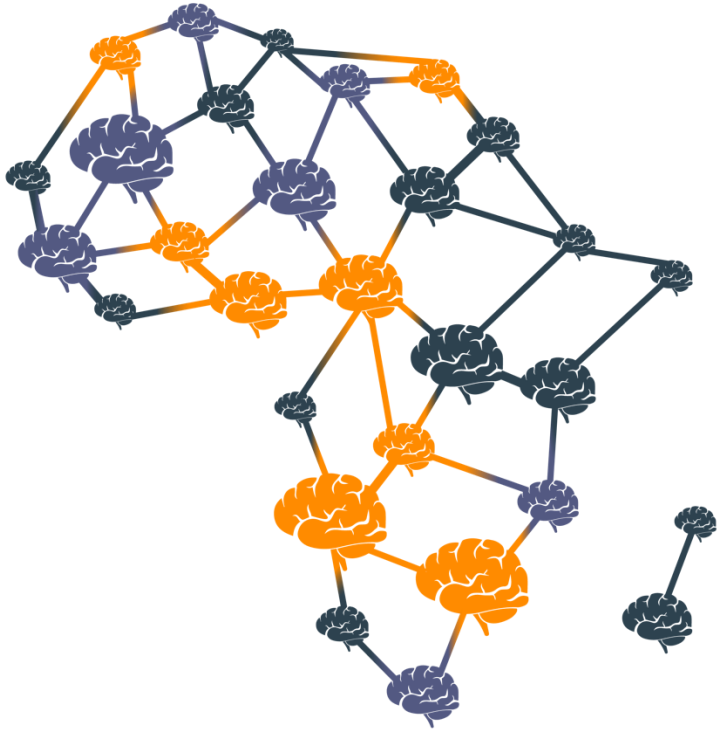
EEG background

Robert Oostenveld

Mikkel C. Vinding

9-14 June 2025
Port Harcourt, Nigeria



African Brain Data Network

Outline

The very basics:

1. What is EEG
2. Introduction to the biophysics of EEG
3. Origin of EEG signals
4. What we measure with EEG

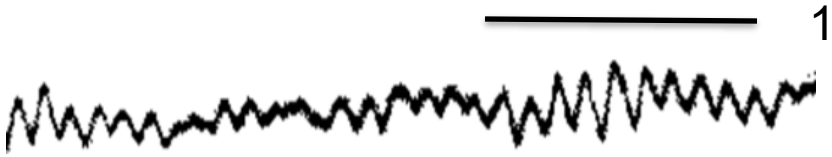
Electro · Encephalo · Graphy (EEG)

A brief history of EEG

Hans Berger reported the first non-invasive human EEG in 1924

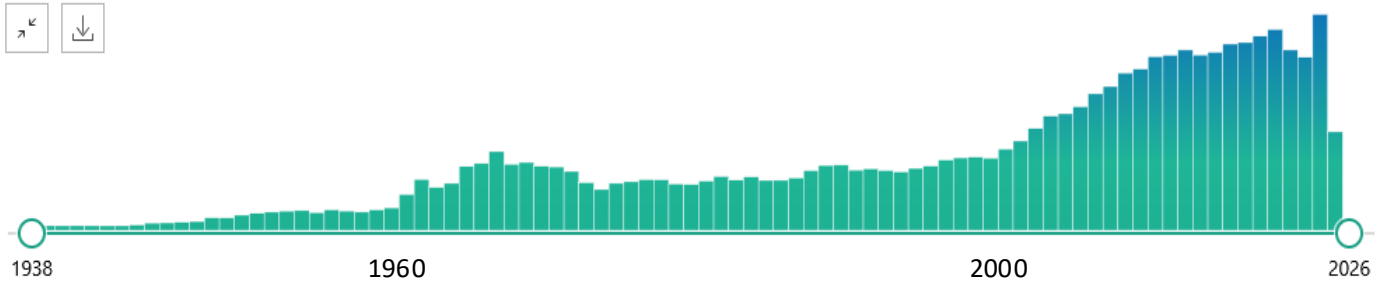
Established measurement

- Known canonical signals
- Standardised measurement schemes



Emerging technology

- Advanced analyses and (open-access) software
- Massive investment in R&D



Comment

https://doi.org/10.1038/s41562-024-01941-5

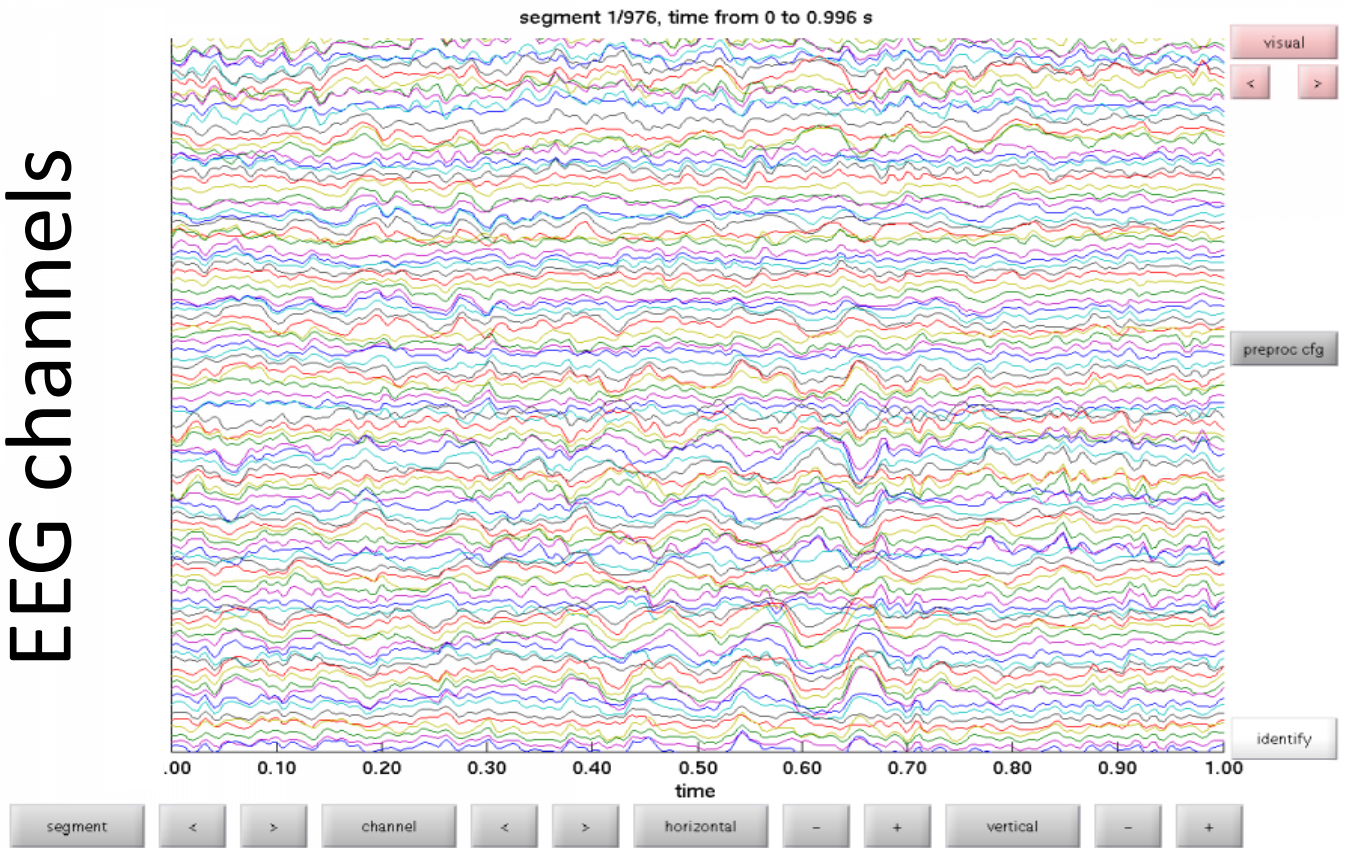
One hundred years of EEG for brain and behaviour research

Faisal Mushtaq, Dominik Welke, Anne Gallagher, Yuri G. Pavlov, Layla Kouara, Jorge Bosch-Bayard, Jasper J. F. van den Bosch, Mahnaz Arvaneh, Amy R. Bland, Maximilien Chaumon, Cornelius Borck, Xun He, Steven J. Luck, Maro G. Machizawa, Cyril Pernet, Aina Puce, Sidney J. Segalowitz, Christine Rogers, Muhammad Awais, Claudio Babiloni, Neil W. Bailey, Sylvain Baillet, Robert C. A. Bendall, Daniel Brady, Maria L. Bringas-Vega, Niko A. Busch, Ana Calzada-Reyes, Armand Chatard, Peter E. Clayson, Michael X. Cohen, Jonathan Cole, Martin Constant, Alexandra Corneyllie, Damien Coyle, Damian Cruse, Ioannis Delis, Arnaud Delorme, Damien Fair, Tiago H. Falk, Matthias Gamer, Giorgio Ganis, Kilian Gloy, Samantha Gregory, Cameron D. Hassall, Katherine E. Hiley, Richard B. Ivry, Karim Jerbi, Michael Jenkins, Jakob Kaiser, Andreas Keil, Robert T. Knight, Silvia Kochen, Boris Kotchoubey, Olave E. Krigolson, Nicolas Langer, Heinrich R. Liesefeld, Sarah Lippé, Raquel E. London, Annmarie MacNamara, Scott Makeig, Welber Marinovic, Eduardo Martínez-Montes, Aleya A. Marzuki, Ryan K. Mathew, Christoph Michel, José d. R. Millán, Mark Mon-Williams, Lilia Morales-Chacón, Richard Naar, Gustav Nilsonne, Guiomar Niso, Erika Nyhus, Robert Oostenveld, Katharina Paul, Walter Paulus, Daniela M. Pfabigan, Gilles Pourtois, Stefan Rampp, Manuel Rausch, Kay Robbins, Paolo M. Rossini, Manuela Ruzzoli, Barbara Schmidt, Magdalena Senderecka, Narayanan Srinivasan, Yannik Stegmann, Paul M. Thompson, Mitchell Valdes-Sosa, Melle J. W. van der Molen, Domenica Veniero, Edelyn Verona,

Examples of EEG

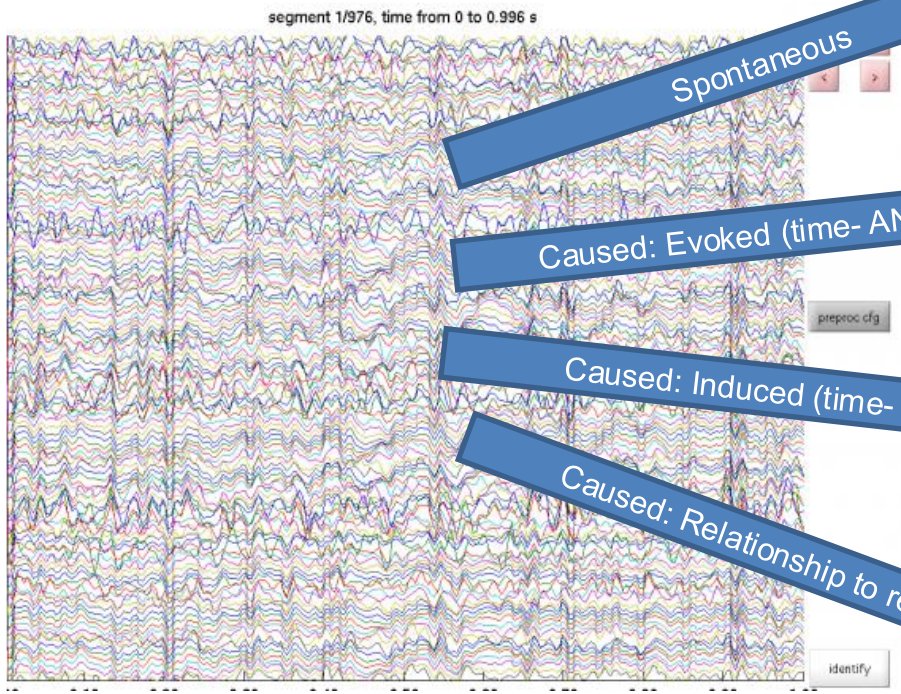
EEG data

Unit: microvolts (µV)



Time

EEG data: a multitude of possible measures



Spontaneous

Caused: Evoked (time- AND phase- locked)

Caused: Induced (time- NOT phase-locked)

Caused: Relationship to reference signal

Spontaneous activity
- Oscillatory activity: Delta, Theta, Alpha, Beta, Gamma
- Broadband features
- ”Events”

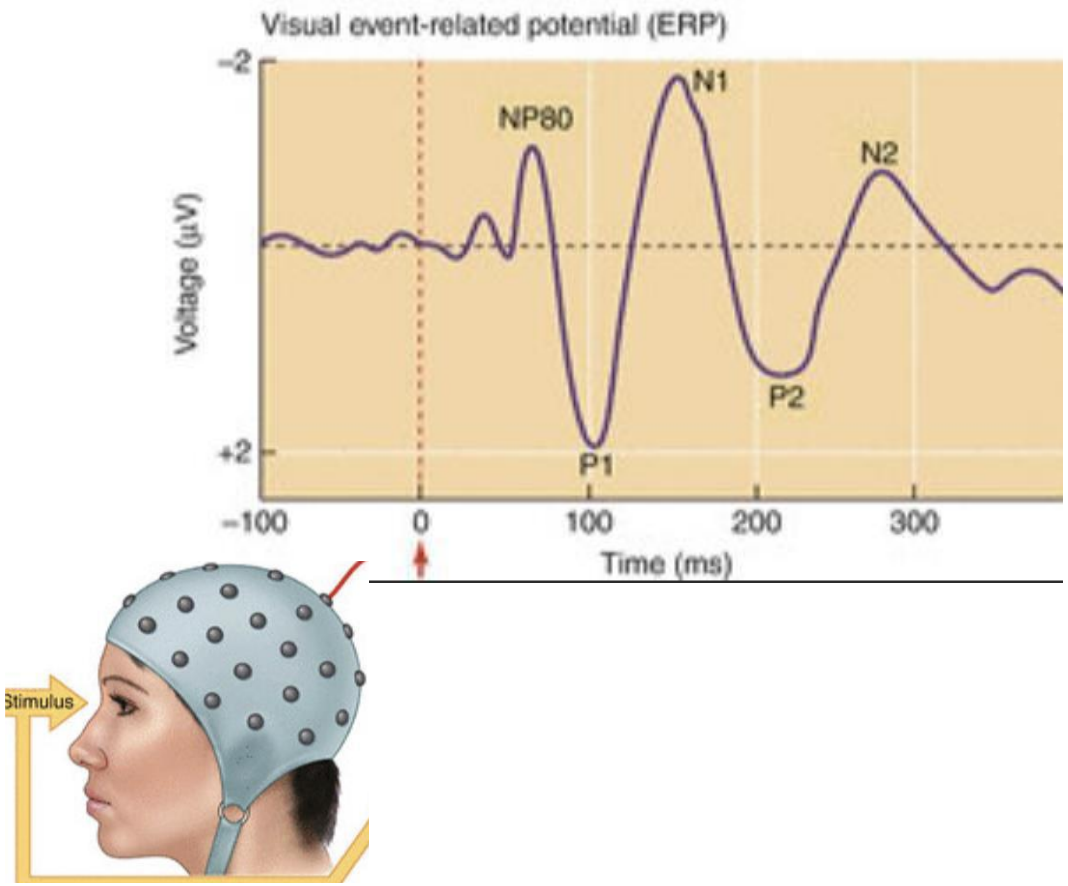
Evoked responses
Event-related potentials (ERP)
All sensory modalities

Induced responses
Event-related modulation of oscillations
All sensory modalities
Brain stimulation

Frequency tagging
Coherence to motor / kinematics
Most sensory modalities

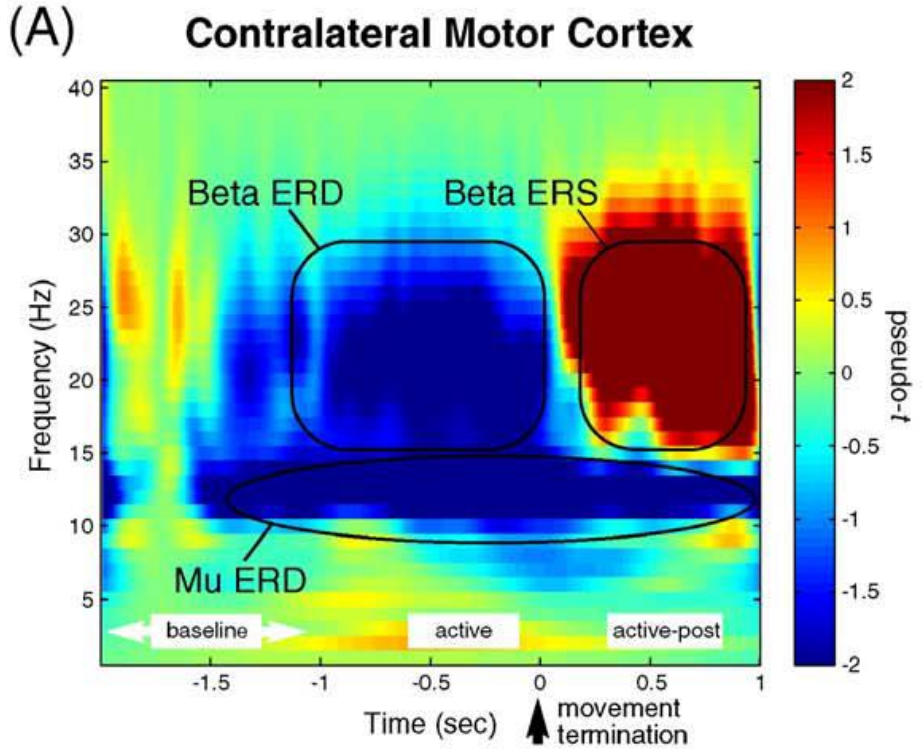
Examples of EEG: Brain response to stimuli

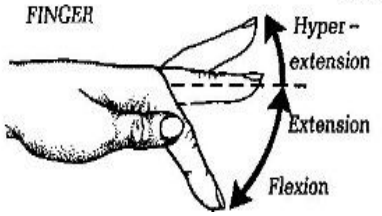
Event-related potentials



Martin & Huettel (2022)

Event-related frequency responses



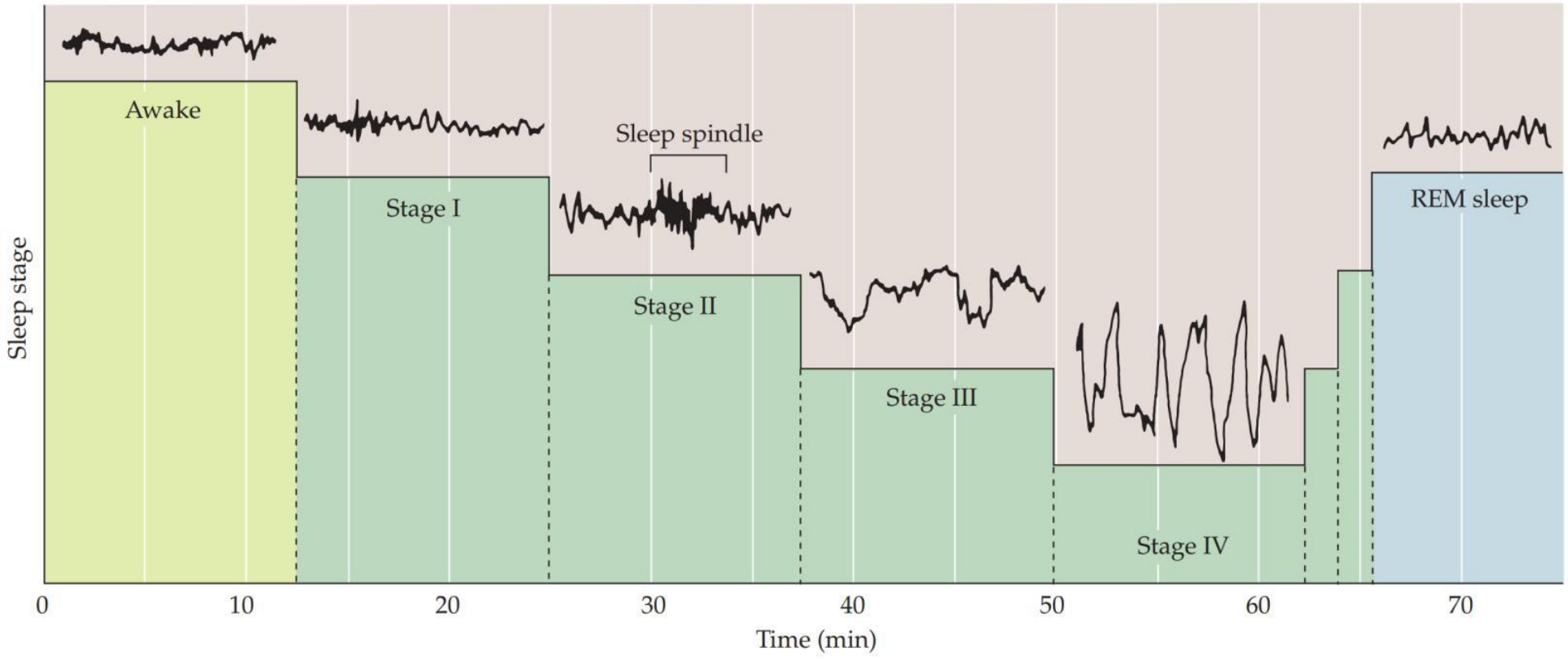


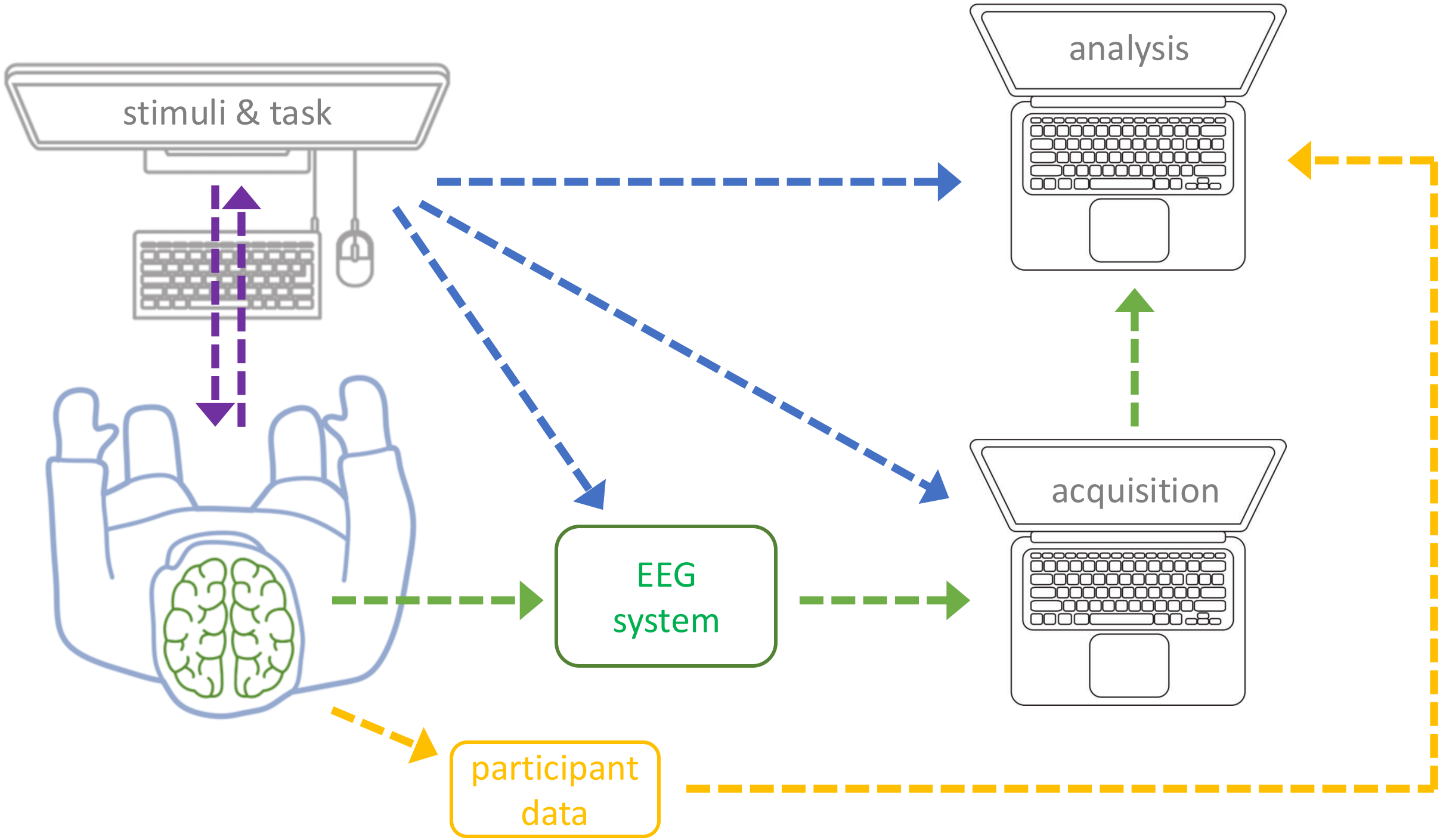
Jurkiewicz et al. (2006)

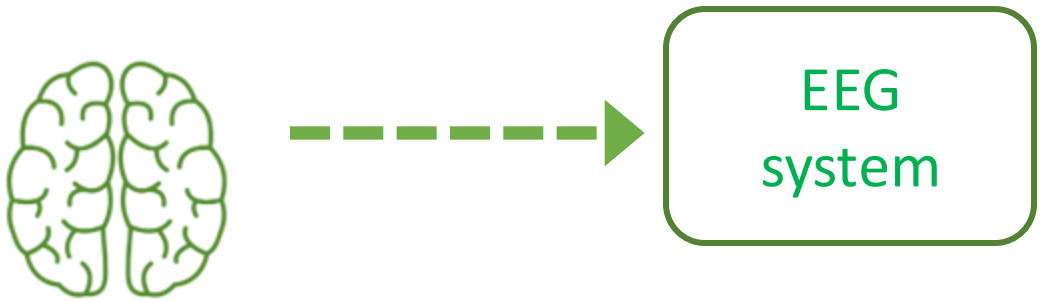
Examples of EEG: epileptic spike detection

https://www.learningeeg.com/

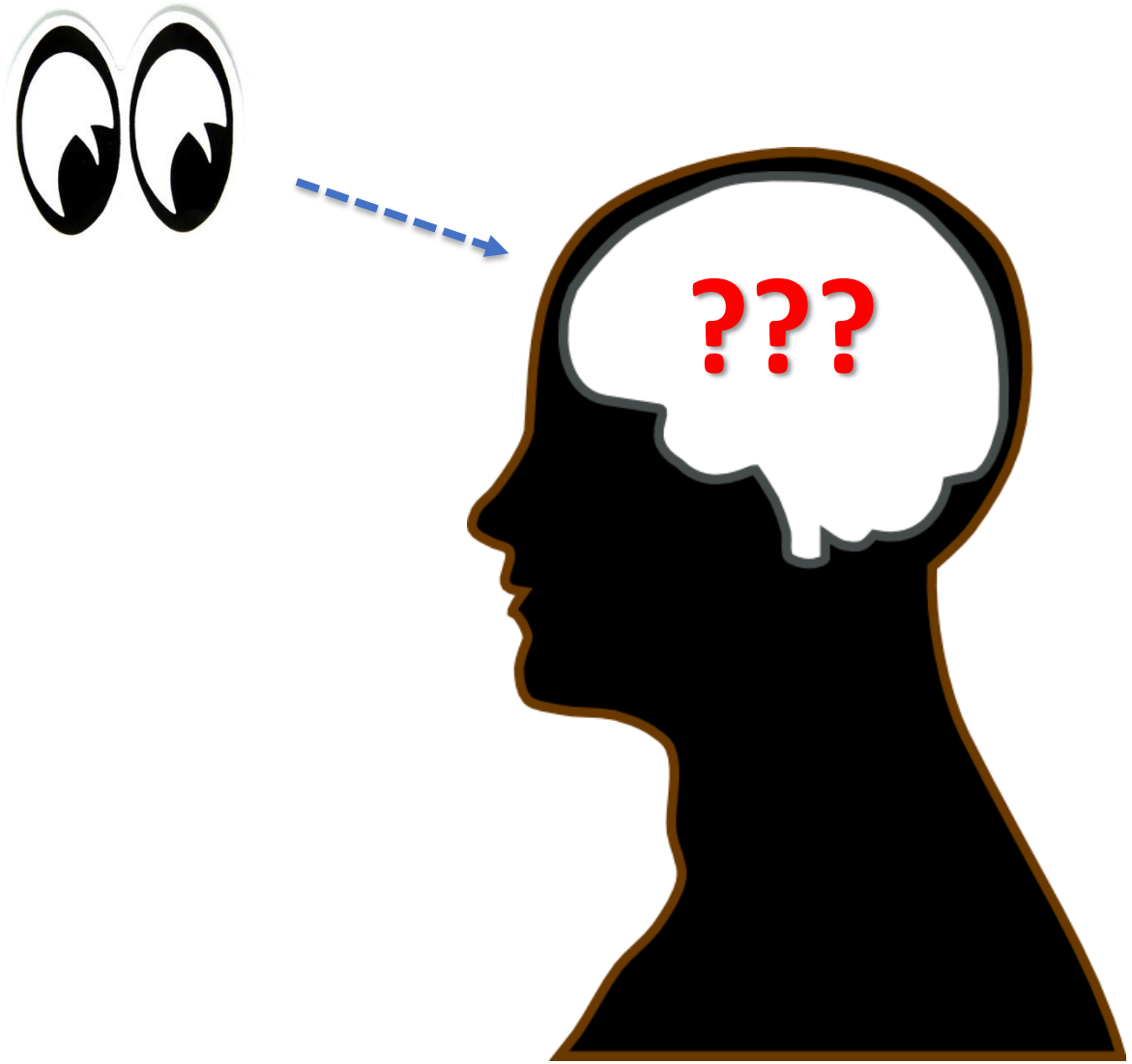
Examples of EEG: Sleep stages in EEG

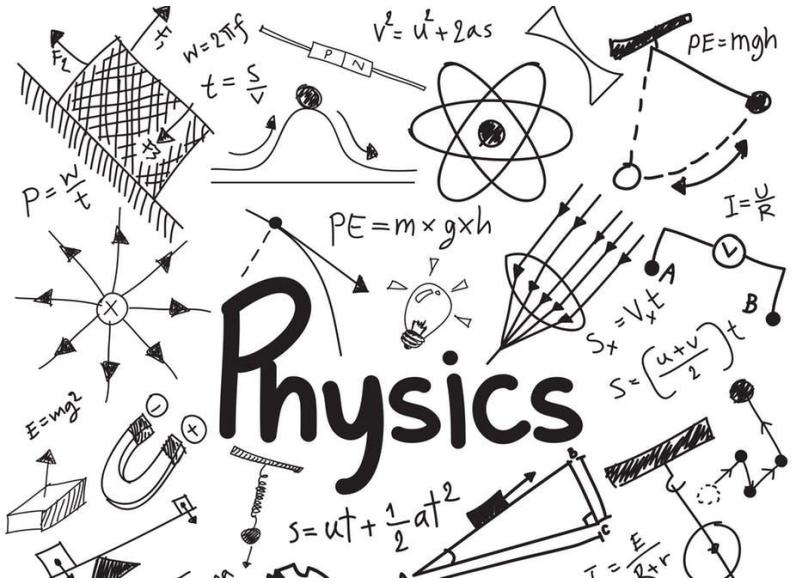



stimuli & task
analysis
acquisition
EEG
system
participant
data

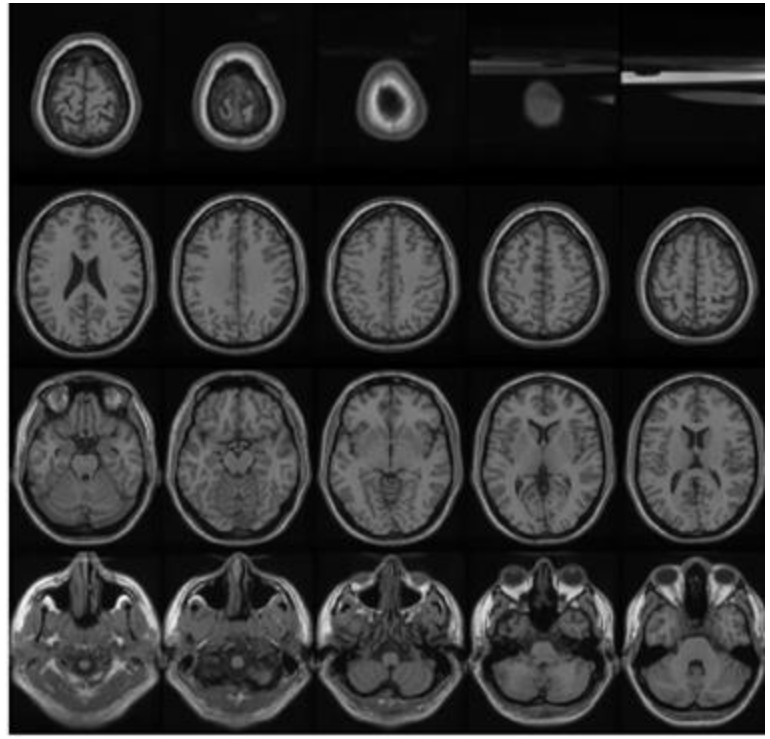

EEG
system

EEG in the neuroimaging landscape



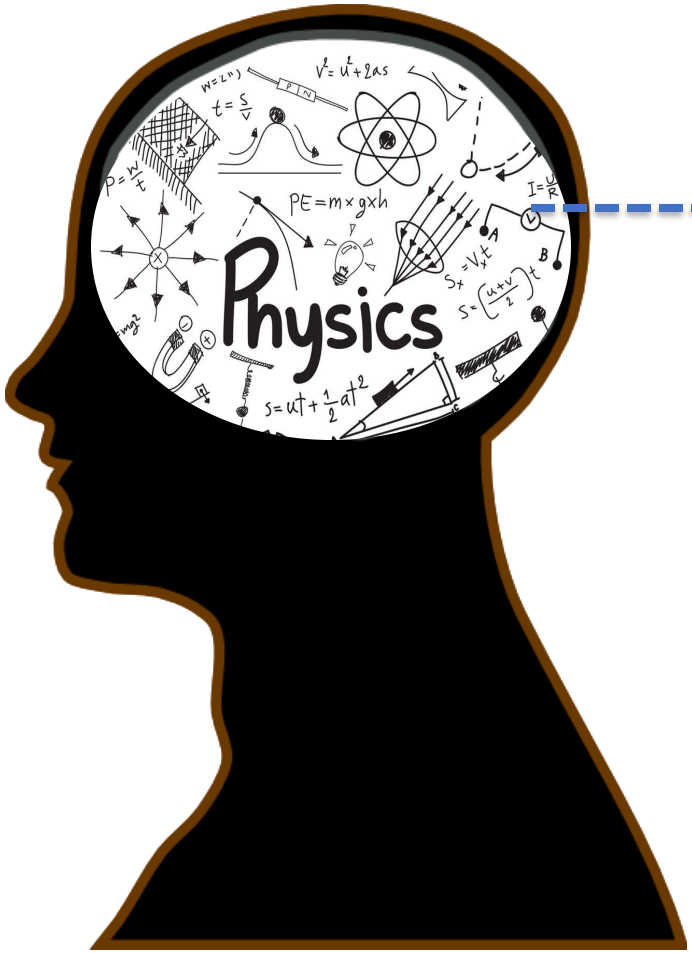

Physics

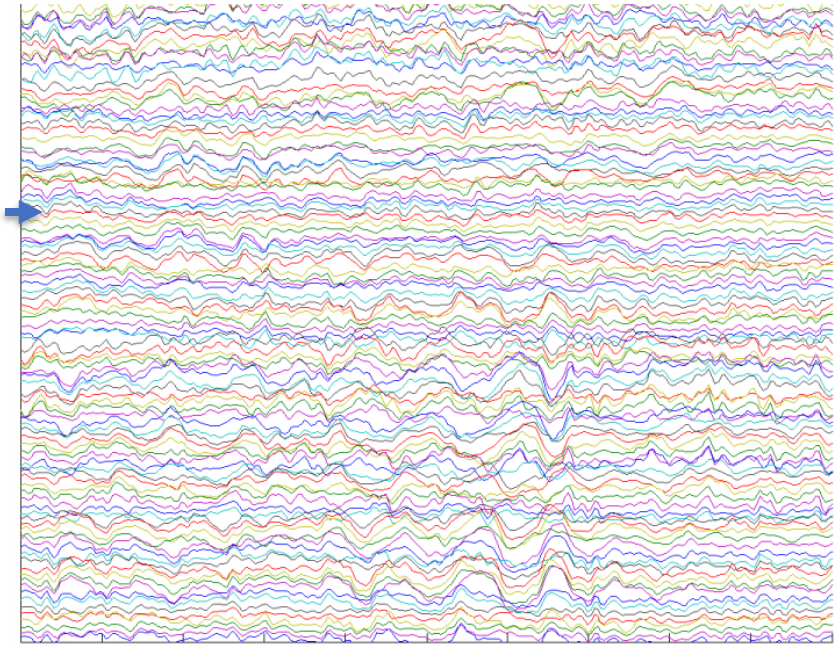

???



”Passive”

EEG





”Functional”

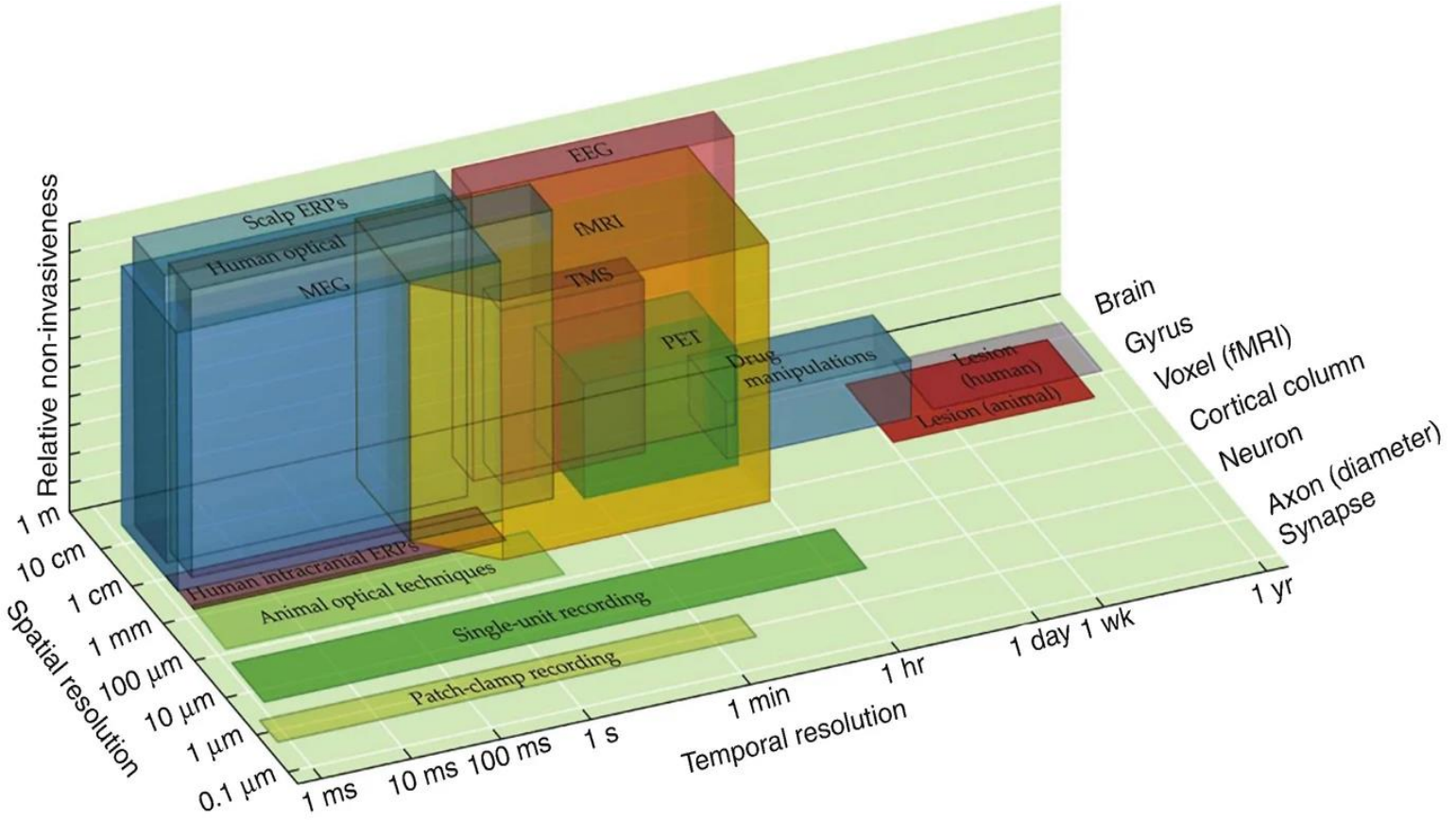
EEG and other imaging techniques

EEG

Measure electric potential at the scalp

High temporal resolution (sub-millisecond)

Low spatial resolution*

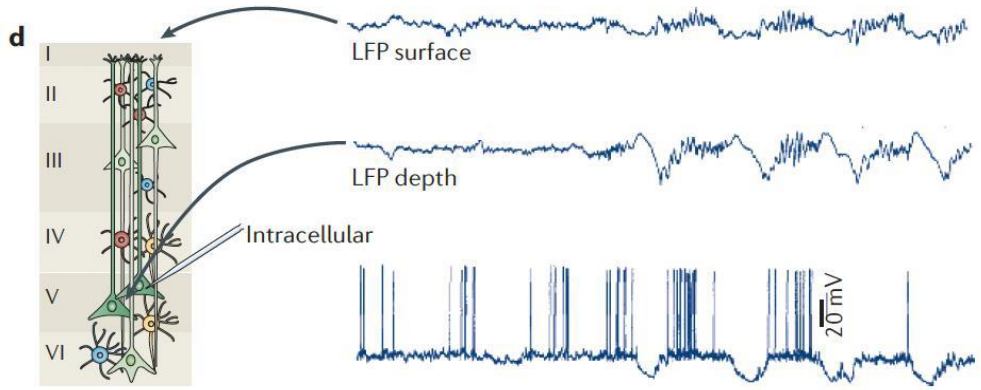


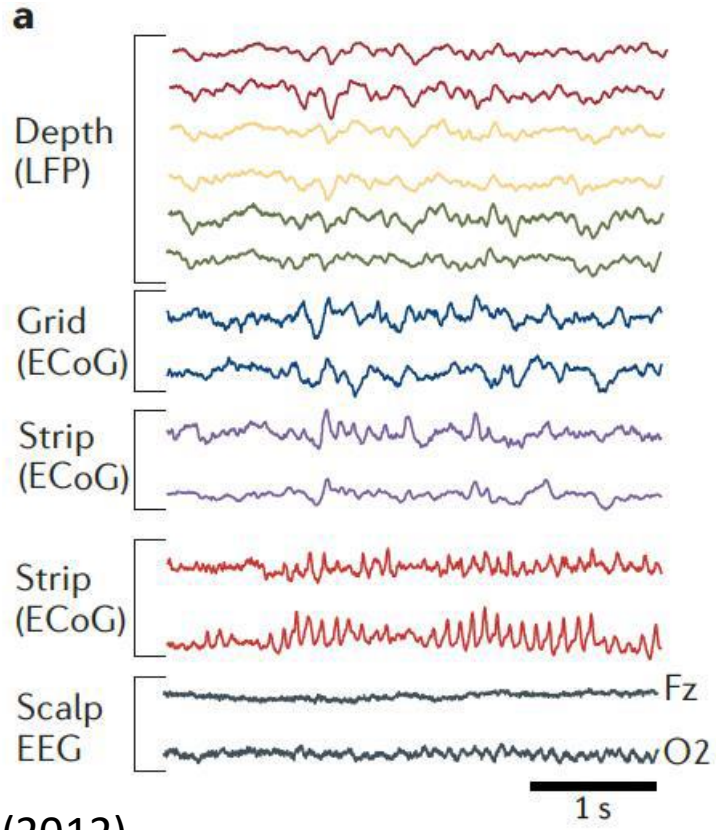
Martin & Huettel (2022)

	EEG	sMRI	fMRI	PET	MEG	CT/CAT
Measurement	Electric potential at the scalp	Tissue types	BOLD	Decay of radioactive tracers	Magnetic field around the scalp	X-rays
Spatial resolution	cm*	mm	mm	mm	cm*	mm
Temporal resolution	< ms	NA	~2-3 s	~30 min	< ms	NA
Good for	Functional electrophysi-ology	Anatomy	Functional	Receptor density	Functional electrophysi-ology	Anatomy
Setting	Flexible*	Fixed	Fixed	Fixed	Fixed	fixed
Active/passive	Passive, non-invasive	Active, non-invasive	Active, non-invasive	Active, usually require contrasts	Passive, non-invasive	Active
Risk	None	Magnetic field	Magnetic field	Radioactive	None	X-rays

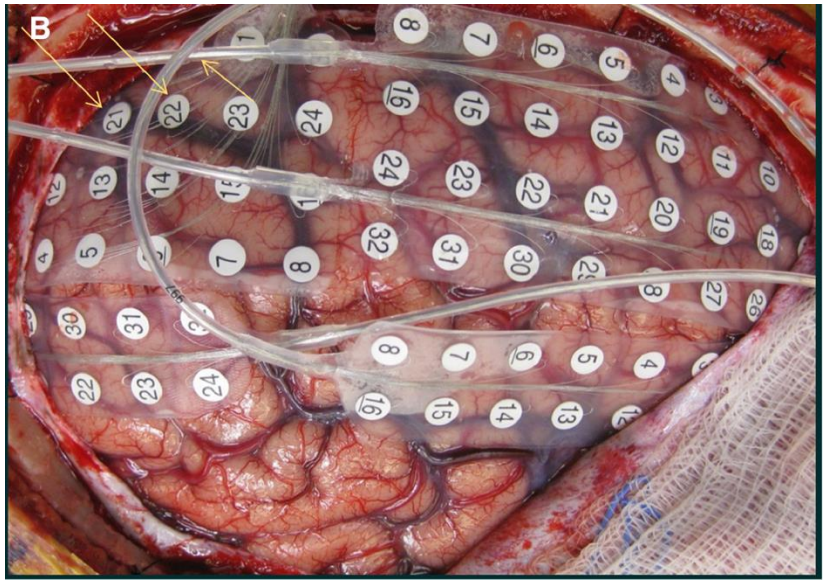
“The brain electrophysiology family”

Greiner et al. (2016)



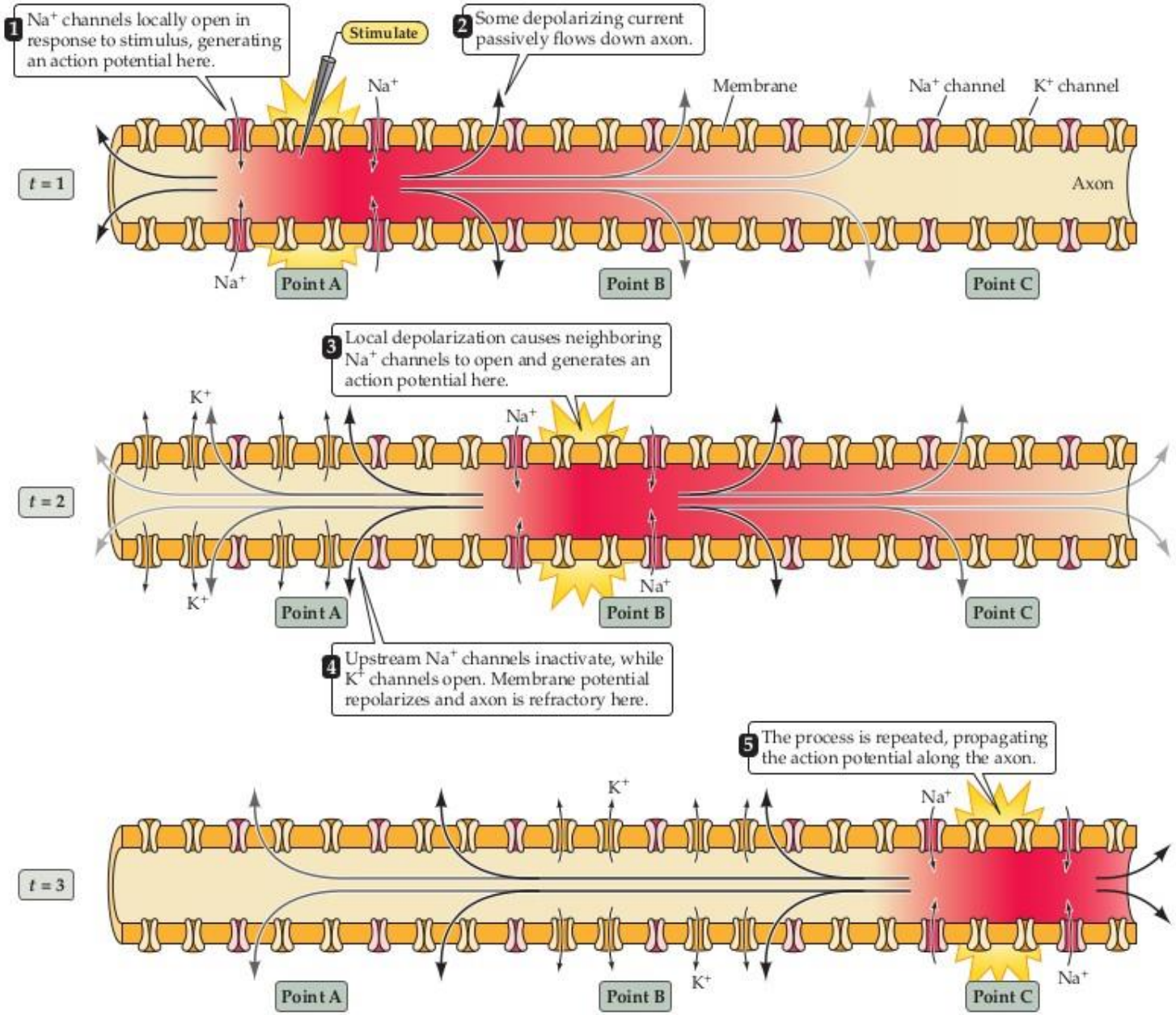


Buzsáki et al. (2012)

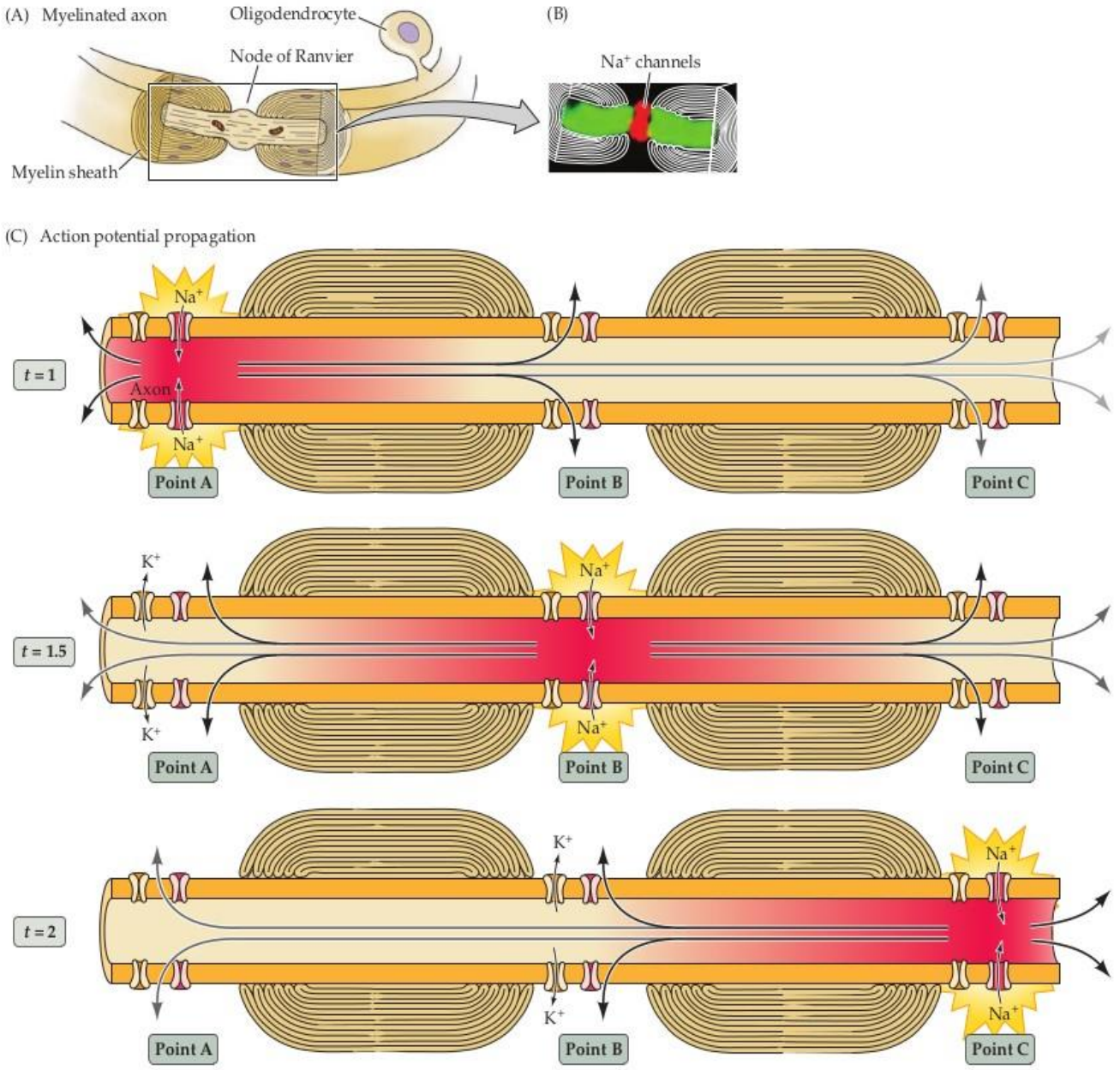


Biophysical origin of EEG signals

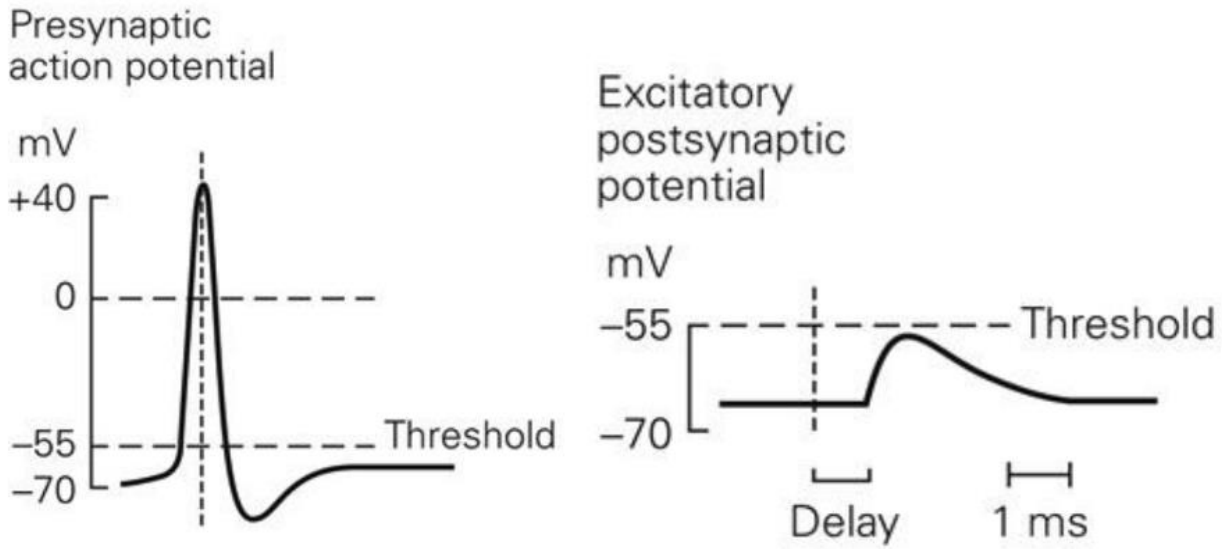
From single cells to scalp potentials

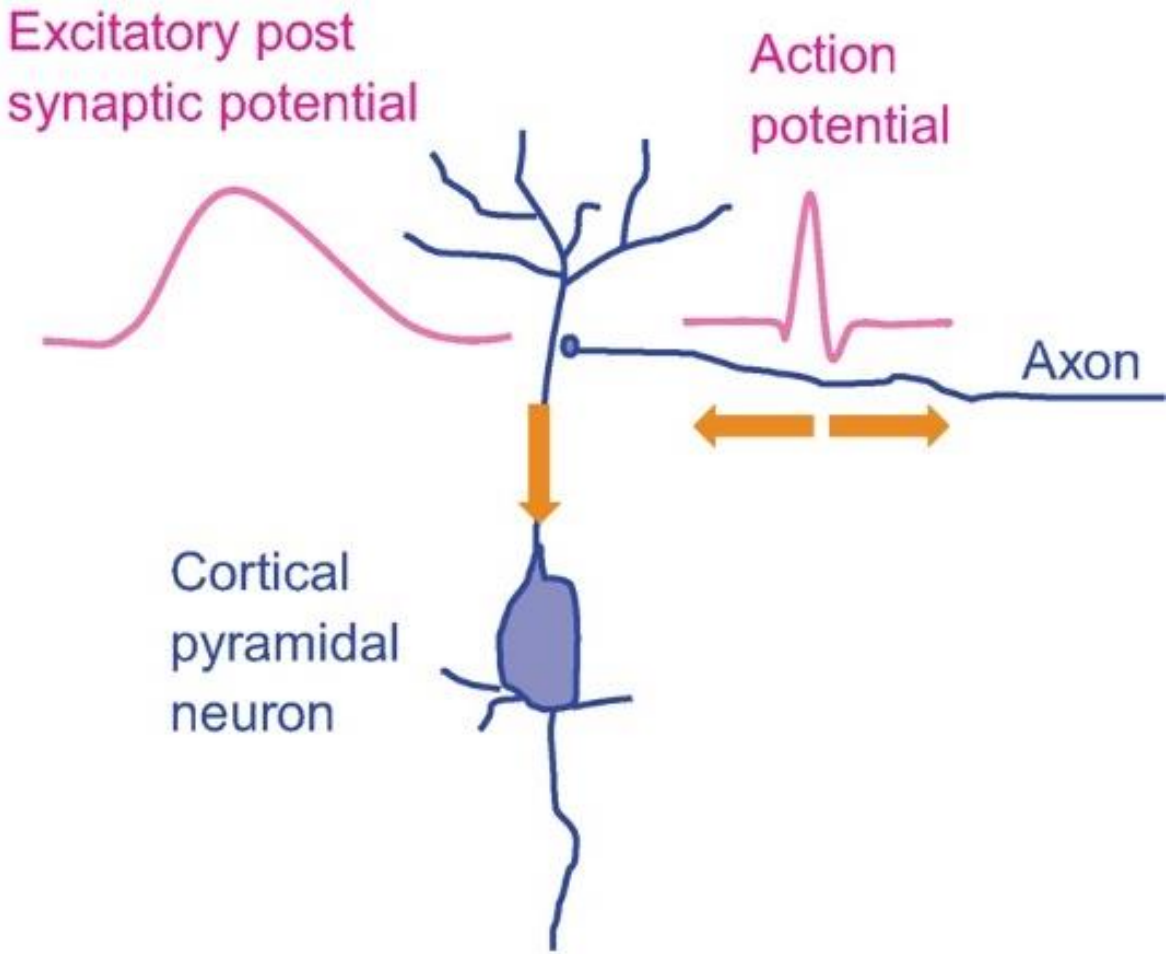


Purves (Neuroscience 6th Ed)



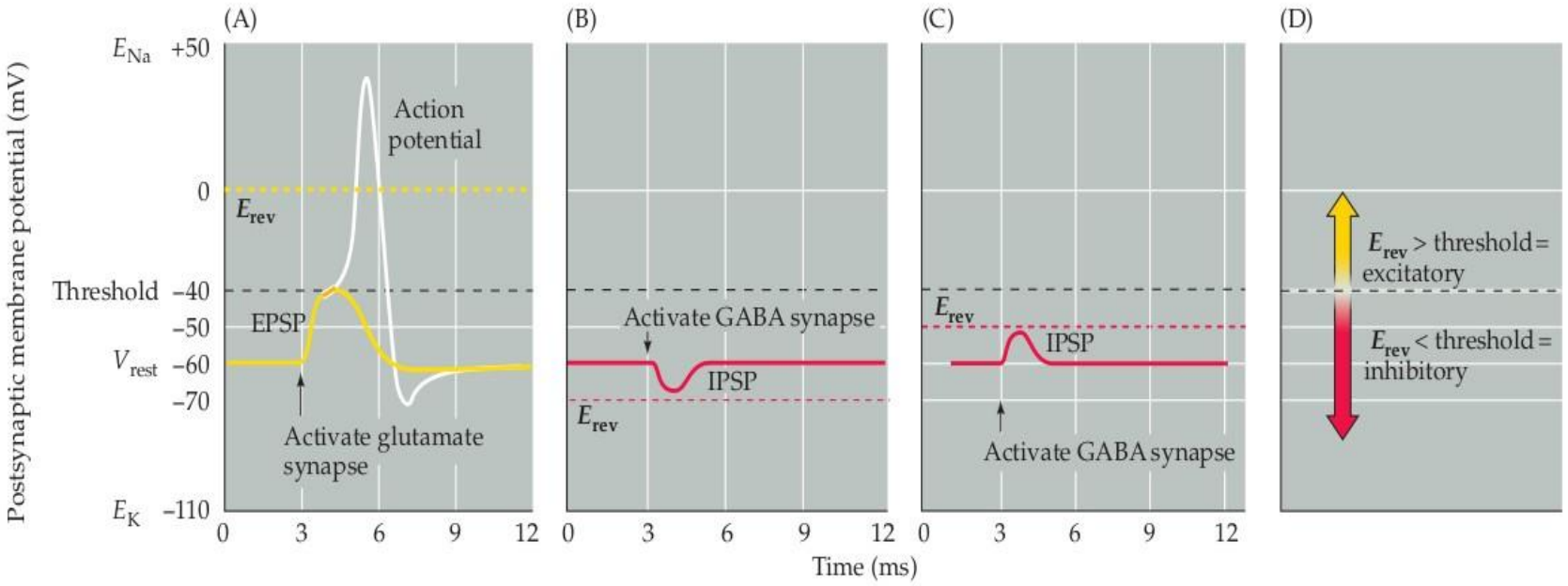
Purves (Neuroscience 6th Ed)

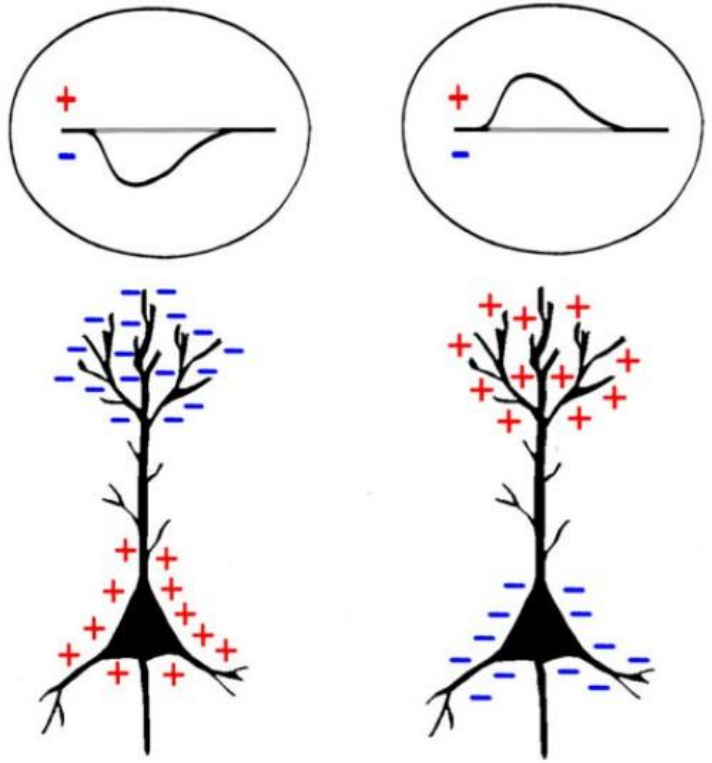




Op de Beeck & Nakatani (2019)

Postsynaptic potentials

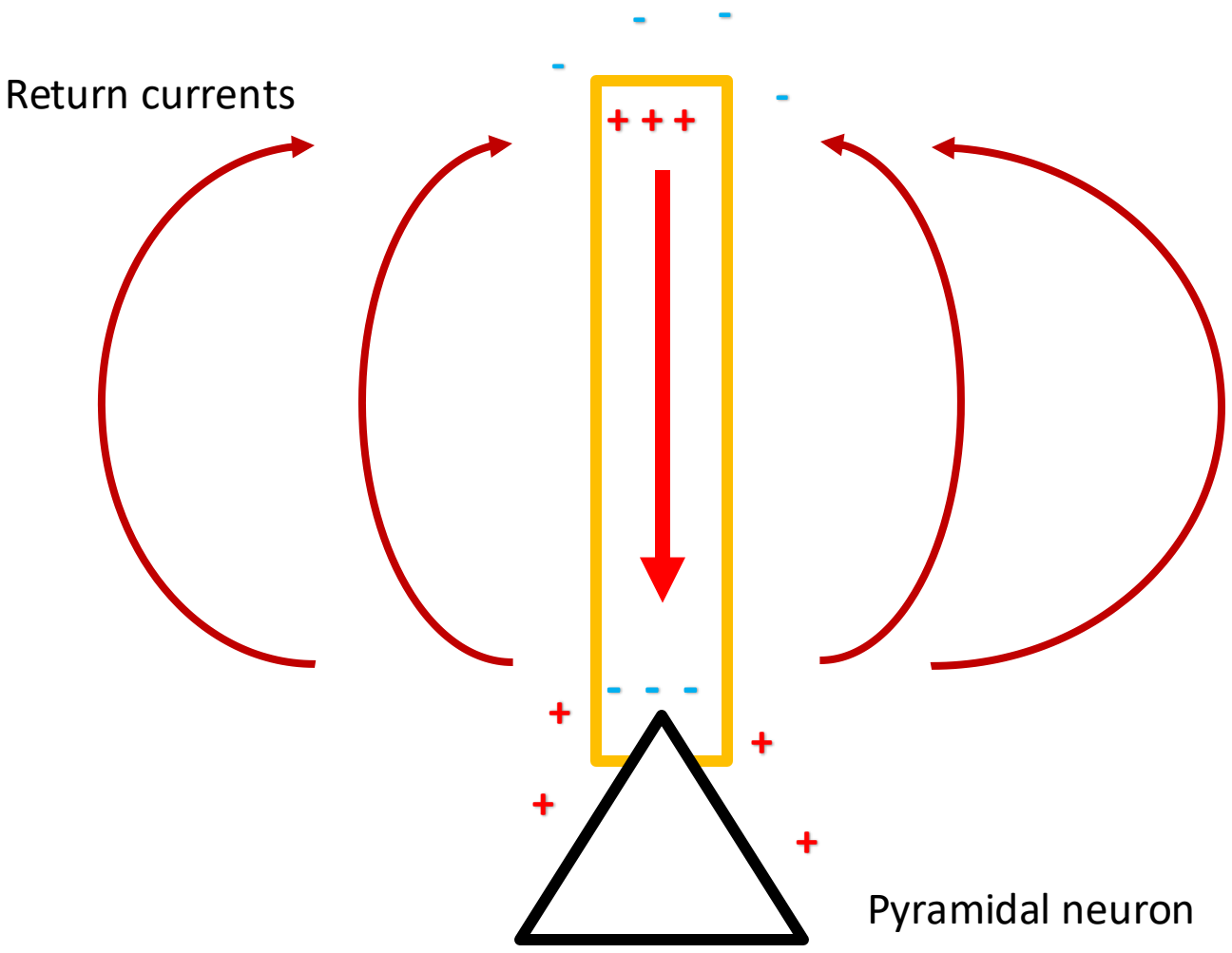




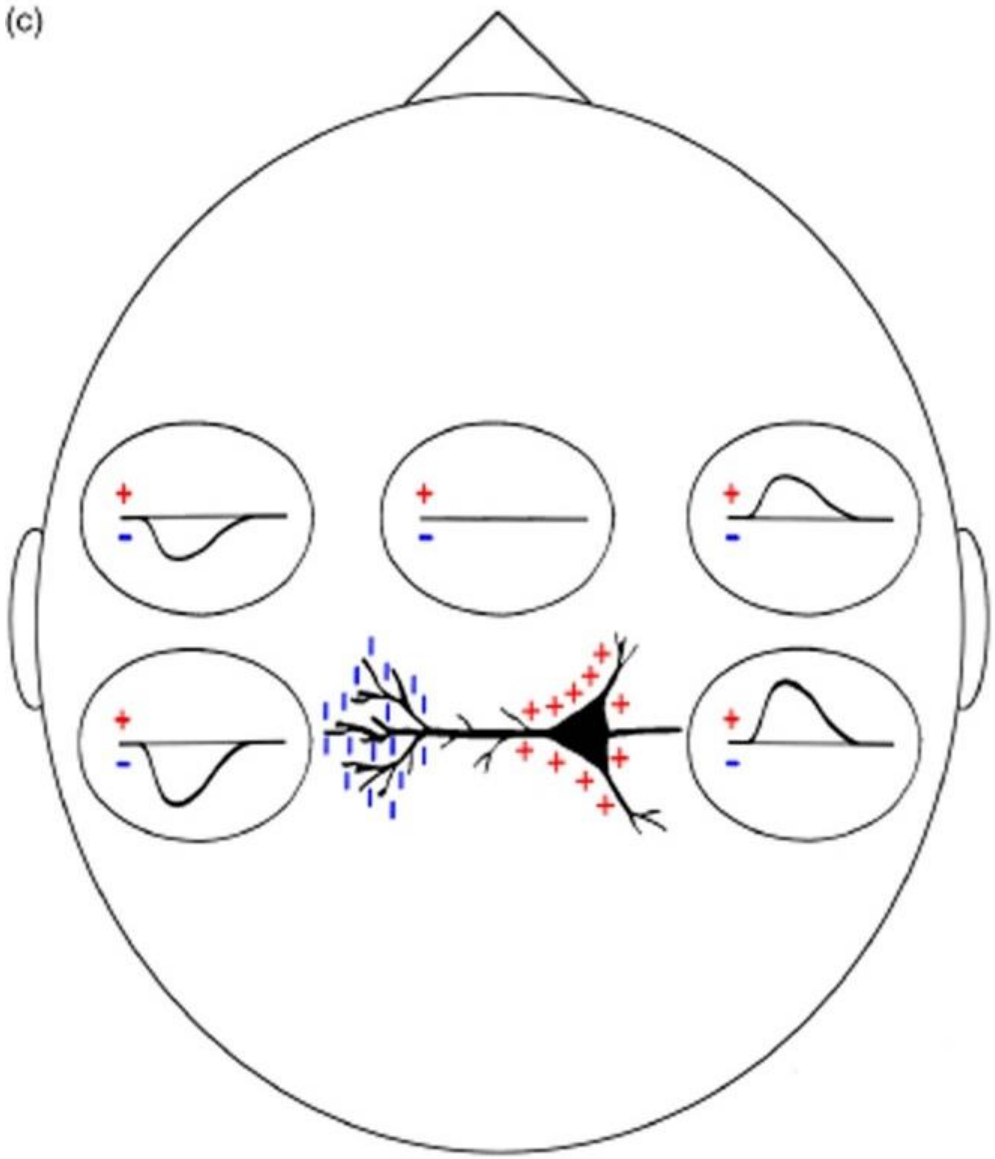
Purves (Neuroscience 6th Ed)

Jackson and Bolger (2014)

Extracellular currents

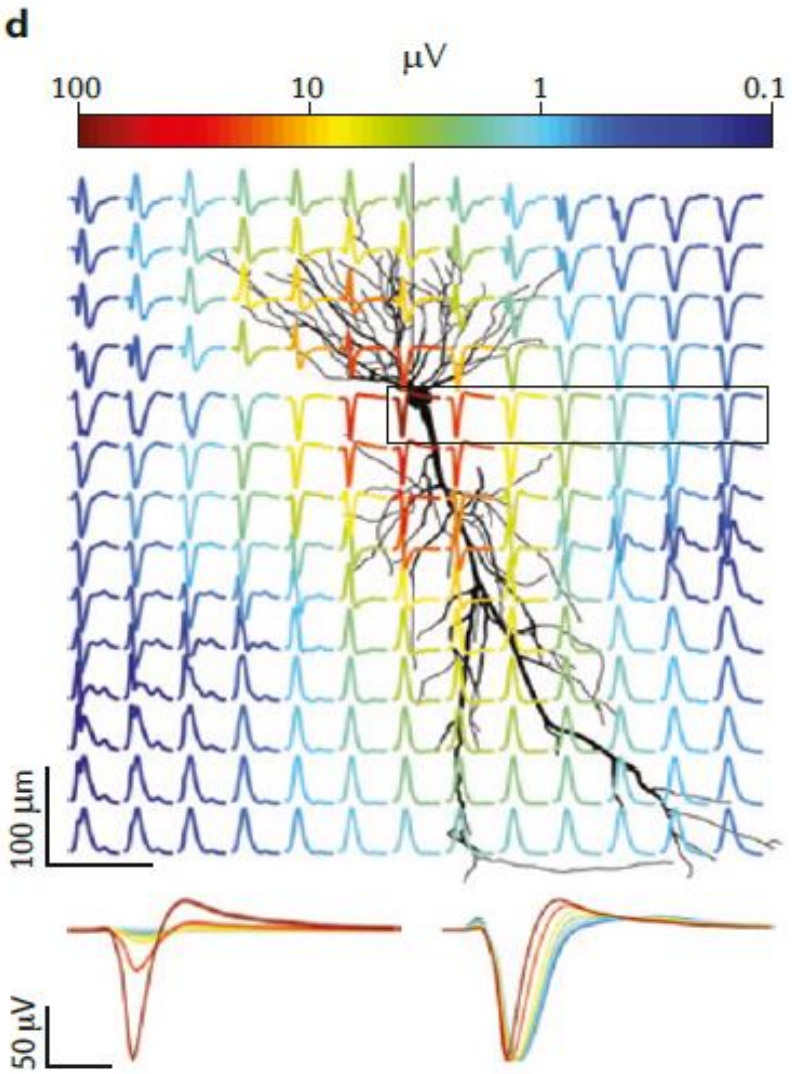


Extracellular currents



Jackson and Bolger (2014)

Extracellular currents



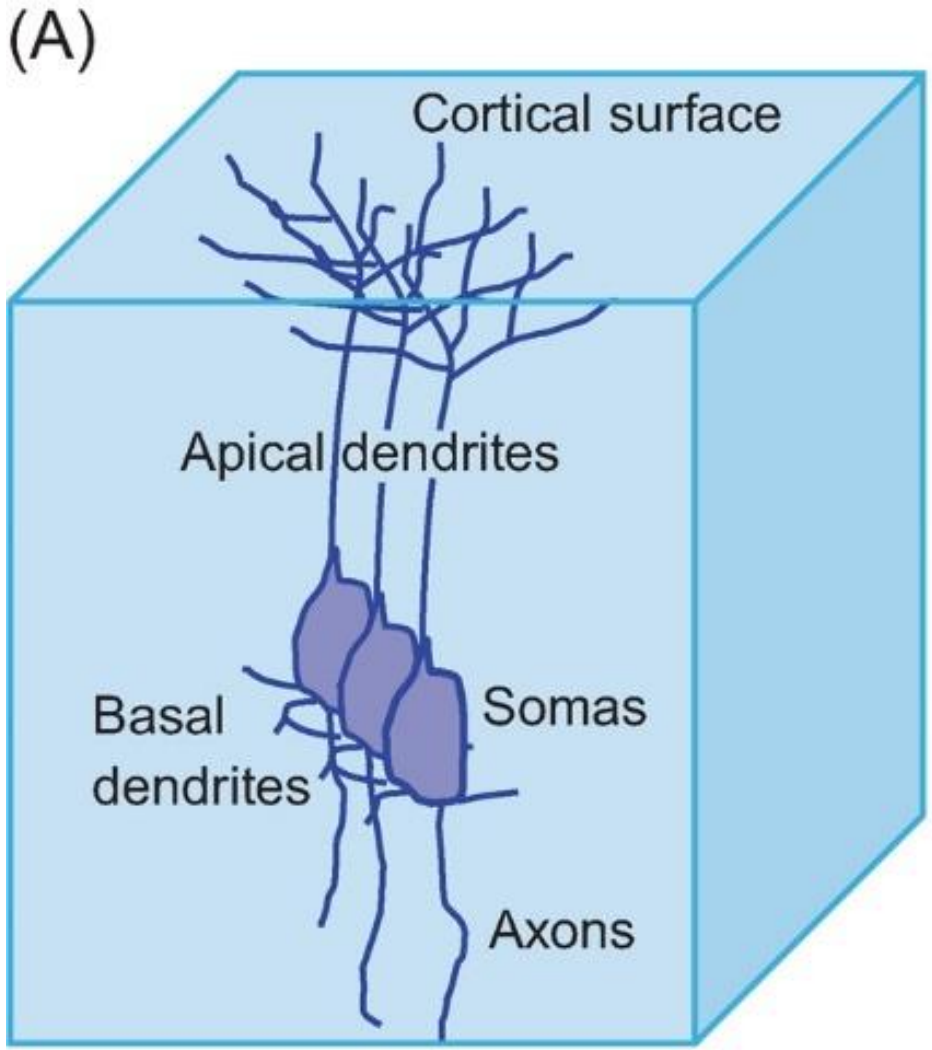
Buzsáki et al. (2012)

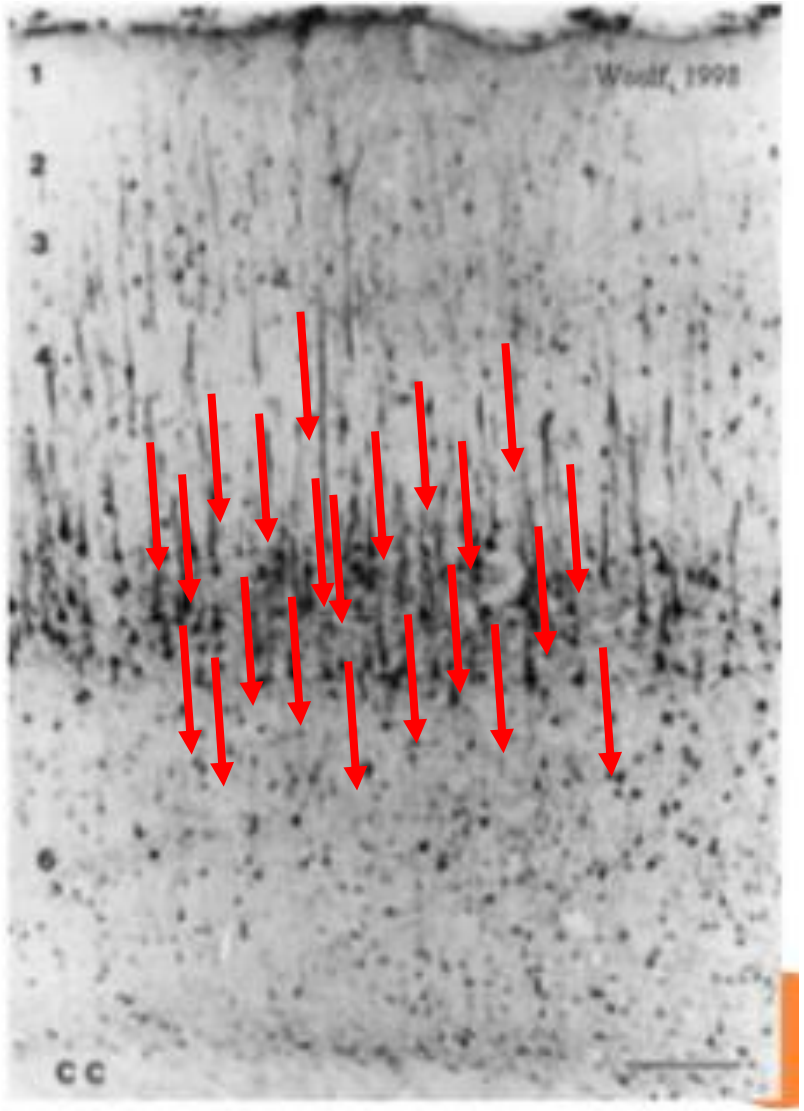
Interm summary

- Electric fields generated by the bioelectric properties of neurons
- Temporal dynamics in the form of AP and PSP
- Extracellular fields
- The electric fields decay rapidly over spatial distance

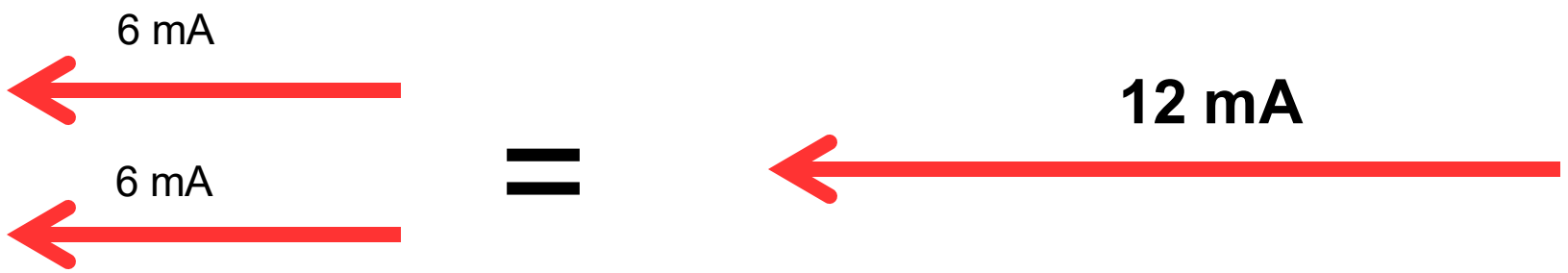
The equivalent current dipole (ECD)

Summation of currents in the head

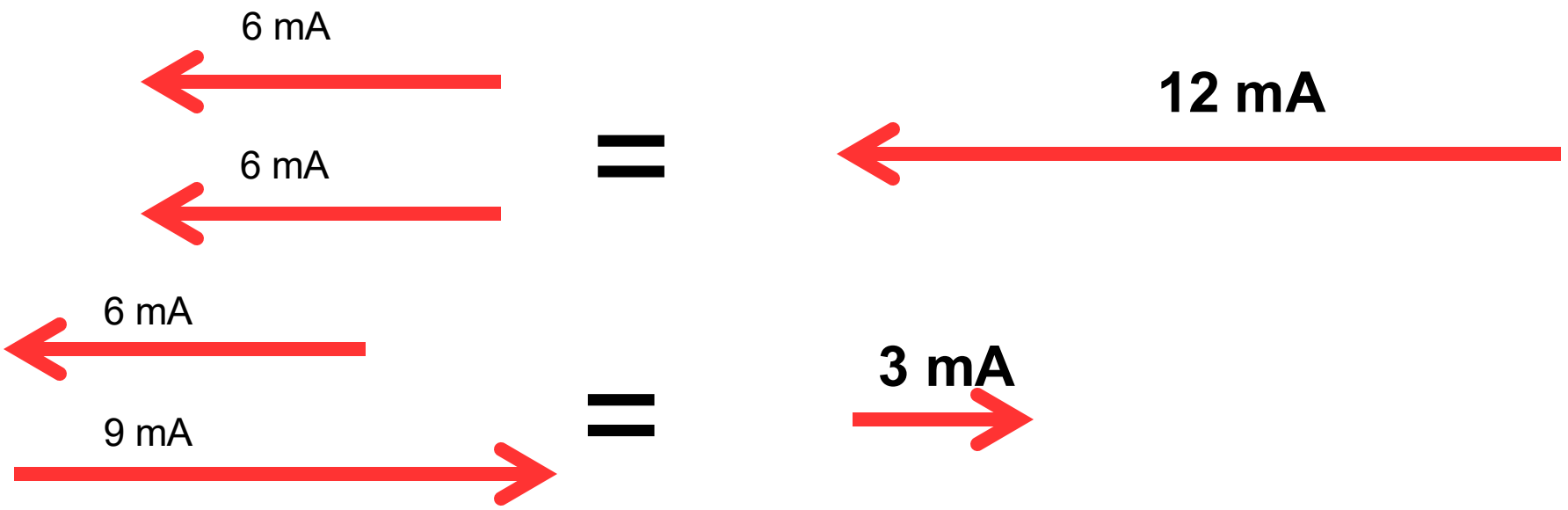

(A)
Cortical surface
Apical dendrites
Basal dendrites
Somas
Axons


Woolf, 1998
1
2
3
6
cc

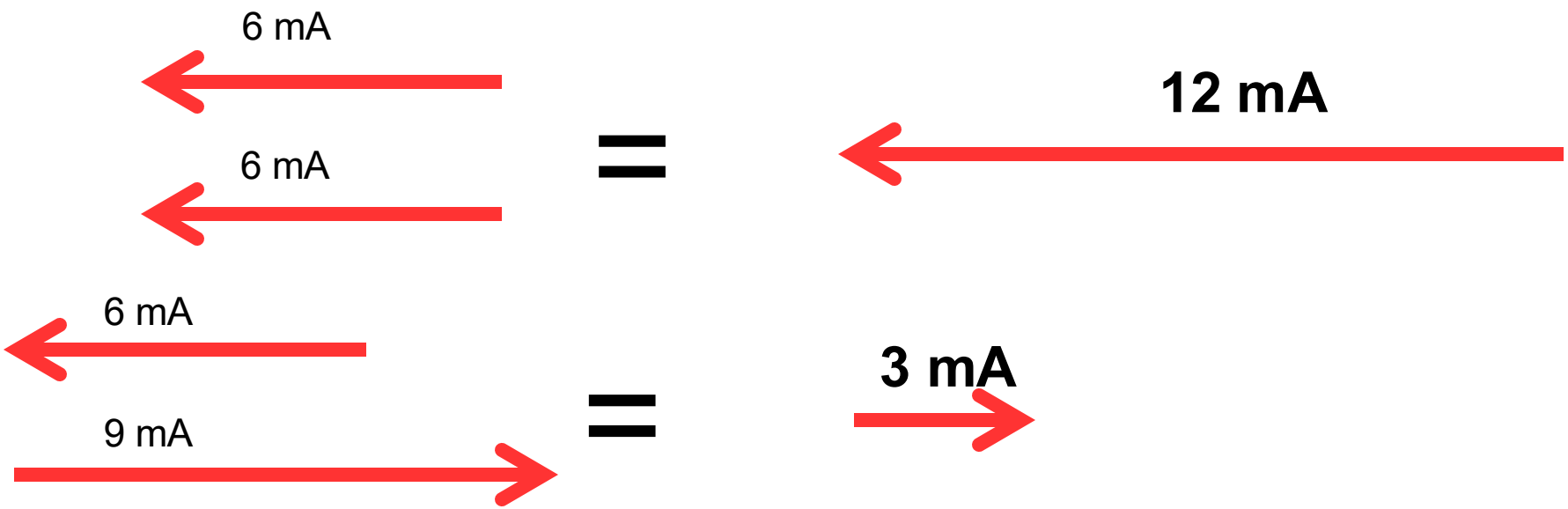
Summation of currents

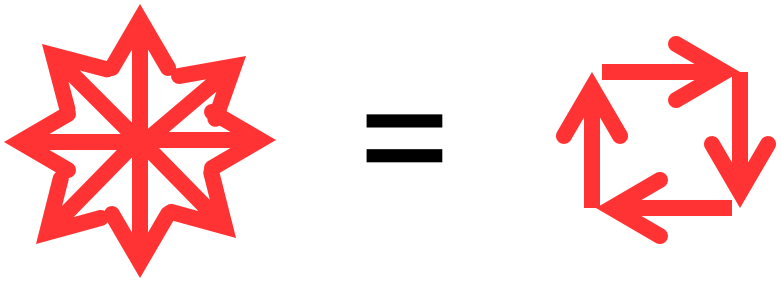


Summation of currents



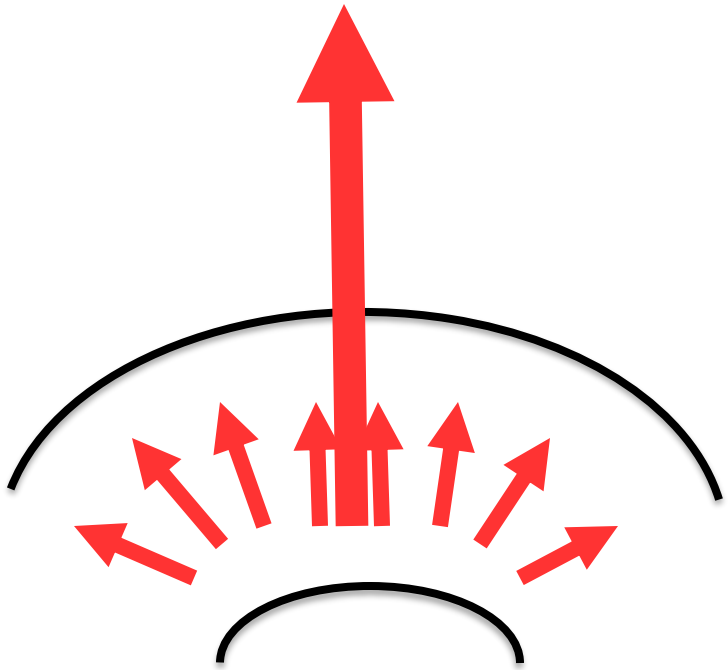
Summation of currents

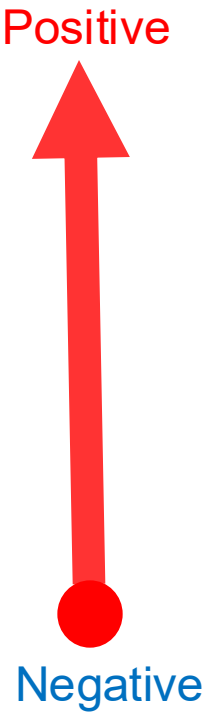




= = 0 mA

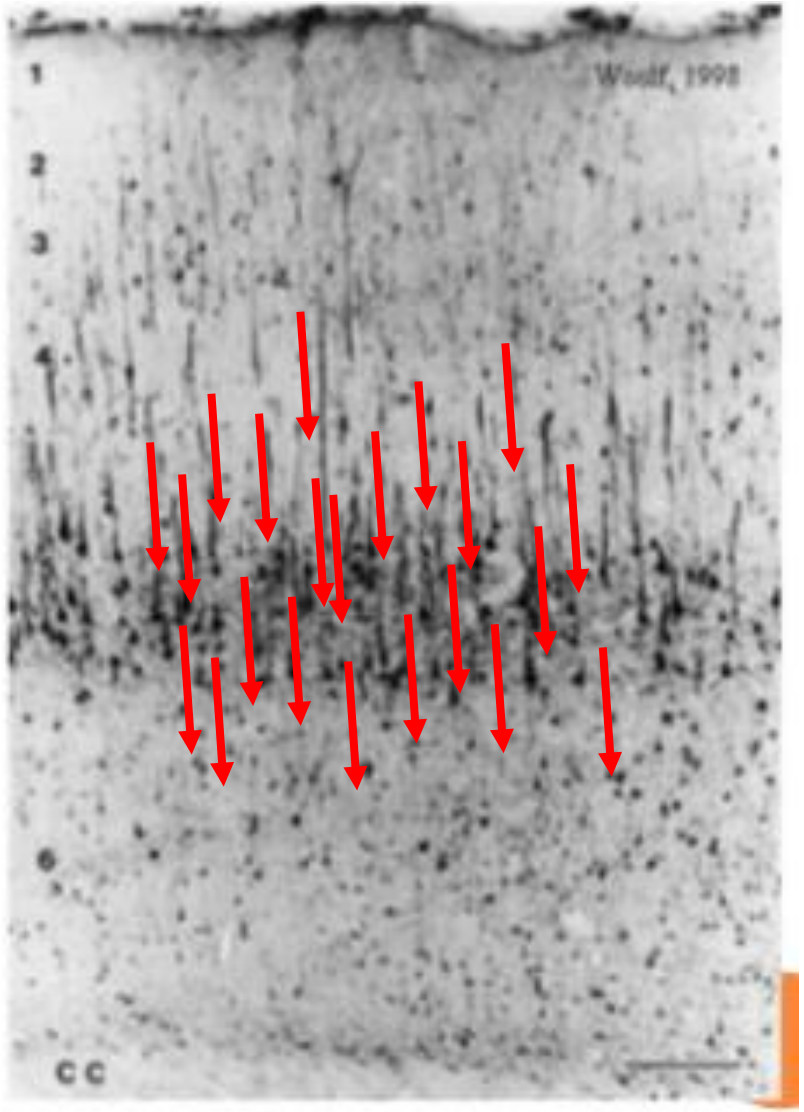
Spatial summation





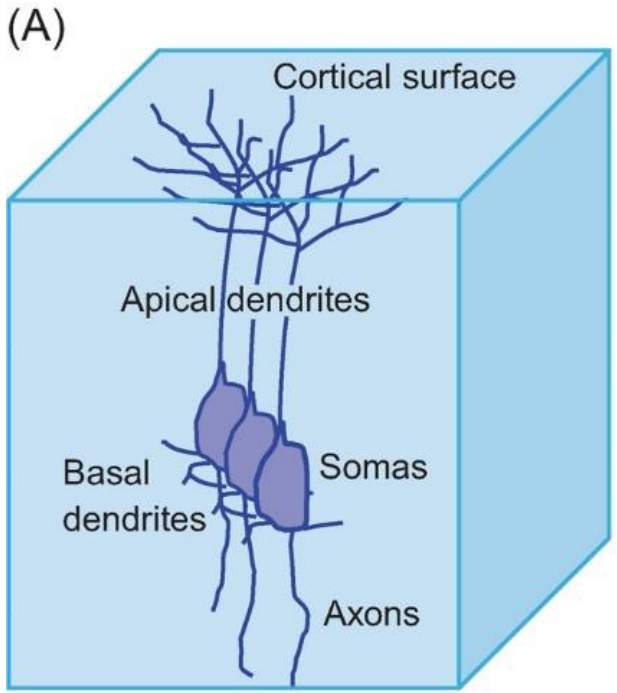
Spatial summation of currents

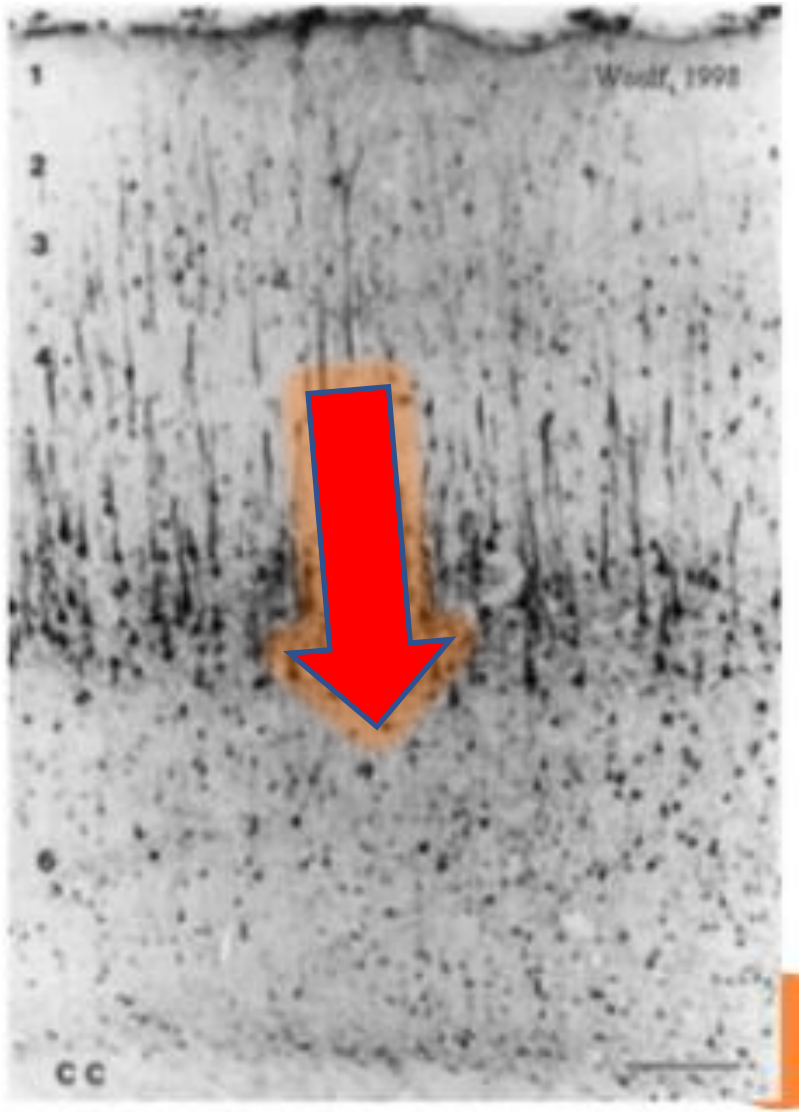
The ordering of the pyramidal neurons creates good conditions for seeing the summation of post-synaptic potential, but not the action potentials



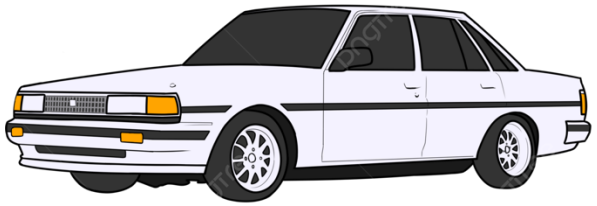
Spatial summation of currents

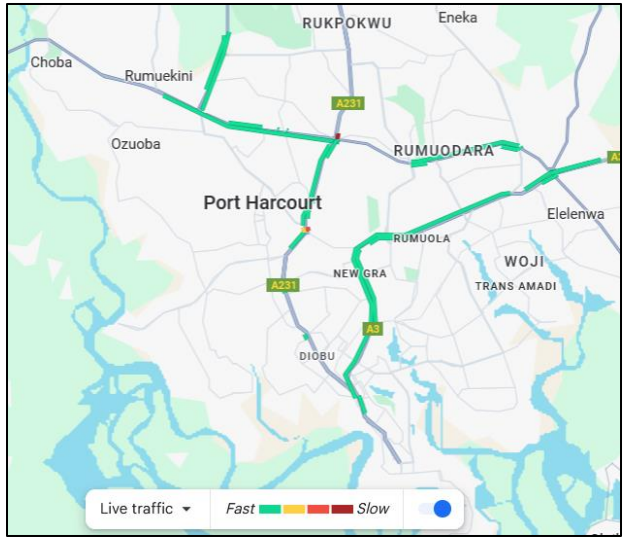
The ordering of the pyramidal neurons creates good conditions for seeing the summation of post-synaptic potential, but not the action potentials

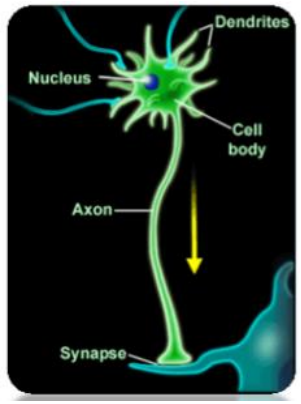


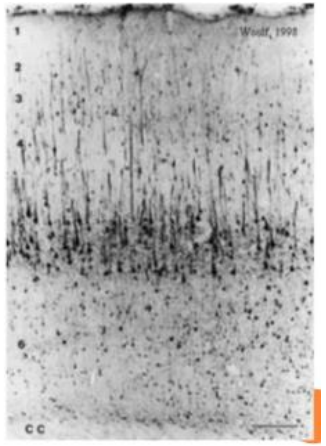


A matter of scale

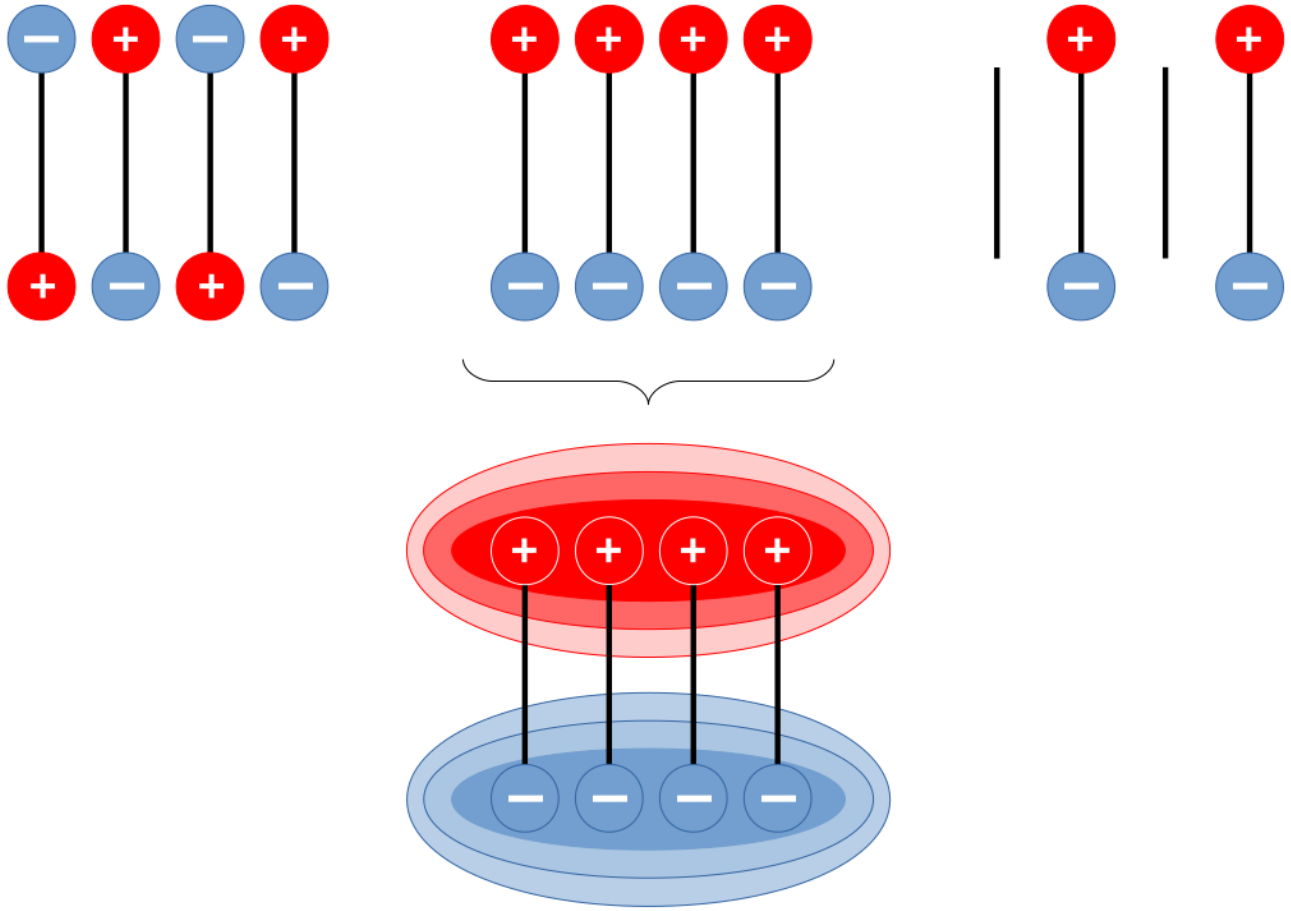




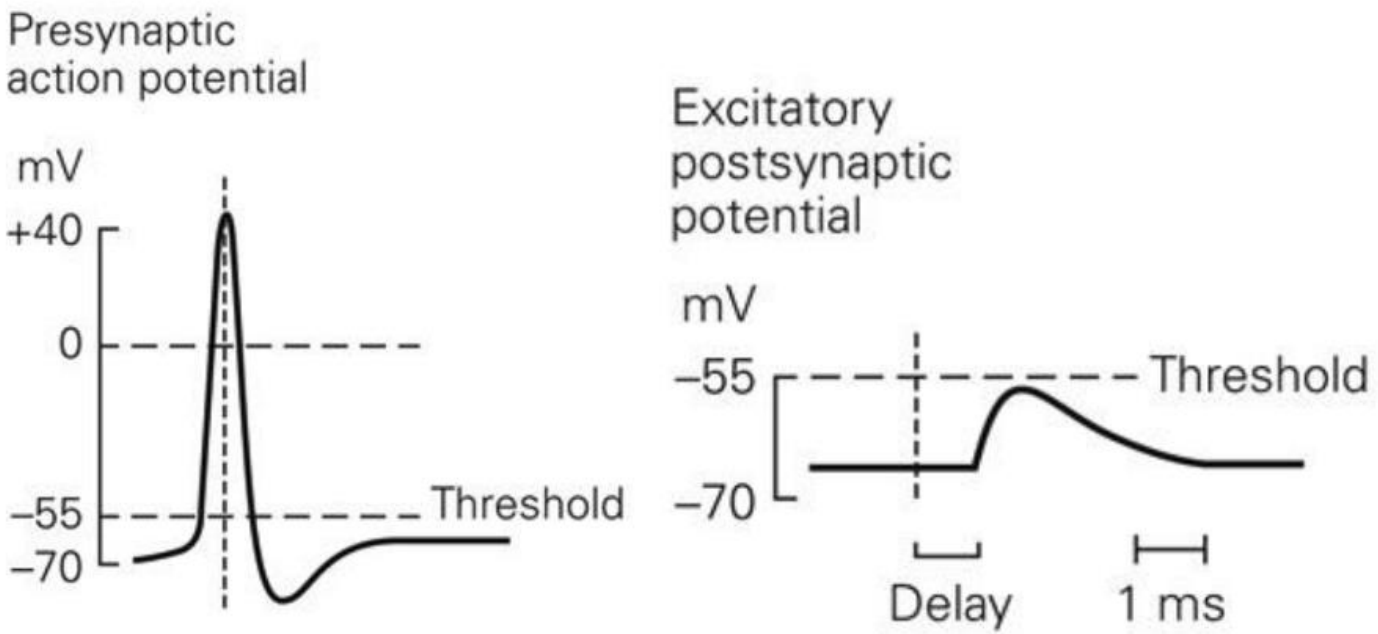




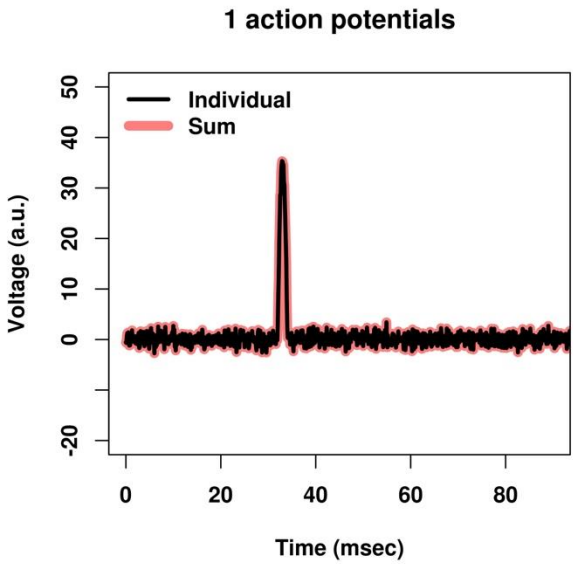
Temporal summation

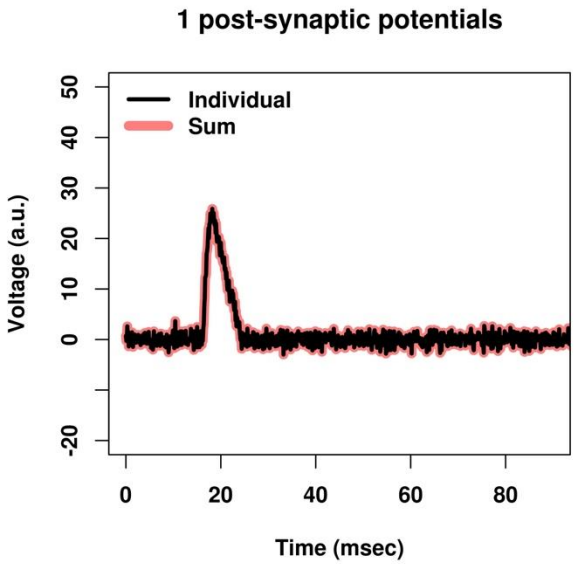


TEMPORAL Summation of currents



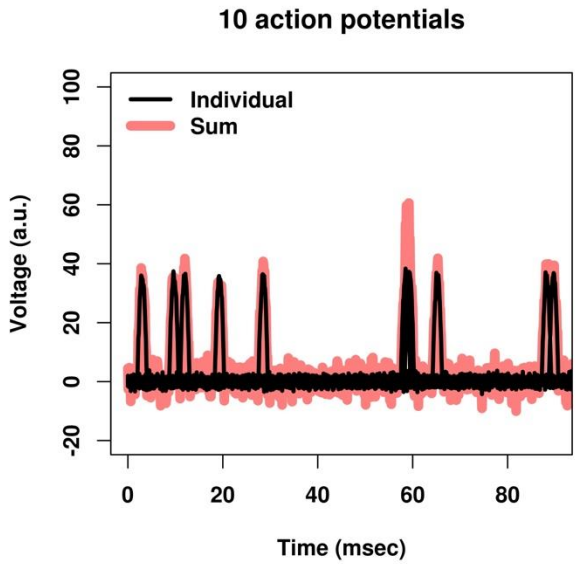
TEMPORAL Summation of currents

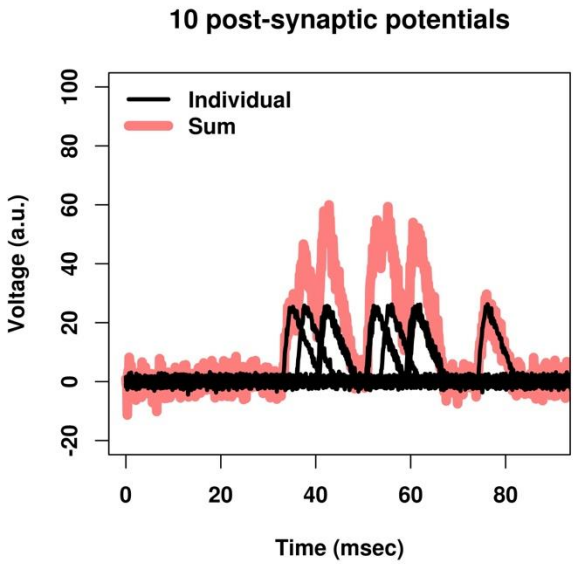




Simulation coutesy of L.M. Andersen

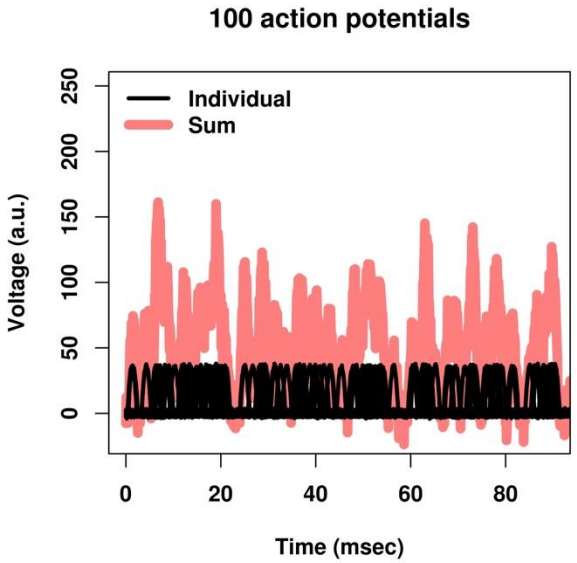
TEMPORAL Summation of currents

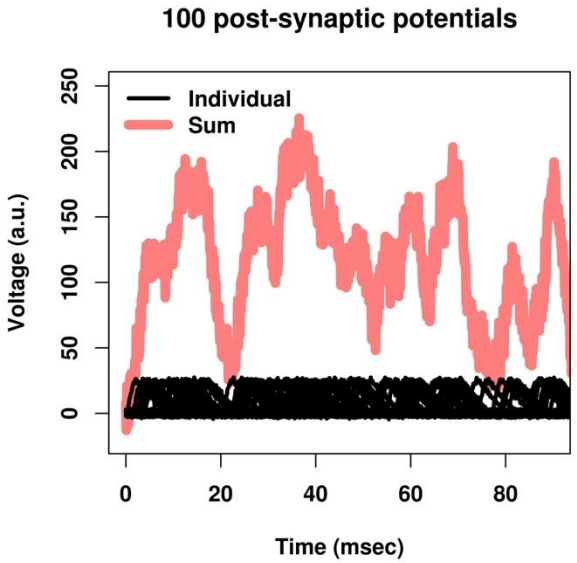




Simulation coutesy of L.M. Andersen

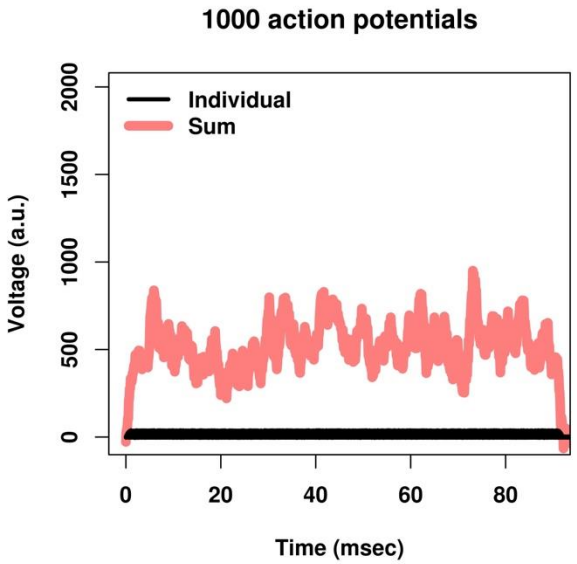
TEMPORAL Summation of currents

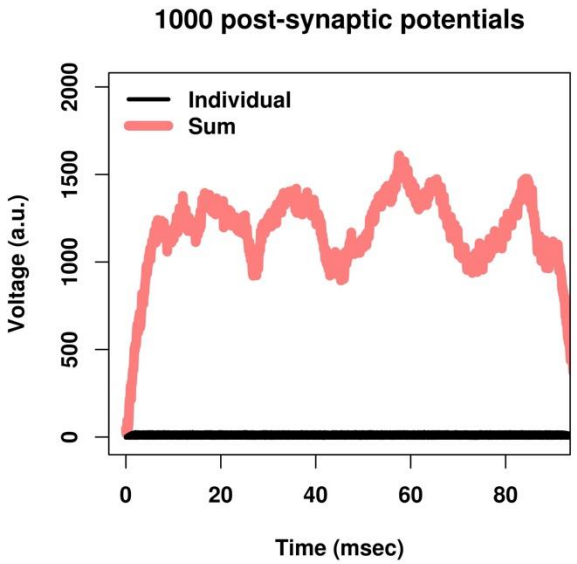




Simulation coutesy of L.M. Andersen

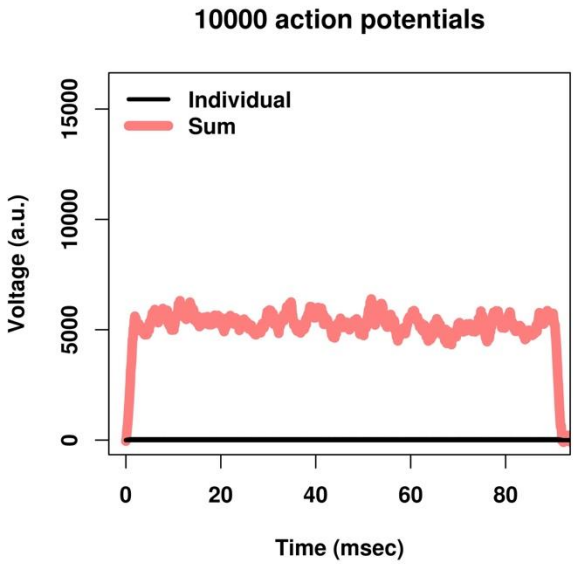
TEMPORAL Summation of currents

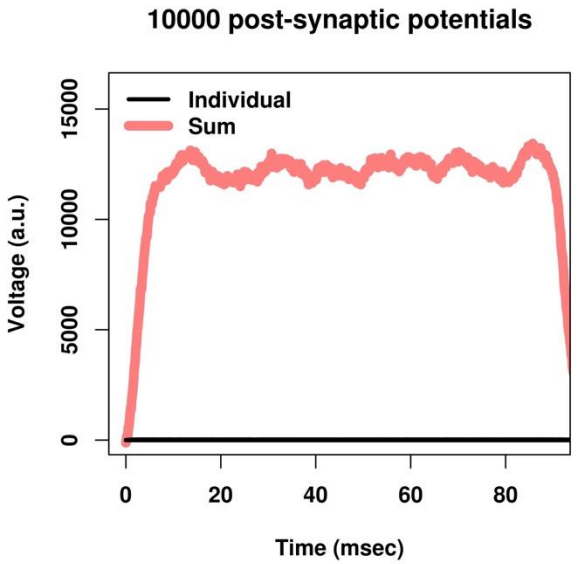




Simulation coutesy of L.M. Andersen

TEMPORAL Summation of currents



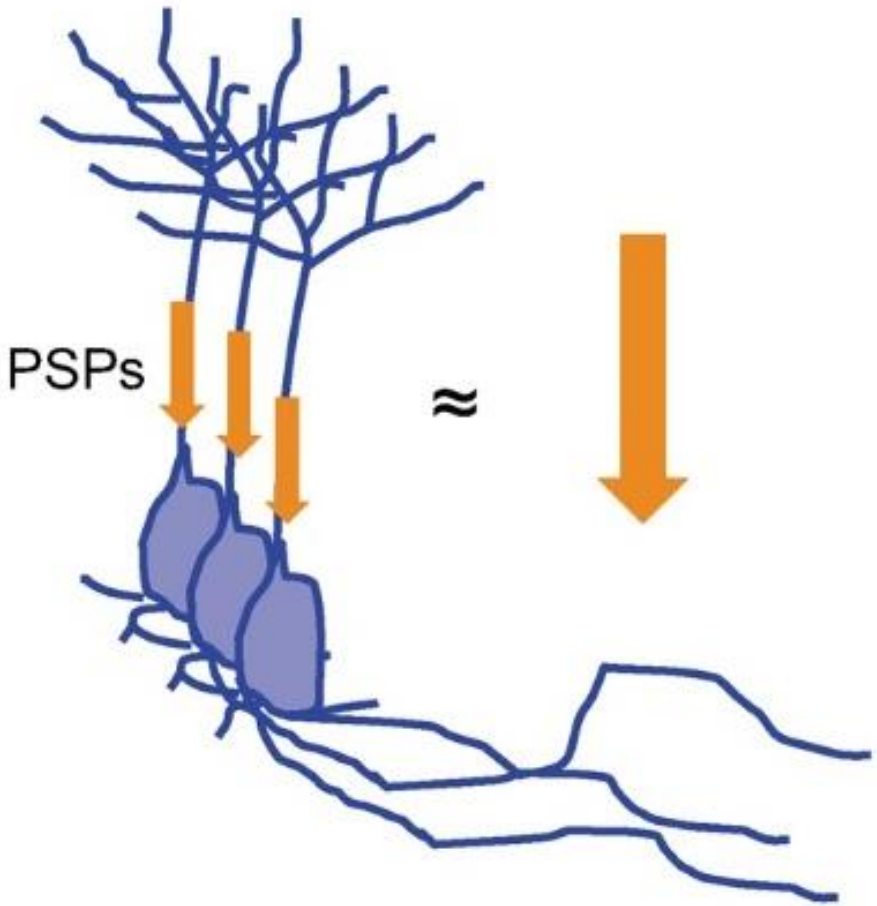


Simulation coutesy of L.M. Andersen

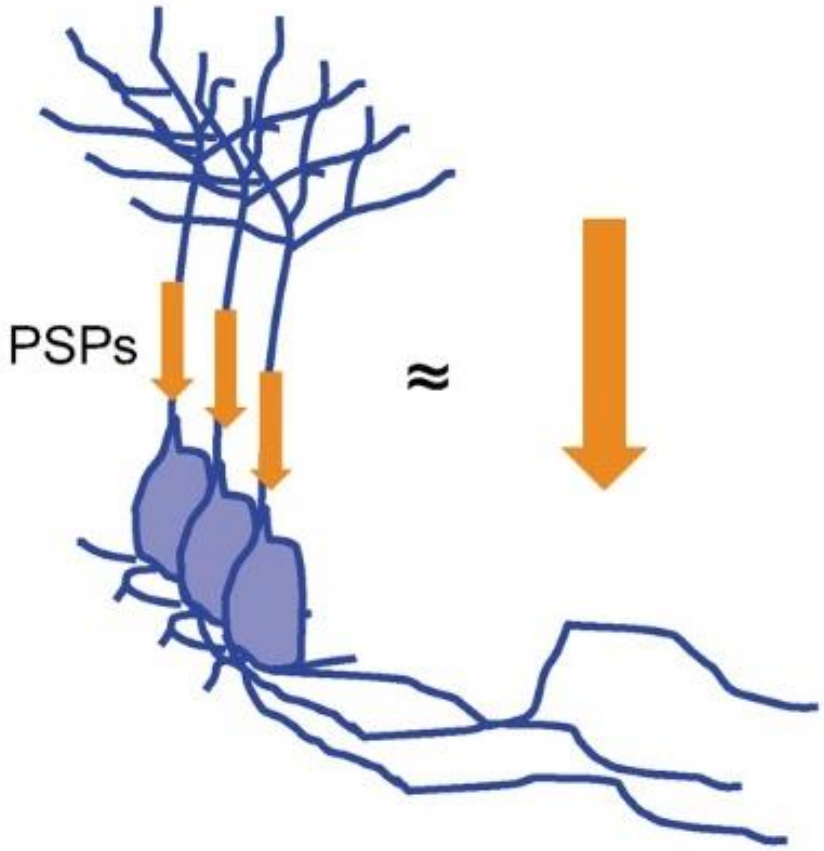
What can we measure outside the head?

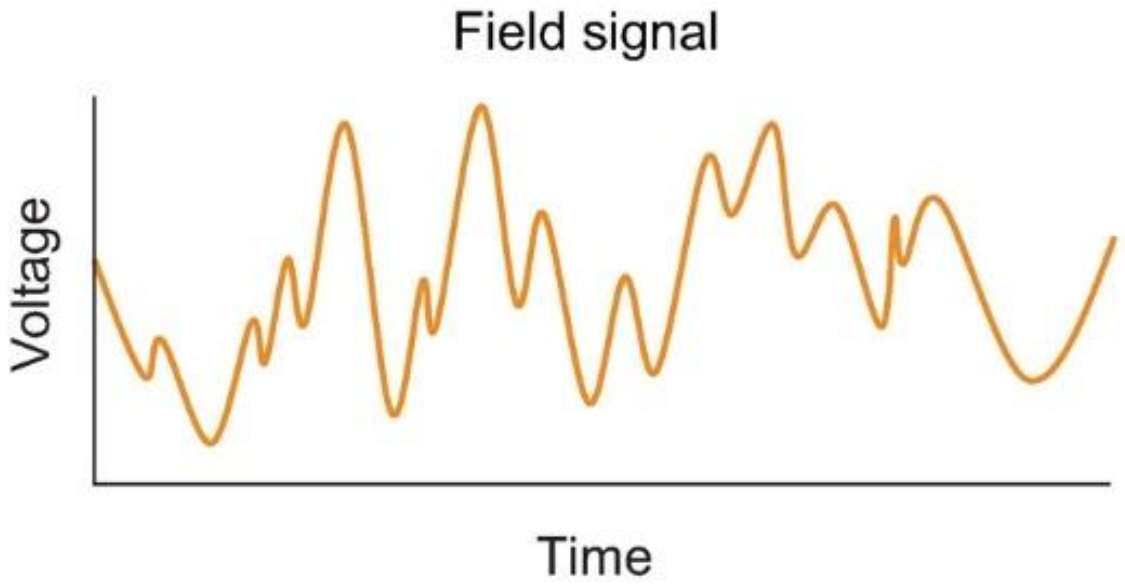
Single neurons can only be seen with *intracranial recordings*, but generate signals many orders too weak to be seen outside the head

We measure the **SPATIAL and TEMPORAL summations** if there are “many” neurons firing at the same time?

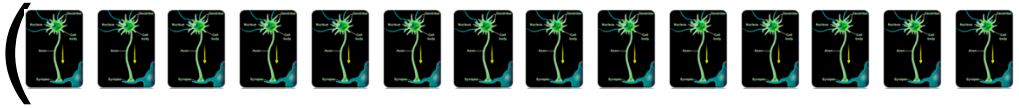


What can we measure outside the head?

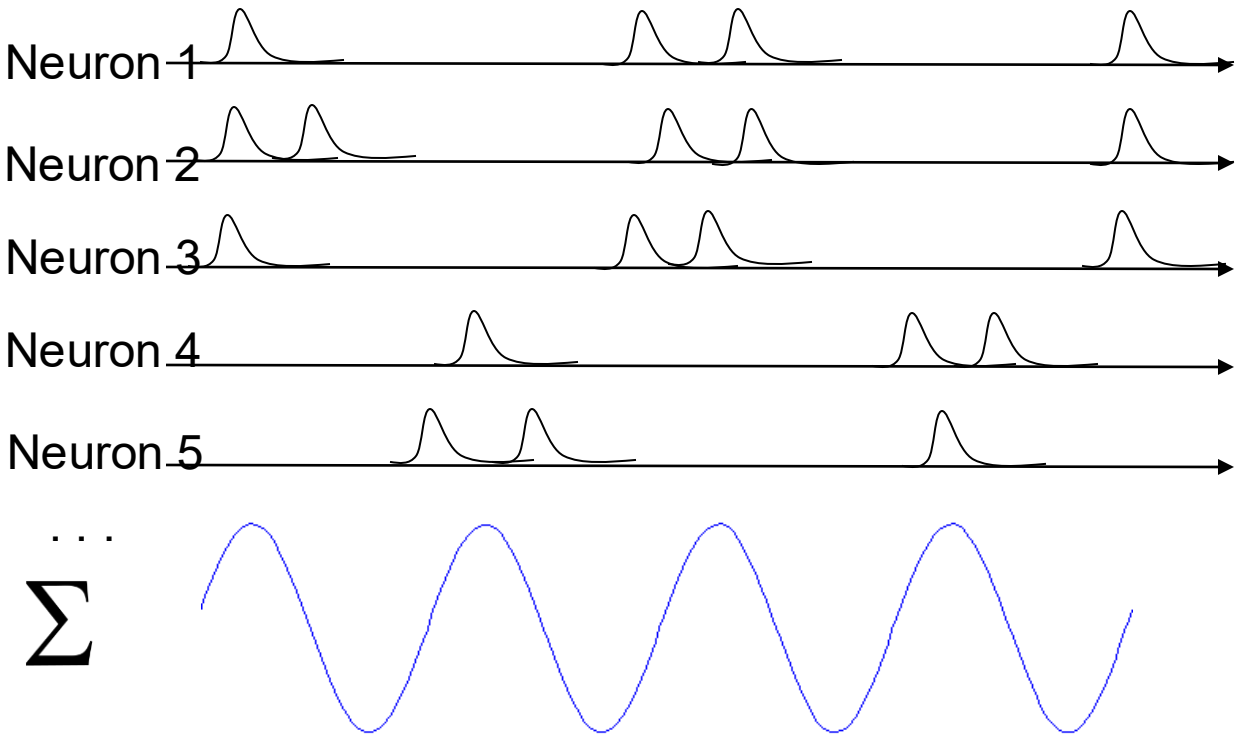


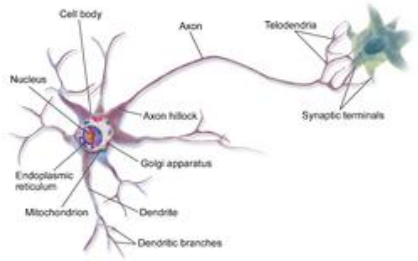


What are the single neurons doing?

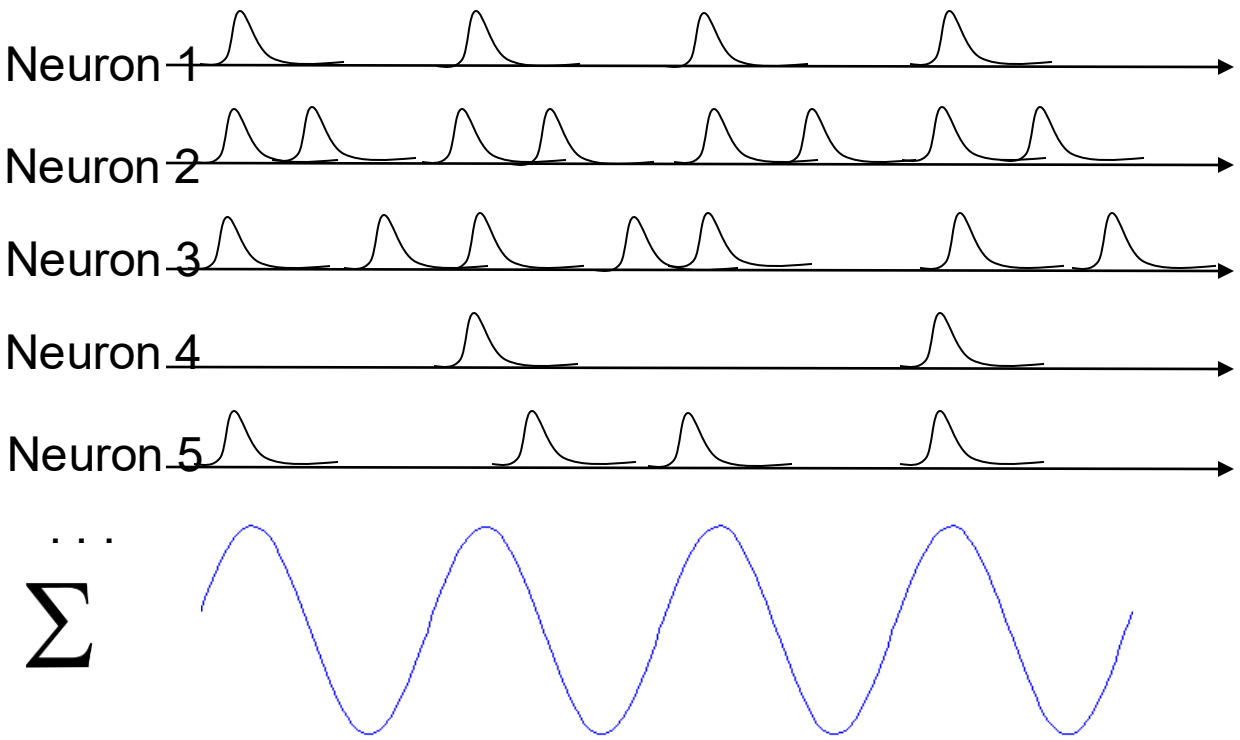
Σ( …)

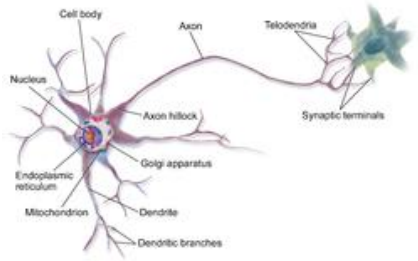
What are the single neurons doing?



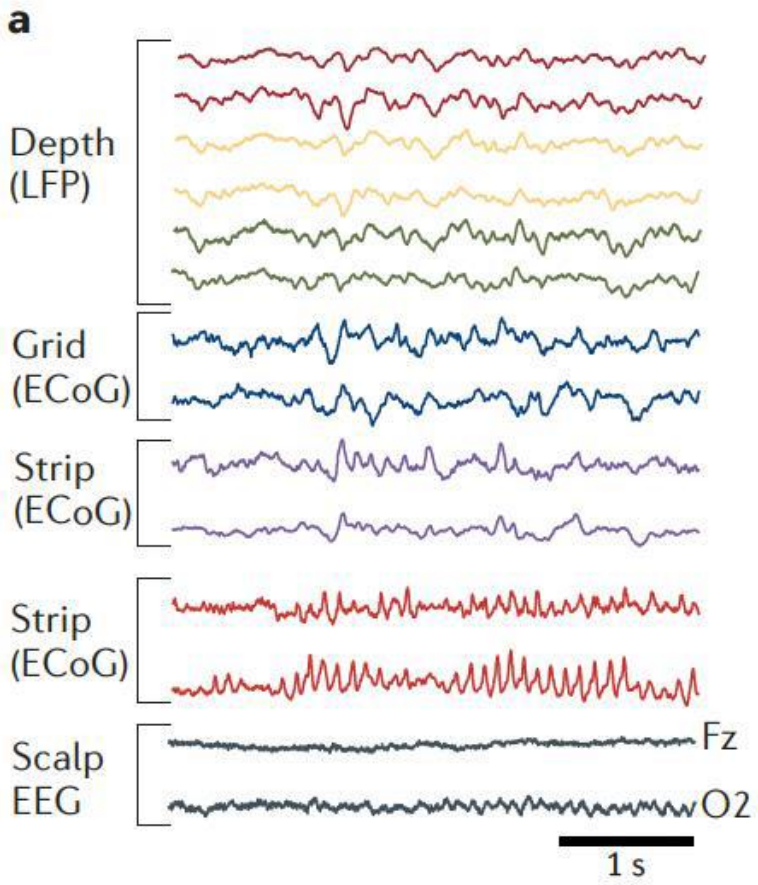


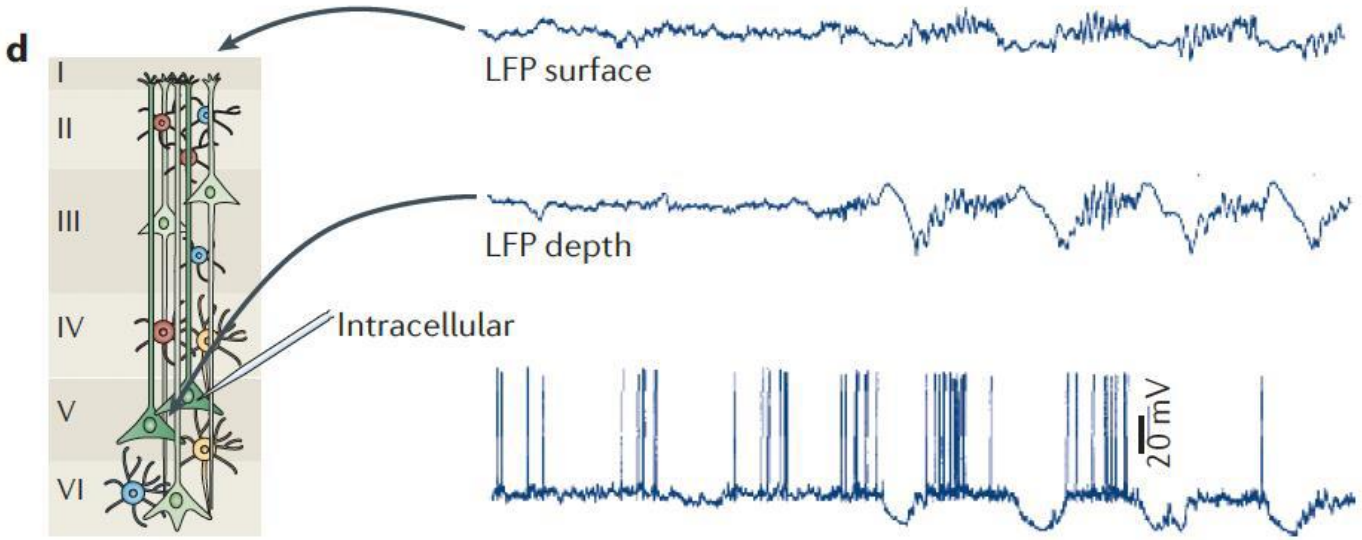
What are the single neurons doing?



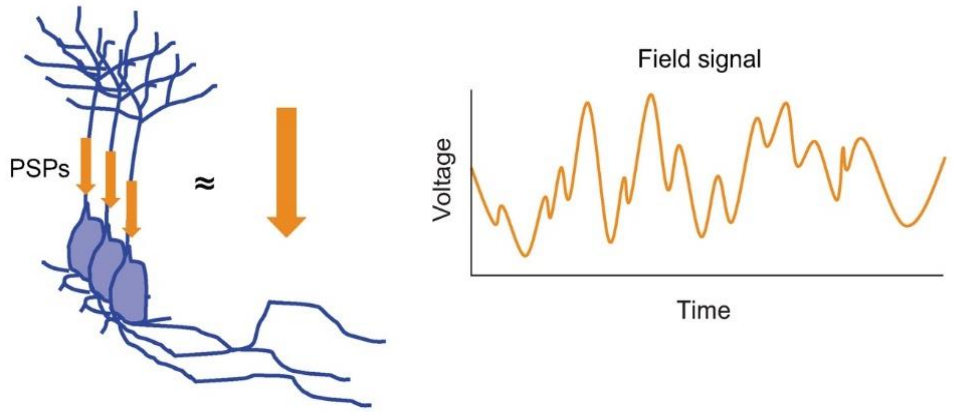


How can cellular electrical captivity be recorded?

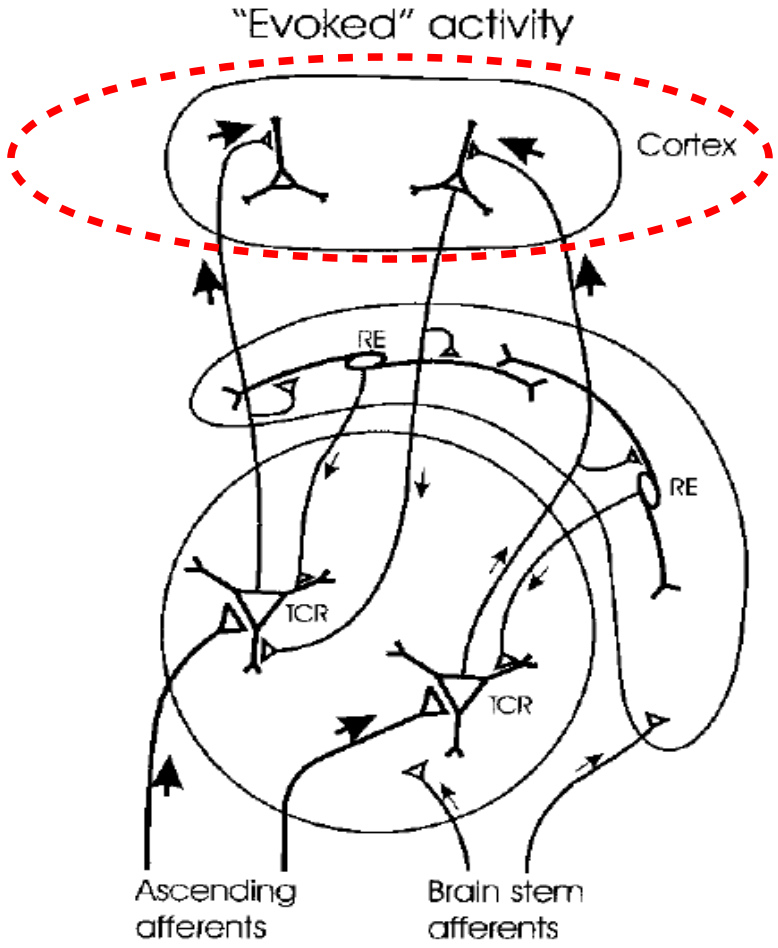




Summary: What we measure (and what we don't)



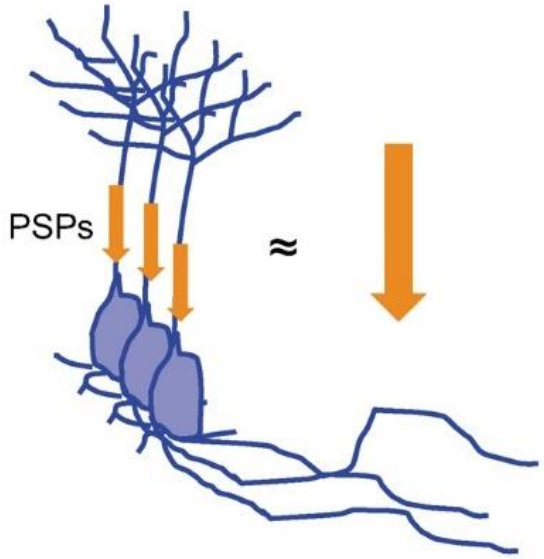
EEG measures the activity of populations of (primarily) pyramidal neurons in the cortex.

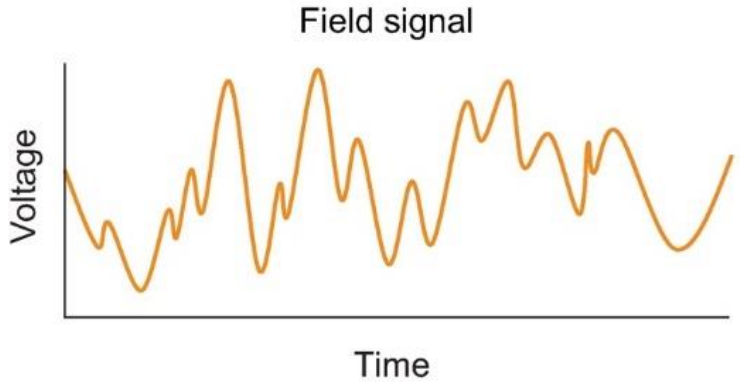


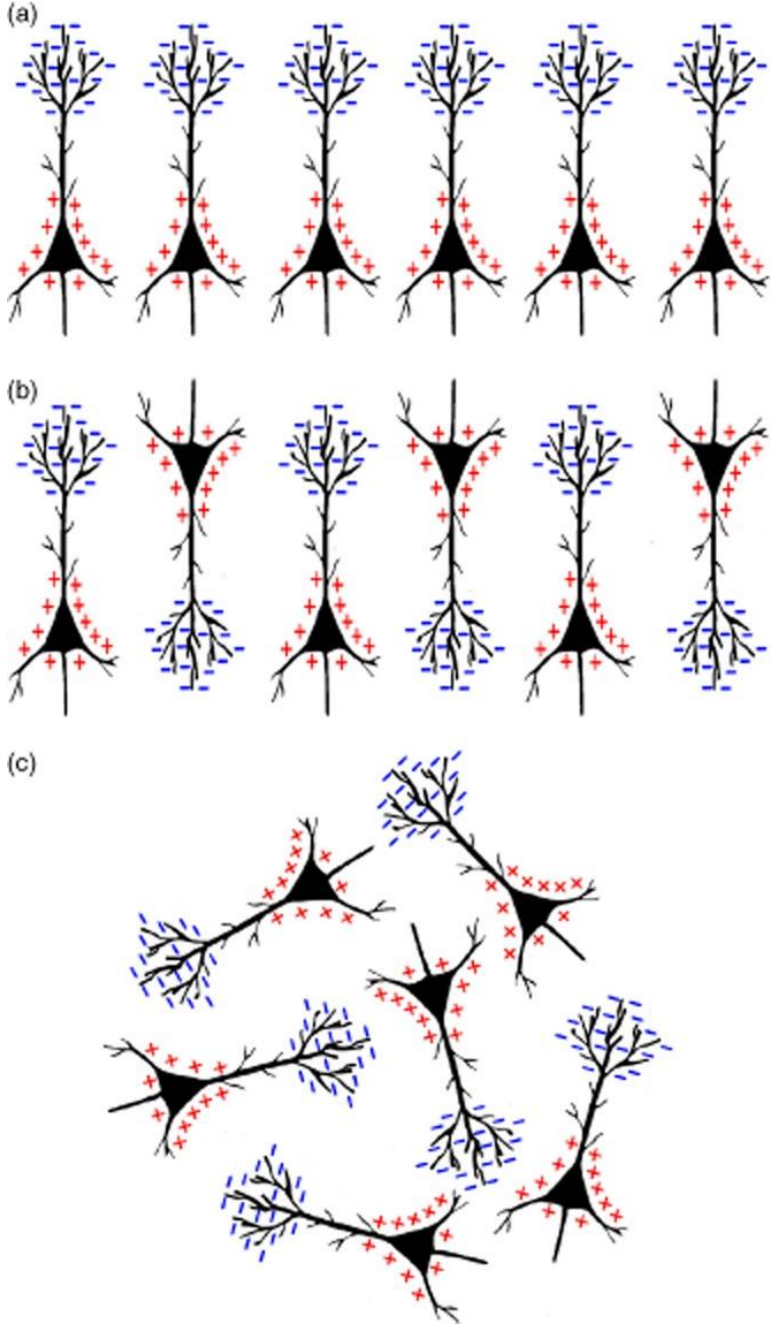
Pfurtscheller & Lopes da Silva (1999)

Discussion

Under what circumstances is the ECD a good approximation and under what circumstances is it not?







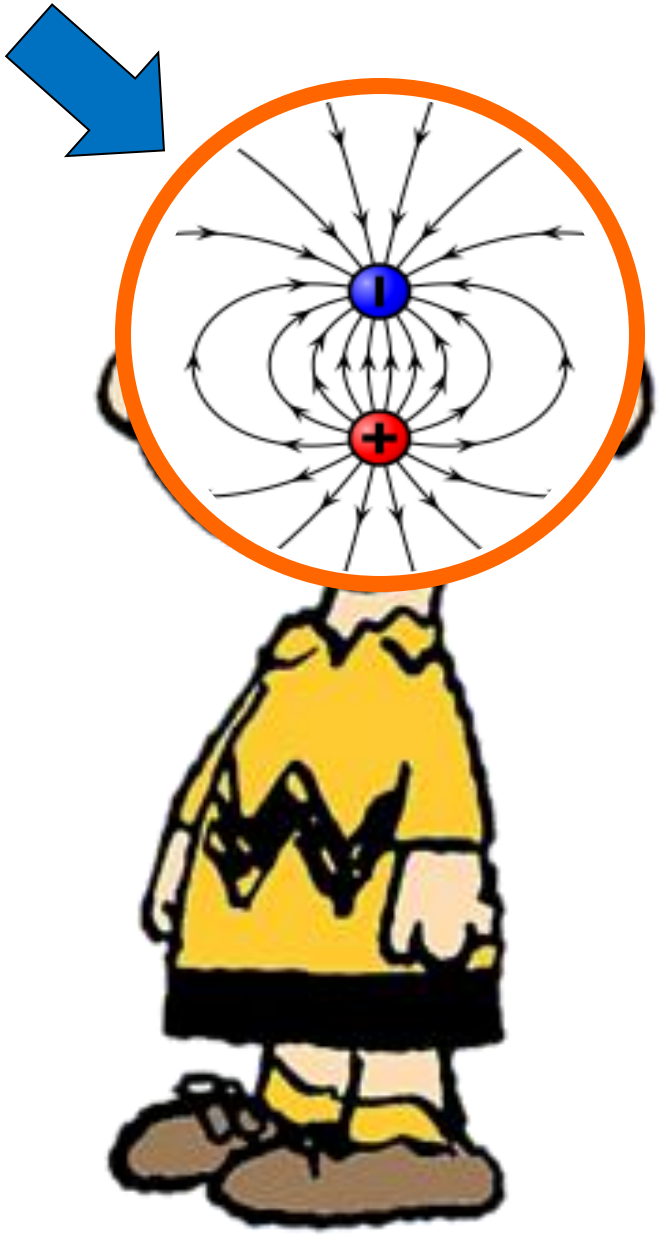
Jackson and Bolger (2014)

BIO-ELECTRIC FIELDS IN A VOLUME

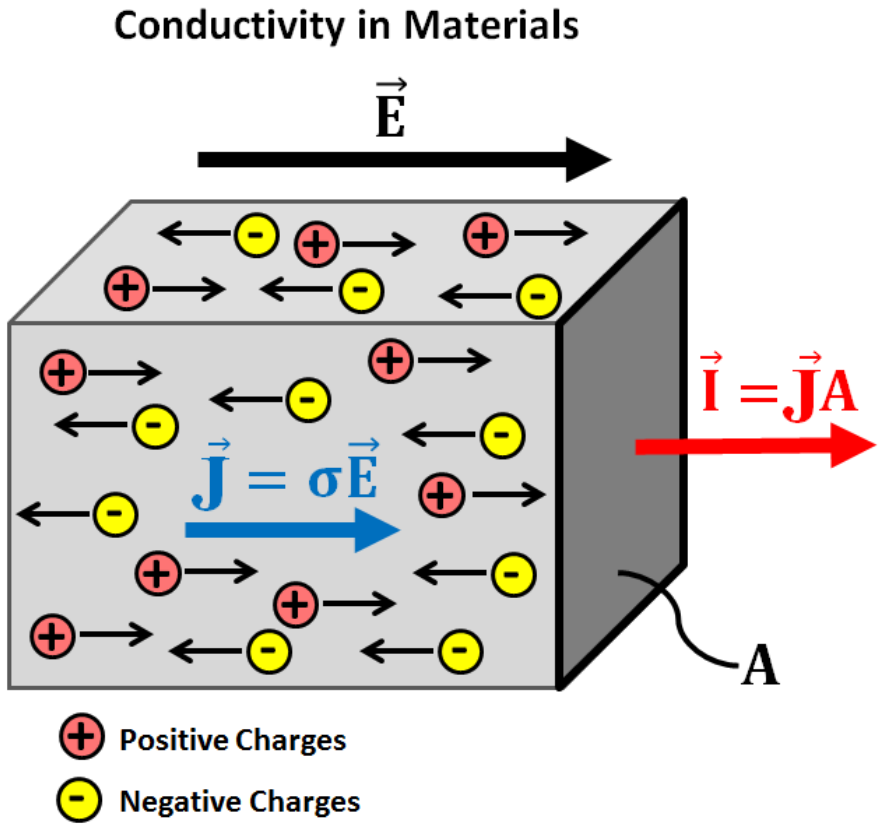
What we actually measure with EEG

Electric currents in a volume

EEG measures the <u>electric field at the scalp</u>

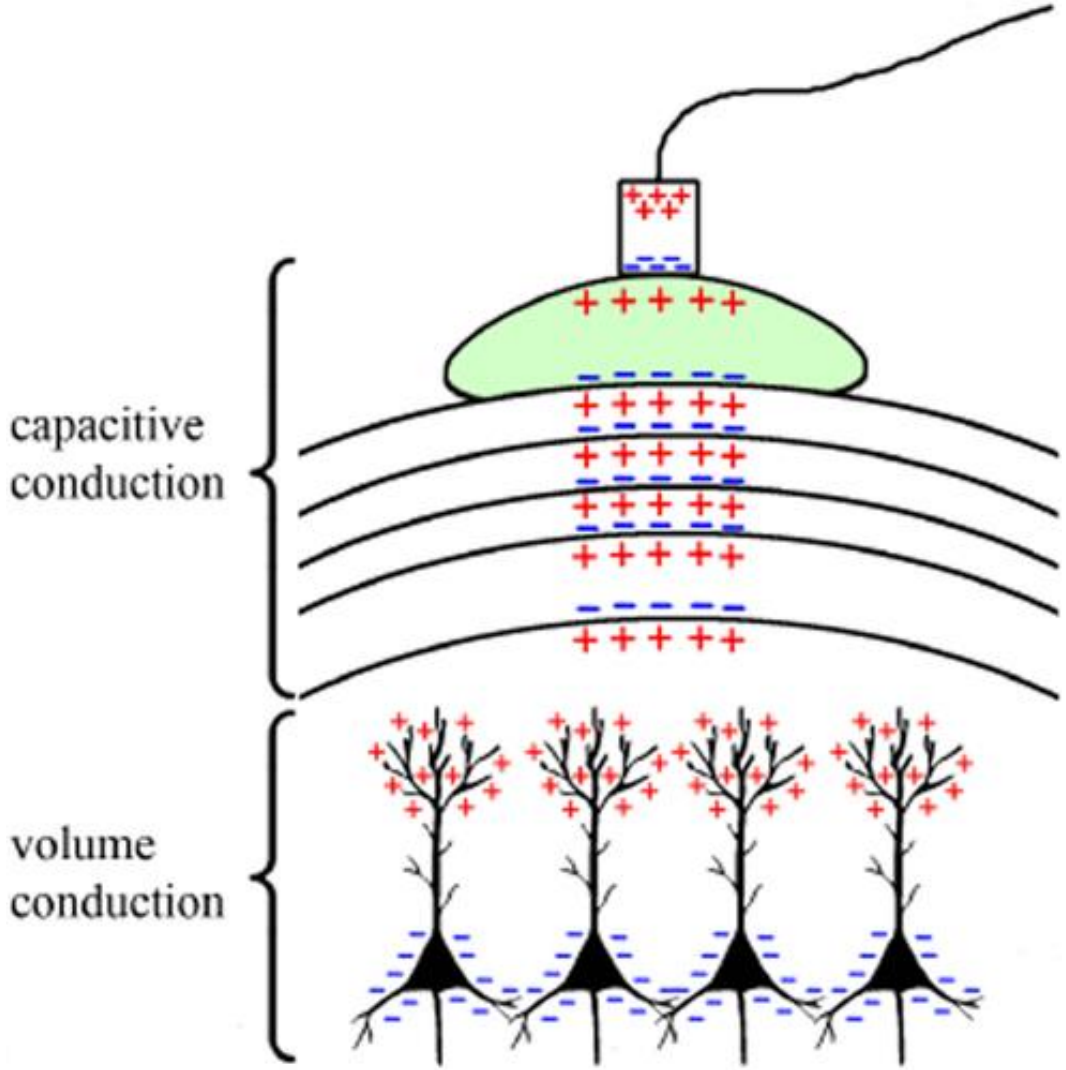


Electric currents in a volume



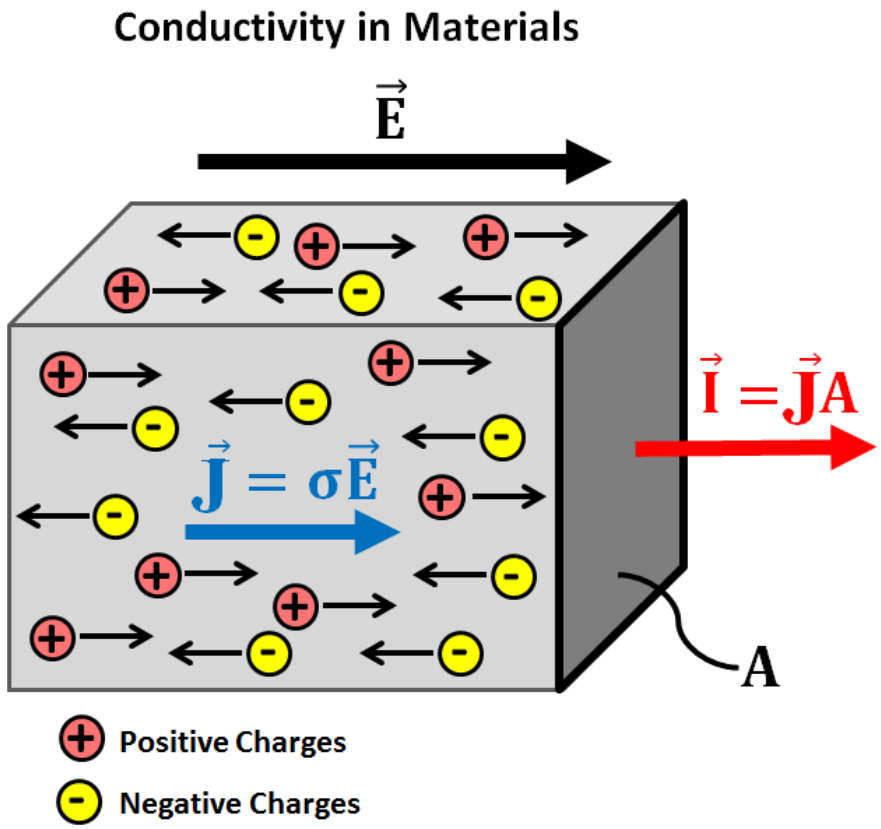
Resistivity

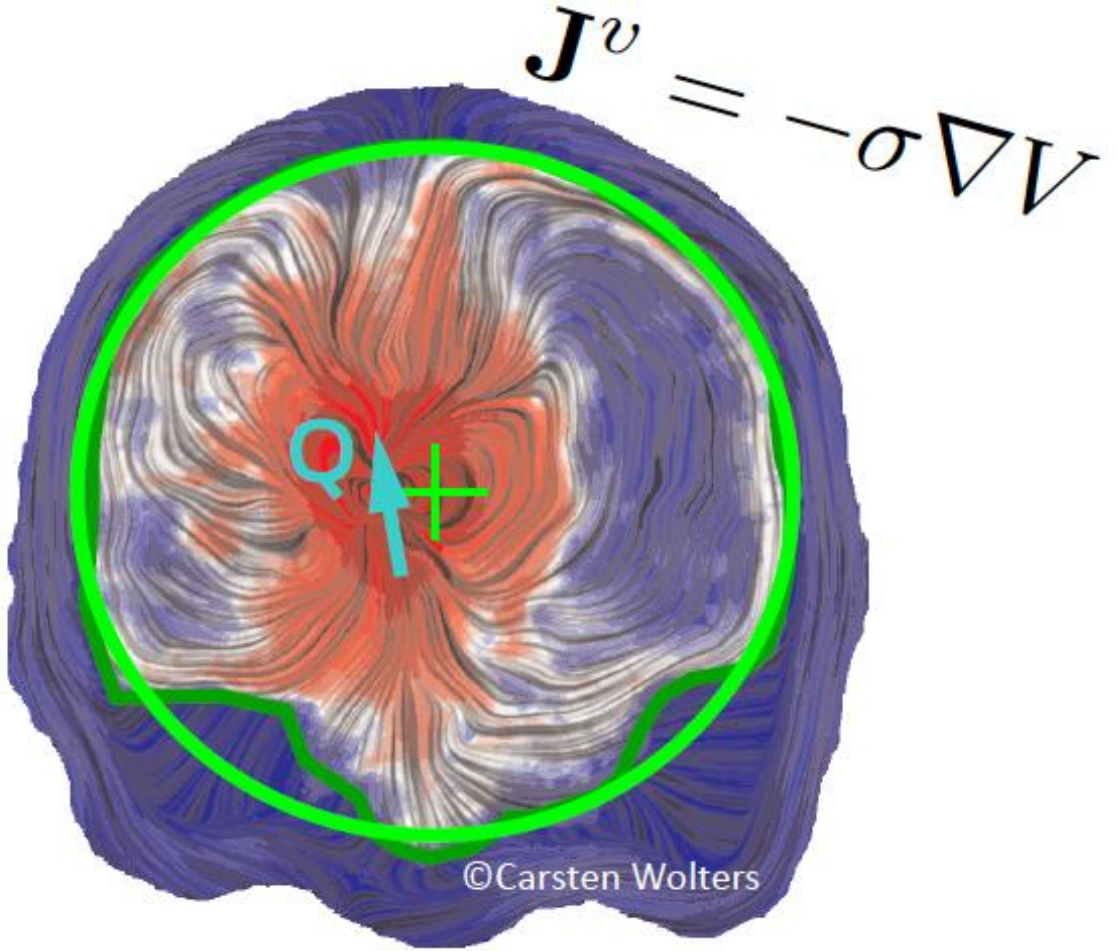
$$\rho = \frac{1}{\sigma}$$



Jackson and Bolger (2014)

Electric currents in a volume

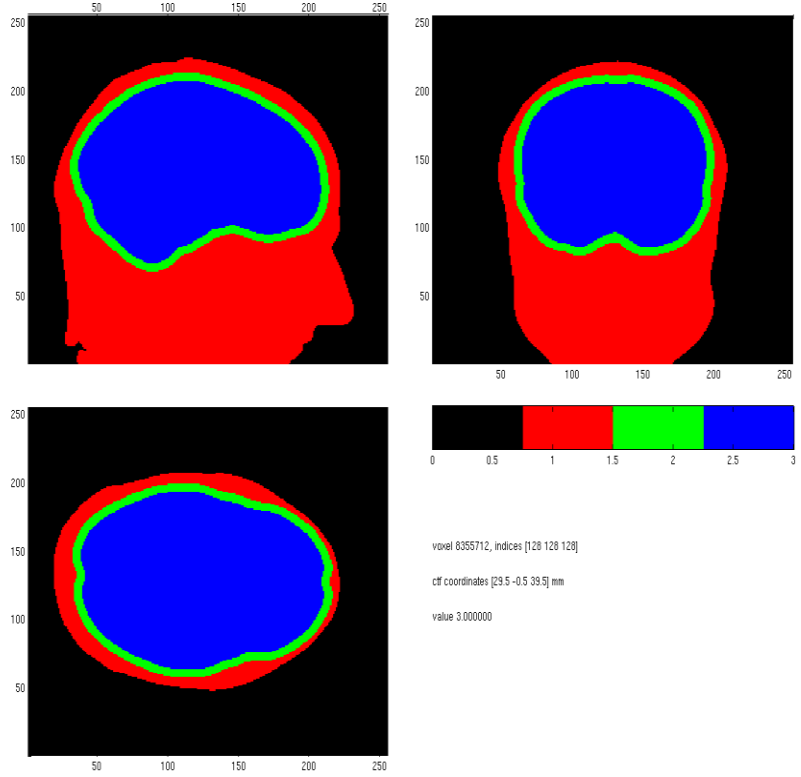




Resistivity

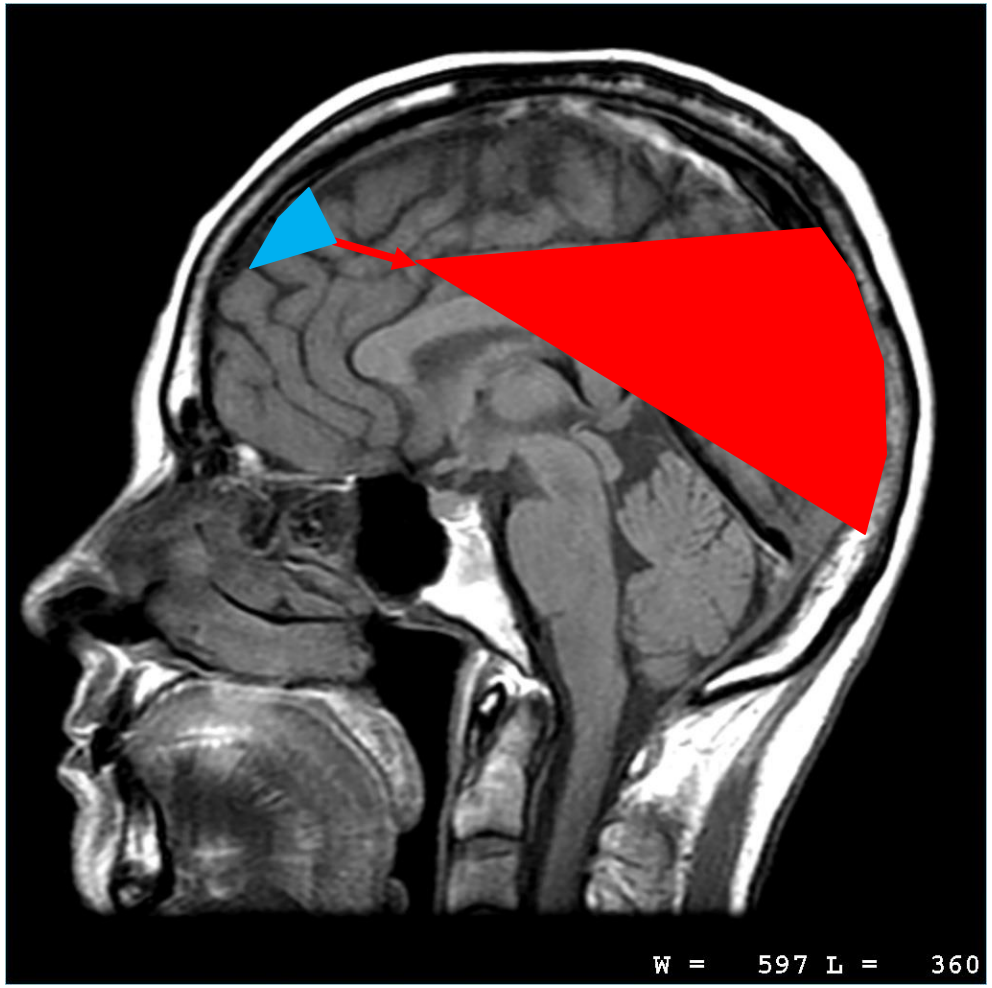
$$\rho = \frac{1}{\sigma}$$

Volume conduction



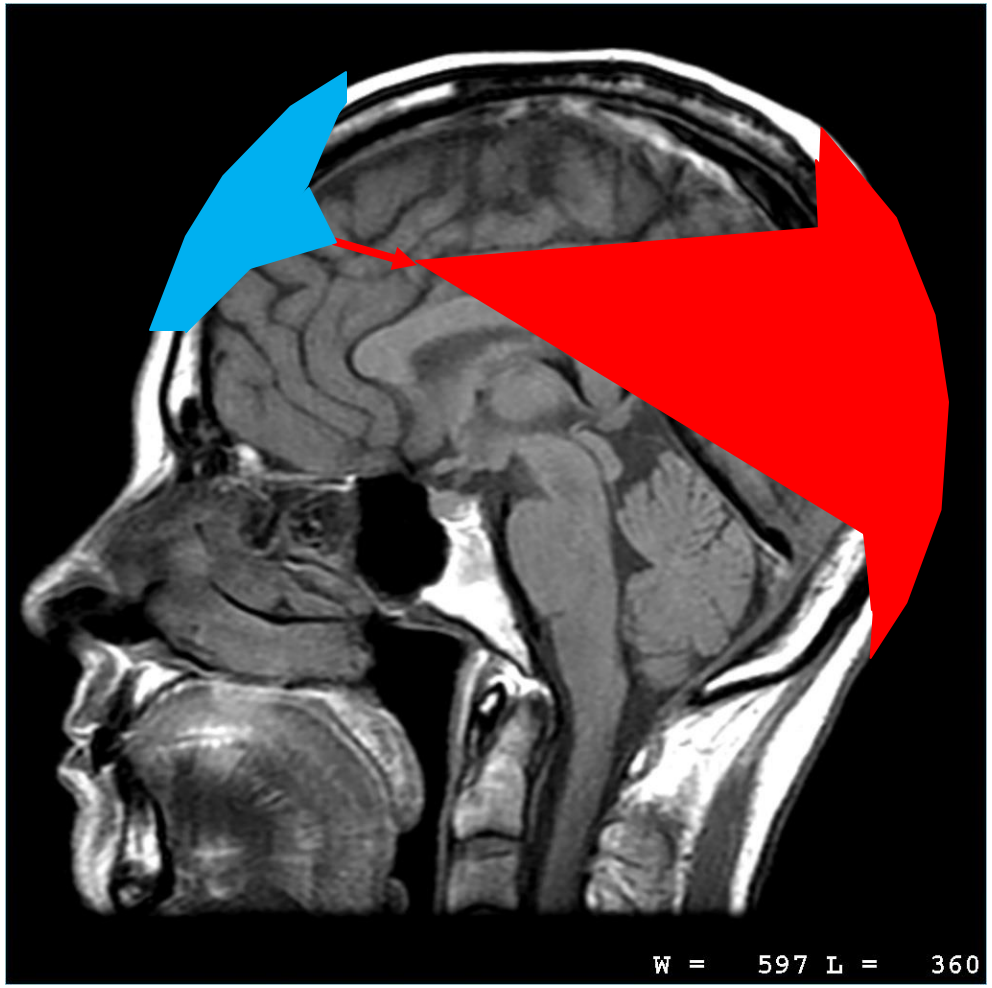
Volume conduction

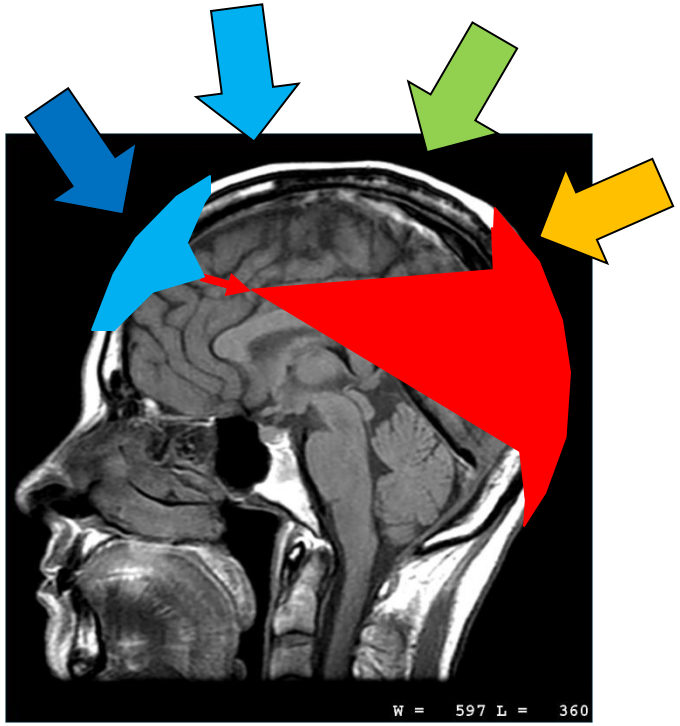
Volume conduction

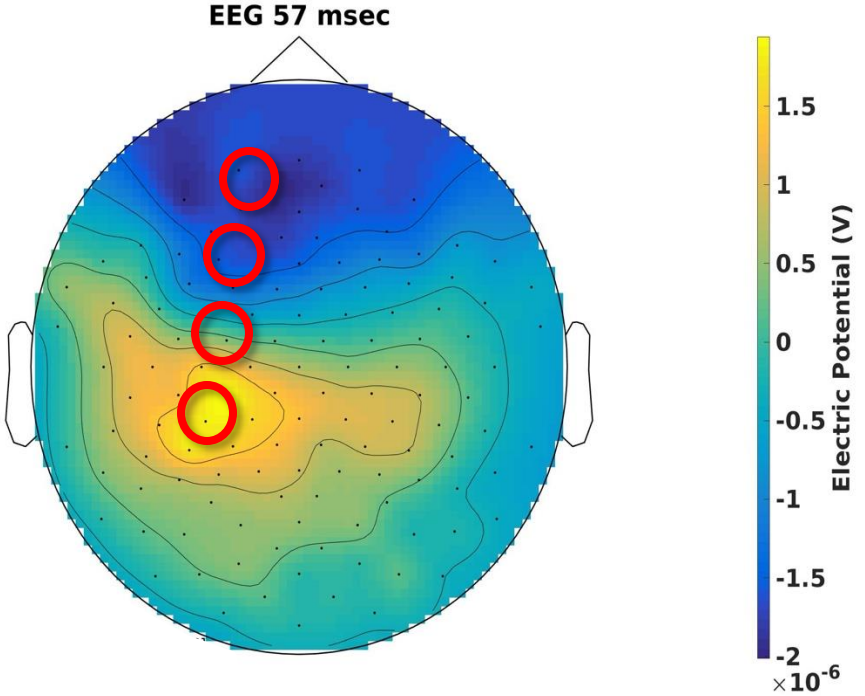


Volume conduction

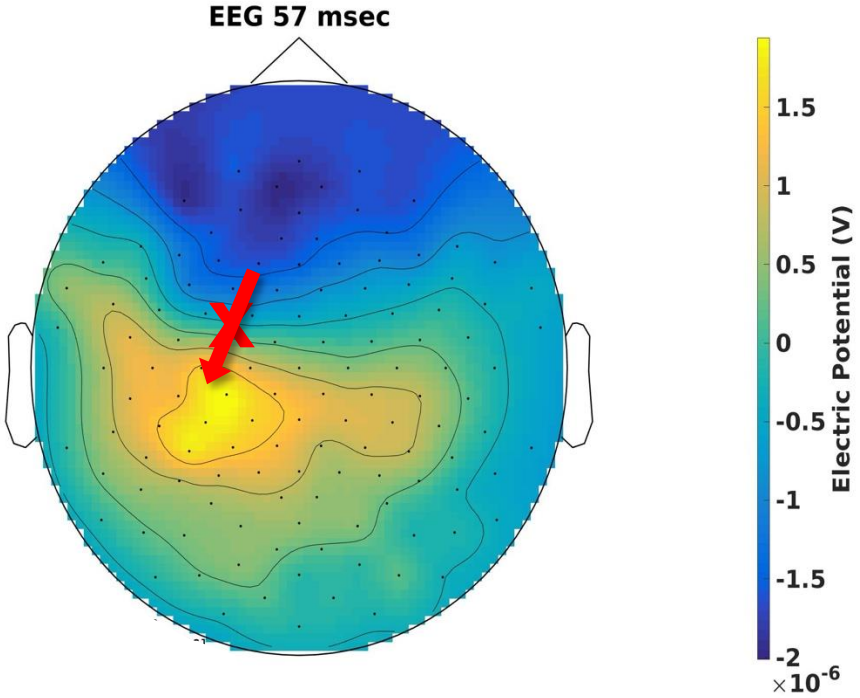
Volume conduction



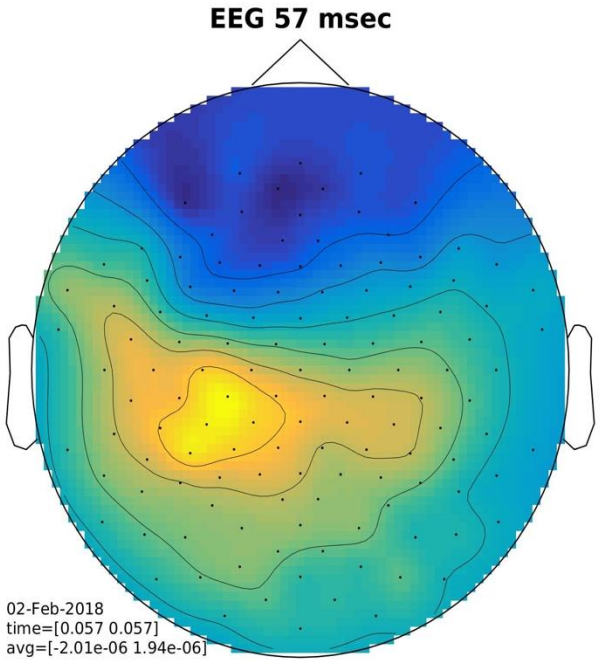

W = 597 L = 360


EEG 57 msec
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Electric Potential (V)
×10-6

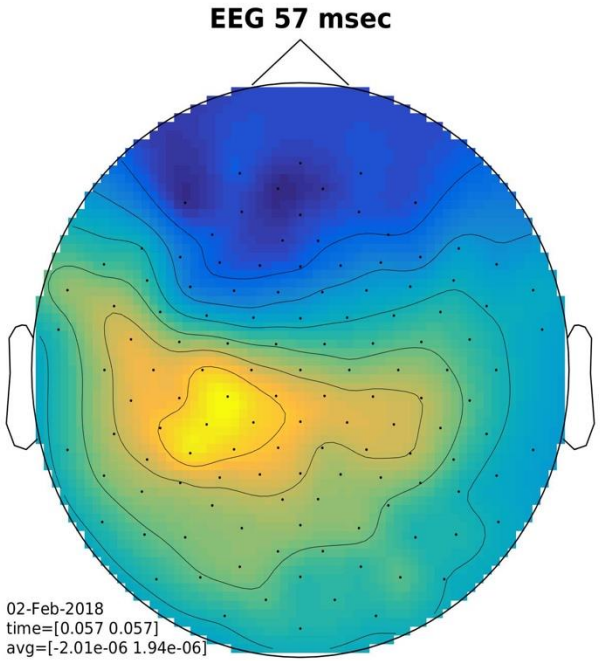
Question: where is the dipole (most likely) located?



The inverse problem

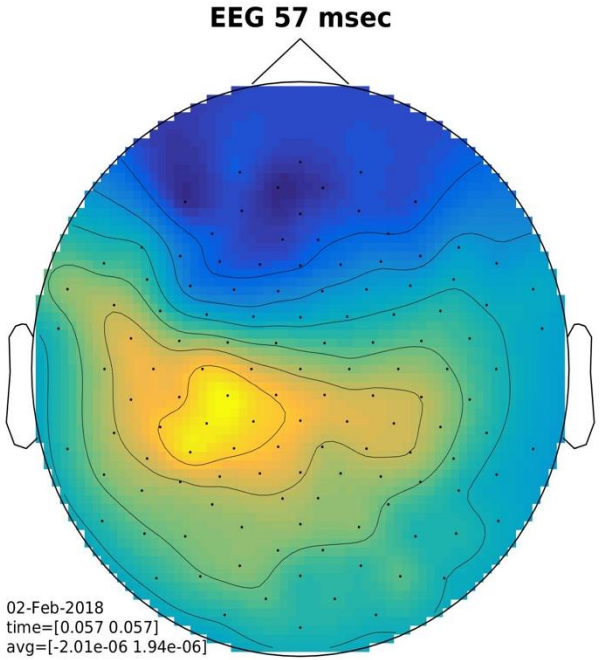


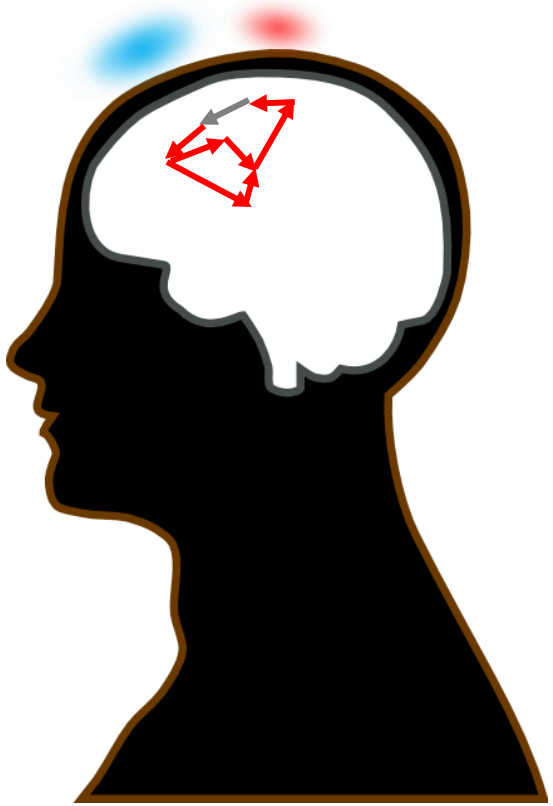
The inverse problem



The inverse problem

For any measures scalp potential there is an infinite number of possible source configurations



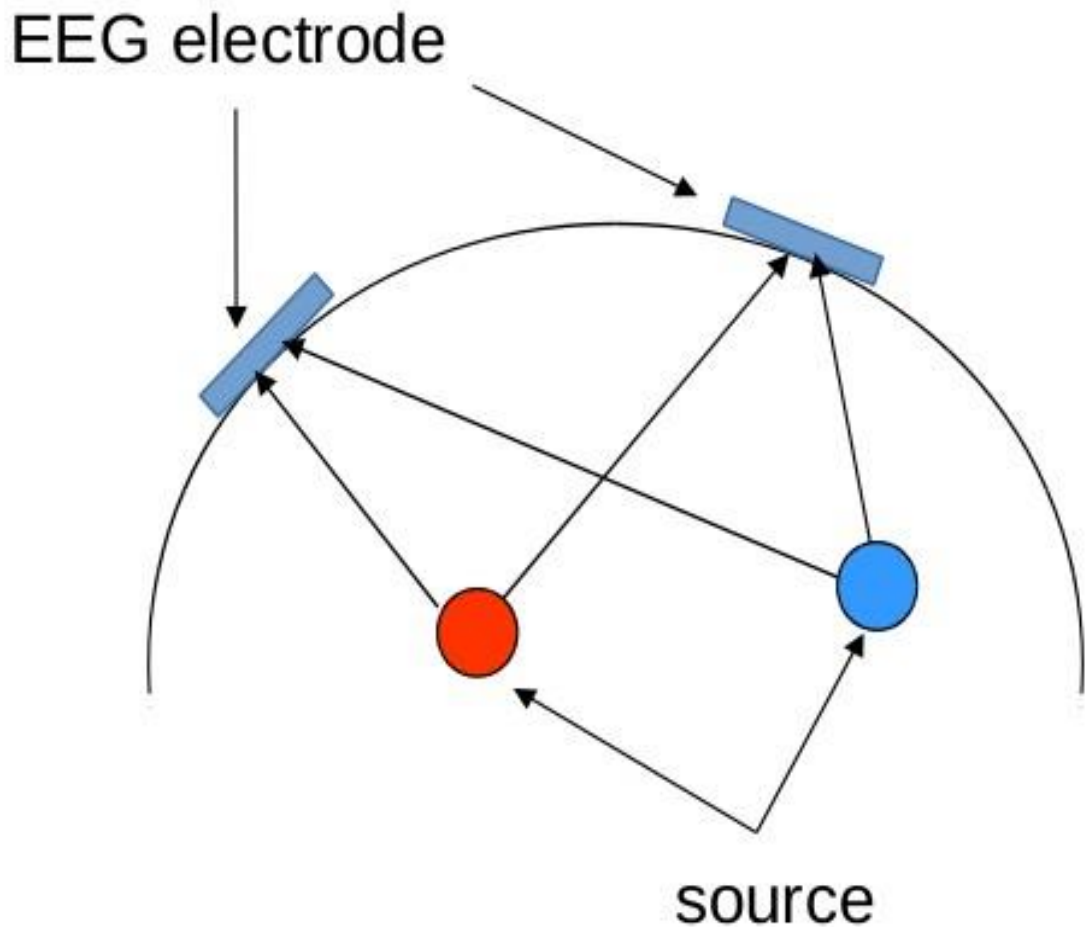


The inverse problem

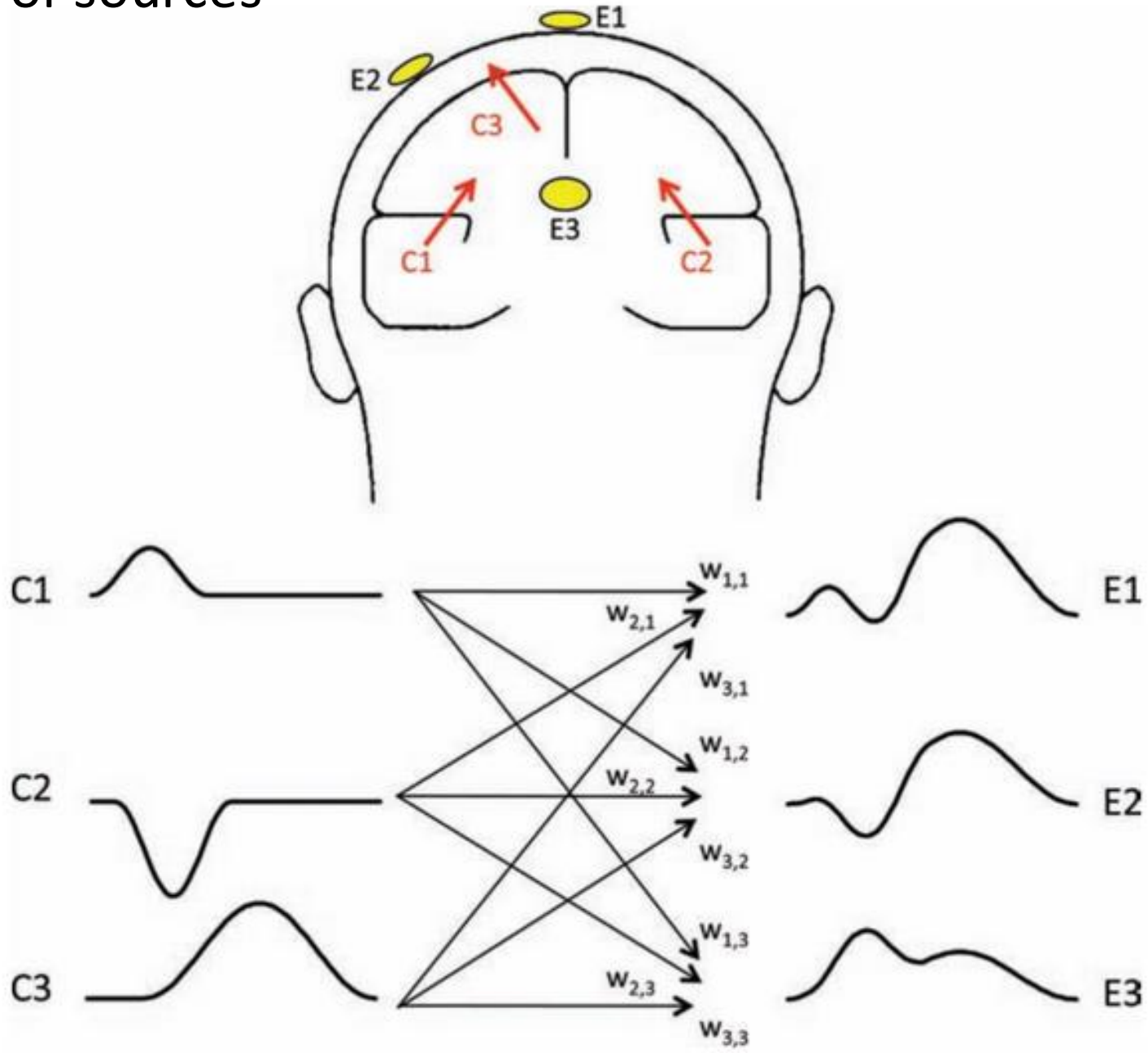
- For any measures scalp potential there is an infinite number of possible source configurations
- Careful interpretation on the relation between scalp potentials and neural generators
  - Spatial location can be deceiving
  - Single dipole? -> probably ok
- Use prior information to interpret signals
- Importance of experimental design

More than one ECD?

Superimposition of sources

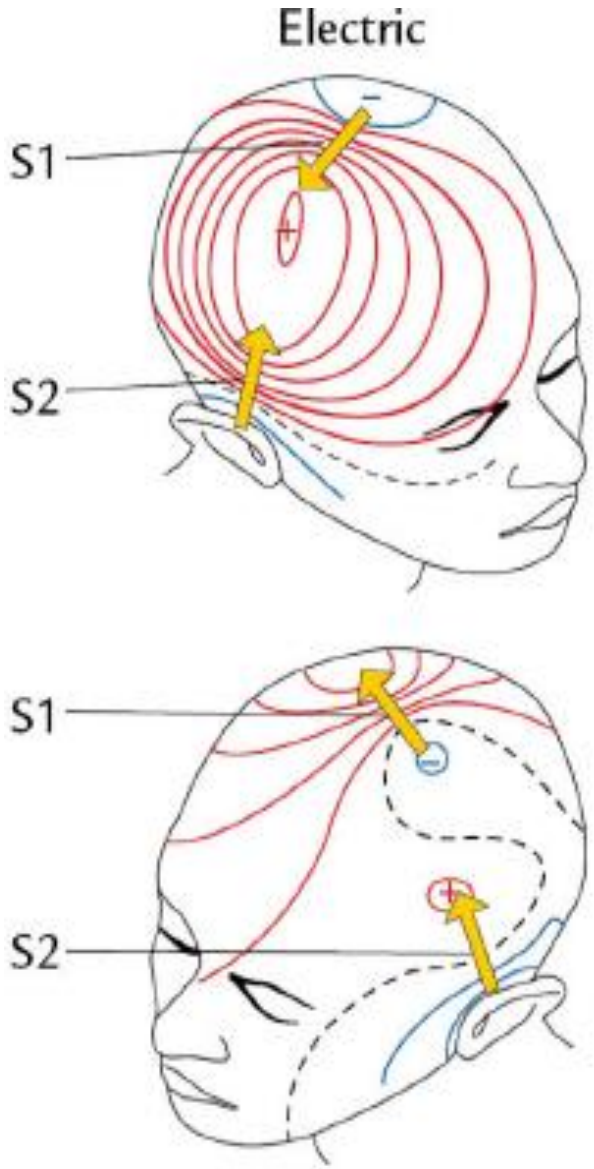


Superimposition of sources



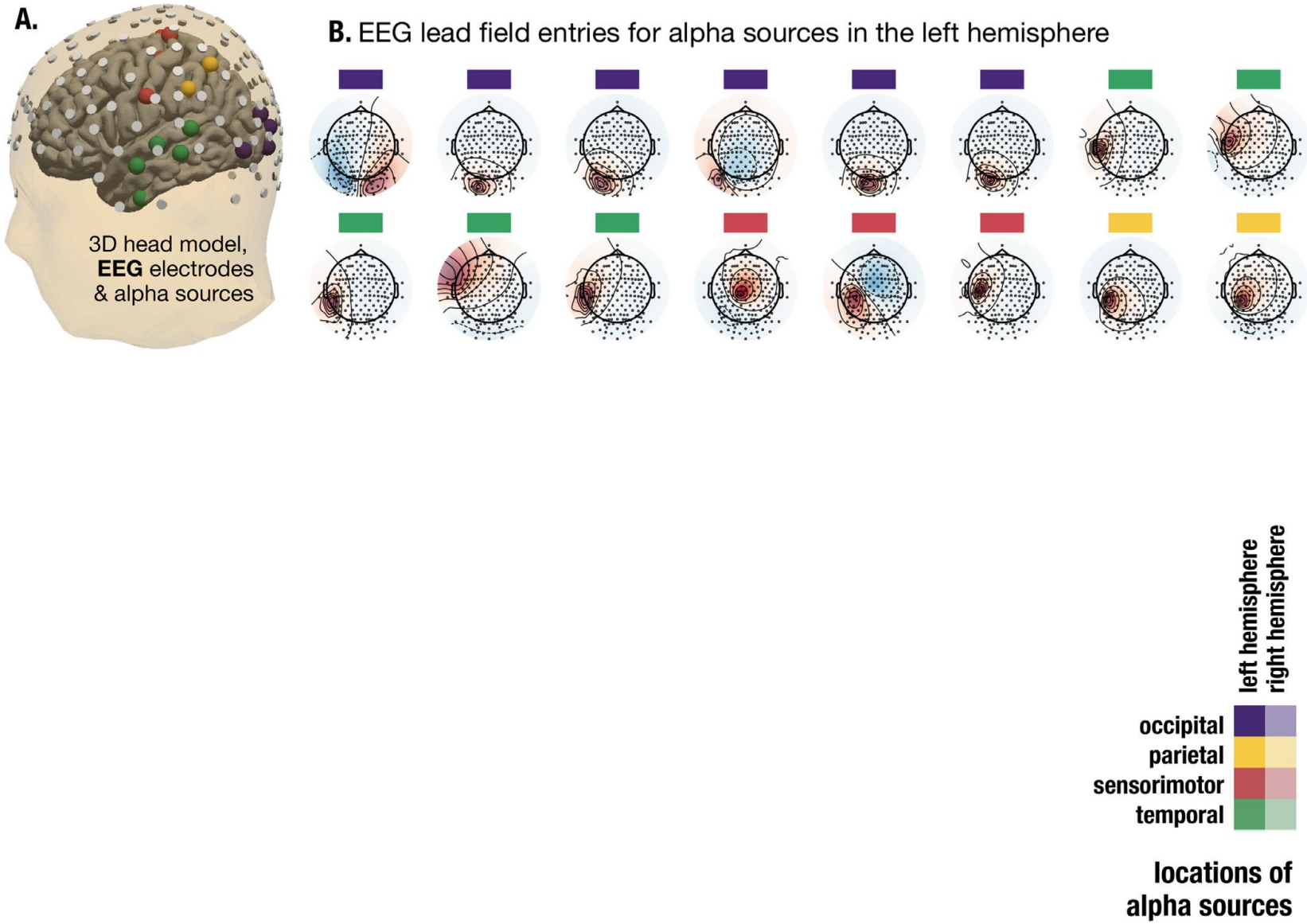
Kappenman & Luck (2012)

Superimposition of sources



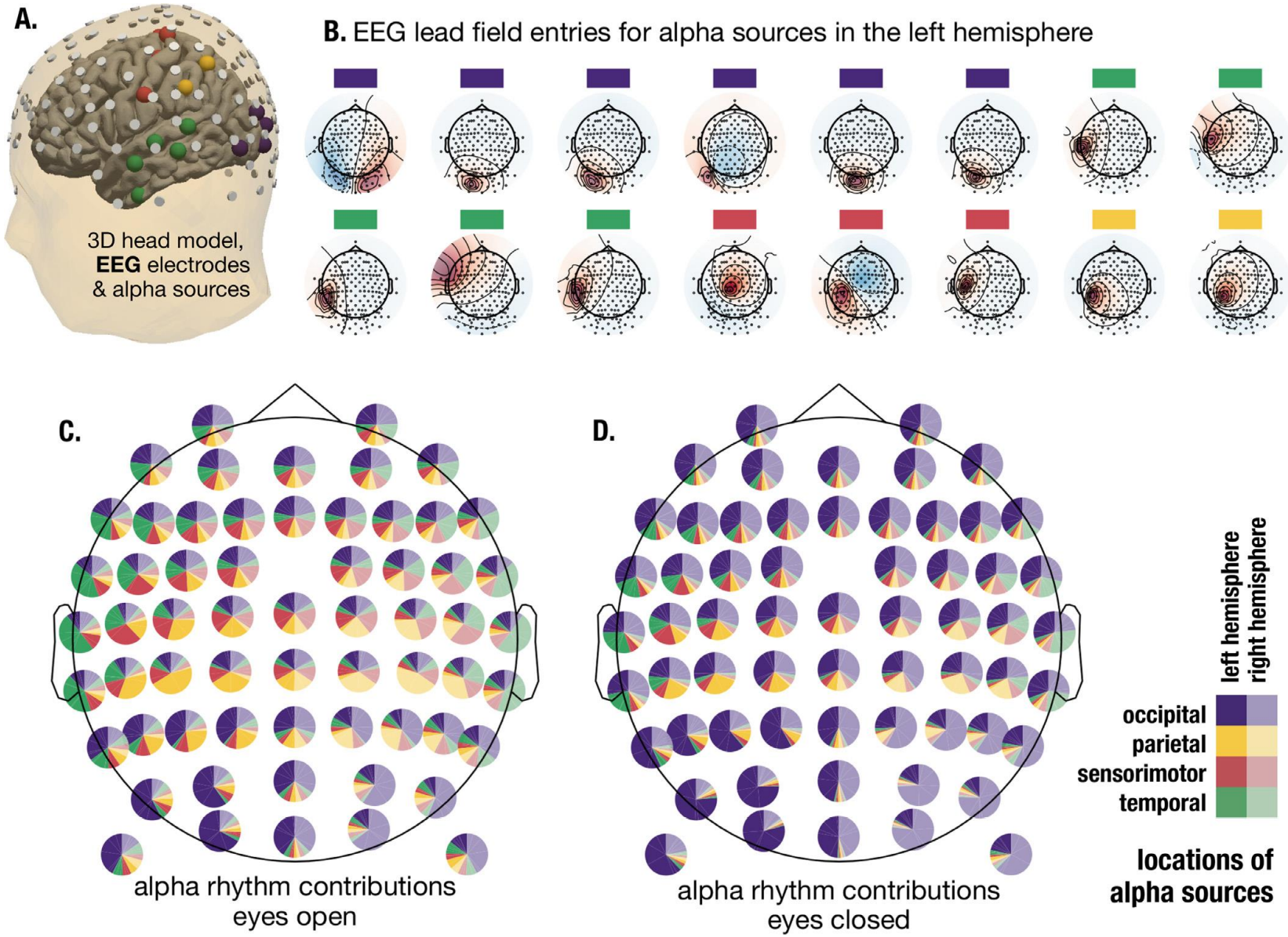
Hari & Puce (2017)

Superimposition of sources: the case of resting state alpha activity



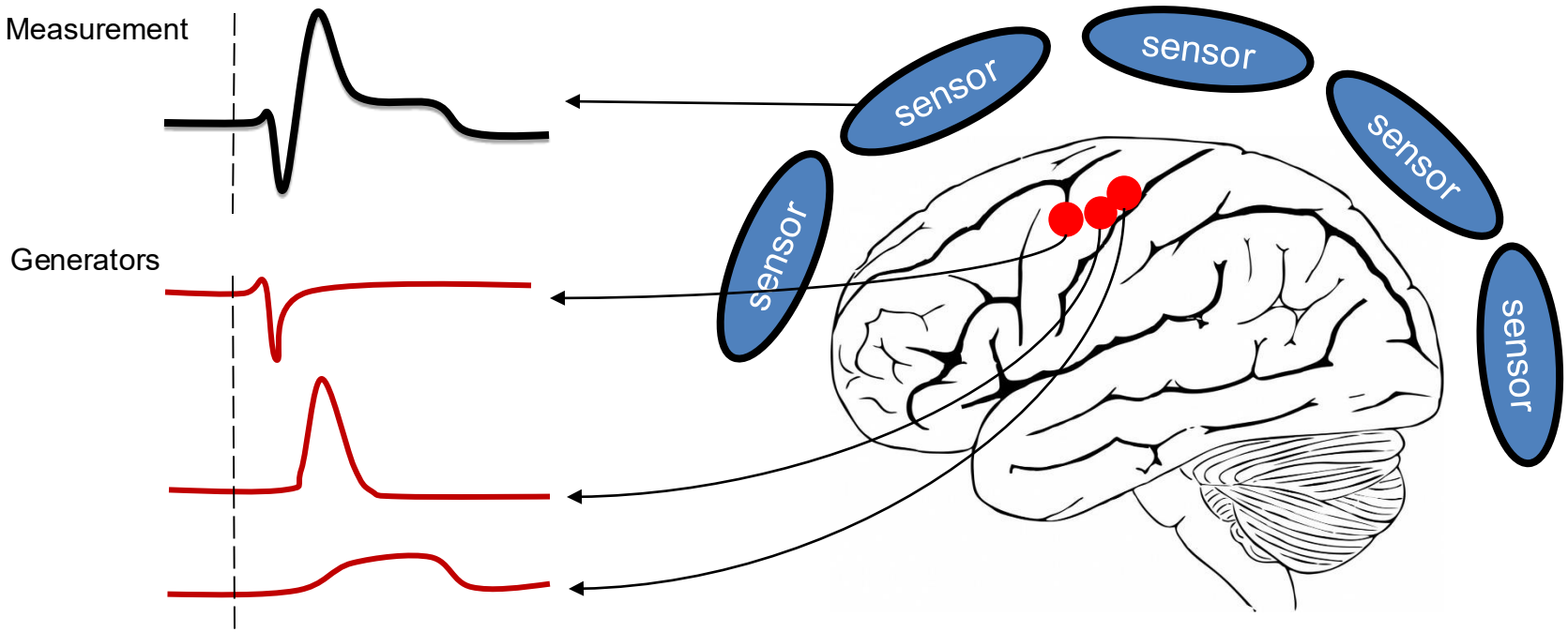
Schaworonkow & Nikulin (2022)

Superimposition of sources: the case of resting state alpha activity

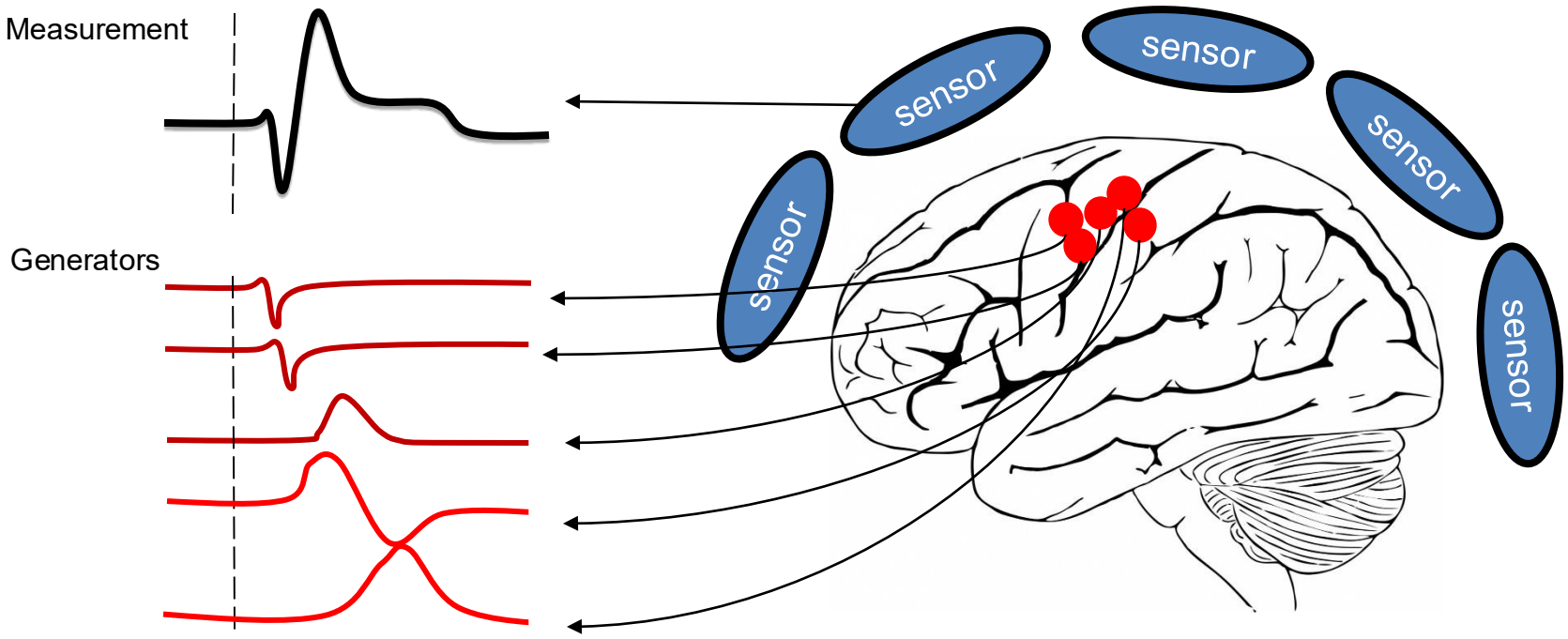


Schaworonkow & Nikulin (2022)

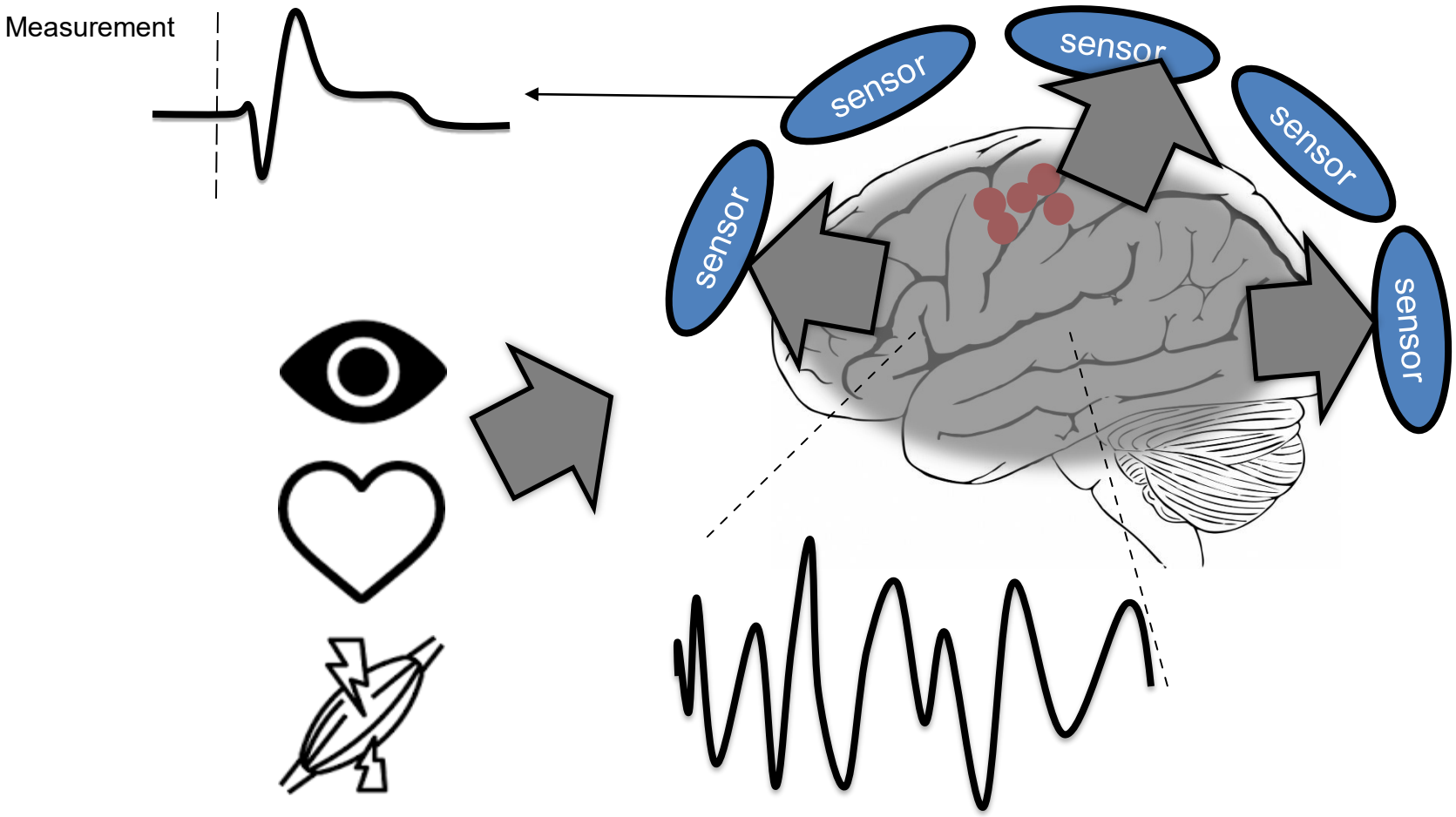
Superimposition of sources



Superimposition of sources

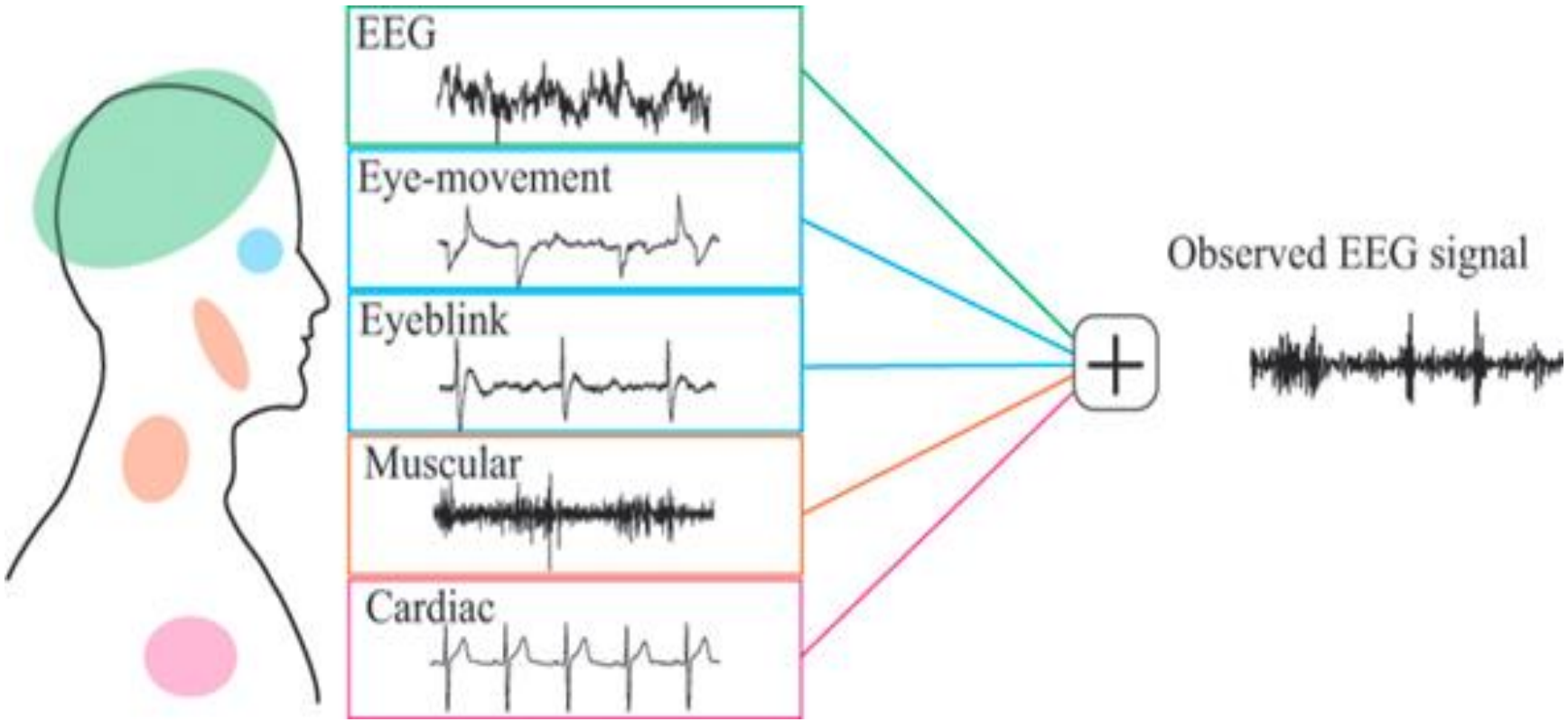


EEG signals (and more)

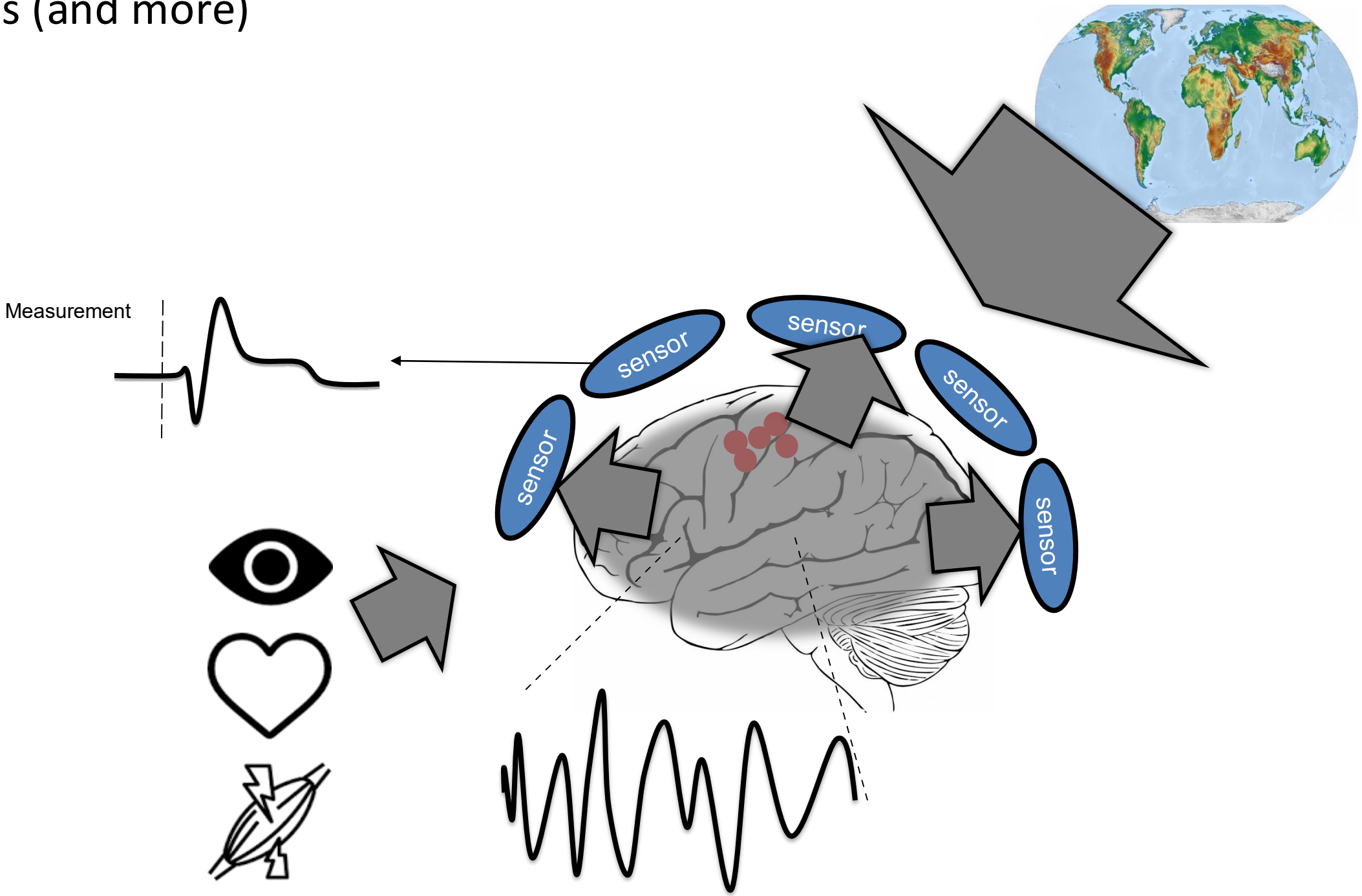


Physiological artefacts

Brain activity	few µV
Brain “noise”	10-50 µV
Physiological noise	10-1000 µV



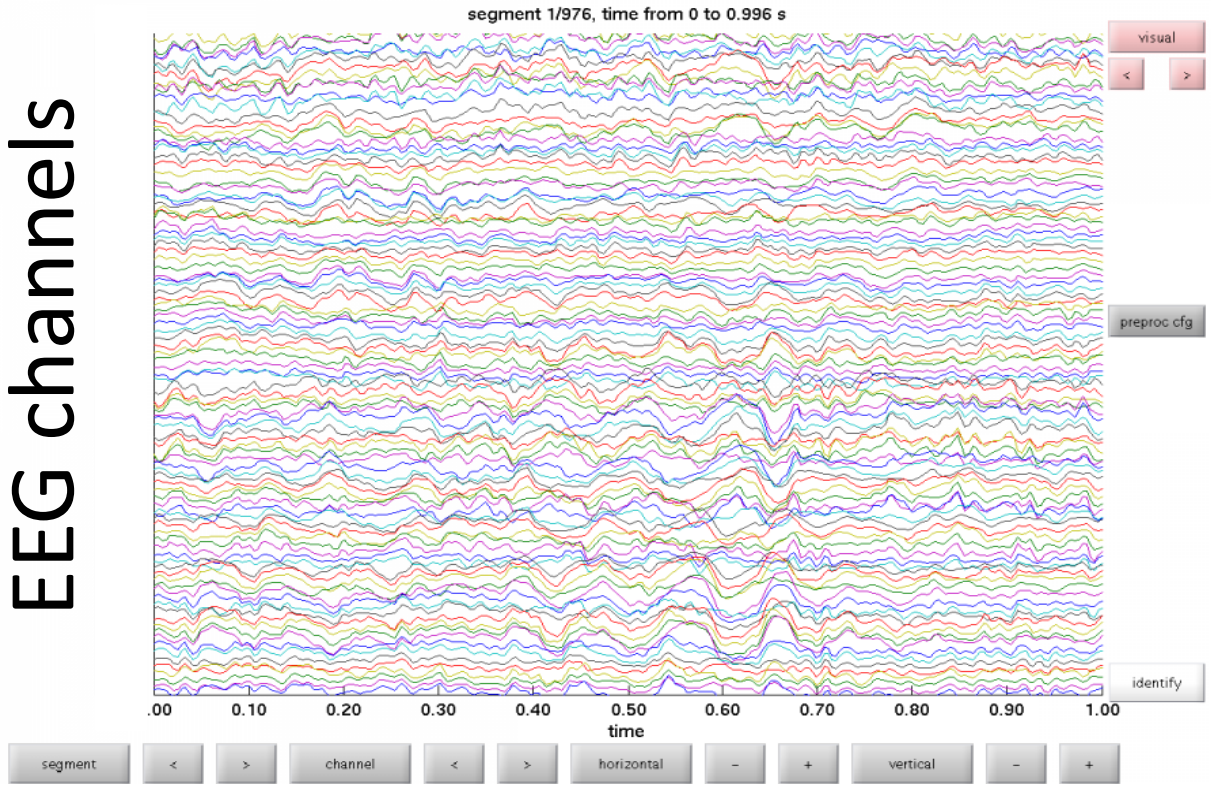
EEG signals (and more)



Summary: the electric field at the scalp

- Specific to location of electrodes
- Summation of electric fields:
  - Signal of interest (task relevant)
  - Brain noise
  - Physiological noise/artefacts
  - Environmental noise

Unit: microvolts (µV)



EEG channels

Time

Discussion

In small groups, take turns to present an idea for an EEG study you would like to do (or perhaps already are working on).

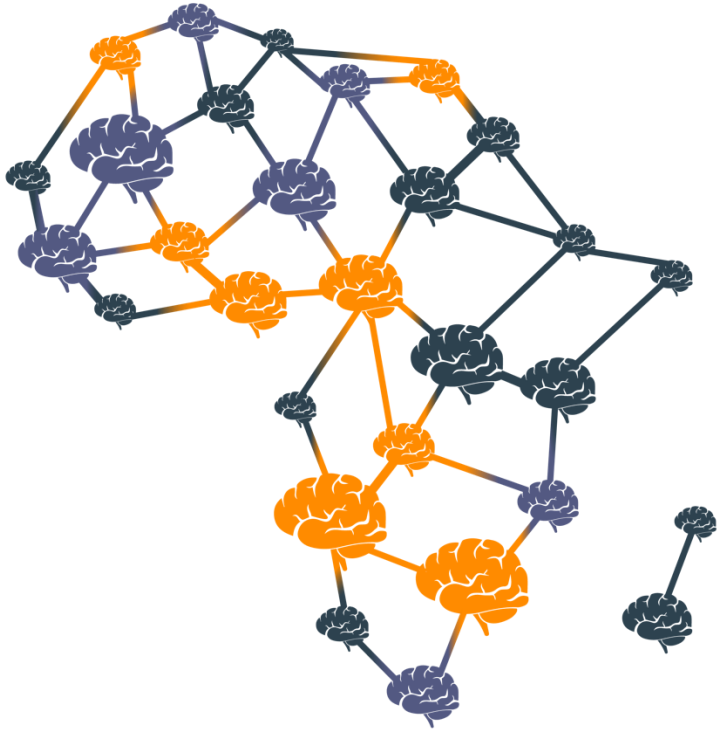
- What is your topic of interest?
- How do you think EEG can be used to understand the topic?

EEG background

Robert Oostenveld

Mikkel C. Vinding

9-14 June 2025
Port Harcourt, Nigeria



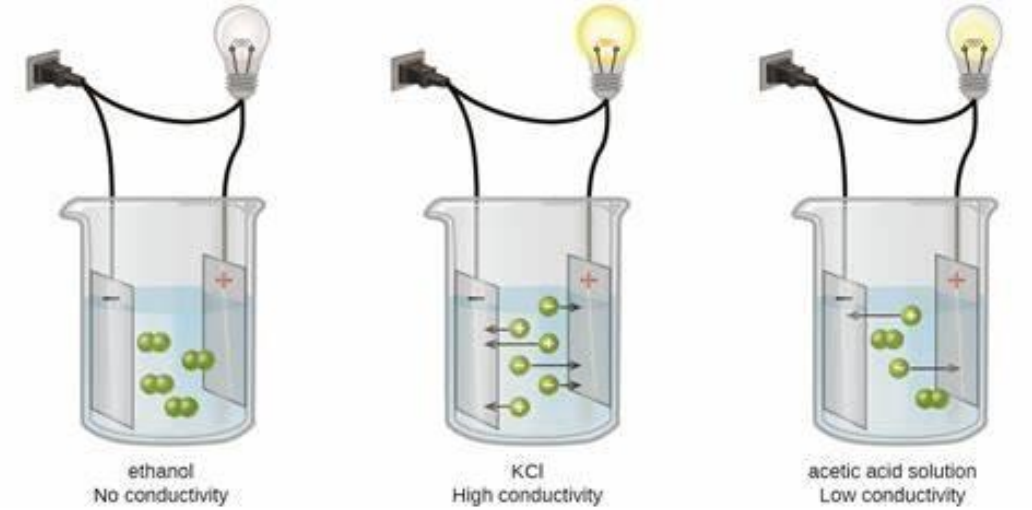
African Brain Data Network

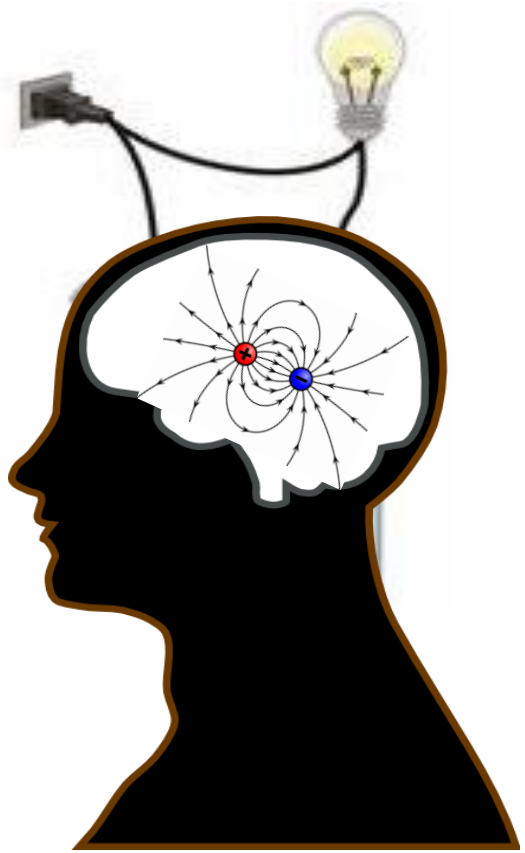
Basic EEG instrumentation

How we measure electric fields at the scalp

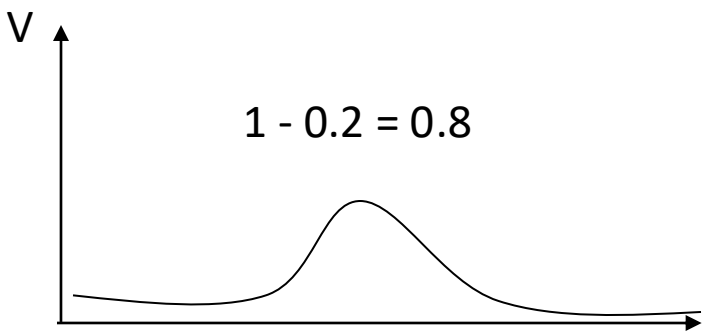
Electrodes

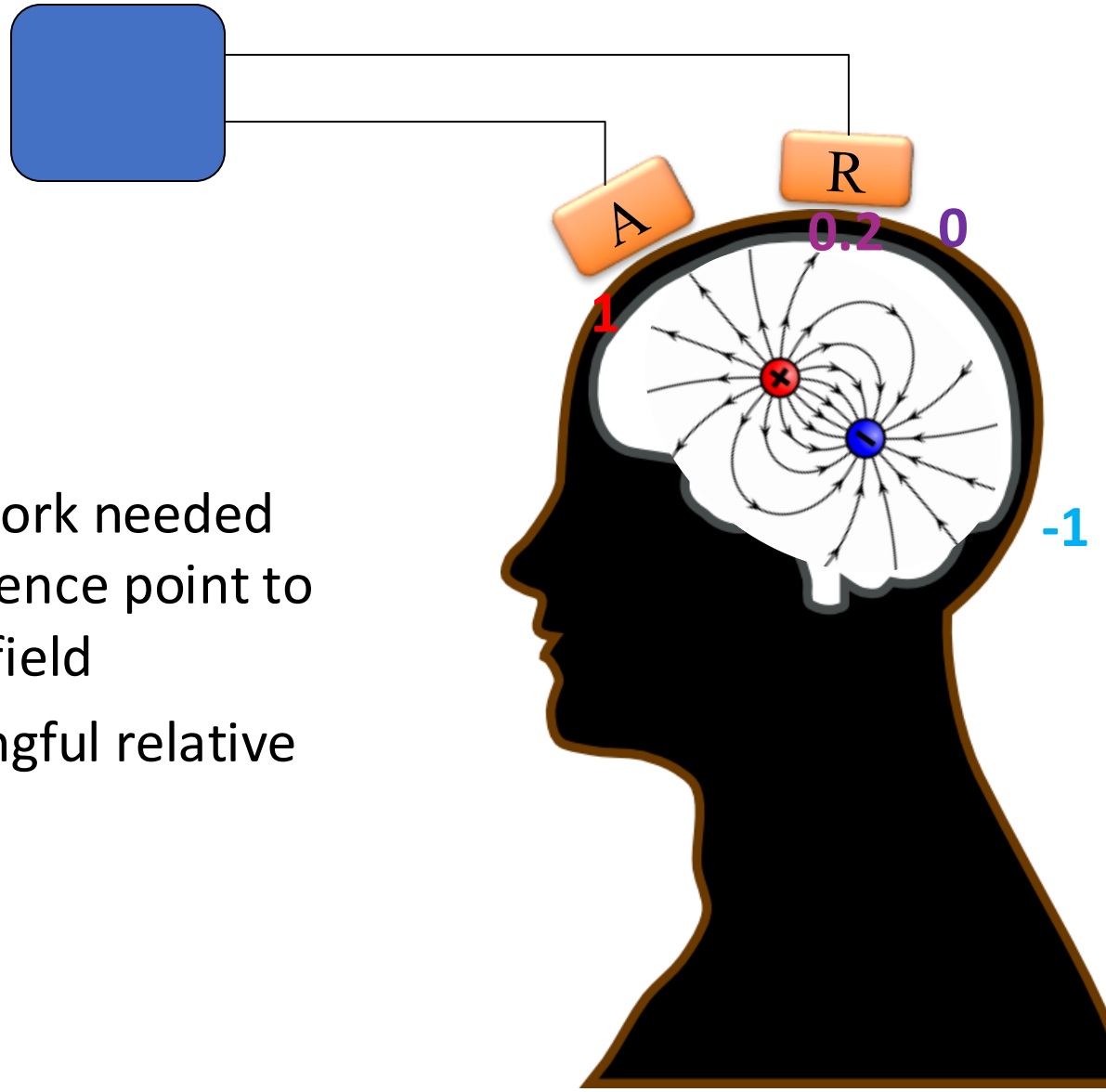
Electrode: A conductor used to establish electrical contact with a nonmetallic part of a circuit





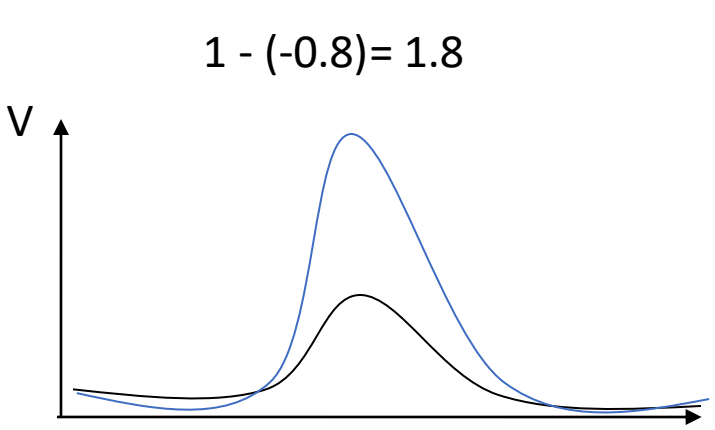
Electrodes

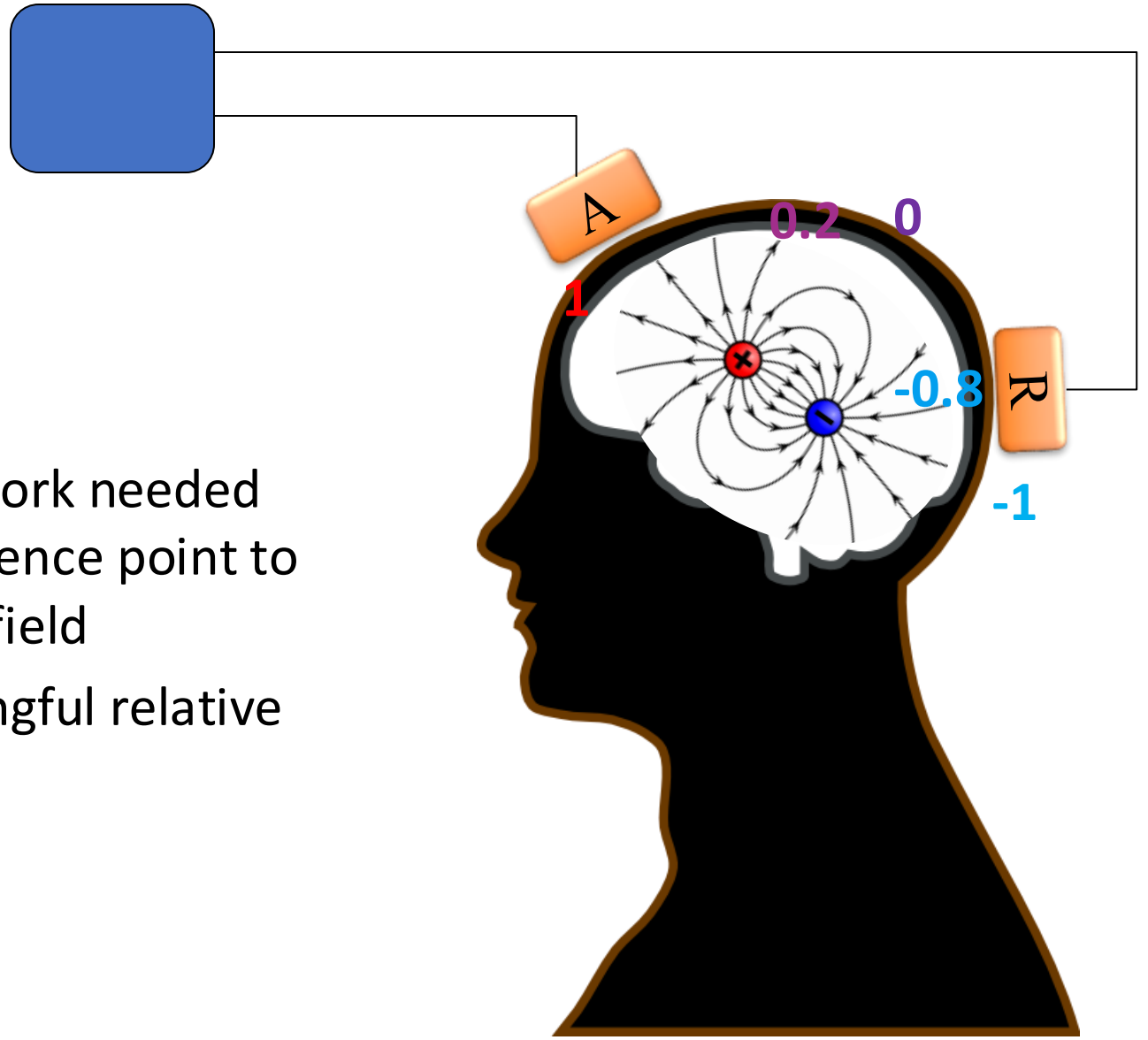




- Electric potential, the amount of work needed to move a unit charge from a reference point to a specific point against an electric field
- An electric potential is only meaningful relative to a reference point

Electrodes



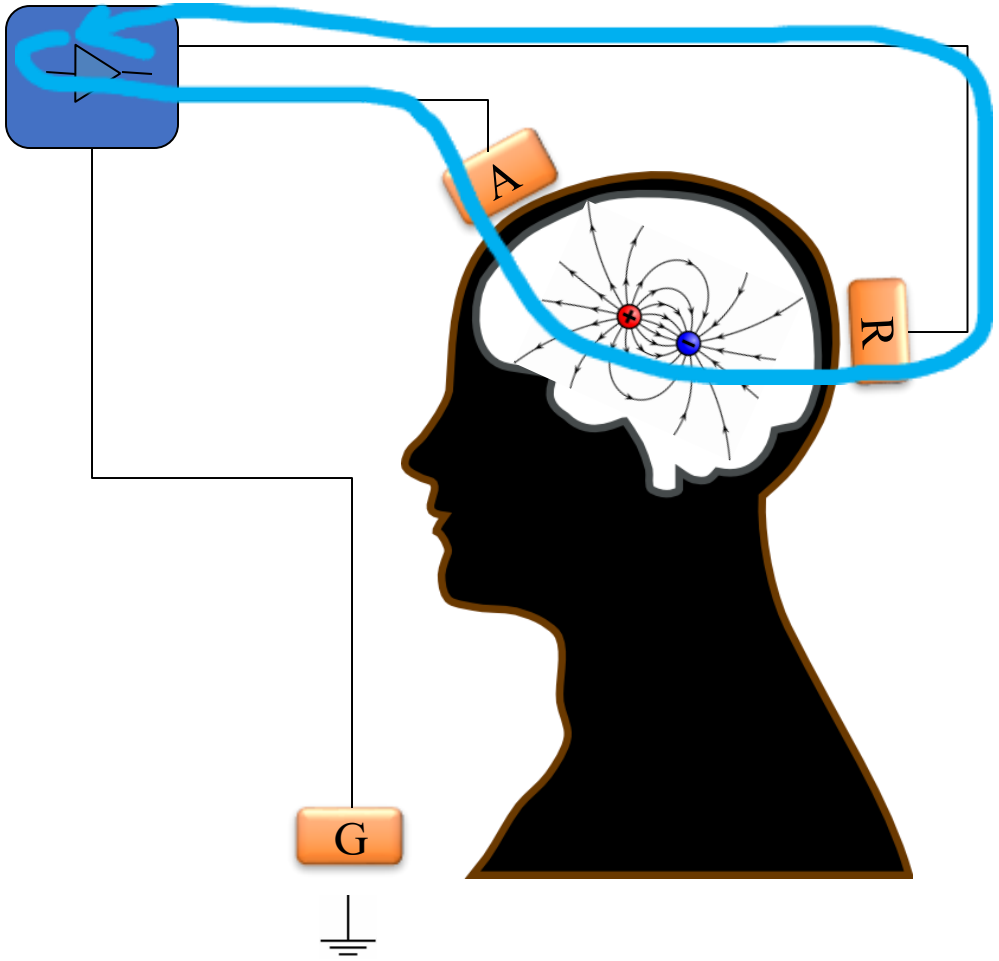


- Electric potential, the amount of work needed to move a unit charge from a reference point to a specific point against an electric field
- An electric potential is only meaningful relative to a reference point

EEG circuit

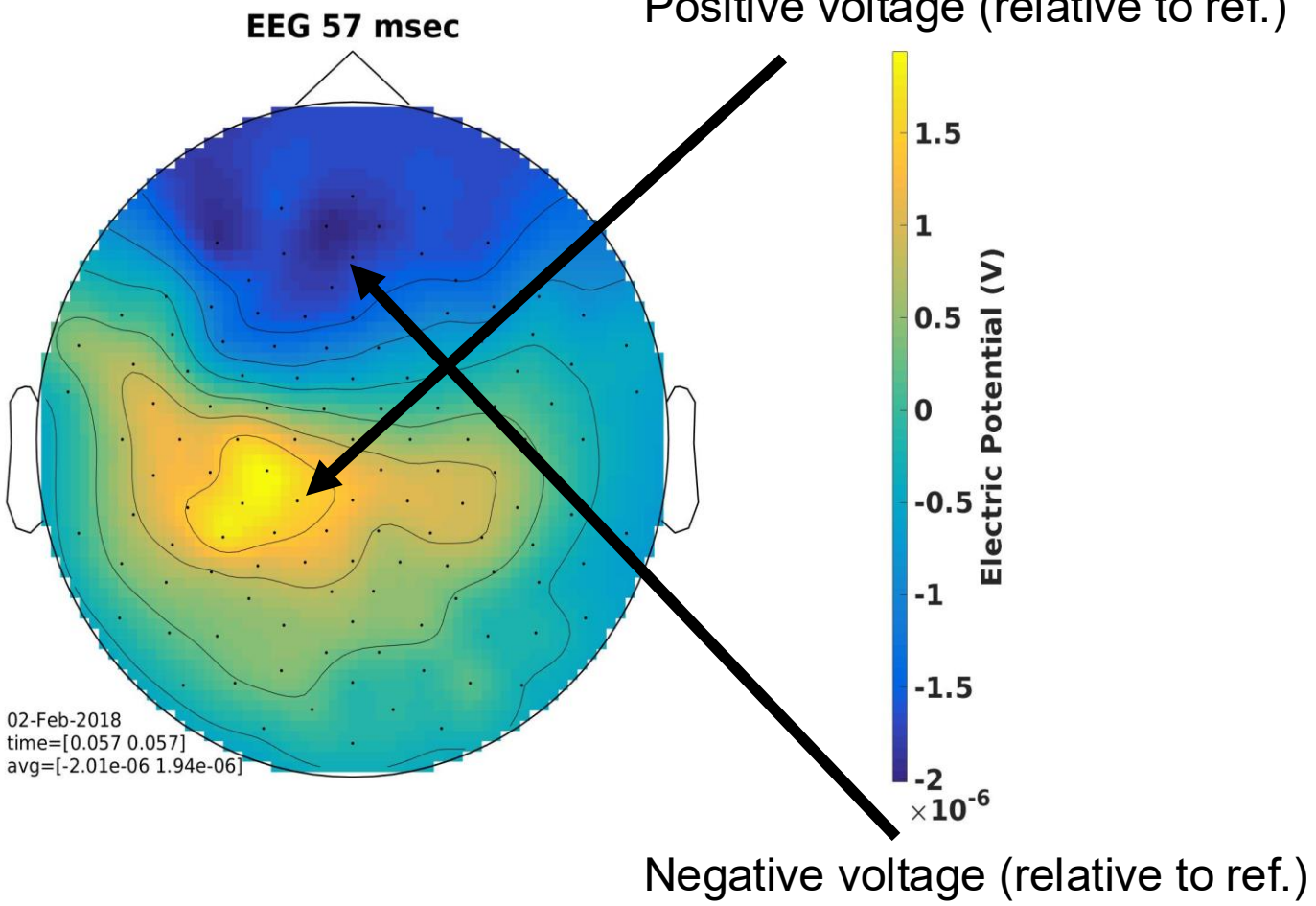
www.biosemi.com

Amplifier



Ground

Electrodes



Positive voltage (relative to ref.)

Negative voltage (relative to ref.)

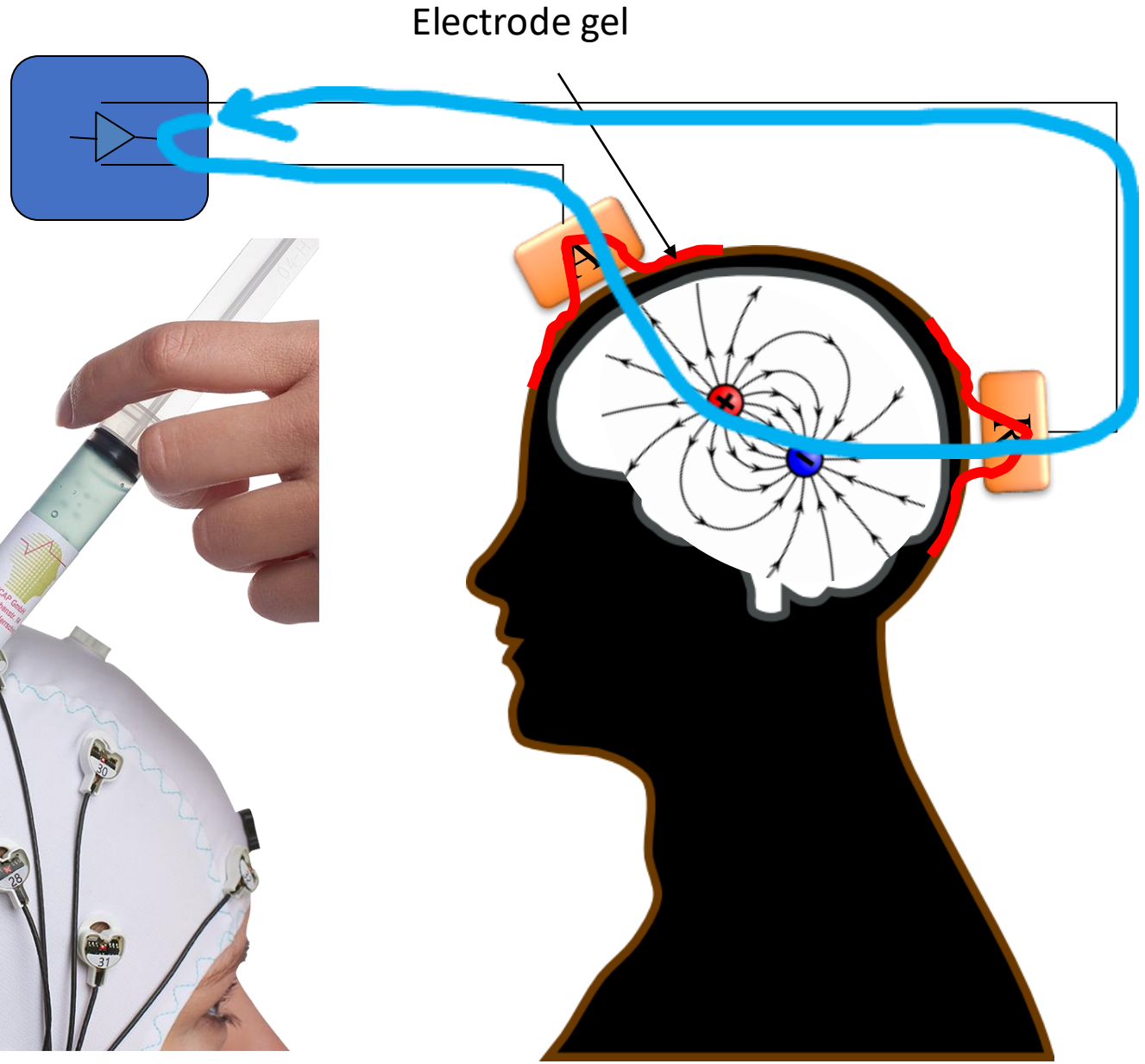
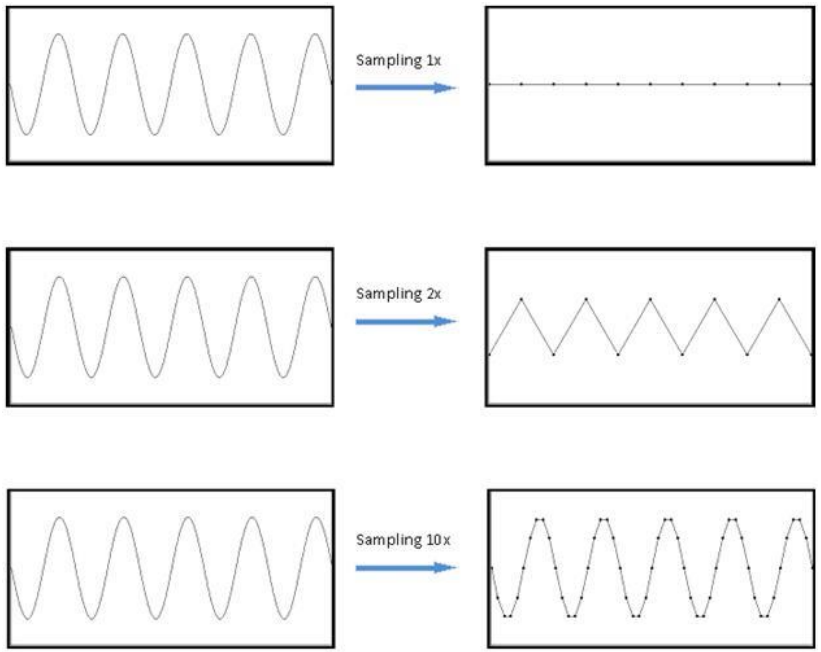


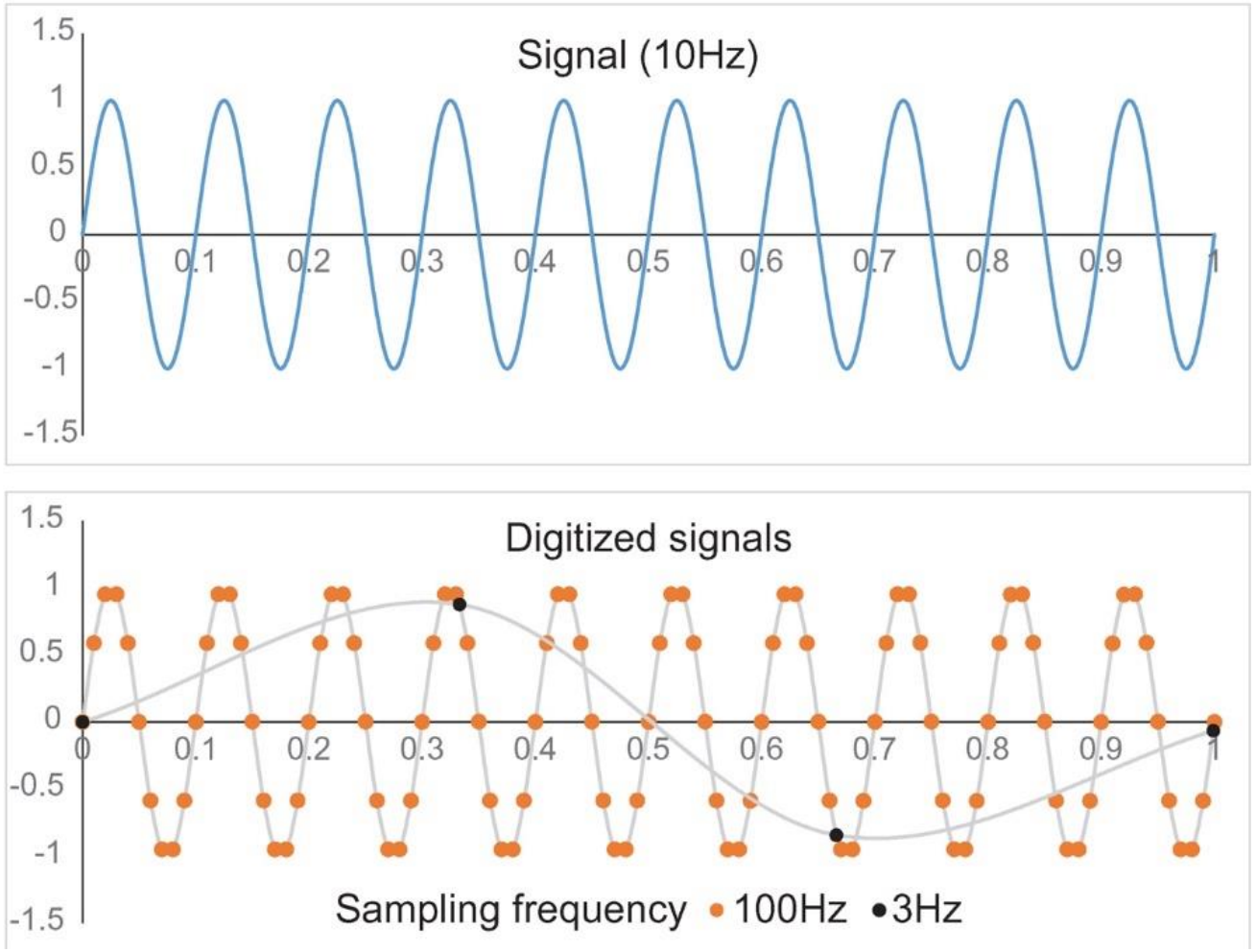
Image from www.brainlatam.com

Data sampling

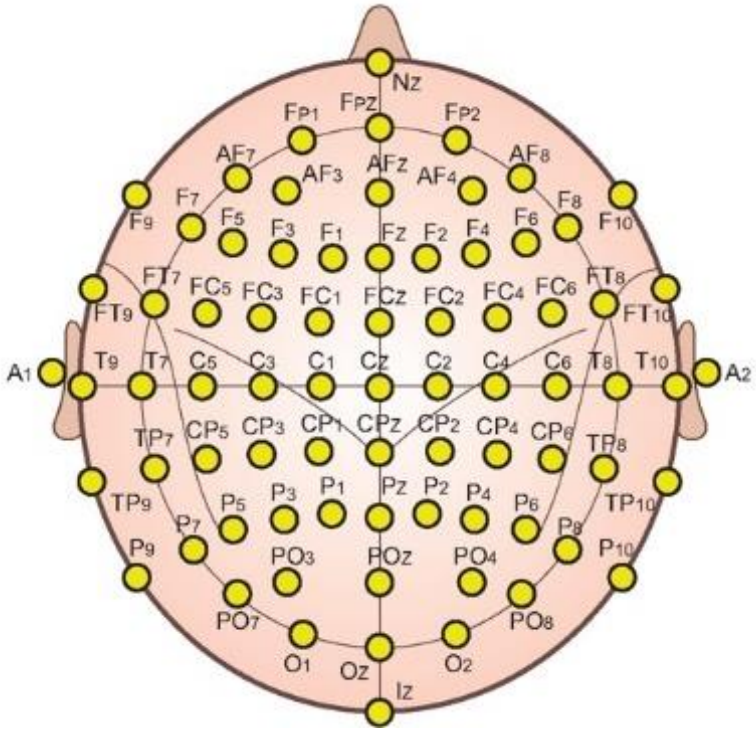
EEG sampling rate is typically
256 – 5000 Hz



A

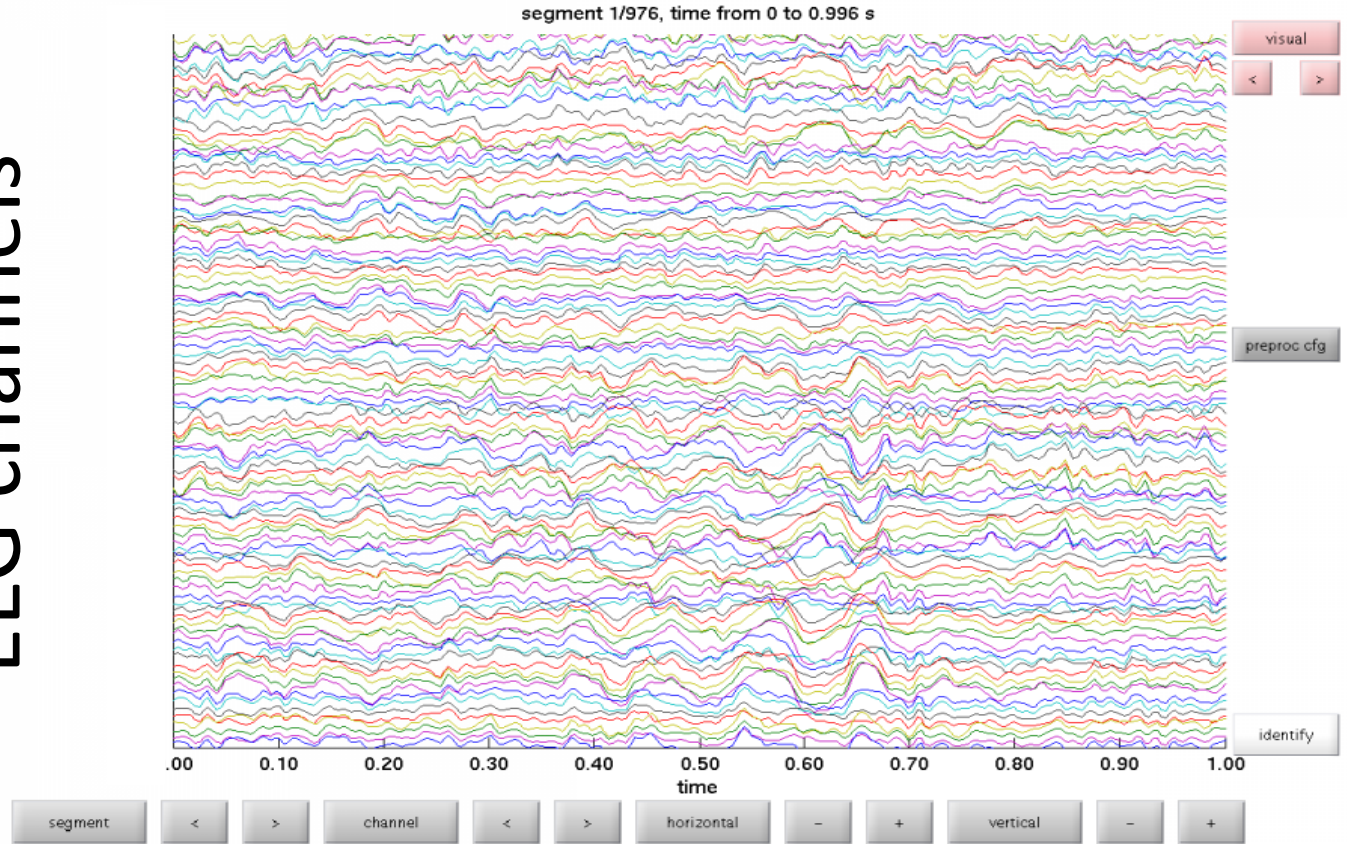


EEG data



Unit: microvolts (µV)

EEG channels



Time

References

Buzsáki G, Anastassiou CA, Koch C (2012) The origin of extracellular fields and currents — EEG, ECoG, LFP and spikes. Nat Rev Neurosci 13:407–420. https://doi.org/10.1038/nrn3241

Greiner HM, Horn PS, Tenney JR, et al (2016) Preresection intraoperative electrocorticography (ECoG) abnormalities predict seizure-onset zone and outcome in pediatric epilepsy surgery. Epilepsia 57:582–589. https://doi.org/10.1111/epi.13341

Hari R, Puce A (2017) MEG-EEG primer. Oxford University Press, New York, NY

Jackson AF, Bolger DJ (2014) The neurophysiological bases of EEG and EEG measurement: A review for the rest of us. Psychophysiology 51:1061–1071. https://doi.org/10.1111/psyp.12283

Jurkiewicz MT, Gaetz WC, Bostan AC, Cheyne D (2006) Post-movement beta rebound is generated in motor cortex: Evidence from neuromagnetic recordings. NeuroImage 32:1281–1289. https://doi.org/10.1016/j.neuroimage.2006.06.005

Kappenman ES, Luck SJ (eds) (2011) The Oxford Handbook of Event-Related Potential Components, 1st edn. Oxford University Press

Martin RS, Huettel SA (2022) Cognitive Functions as Revealed by Imaging of the Human Brain. In: Pfaff DW, Volkow ND, Rubenstein JL (eds) Neuroscience in the 21st Century. Springer International Publishing, Cham, pp 3087–3113

Mushtaq F, Welke D, Gallagher A, et al (2024) One hundred years of EEG for brain and behaviour research. Nat Hum Behav 8:1437–1443. https://doi.org/10.1038/s41562-024-01941-5

Purves D (ed) (2018) Neuroscience, Sixth edition. Oxford University Press, New York

Schaworonkow N, Nikulin VV (2022) Is sensor space analysis good enough? Spatial patterns as a tool for assessing spatial mixing of EEG/MEG rhythms. NeuroImage 253:119093. https://doi.org/10.1016/j.neuroimage.2022.119093