Basis of the Electroencefalography (EEG) Signal

Summary

Intro to EEG

Basics of the EEG-signal

EEG frequency spectrum

…brief intro to ERP’s

Intro to EEG

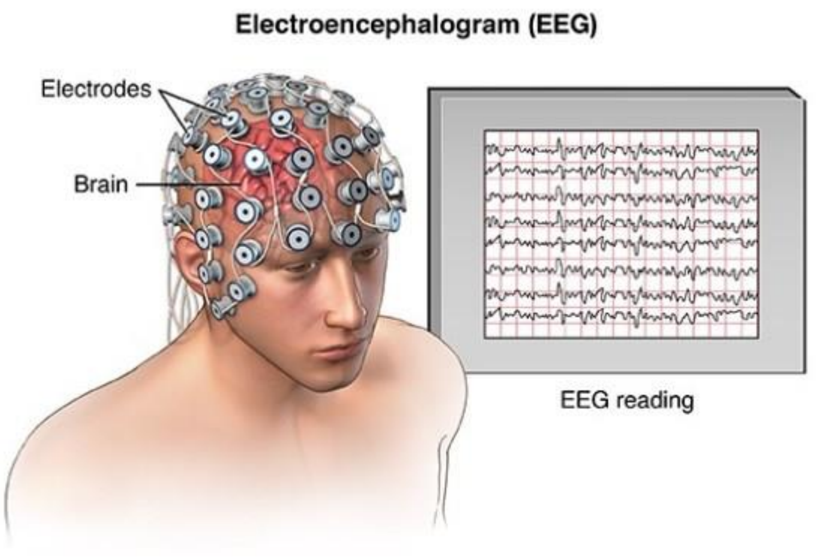
- Electroencephalogram

Electric

Brain

Picture

- Electrodes on the scalp measure electrical activity generated by thousands of synchronised neurons
- Direct non-invasive measure of neuronal activity!
- Really good temporal resolution: sampling rates of 1024hz – 4096hz with modern systems

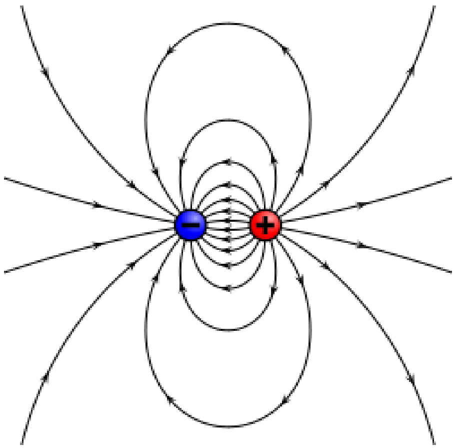


https://www.brightbraincentre.co.uk/electroencephalogram-eeg-brainwaves/

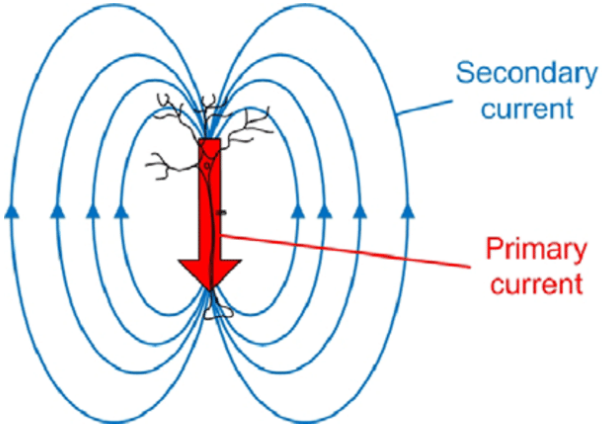
Basis of the EEG-signal

Some physics…

- Electric potentials generated by neurons can be modeled with dipoles
- Dipole: a separation of electrical charges. Quantified by dipole moment (μ)
- Electric current flows from the negative pole to the positive
- Happens in neurons all the time: action potentials
- Primary vs. secondary current
- However, single current is too small to measure…



https://en.wikipedia.org/wiki/Dipole

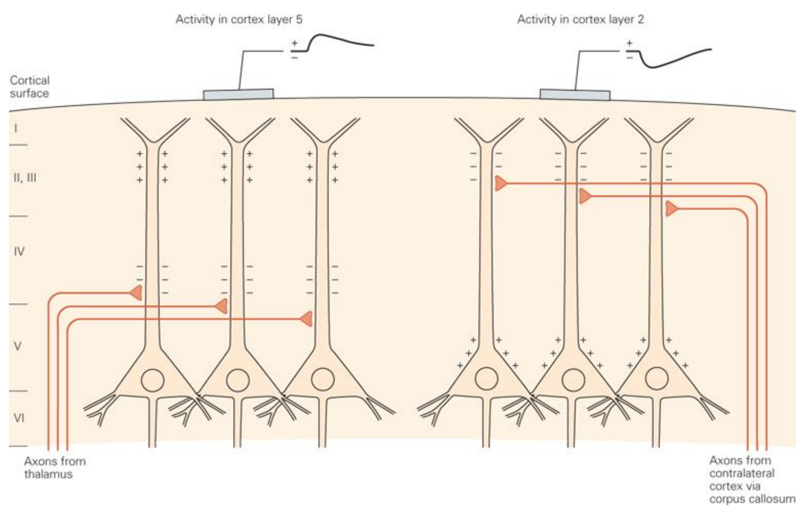


Becker (2014)

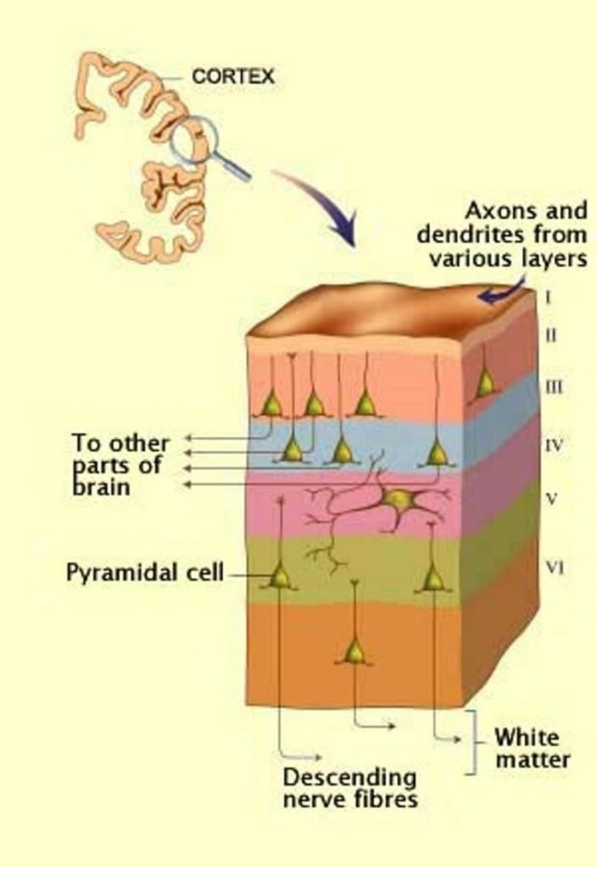
Basis of the EEG-signal

Some neuroanatomy…

- Neocortex consists of six distinct layers.
- Distinct (messy!) neuronal organisation and connections across layers.
- Luckily giant pyramidal cells projecting from layer 5 are lined perpendicular to the surface!



Kandell, Schwartz and Jessell (2000)

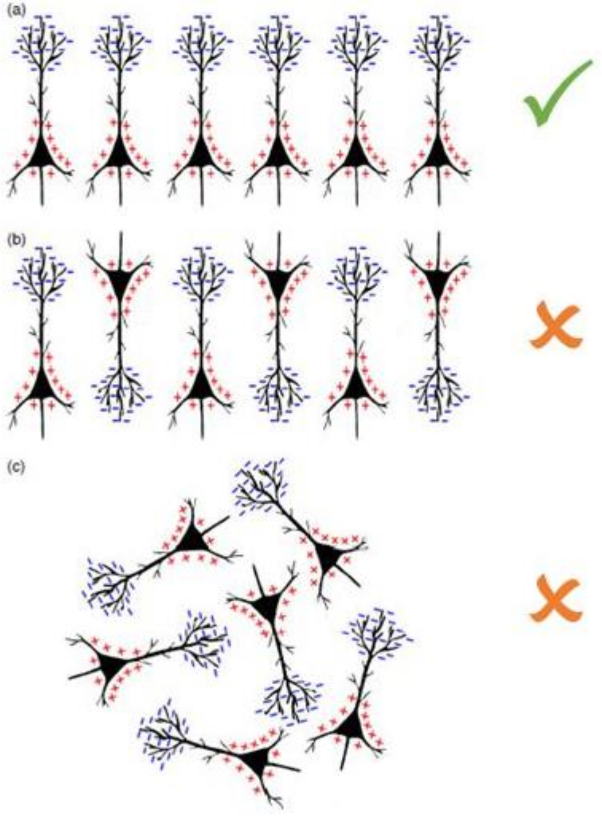


https://www.brightbraincentre.co.uk/electroencephalogram-eeg-brainwaves/

Basis of the EEG-signal

Some physics + neuroanatomy…

- *How does the organisation of the pyramidal neurons help us?*
- *As noted, one dipole generated by one action potential is too small to measure…*
- *…the summation of tens of thousands is not*
- *Since pyramidal neurons point to the same direction, charges don't cancel out*
- *We can measure the summed diapoles!*

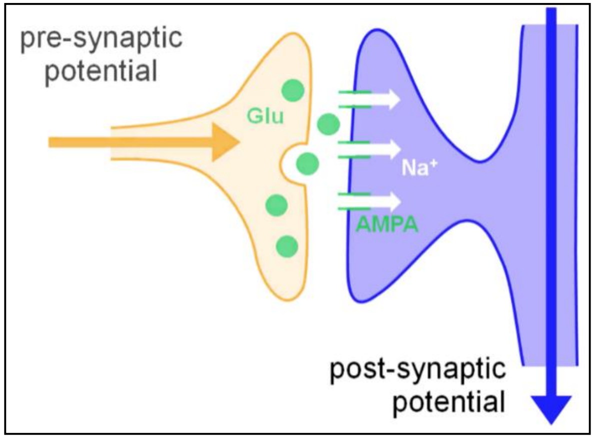


Jackson and Bolger, (2014)

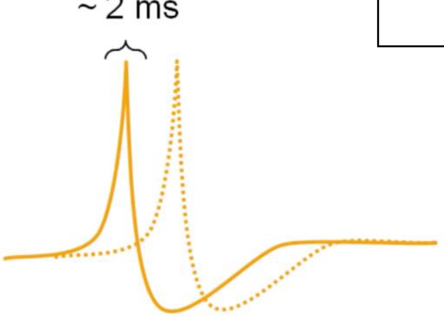
Basis of the EEG-signal

Pre- vs. post-synaptic potentials

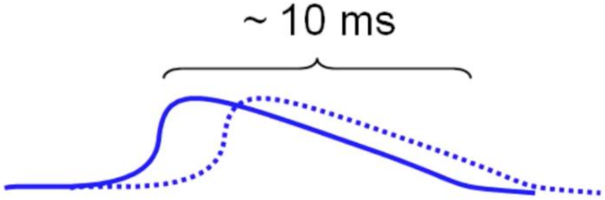
- *Pre and post-synaptic potentials differ in characteristics*



- *Pre-synaptic: Short and biphasic*



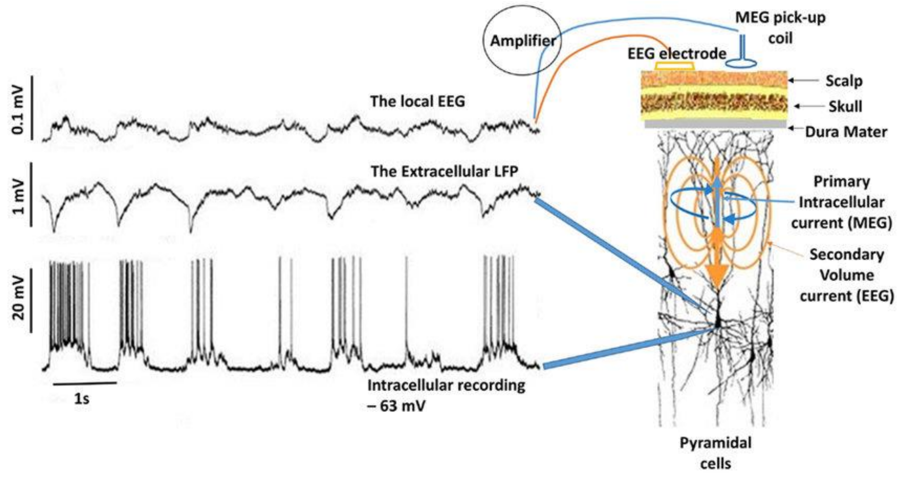
- *Post-synaptic: Longer and monophasic*



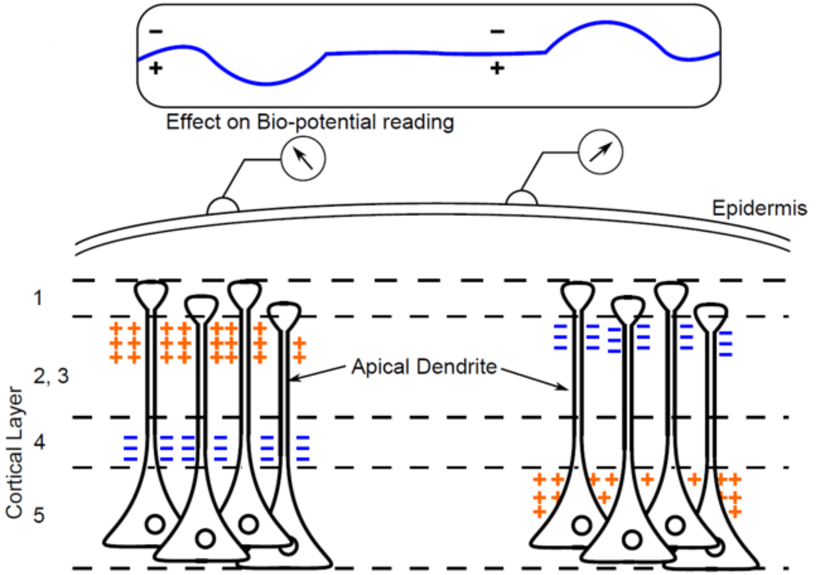
Basis of the EEG-signal

So we are measuring:

- The summed dipoles generated (mostly) by the sychnorised post-synaptic potentials of tens of thousands of pyramidal neurons in Layer 5
- … plus noise
- What does this correspond to? Can we localise the source?



Adjamian (2014)

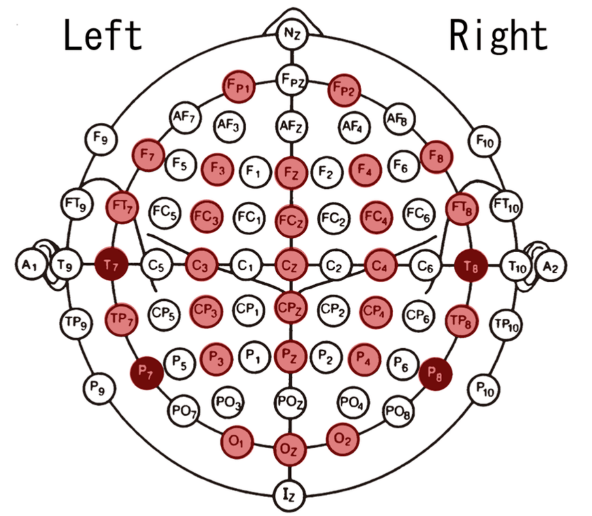


https://www.brightbraincentre.co.uk/electroencephalogram-eeg-brainwaves/eeg-dipoles/

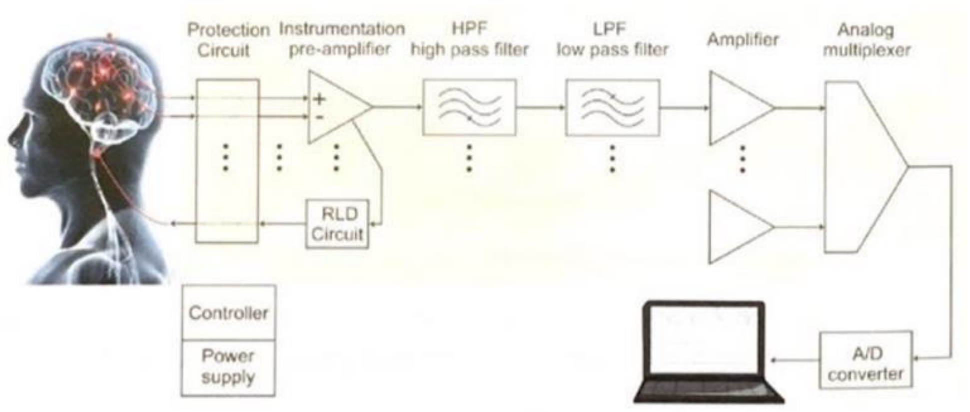
Basis of the EEG-signal

How do we measure it?

- Electrodes placed on scalp, standardised placement: 10-20 system (More recent 10-5)
- EEG uses differential amplifiers to produce each channel
- The way the electrodes are connected to the amplifiers are referred to as a montage



Ueda, Sakai and Yanagisawa, (2019)

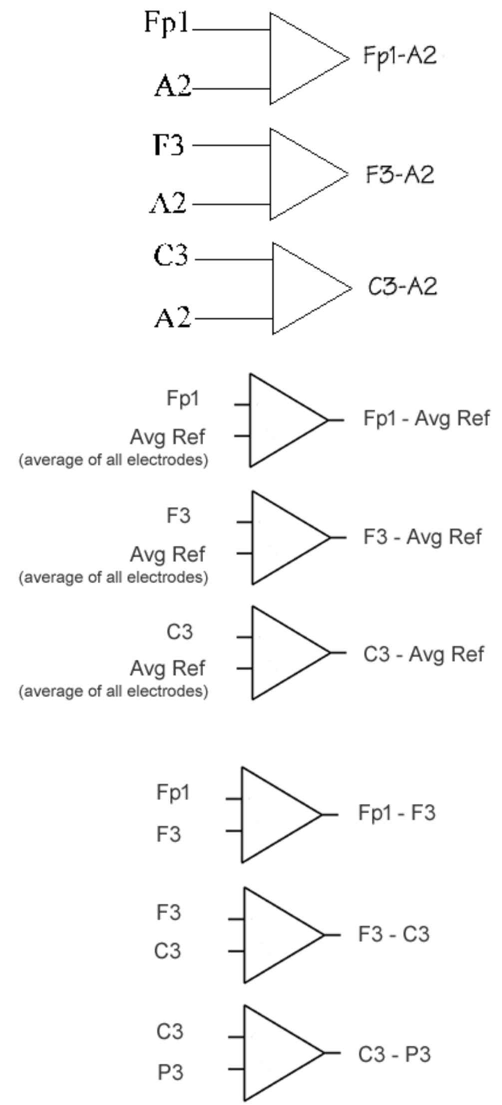


Modir (2017)

Basis of the EEG-signal

Standard recording derivations

- Common reference derivation: a reference electrode is substracted from the scalp electrode. The same reference electrode is used for every amplifier
- Average reference derivation: Activity from all electrodes is summed, averaged and passed through a high value resistor. The resulting signal is used as the 'reference electrode'
- Bipolar derivation: electrodes are sequentially linked together. E.g. from the back to the front.



https://www.ebme.co.uk/articles/clinical-engineering/introduction-to-eeg

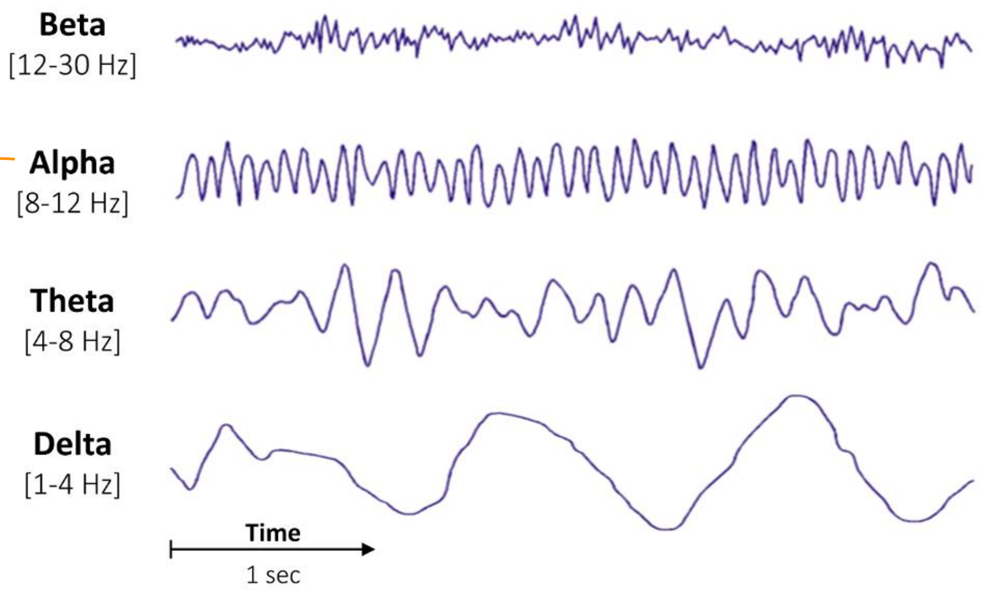
So what do we get from recording EEG?

EEG frequency spectrum as a classification system

- Beta: Seen in a symmetrical distribution on both sides. Dominant when alert/anxious/eyes are open
- Alpha: Seen in posterior regions. Higher amplitude on the dominant hemisphere. Appears with relaxing/closed eyes

Pretty regular amplitude

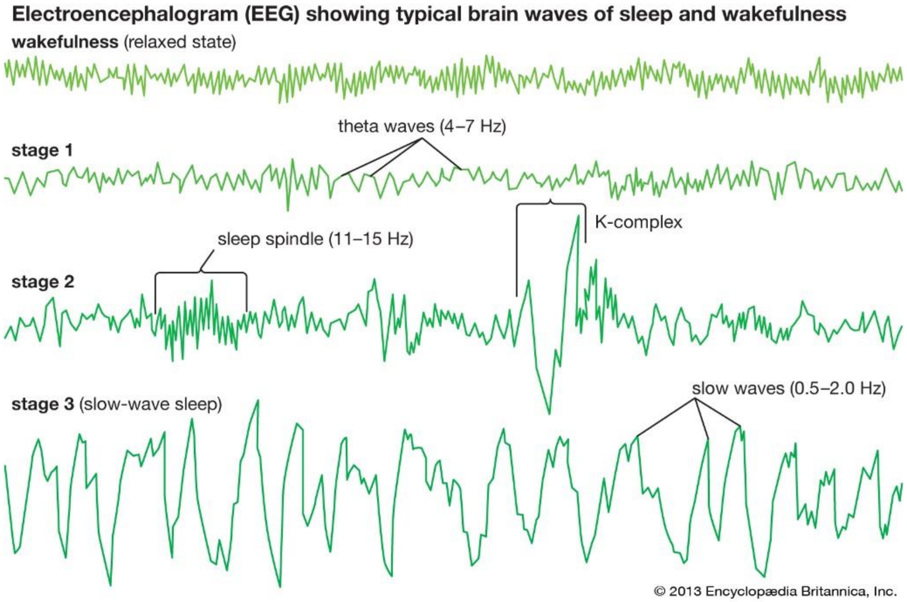
- Theta: ’slow activity’. Seen in sleep and children under 13 years old
- Delta: Lowest frequency/highest amplitude. Appears in stages 3 and 4 of sleep.



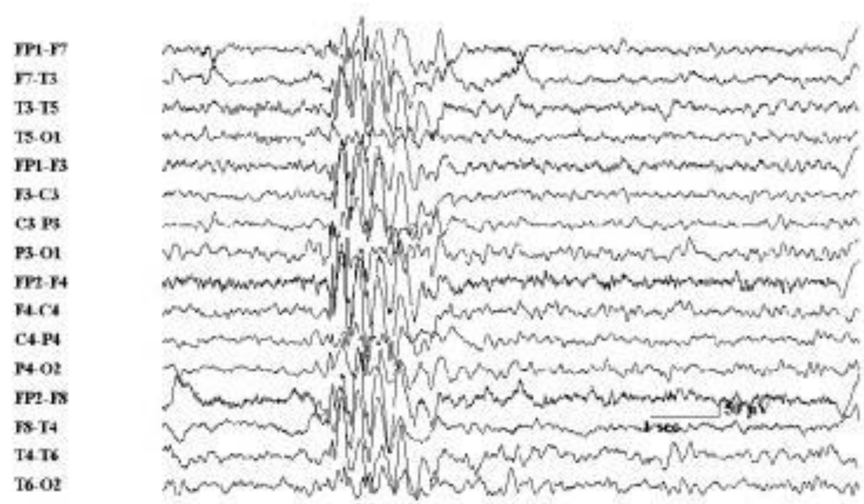
https://raphaelvallat.com/bandpower.html

Some applications

- *Sleeping disorders (Friedman, 1986)*
- *Main tool for diagnosing epilepsy. Current research is looking at automated ways using machine learning. (Tiwari et al., 2017)*
- *Brain-Computer interfaces (*Spüler, 2017*)*



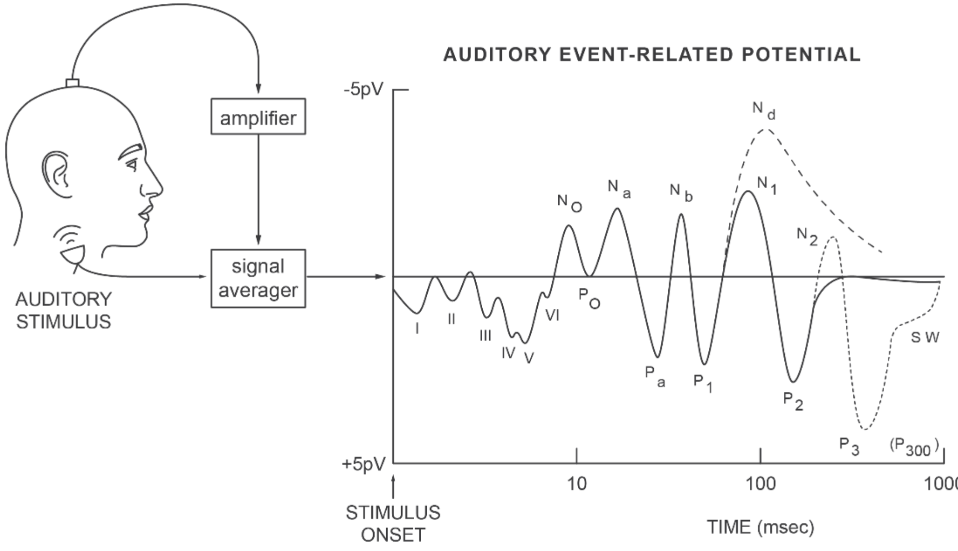
https://www.britannica.com/science/electroencephalography



https://emedicine.medscape.com/article/1138154-overview

ERP’s (briefly)

- *ERP = Event related potential*
- *An EEG waveform associated with a certain action or mental event*
- *Remember that EEG-data is noisy!*
- *How can we examine small waveforms associated with specific events?*
- *By a lot of repetition: random noise should cancel itself out, but systematic variance should remain!*



https://medium.com/@mindpass2050/the-stimulus-reaction-challenge-d86cd57e22fe

Basis of the MEG Signal

Overview

MEG basics

EEG vs. MEG

Advantages & Disadvantages

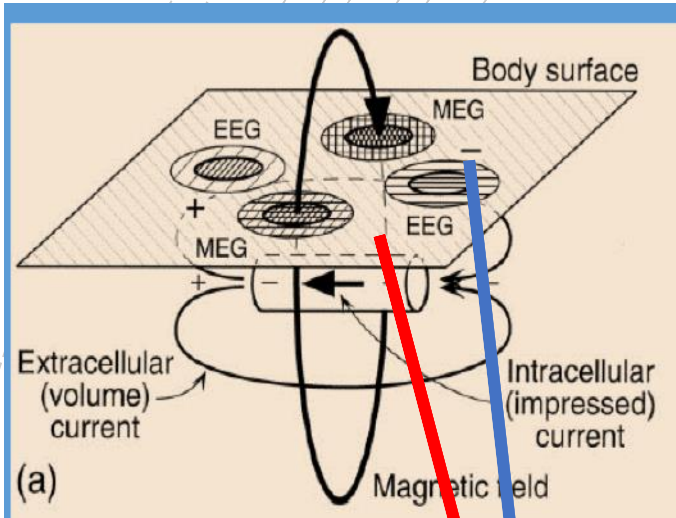
Summary

MEG: introduction

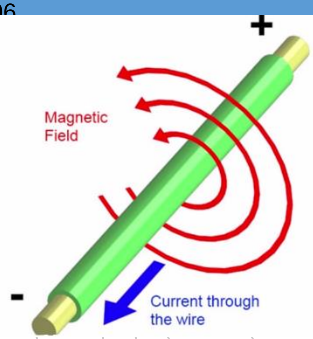
http://www.admin.ox.ac.uk/estates/capitalprojects/previouscapitalprojects/megscanner/

- **Magnetoencephalography**
- Direct external recordings of **magnetic fields** created by electrical currents in cortex
- Measured in **fT** to **pT**
- Role of MEG in neuroimaging:
  - **Neural correlates** of cognitive/perceptual processes
  - **Localise** affected regions before surgery(?), determine regional and network functionality

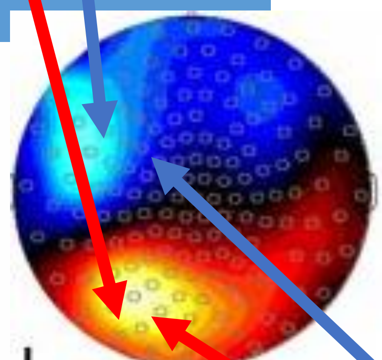
MEG: basis of the signal



Tiege & Zlobinski, 2006



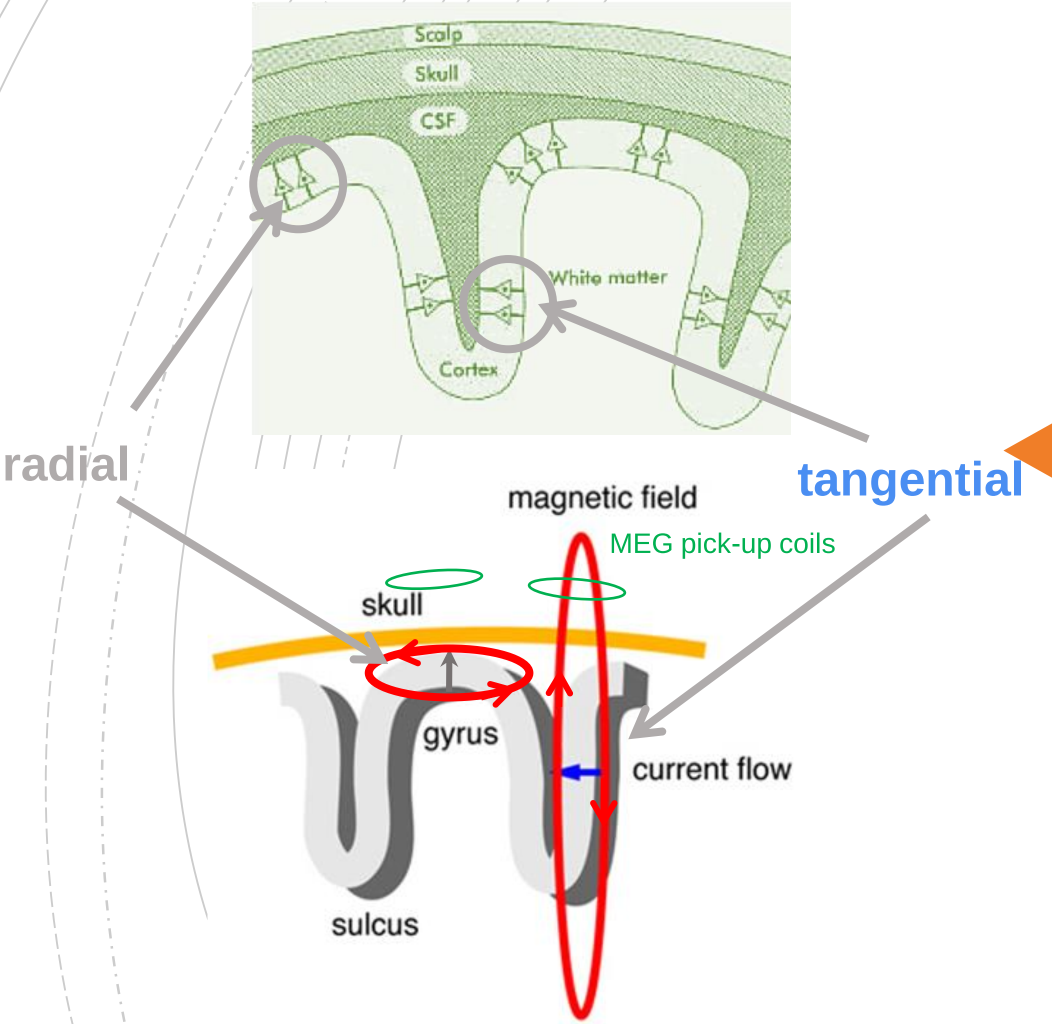
http://www.youtube.com/watch?v=CPj4jJACeIs



Ochi et al. 2011

- **EEG and MEG** both measure the neuronal activities but **EEG** detects synchronised electrical activity of large groups of neurons, whereas **MEG** detects the tiny changes in magnetic fields
- Recall: **large pyramidal neurons** in layer V of cortex, arranged in parallel, similarly-oriented, perpendicular to surface, fire synchronously
- Dipolar current flow generates a **magnetic field.**
  TRY IT: 'Right hand grip'!
- **10,000 to 50,000** active neurons required for detectable signal
- **Scalp topography:**
  - **Influx maxima** 'source'
  - **Efflux maxima** 'sink'

MEG: tangential vs. radial



- MEG magnetic field **not distorted** by conductive properties of scalp/head
- MEG coil not sensitive to **perfectly radial sources**
- But in practice, only a **small proportion (<1%)** of cell populations are perfectly radial – i.e. on top of gyri

Tiege and Zlobinski, 2006

MEG: scale of magnetic field

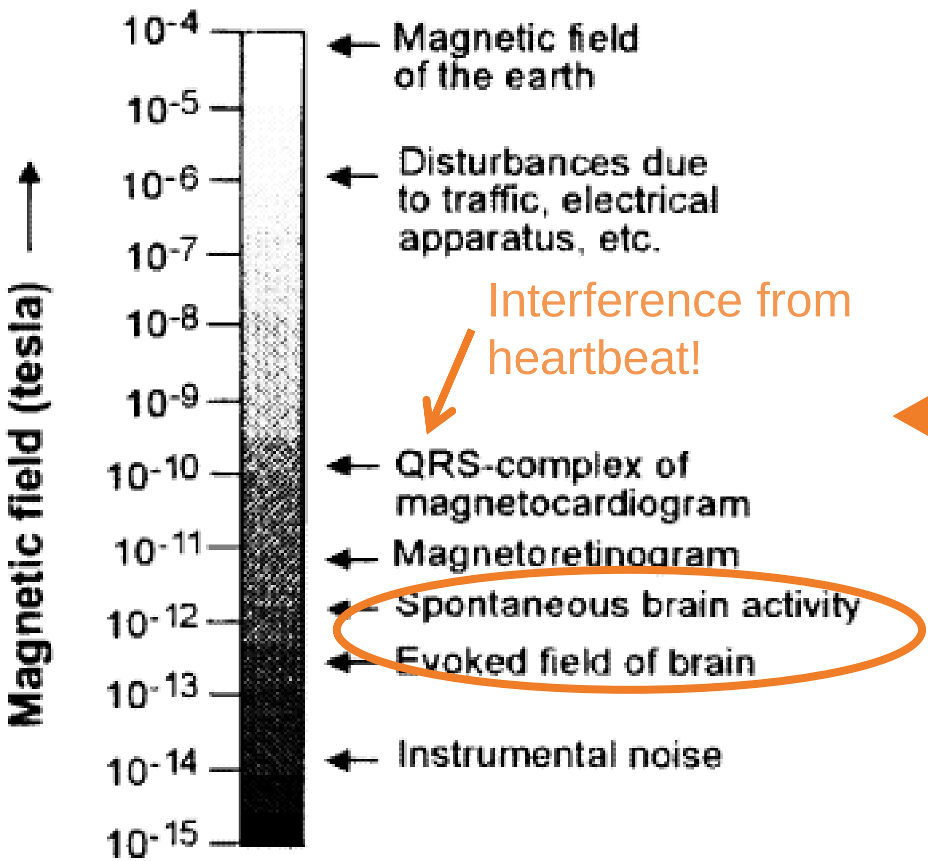


Figure I.3: *Comparison of field strengths*

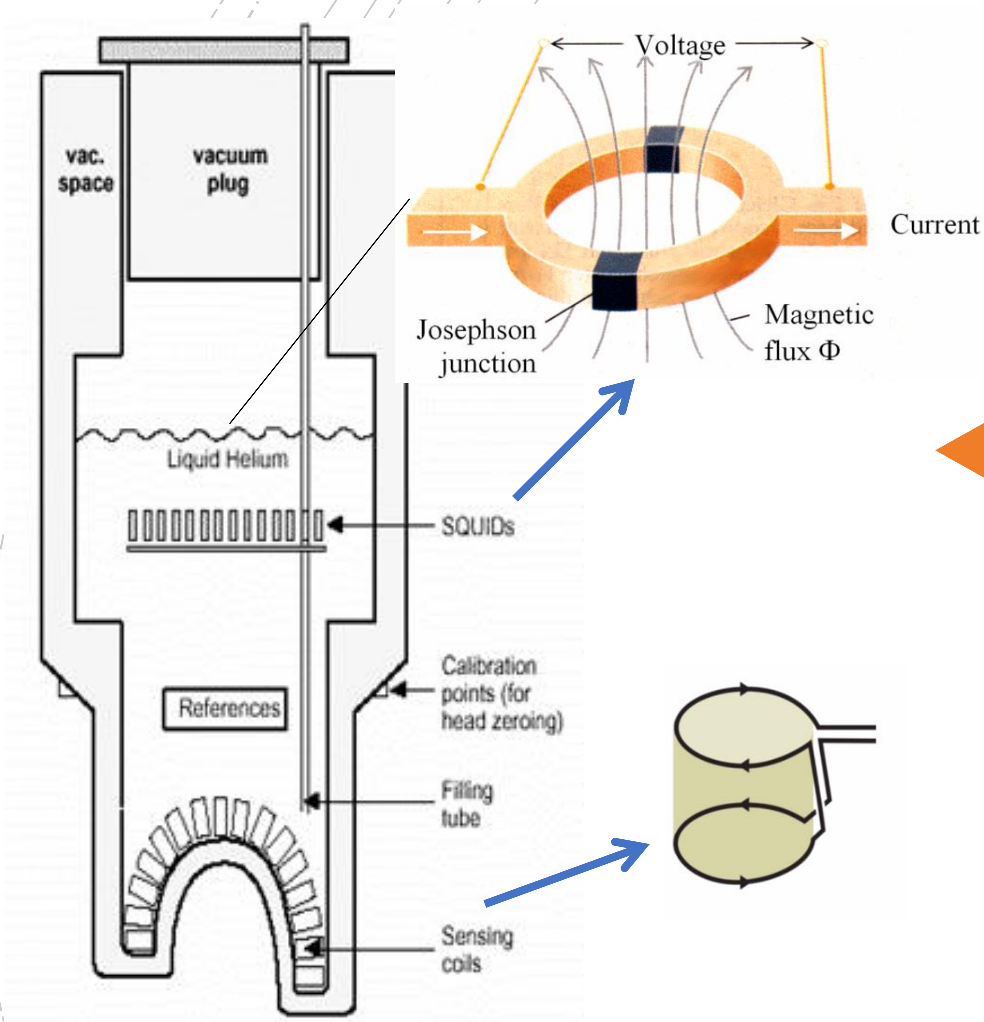
- MEG signal is **tiny!**
- **Interference** from electrical equipment, traffic, the earth, participant's heartbeat etc.
- Requires **magnetically shield rooms** and **supersensitive magnetometers**

MEG: magnetically shielded room (MSR)

Brock & Sowman (2014)

- 3, 5 or 6 layers with different magnetic properties to protect from different frequencies of magnetic interference

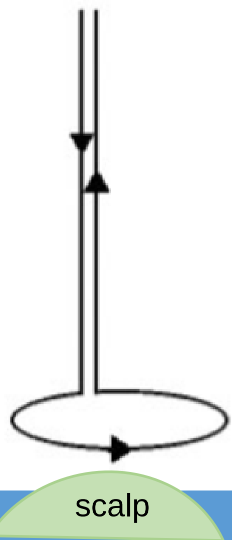
MEG is super-cool

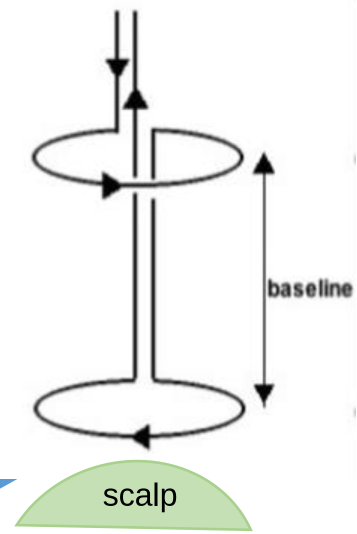


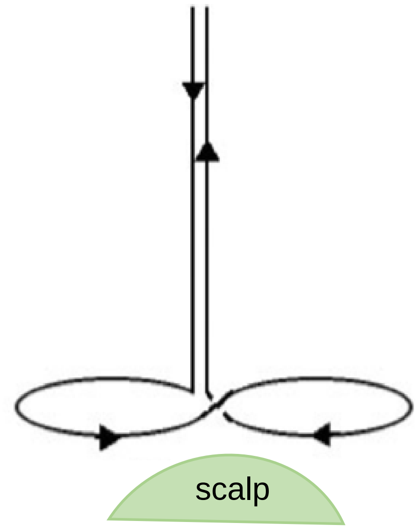
- **SQUID**
- **S**uperconducting **QU**antum **I**nterference **D**evice, immersed in super-cool liquid helium
- Sensitive to field changes in order of **femto-Tesla** (10^{-15})
- Superconductive ring with two **Josephson junctions**
- **Flux transformers** (coils)
  - Magnetometers
  - Gradiometers (planar/axial)

http://www.csiro.au/~/media/CSIROau/Images/Maps%20%20Graphs/SQUID_CESRE_ind/High_Resolution.gif

MEG: flux transformers





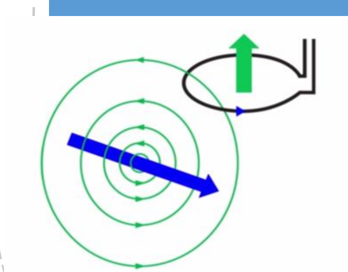


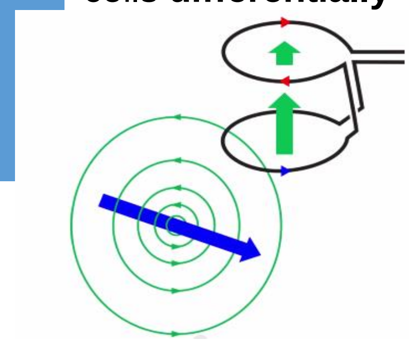
Axial magnetometer

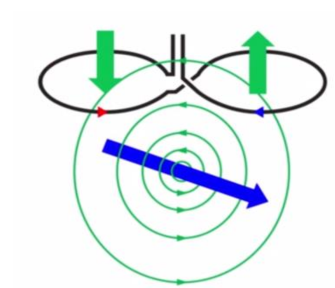
Single superconducting coil – highly sensitive but affected by environmental noise

Axial/planar gradiometers (1st order)

Two oppositely-wound coils – environmental noise affects both electrodes : **no net noise.** Sources from cortex affect coils **differentially**



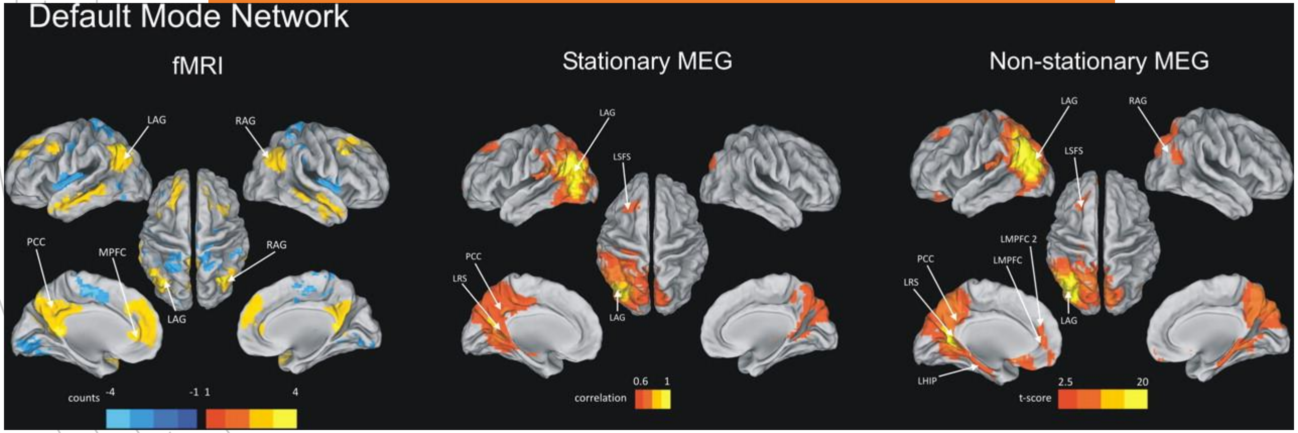




http://www.youtube.com/watch?v=CPj4jJACeIs

MEG: applications

- **Excellent spatial resolution**
  - good for functional mapping of specific cortex (M1, V1) during behavioural, cognitive, perceptive tasks
- **Surgical planning (?)** in patients with brain tumours or intractable epilepsy
- **Research** into whole-brain network connectivity
  - Millisecond temporal resolution

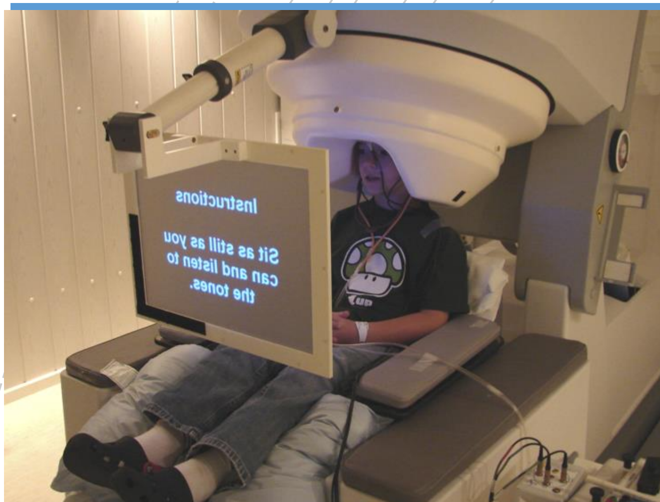


de Pasquale et al (2010)

EEG vs. MEG

	EEG	MEG
Signal magnitude	10 mV (easily detectable) ✓	10 fT (magnetic shielding required)
Measurement	Secondary currents	Primary currents ✓
Signal purity	Distortion by skull/scalp	Little effect by skull/scalp ✓
Temporal resolution	~1ms	~1ms
Spatial resolution	~1cm	<1cm ✓
Experimental flexibility	Moves with subject ✓	Subject must remain stationary
Dipole orientation	Tangential and radial ✓	Tangential better

EEG/MEG advantages

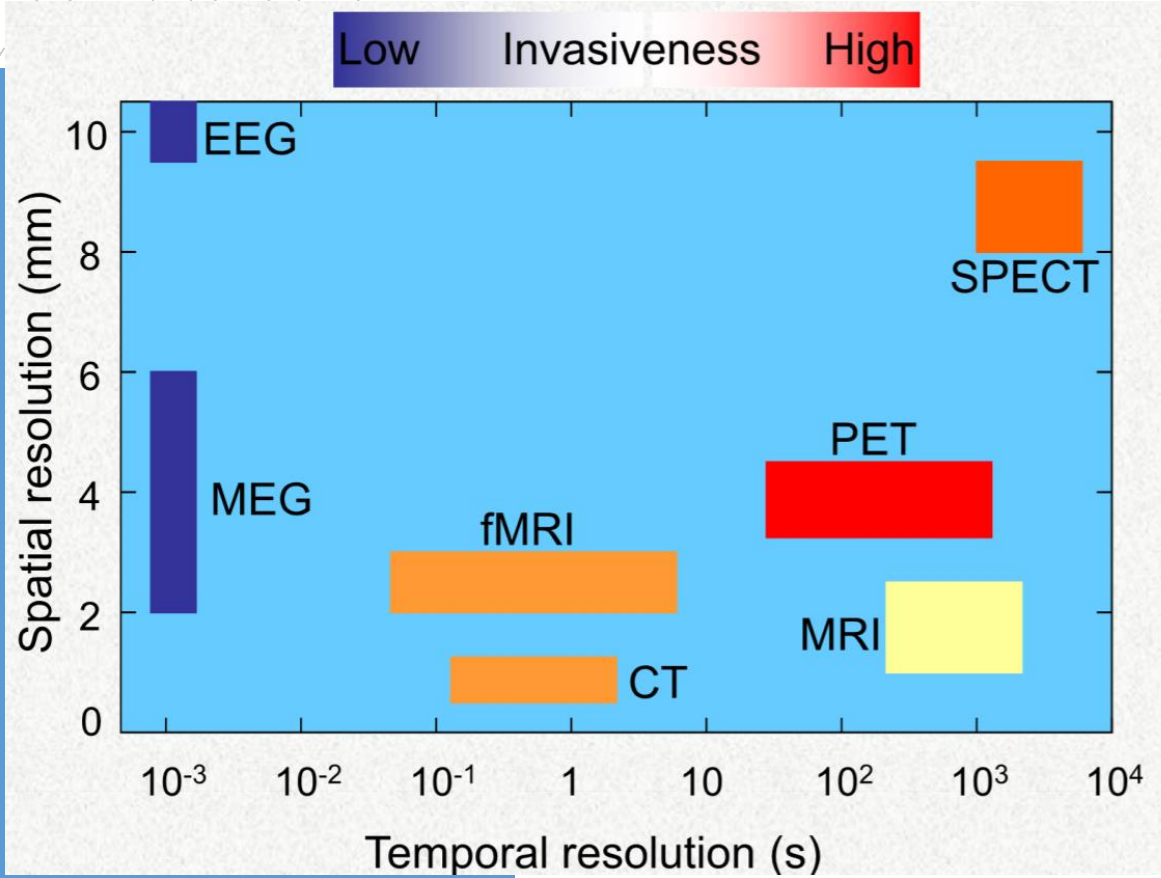


- ✓ **Non-invasive**
- ✓ **Direct** measurements of neuronal function (unlike fMRI)
- ✓ High **temporal resolution** (1ms or less, 1000x better than fMRI)
- ✓ Easy to use **clinically** (adults, children)
- ✓ **Quiet!** (can study auditory processing)
- ✓ **Affordable**, EEG is portable
- ✓ Subjects can perform tasks **sitting up** (more natural than MRI scanner)

https://www.colbertnewshub.com/2013/04/05/april-4-2013-dr-francis-collins/

https://medicalxpress.com/news/2015-02-brain-imaging-links-language-chromosome.html

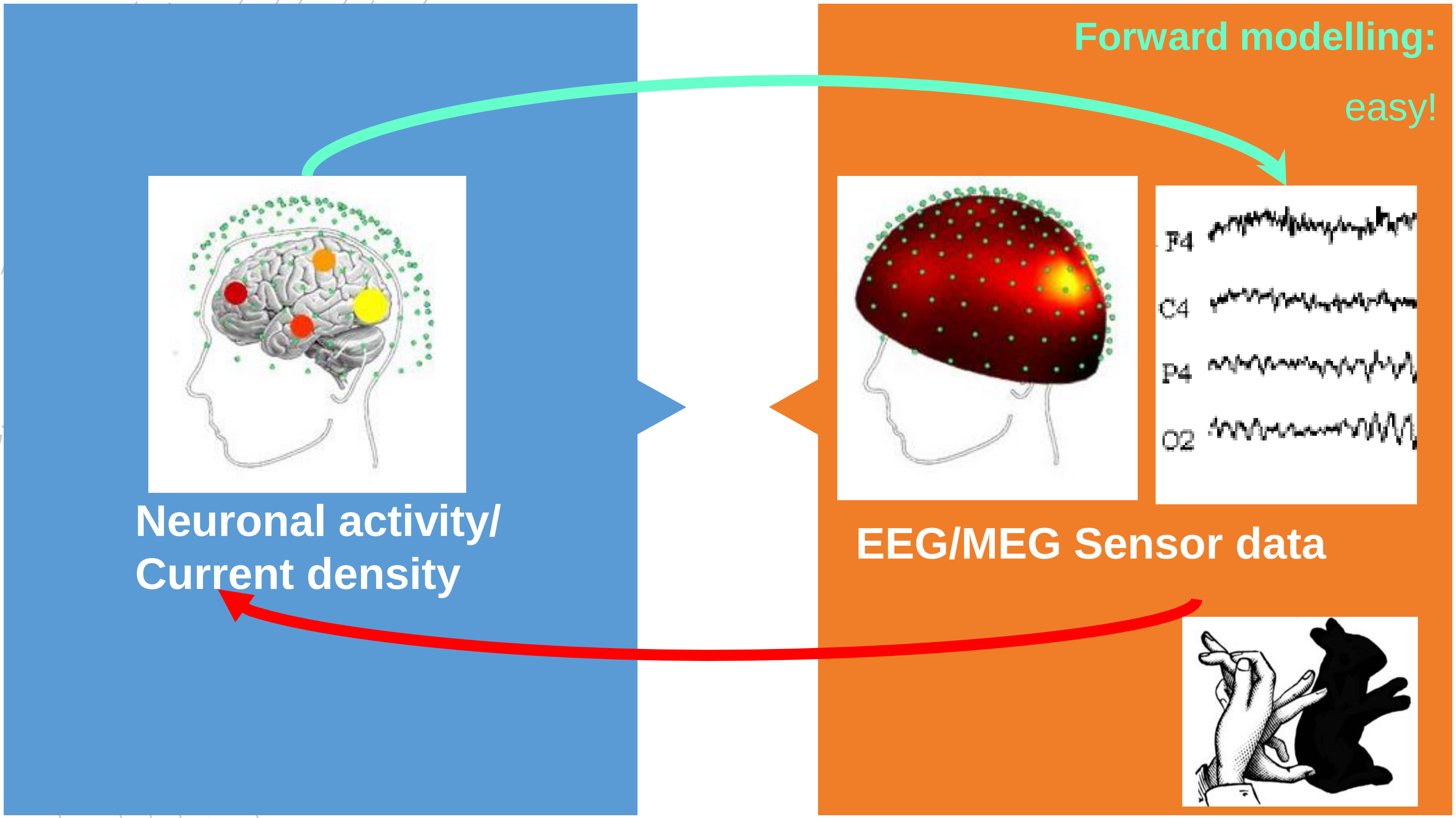
EEG/MEG disadvantages



- Not as good **spatial localisation** as fMRI, MRI, CT
- **Sensitivity depth** only ~4cm (c.f. whole brain sensitivity of fMRI)
  - Sensitivity loss proportional to square of distance from sensor
- 3D Source reconstruction is ill-posed? **forward** and **inverse problems**

https://ngp.usc.edu/files/2013/06/Syed__EEG_MEG.pdf

Forward & inverse problems



https://www.youtube.com/watch?v=AogBOXtXk1s

→**SOLUTION:** Use forward models for inverse problem. Source localisation models and algorithms; iterative source reconstruction

Summary

Direct, non-invasive measures of cortical electrical activity

- **EEG**: secondary currents,
- **MEG**: magnetic fields

Good **spatial & temporal** resolution

Depth sensitivity?

- Add thalamus, hippocampus, amygdala to MEG source reconstruction models (!)

Spontaneous or **evoked** neural activity;

Applications in epilepsy, sleep, Alzheimer’s disease biomarkers(?), schizophrenia(?), autism(?), whole-brain functional networks

Sources

Images from:
https://en.wikipedia.org/wiki/Dipole
https://www.brightbraincentre.co.uk/electroencephalogram-eeg-brainwaves/
https://www.brightbraincentre.co.uk/electroencephalogram-eeg-brainwaves/
https://www.brightbraincentre.co.uk/electroencephalogram-eeg-brainwaves/eeg-dipoles
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https://www.youtube.com/watch?v=AogBOXtXk1s