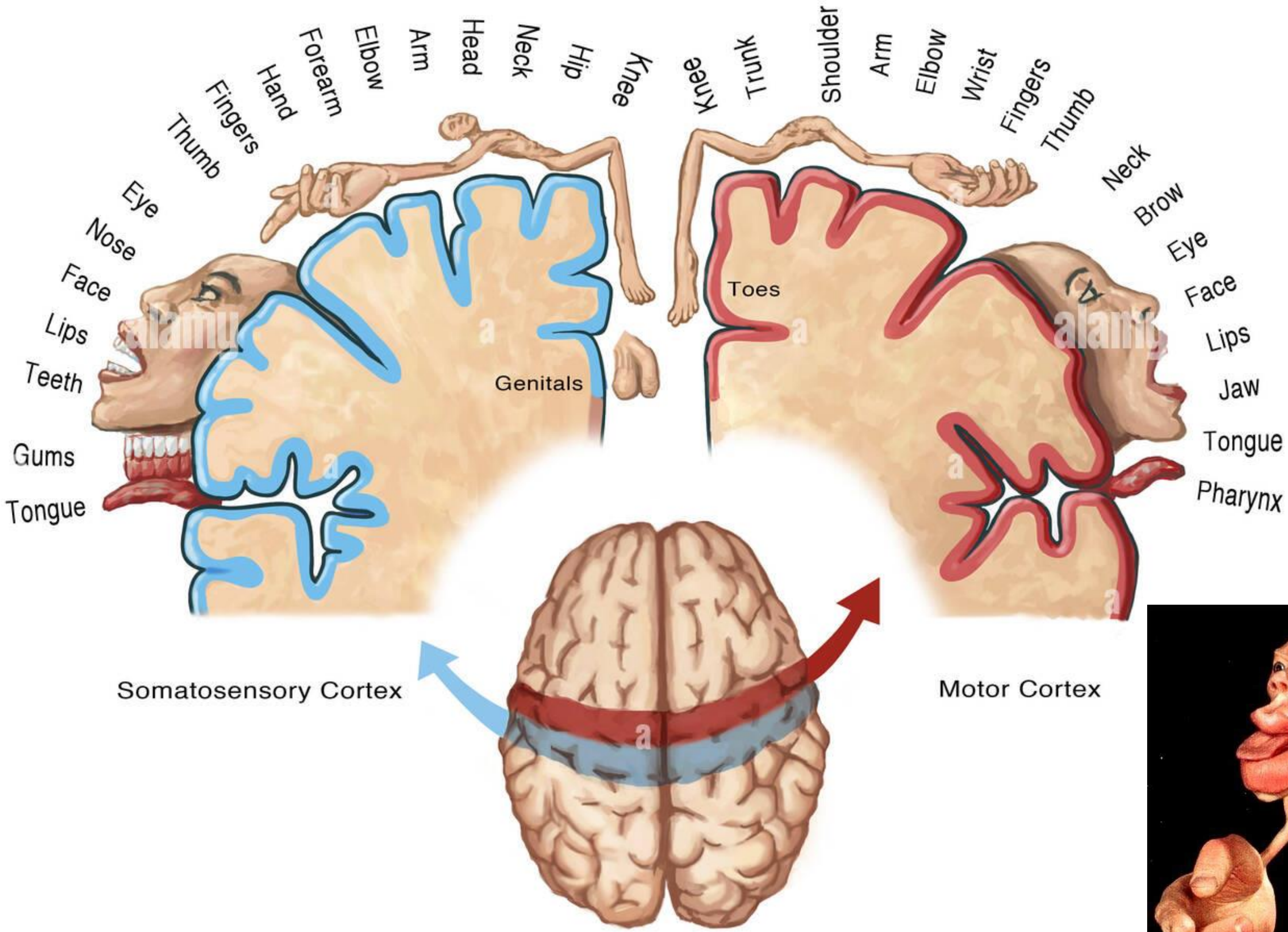

Parietal
Frontal
Motor cortex
Somatosensory cortex
Speech
Smell
Hearing
Vision
Occipital
Temporal

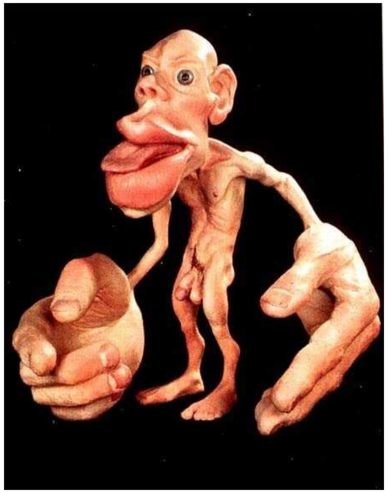

(a) Lateral view
Precentral gyrus
Central sulcus
Postcentral gyrus
Frontal lobe
Parietal lobe
Occipital lobe
Olfactory bulb
Sylvian fissure
Temporal lobe
Cerebellum


LEFT HAND
RIGHT HAND
Prefrontal cortex
Prefrontal cortex
Speech center
Writing (right-handed)
Analysis by touch
Auditory cortex (right ear)
Auditory cortex (left ear)
General interpretive center (language and mathematical calculation)
Spatial visualization and analysis
Visual cortex (right visual field)
Visual cortex (left visual field)


Parietal
Frontal
Motor cortex
Somatosensory cortex
Motor nerves
Sensory nerves
Occipital
Temporal

Sensorimotor information processing in the motor and somatosensory cortices

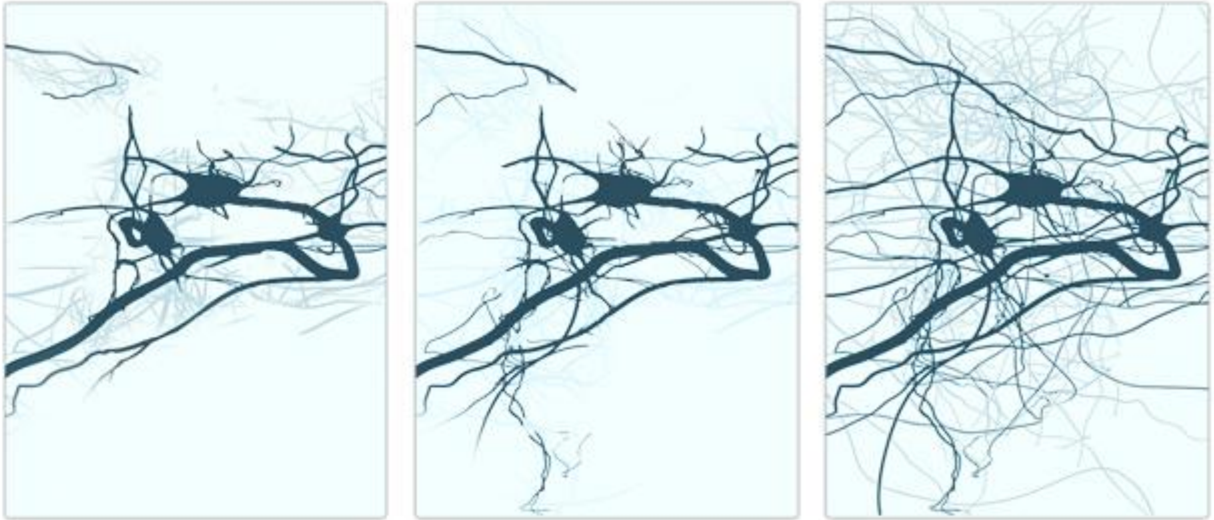




Neural plasticity

- Ability of neurons to reorganize neural connections throughout life to compensate for injury and disease or to adjust their activity in response to the environment

- Synaptic pruning: deletion or creation of new connections between neurons



Skill acquisition and longitudinal studies

- Formation of new memories require novel connections to be made, and the strengthening of existing ones related to the skill, type of information to store

- Forgetting is also part of neural plasticity as unused connections over time weakens and the wiring of the neurons changes to adapt to environmental demands more efficiently