FRIEDRICH-ALEXANDER
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FACULTY OF ENGINEERING

Cognitive Neuroscience for AI Developers

Methods of Cognitive Neuroscience: Lesioning, Neuroimaging

Motivation

- Different techniques (imaging, lesioning) are necessary as different time-scales and spatial resolutions are covered

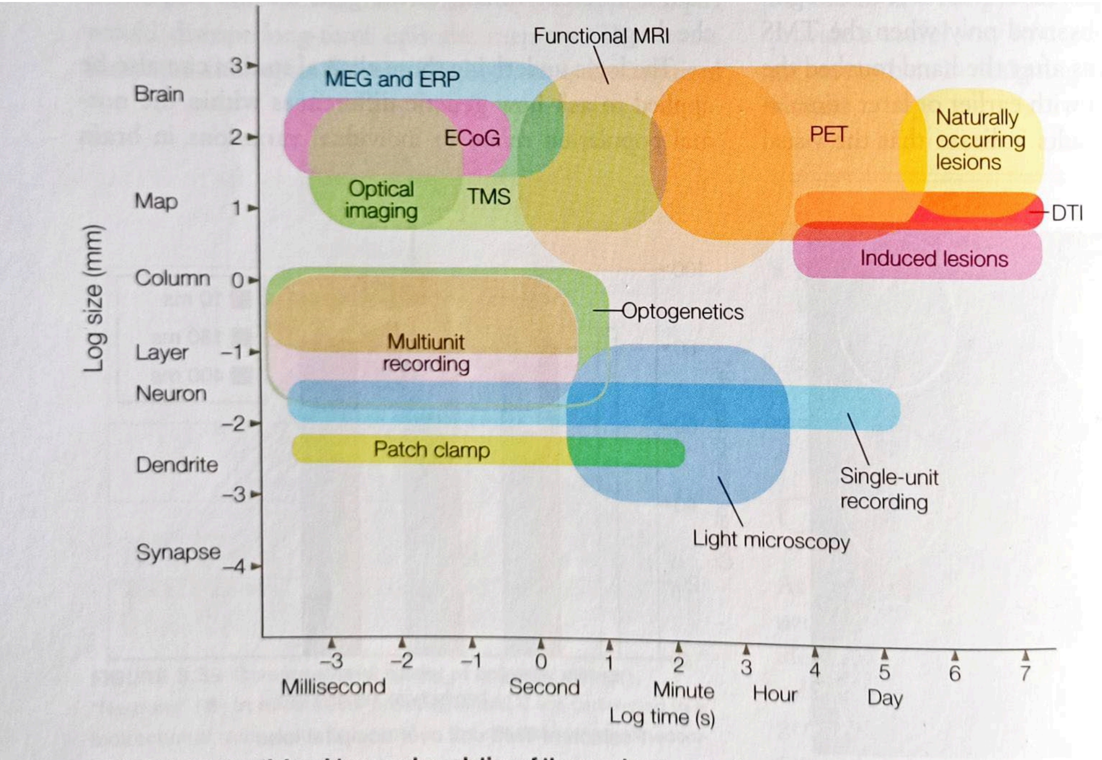

FIGURE 3.41 Spatial and temporal resolution of the prominent methods used in cognitive neuroscience.

Motivation

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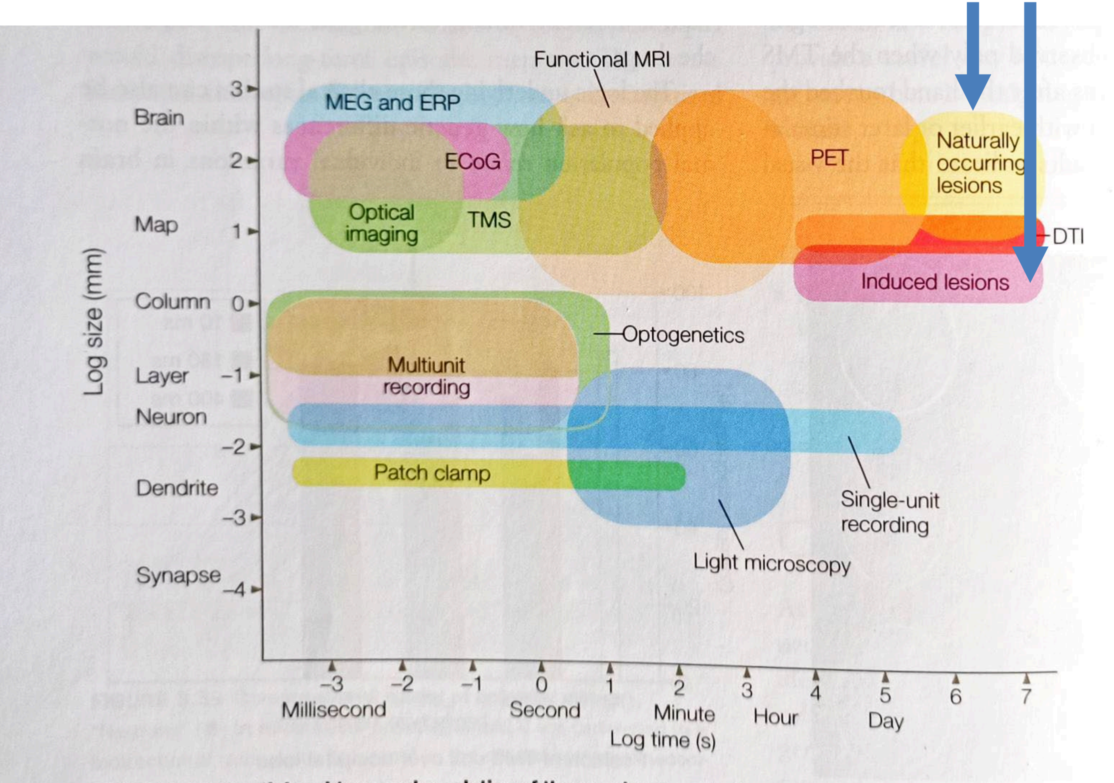


FIGURE 3.41 Spatial and temporal resolution of the prominent methods used in cognitive neuroscience.

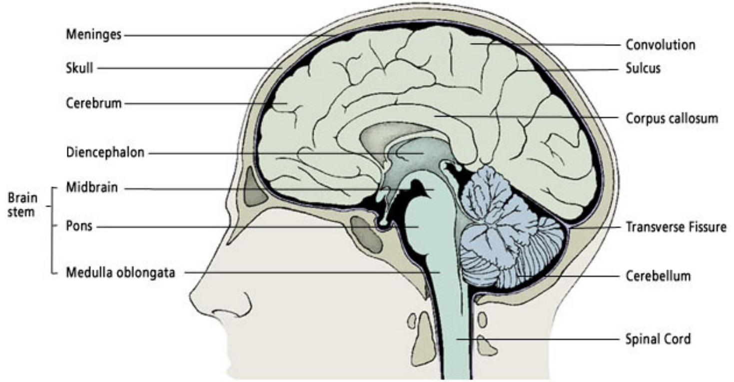
Lesion studies in general

But first: Very brief overview of brain anatomy

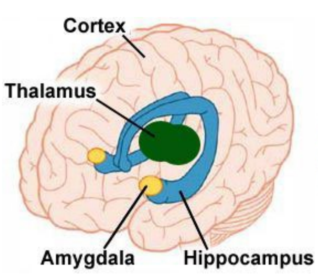
in detail: later lecture

- **peripheral nervous system**: transforms environmental stimuli into neuronal signal (-> spinal chord -> brain)
- **Brainstem**: pre-processing of the signal coming from periphery
- **Thalamus**: controls which signal is transmitted to cortex
- **Cortex**: Higher processing an perception: conscious perception, voluntary movements, language, math reading, memory storage and retrieval
- **Hippocampus**: spatial orientation, memory formation and distribution
- Brain is (nearly) mirror symmetrical
- **Corpus callosum**: nerve fibers connecting both hemispheres (especially cortex areas)

The Major Portions of the Brain Include the Cerebrum, Cerebellum and Brain Stem



https://www.atlantabrainandspine.com/brain-anatomy/



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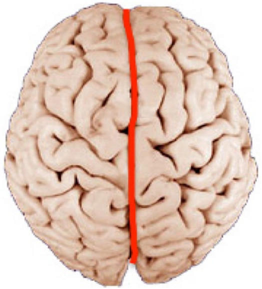
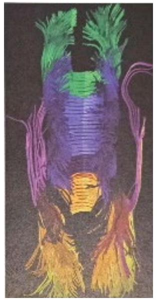




https://www.mdpi.com/2227-7080/5/2/16

Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Lesion studies

In general:

- to draw conclusions about function of a certain part of the brain by studying impairment / functional deficit caused by damage to this brain part
- Some kind of „reverse engineering“ -> what can brain do without certain parts

Lesions e.g. due to

- injuries after accidents
- Disorders
- **surgeries** to treat e.g. epilepsy

Brain Disorders:

Vascular disorders

- Stroke: Bloodflow stops cause of occlusion of arteries
- Cerebral hemorrhage

Tumors

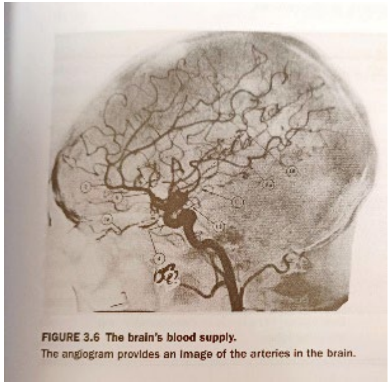
- Abnormal growth of tissue with no function (most caused by glial cells, benign, malignant)

Degenerative disorders

- E.g. Huntington disease, Alzheimer’s disease, AIDS

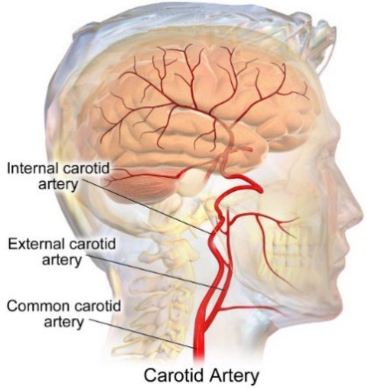
Examples for brain disorders

<u>Vascular disorders:</u>



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Blood supply of the brain: Angiography
- Injection of dye
- X-ray study



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

- Stroke: occlusion of arteries
- Cerebral hemorrhage: breakage of blood vessels (e.g. high blood pressure)

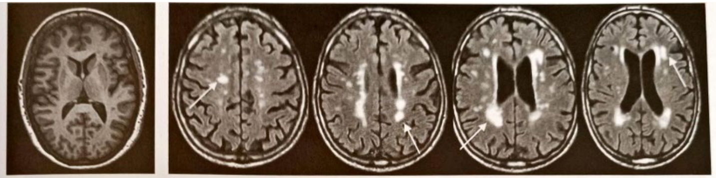
Examples for brain disorders

<u>Degenerative disorders:</u>
2 examples

Alzheimer's disease
- Atrophy of the cerebral cortex and hippocampus
- Reason: unknown

Huntington disease
- Genetic
- Atrophy interneurons

MRI scan (Alzheimer's disease)



a b

FIGURE 3.8 Degenerative disorders of the brain.
(a) Normal brain of a 60-year-old male. (b) Axial slices at four sections of the brain in a 79-year-old male with Alzheimer's disease. Arrows show growth of white matter lesions.

Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Disorder	Type	Most Common Pathology
Alzheimer's disease	Degenerative	Tangles and plaques in limbic and temporoparietal cortex
Parkinson's disease	Degenerative	Loss of dopaminergic neurons
Huntington's disease	Degenerative	Atrophy of interneurons in caudate and putamen nuclei of basal ganglia
Pick's disease	Degenerative	Frontotemporal atrophy
Progressive supranuclear palsy (PSP)	Degenerative	Atrophy of brainstem, including colliculus
Multiple sclerosis	Possibly infectious	Demyelination, especially of fibers near ventricles
AIDS dementia	Viral infection	Diffuse white matter lesions
Herpes simplex	Viral infection	Destruction of neurons in temporal and limbic regions
Korsakoff's syndrome	Nutritional deficiency	Destruction of neurons in diencephalon and temporal lobes

Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Famous examples of lesion studies and consequences

Lesion studies:
What we can learn from brain injuries

Source: wikipedia.org

- **Phineas Gage 1823-1860**
- American railroad construction foreman
- 1848 Gage survived a fatal accident
- large iron rod completely driven through his head
- destroying brain's **left frontal lobe**
- dramatic changes in **personality and behavior**

Source: wikipedia.org

His friends said: Gage is “no longer Gage“ !

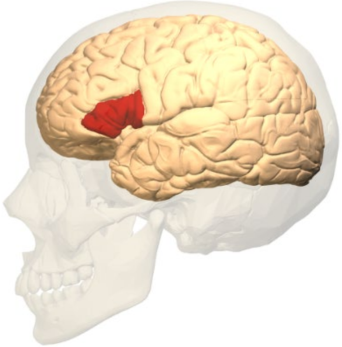
Lesion studies:
What we can learn from brain injuries

Source: wikipedia.org

Pierre Paul Broca (1824-1880)
French physician, anatomist and anthropologist

- 1861 he reported impairments in one patient (named 'Tan')
- Tan could understand language
- lost the **ability to speak** after injury to the **left posterior inferior frontal gyrus**
  -> tan was only word he could say

-> brain region was named Broca's area (important for speech production)



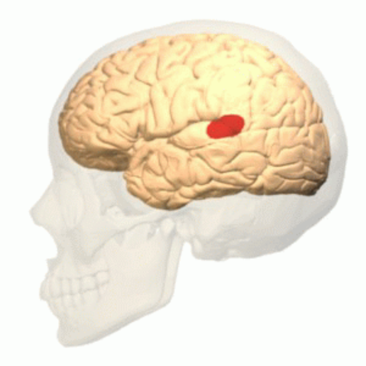
Source: wikipedia.org

Lesion studies:
What we can learn from brain injuries

Source: wikipedia.org

Carl Wernicke (1848-1905)
German physician, anatomist, psychiatrist and neuropathologist

study of receptive aphasia (1876):
- impaired **comprehension of written and spoken language** after injury to the **left superior temporal gyrus**
- However he could speak (made no sense)



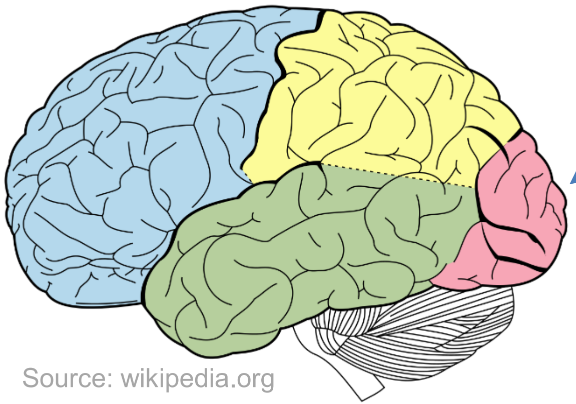
Source: wikipedia.org

-> Wernickes's area (important for speech comprehension)

Lesion studies:
What we can learn from brain injuries

Cortical blindness

total or partial loss of **vision** in a normal-appearing eye caused by damage to the **occipital cortex**

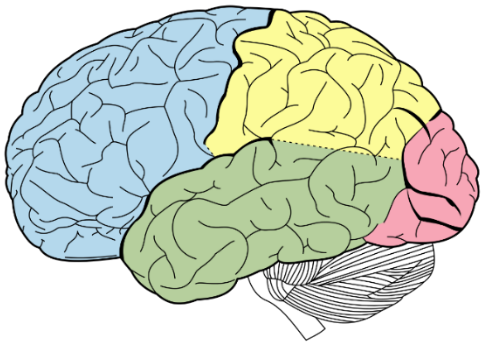


Source: wikipedia.org

- Inability to report visual stimuli
- But however sometimes people behave as if the have seen the object
- People report to see nothing but are able to point towards the stimulus

Lesion studies:
What we can learn from brain injuries

Cortical blindness



Source: wikipedia.org

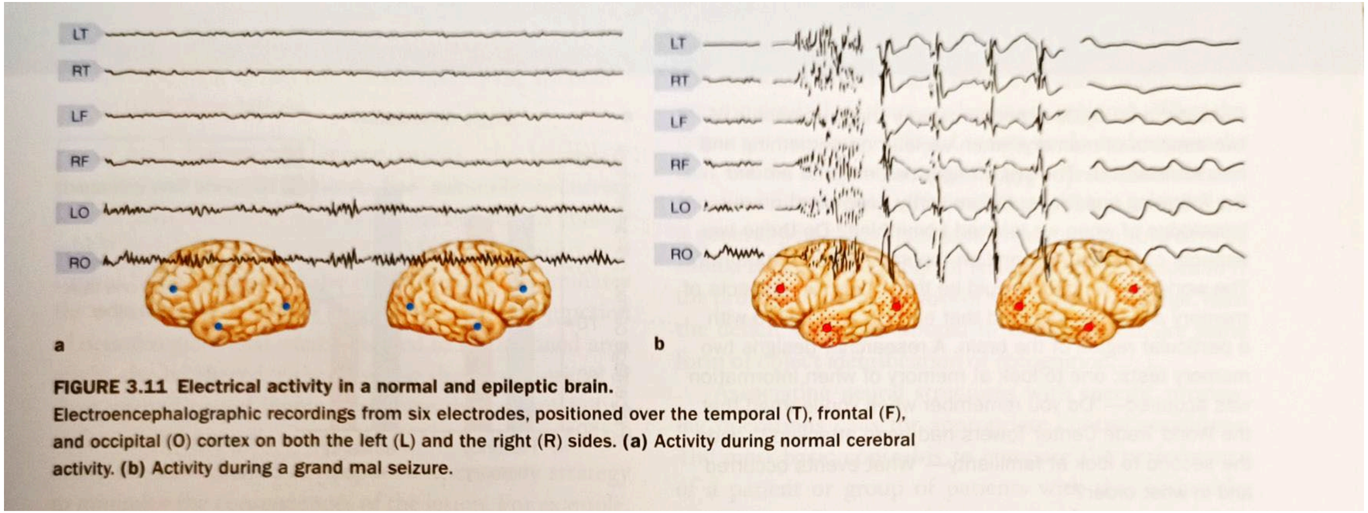
How is this possible?

- 10 different pathways from eye to the brain have been identified (most important pathway superior colliculus, lateral geniculate body, V1)
- Other routes are evolutionary more ancient
- These routes were not removed but further routes were added

Lesion studies
(brain surgeries, epilepsy)

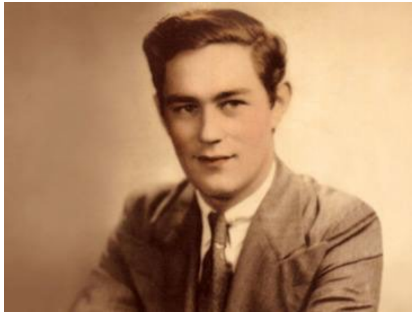
Epilepsy:

- Abnormal hyperactivity in the brain
- Leads to seizures -> loss of consciousness, shaking…
- Were often treated by lobectomies…. (lobectomy: resection of cortical lobe)
- After lobectomy -> scientific evaluation of the effects

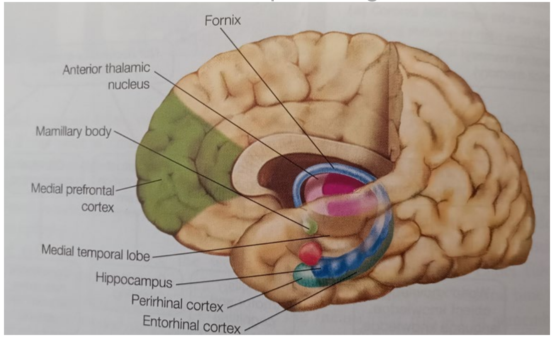


Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Lesion studies:
What we can learn from brain surgeries



Source: wikipedia.org



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Henry Gustav Molaison, known widely as patient **H.M.**
1926-2008

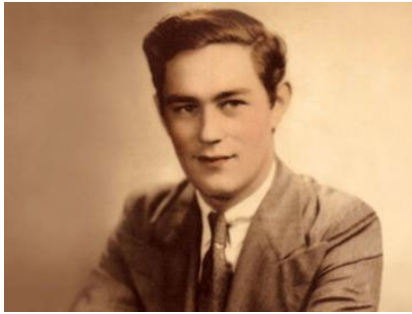
In 1953: bilateral medial temporal lobectomy:
surgical resection of the anterior two thirds of his hippocampi, parahippocampal cortices and entorhinal cortices
in an attempt to cure his epilepsy

Surgery was successful in controlling his epilepsy
severe side effect: he became unable to form new memories

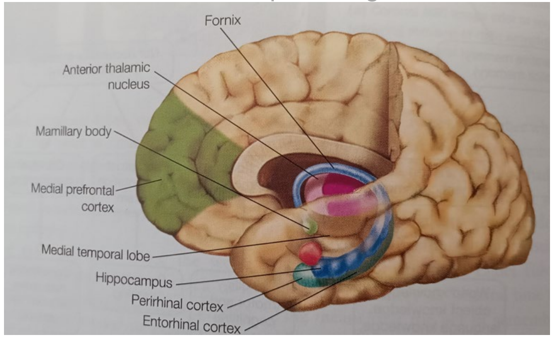
H.M. was widely studied from late 1957 until his death in 2008

Lesion studies:

What we can learn from brain surgeries



Source: wikipedia.org



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

His case played an important role in:

- development of theories that explain the link between brain function and memory
- development of cognitive neuropsychology branch of psychology that aims to understand how the structure and function of the brain relates to specific psychological processes

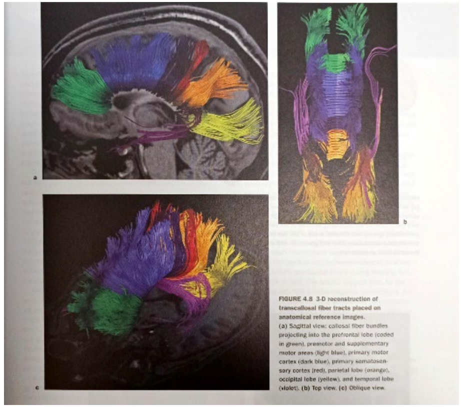
- Unable to form new explicit memories: experiences
- Only short-term memory of a few minutes
- Still able to learn new motor skills: playing an instrument

Lesion studies:

What we can learn from brain surgeries

Source: https://psych.ucsb.edu/people/michael-gazzaniga

Michael Gazzaniga, Professor of psychology born 1939

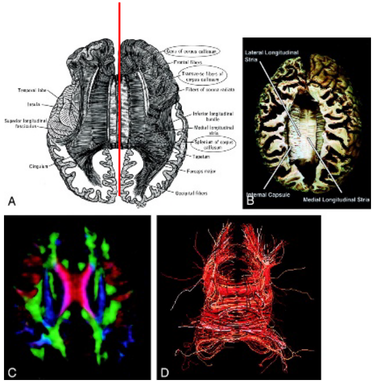


Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

one of the leading researchers in cognitive neuroscience and the study of the neural basis of mind

Split-brain patients:
Dissection of the corpus callosum to treat epilepsy

-> Patient W.J.

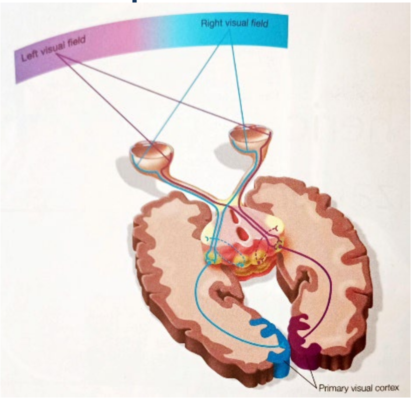


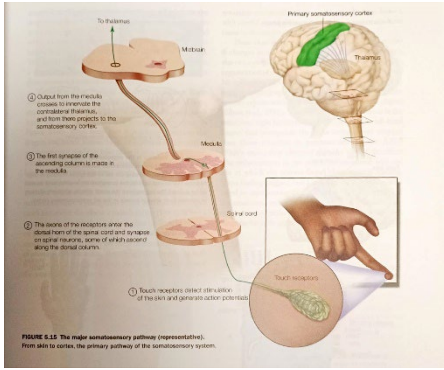
Jellison, B. J., Field, A. S., Medow, J., Lazar, M., Salamat, M. S., & Alexander, A. L. (2004). Diffusion tensor imaging of cerebral white matter: a pictorial review of physics, fiber tract anatomy, and tumor imaging patterns. *American Journal of Neuroradiology*, *25*(3), 356-369

Cut brain along medial longitudinal fissure

Patient W.J.

- World War II paratrooper who got hit in the head with a rifle butt, after which he started having seizures
- Before his operation to try to fix the seizures, Gazzaniga tested his brain functions
- presenting stimuli to the left and right visual fields and identifying objects in his hands that were out of view. W.J. was able to perform these tasks perfectly
- -> Dissection of the corpus callosum





Important: sensory and motor pathways cross in the brain
-> right visual field, right hand input -> processed in left cortex
-> left cortex controls right hand

Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

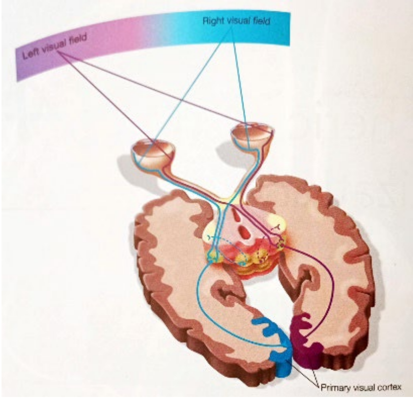
Patient W.J.

- After surgery: both hemispheres could not communicate with each other
- stimuli presented to the right visual field: could verbally report what he had seen
- stimuli presented to the left visual field: could not verbally report but press left button (right hemisphere)

-> lateralization of brain functions -> later in lecture

- conflicts between the hemispheres: left hand opens a door, right hand tries to stop left hand

Cognitive neuroscience,
Gazzaniga, Ivry, Mangun, 2014



Source: wikipedia.org

Antonio Damasio, Professor of psychology, philosophy, neurology
born 1944

- Created world‘s largest data base of brain injuries
- Identified brain regions crucial to maintain different degrees of consciousness
- Explores relationship between brain and consciousness
- Developed his own theory how consciousness emerges in the brain
- Damasio's research in neuroscience has shown that emotions play a central role in social cognition and decision-making

Non-invasive lesion studies

Transcranial magnetic stimulation (TMS)

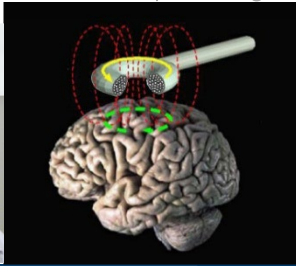
- **changing magnetic field used to cause electric current at a specific area of the brain through electromagnetic induction**
    - electric pulse generator connected to a magnetic coil, which is connected to the scalp
    - stimulator generates changing electric current within the coil which induces a transient magnetic field
    - magnetic field causes a second inductance of inverted electric charge within the brain itself -> hyperactivity -> area temporally switched off due to refractory period

- exact mechanisms of neural discharge not well understood

- used clinically to measure function of specific brain circuits in humans

- e.g. used to treat tinnitus

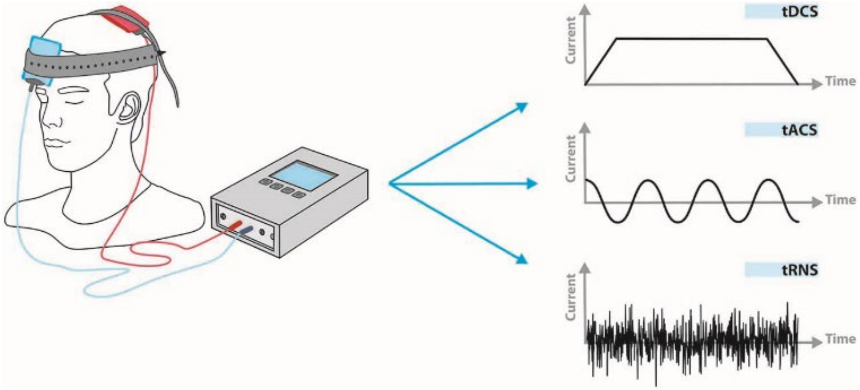
Source: wikipedia.org



Transcranial direct current stimulation (tDCS)

- Already the old Greeks used this method (electric torpedo fish) to numb people during and to alleviate pain during birth
- Today: two small electrodes (1-2mV)
- Neurons below the anode become depolarized -> more excitable
- Neurons below cathode become hyperpolarized -> less excitable
- Used to treat neurological conditions (e.g. chronic pain)

-> huge advantage of tDCS and TMS: people are their own control group



https://www.frontiersin.org/files/Articles/235394/fnhum-11-00159-HTML/image_m/fnhum-11-00159-g001.jpg

Lesion studies in animal experiments

- Frequently performed in animal experiments with cats or rodents
- Provides opportunity to systematically compare different lesions
- To draw conclusions about function of certain parts of the brain

Lesion studies in AI

PLOS | COMPUTATIONAL BIOLOGY

RESEARCH ARTICLE

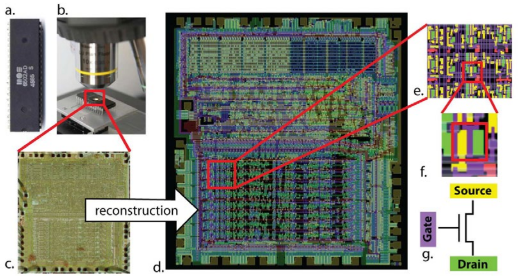
Could a Neuroscientist Understand a Microprocessor?

Eric Jonas[1]*, Konrad Paul Kording[2,3]

Jonas, E., & Kording, K. P. (2017). Could a neuroscientist understand a microprocessor?. *PLoS computational biology*, *13*(1), e1005268.

Lesion studies in AI

- Emulated micro-processor (MOS 6502) as model system -> used for Apple I, Commodore 64, Atari Video Game system
- Behavior of the model system -> Donkey Kong, Space invaders, Pitfall
- Perform experiments on this model



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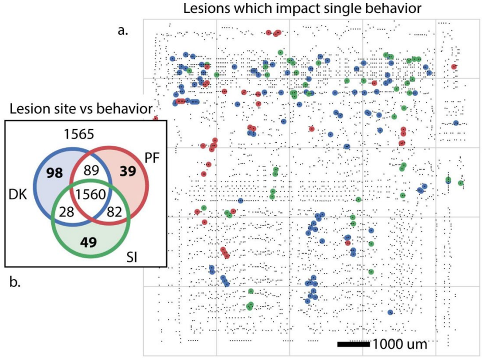
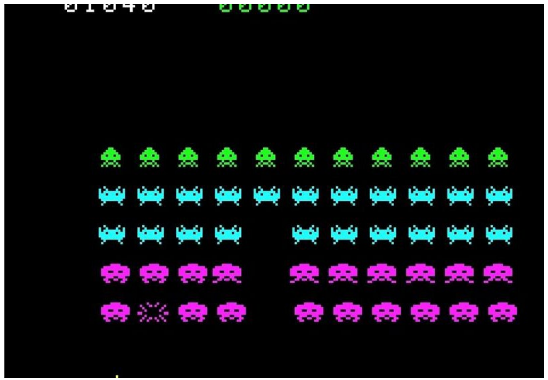


- Lesion each transistor individually
- In some cases the games do not boot



Jonas, E., & Kording, K. P. (2017). Could a neuroscientist understand a microprocessor?. *PLoS computational biology*, *13*(1), e1005268.

https://www.spiegel.de/geschichte/30-jahre-space-invaders-a-947371.html

Lesion studies in AI

- In contrast to biological brains, AI systems can be completely read out
- Location and expansion of lesion can be controlled

- Lesioning of individual neurons, connections or layers to reverse-engineer function of an artificial deep neural network

- However if lesion studies are the right way to unravel the brain/AI is questionable

PLOS | COMPUTATIONAL BIOLOGY

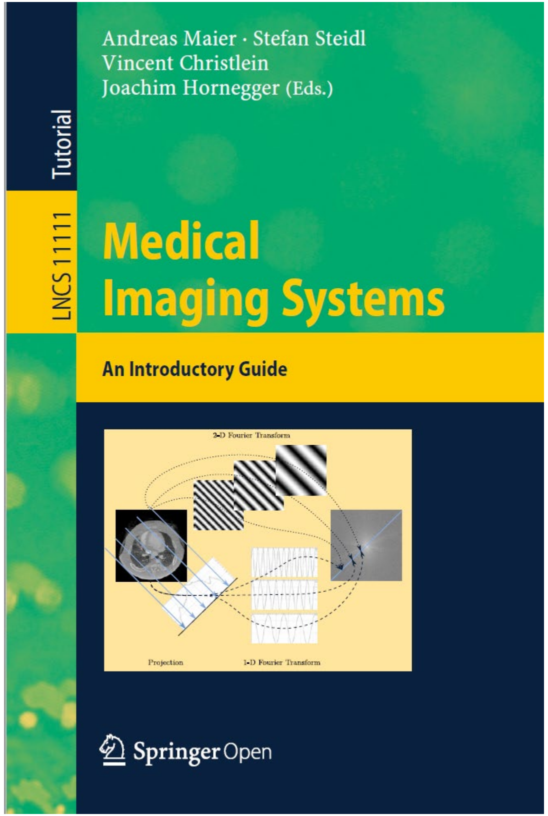
RESEARCH ARTICLE

Could a Neuroscientist Understand a Microprocessor?

Eric Jonas[1*], Konrad Paul Kording[2,3]

No!

Neuroimaging: Brain structure and function


Andreas Maier · Stefan Steidl
Vincent Christlein
Joachim Hornegger (Eds.)
Tutorial
LNCS 11111
Medical
Imaging Systems
An Introductory Guide
2-D Fourier Transform
Projection
1-D Fourier Transform
Springer Open

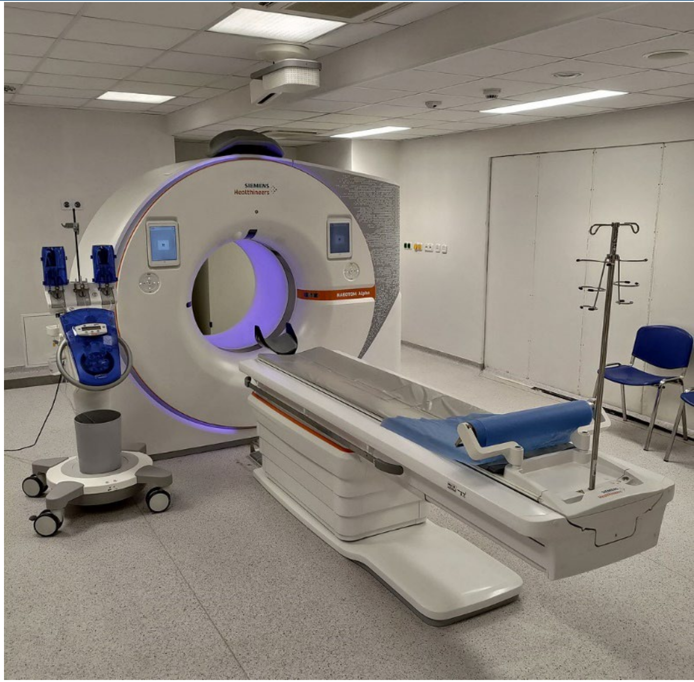
Methods to analyze Brain structure

Methods used to investigate Brain Structure

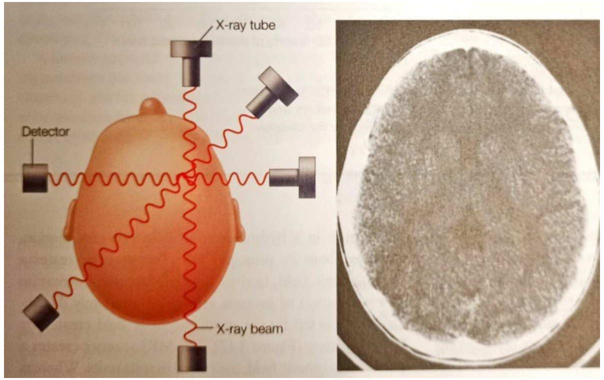
- Computed Tomography (CT)
- Magnetic Resonance Imaging (MRI)
- Diffusion Tensor Imaging (DTI, special form of MRI)
- Photo-Acoustic Imaging

Computed Tomography (CT)

- Commercially introduced in 1983
- Normal X-ray (Röntgen) -> 2D images
- Sensor and X-ray emitter rotate
- CT: Calculate 3D reconstruction from 2D images (spatial resolution: 0.5-1cm)



https://en.wikipedia.org/wiki/CT_scan#/media/File:Modern%C3%AD_v%C3%BDpo%C4%8Detn%C3%AD_tomografie_s_p%C5%99%C3%ADmo_digit%C3%A1ln%C3%AD_detekc%C3%AD_rentgenov%C3%A9ho_z%C3%A1%C5%99en%C3%AD.jpg

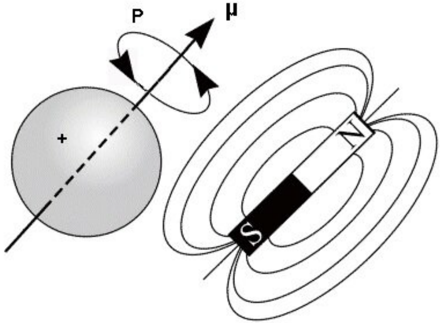


Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Magnetic Resonance Imaging (MRI)

- Far better spatial resolution than CT (below 1mm)
- Exploits the magnetic properties of protons (hydrogen ions in water)
- Protons have a spin -> small magnets

https://en.wikipedia.org/wiki/Magnetic_resonance_imaging#/media/File:Siemens_Magnetom_Aera_MRI_scanner.jpg



Costs around 1 Million $ per Tesla!

Sarracanie, M., LaPierre, C. D., Salameh, N., Waddington, D. E., Witzel, T., & Rosen, M. S. (2015). Low-cost high-performance MRI. *Scientific reports*, *5*(1), 15177.

Earth magnetic field: ~40μT

Grappone, J. M., Biggin, A. J., & Hill, M. J. (2019). Solving the mystery of the 1960 Hawaiian lava flow: implications for estimating Earth's magnetic field. *Geophysical Journal International*, *218*(3), 1796-1806.

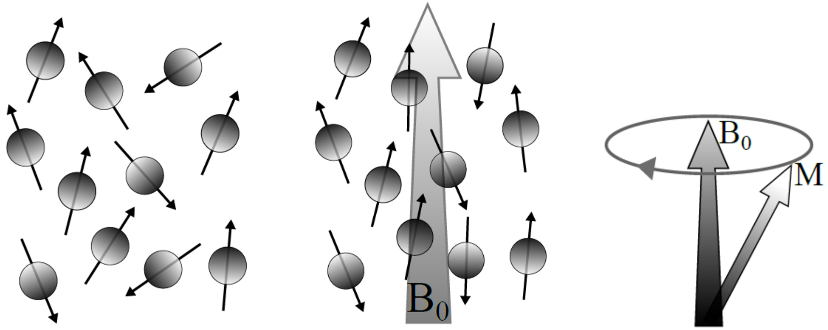
https://www.researchgate.net/publication/336777823_The_nuclear_magnetic_resonance_and_the_magnetic_resonance_imaging_process_Introducing_random_differential_equation_systems_for_Bloch_equations_model/figures?lo=1

Magnetic Resonance Imaging (MRI)- Step-by-Step

- 1.Step:
  - A huge magnetic field (**B0**) is applied (now up to 7T, Main Magnet)
  - Protons partially align in magnetic field B0 of scanner (for 1T only 3 of 1 Million)
  - Protons do not align instantaneously
  - Precession of net magnetization M (M: sum of all aligned protons) around B0

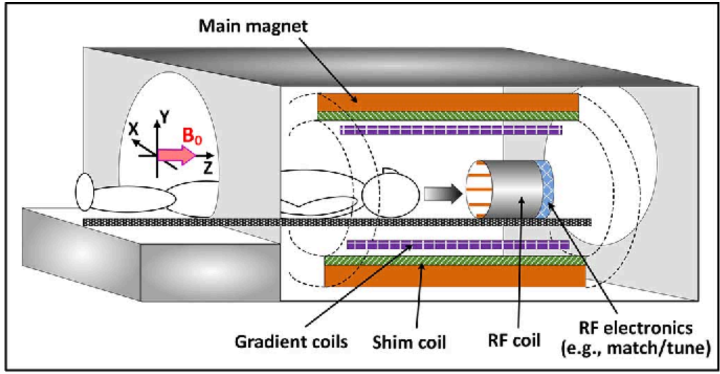
$$f_\ell = \gamma \cdot \|B_0\|$$

Frequency of precession: **Larmor Frequency**



(a) Random spins (b) Partially aligned spins (c) Precession

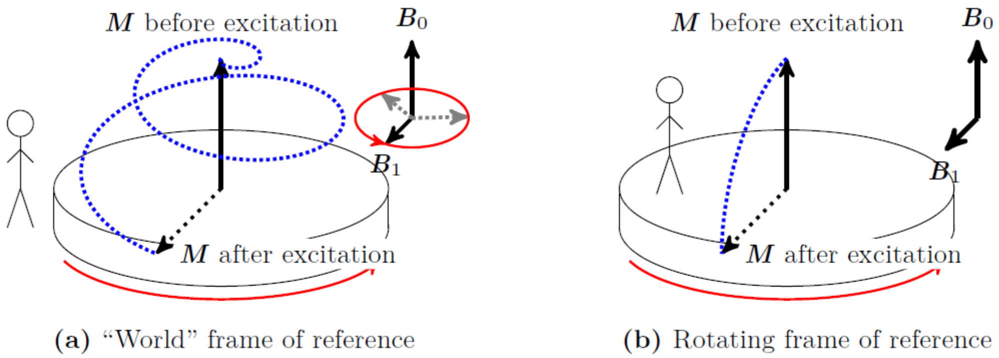
Maier, A., Steidl, S., Christlein, V., & Hornegger, J. (Eds.). (2018). Medical imaging systems: An introductory guide.



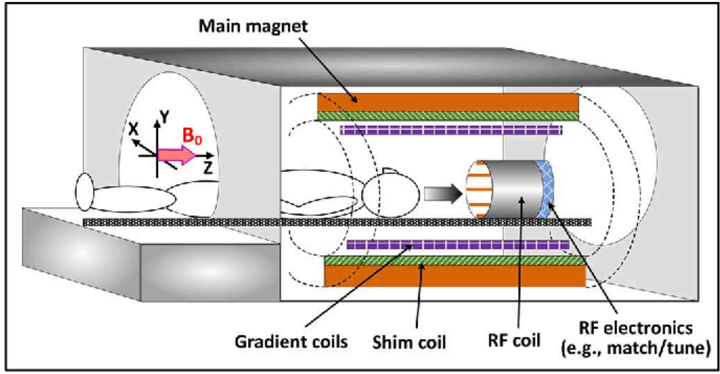
Sohn, S. M., DelaBarre, L., Gopinath, A., & Vaughan, J. T. (2014). RF head coil design with improved RF magnetic near-fields uniformity for magnetic resonance imaging (MRI) systems. *IEEE transactions on microwave theory and techniques*, *62*(8), 1784-1789.

Magnetic Resonance Imaging (MRI)- Step-by-Step

- 2 .Step:
    - Excitation of the aligned magnets
    - B1 is applied (magnetic field orthogonal to B0 and resonance frequency of M)



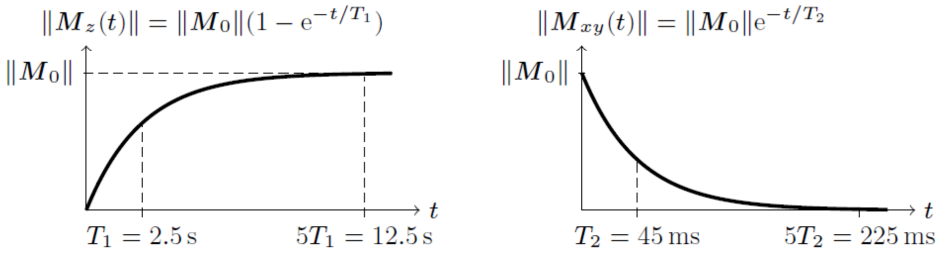
Maier, A., Steidl, S., Christlein, V., & Hornegger, J. (Eds.). (2018). Medical imaging systems: An introductory guide.



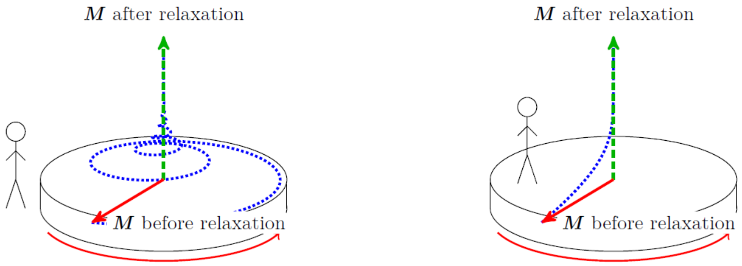
Sohn, S. M., DelaBarre, L., Gopinath, A., & Vaughan, J. T. (2014). RF head coil design with improved RF magnetic near-fields uniformity for magnetic resonance imaging (MRI) systems. *IEEE transactions on microwave theory and techniques*, *62*(8), 1784-1789.

Magnetic Resonance Imaging (MRI)- Step-by-Step

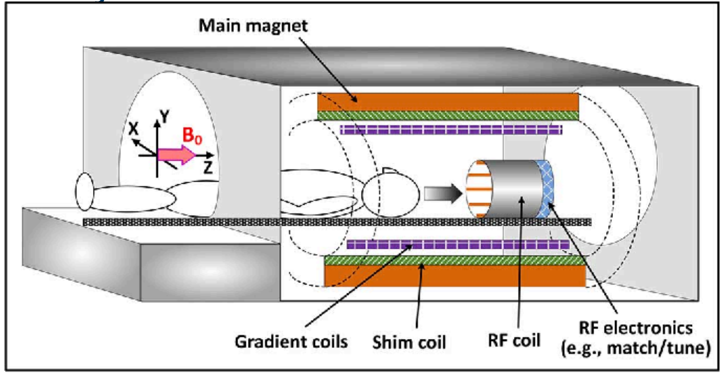
- 3 .Step:
  - B1 is turned of
  - M realigns with B0 -> relaxation
  - T1: Time it takes to re-increase the z-component of the net magneti-zation Mz
  - T2: time it takes to re-decrease the xy-component of Mxy



(a) Longitudinal magnetization recovery **(b)** Transverse magnetization decay



(a) "World" frame of reference **(b)** Rotating frame of reference



Maier, A., Steidl, S., Christlein, V., & Hornegger, J. (Eds.). (2018). Medical imaging systems: An introductory guide.

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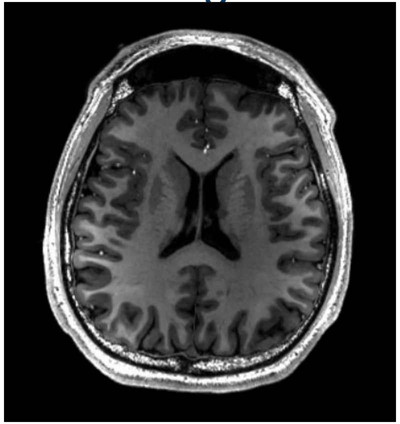
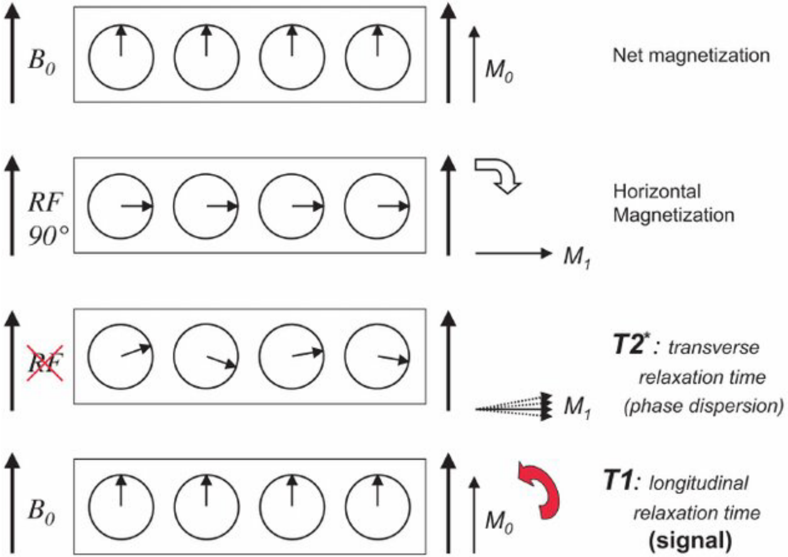
Magnetic Resonance Imaging (MRI)- Simple Summary

- 1) Protons align in magnetic field of scanner
- 2) Protons are disturbed by radio waves (RF coil)
- 3) Protons re-align in magnetic field and emit energy via radiation (RF coil switched off)
- 4) Sensor detects the radiation emitted

  by the change of orientation of proton spins



https://en.wikipedia.org/wiki/Magnetic_resonance_imaging_of_the_brain#/media/File:MRI_of_Human_Brain.jpg



https://www.researchgate.net/publication/228686551_Principles_of_Functional_Magnetic_Resonance_Imaging_and_its_Applications_in_Cognitive_Neuroscience/figures?lo=1

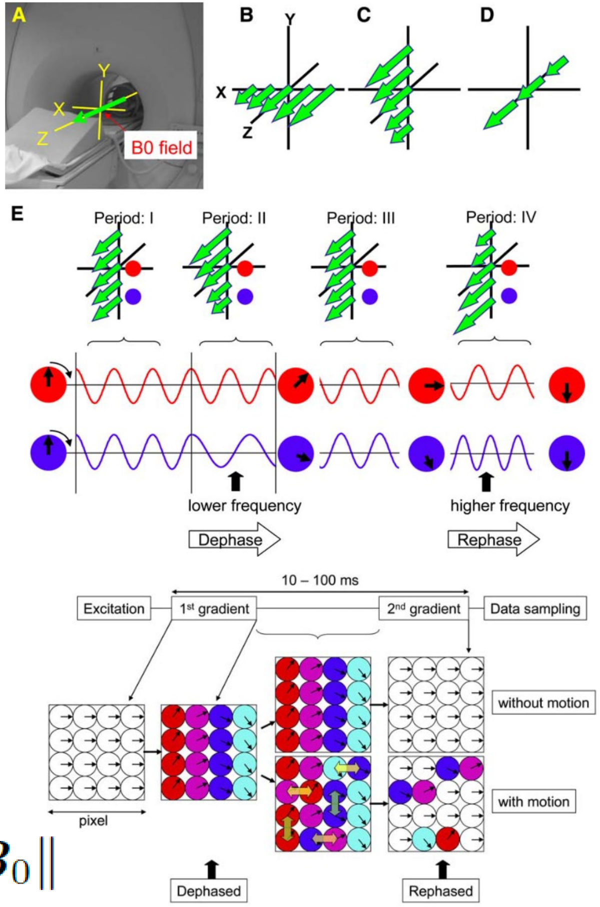
Diffusion Tensor Imaging (MRI)

- Measure the motion of water contained in axons
- Used to unravel the wiring scheme of the brain (connectome)

Idea (just an overview):

- **1)** Change the precessing frequency (Larmor frequency) by magnetic field gradient -> dephase protons
- **2)** Magnetic field gradient in opposite direction -> rephase protons (only if they did not move) -> signal change shows movement of protons

- Diffusion of water in brain is not isotropic because myelinated axons restrict the diffusion of water

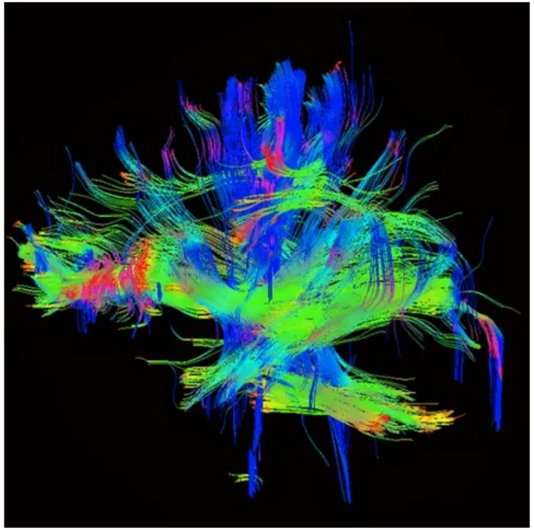


$$f_\ell = \gamma \cdot \|B_0\|$$

Mori, S., & Zhang, J. (2006). Principles of diffusion tensor imaging and its applications to basic neuroscience research. *Neuron*, *51*(5), 527-539.

O'Donnell, L. J., & Westin, C. F. (2011). An introduction to diffusion tensor image analysis. *Neurosurgery Clinics*, *22*(2), 185-196.

Diffusion Tensor Imaging (MRI)

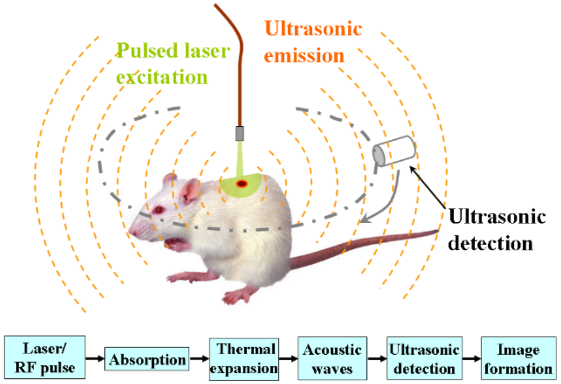


- Calculate a 3D diffusion tensor
- Colors represent the direction of major eigen-vector of the diffusion tensor
- White matter tracts (including injuries) of brain can be shown

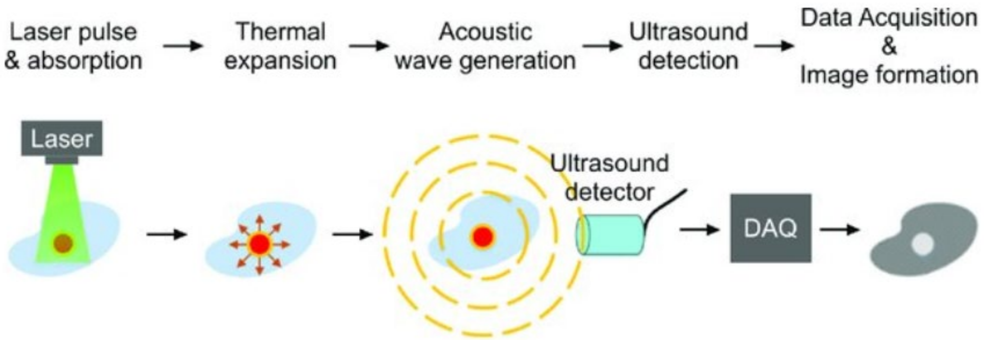
https://www.siemens-healthineers.com/magnetic-resonance-imaging/options-and-upgrades/clinical-applications/syngo-dti-tractography

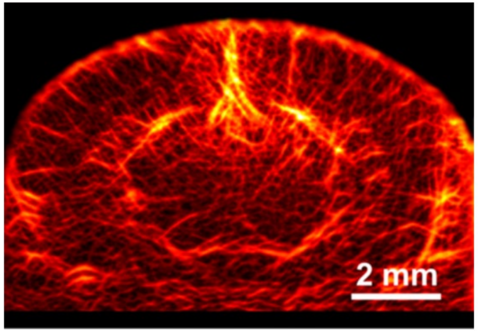
Photo-Acoustic Imaging (Opto-Acoustic Imaging)

- Absorption of laser pulse in tissue
- Thermal expansion -> sound wave
- Ultra-sound detector receives sound waves
- Could already be used to track brain function (blood flow etc.)



https://en.wikipedia.org/wiki/Photoacoustic_imaging#/media/File:PASchematics_v2.png





https://www.researchgate.net/publication/334706068_Review_of_Cost_Reduction_Methods_in_Photoacoustic_Computed_Tomography/figures?lo=1

Steinberg, I., Huland, D. M., Vermesh, O., Frostig, H. E., Tummers, W. S., & Gambhir, S. S. (2019). Photoacoustic clinical imaging. *Photoacoustics*, *14*, 77-98.

Zhang, P., Li, L., Lin, L., Hu, P., Shi, J., He, Y., ... & Wang, L. V. (2018). High-resolution deep functional imaging of the whole mouse brain by photoacoustic computed tomography in vivo. *Journal of biophotonics*, *11*(1), e201700024.

Methods to analyze Brain processes (function)

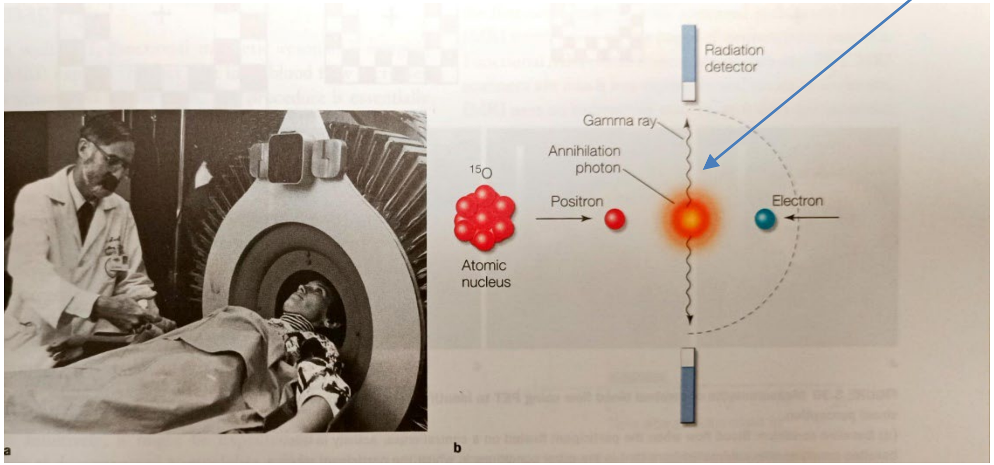
Methods used to investigate Brain Function

- EEG, MEG, Single Cell Recordings etc. -> electrophysiology lecture -> good temporal resolution but bad spatial resolution
- Positron Emission Tomography (PET)
- Functional Magnetic Resonance Imaging (fMRI)
- Functional Near Infrared Spectroscopy (fNIRS)

Positron Emission Tomography (PET)

- Measure local variations in cerebral blood flow
- Radioactive “tracer” is injected (^{15}O)-> decays and emits positron
- Positron annihilates with electron -> two photons (gamma rays) are produced
- Photons are measured in gamma ray detector
- LOR: Line of response

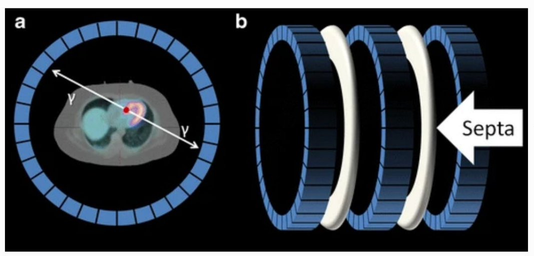
LOR



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Positron Emission Tomography (PET): Reconstruction

- Better detectors were developed -> higher efficiency and better spatial resolution
- 2D->3D System -> coincidence events can be detected across several detector rings
- Time of flight analysis was introduced (TOF) -> Where did event occur along the LOR



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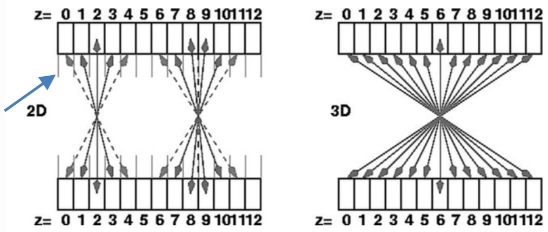
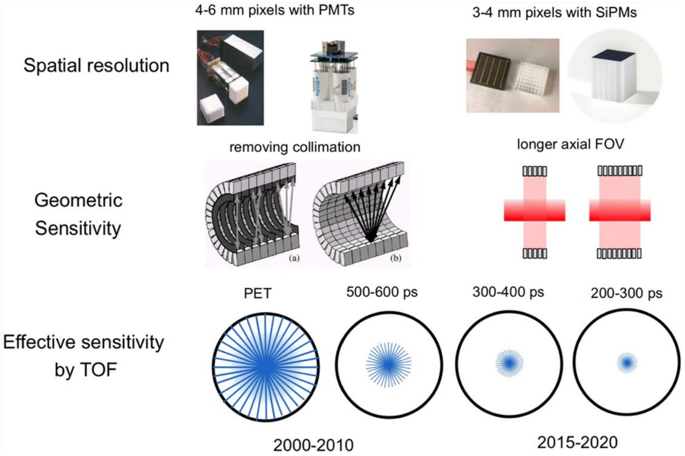


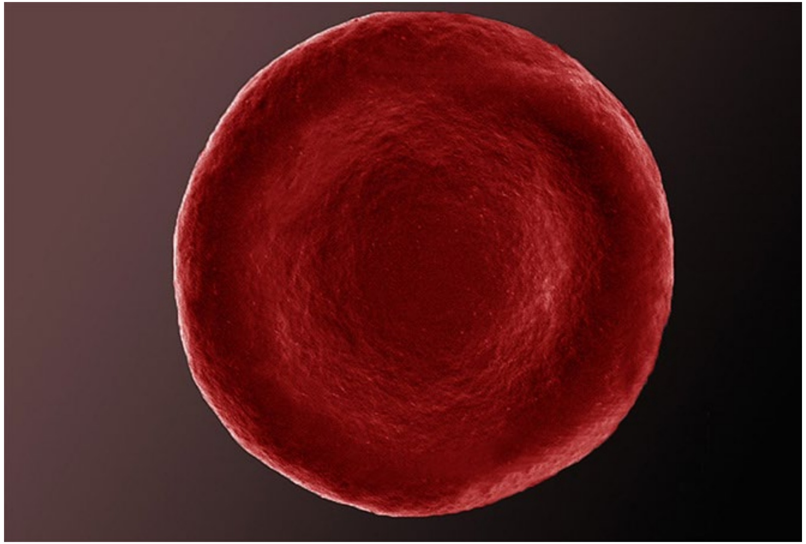
Volkow, N. D., Mullani, N. A., & Bendriem, B. (1988). Positron emission tomography instrumentation: an overview. *American journal of physiologic imaging*, *3*(3), 142-153.



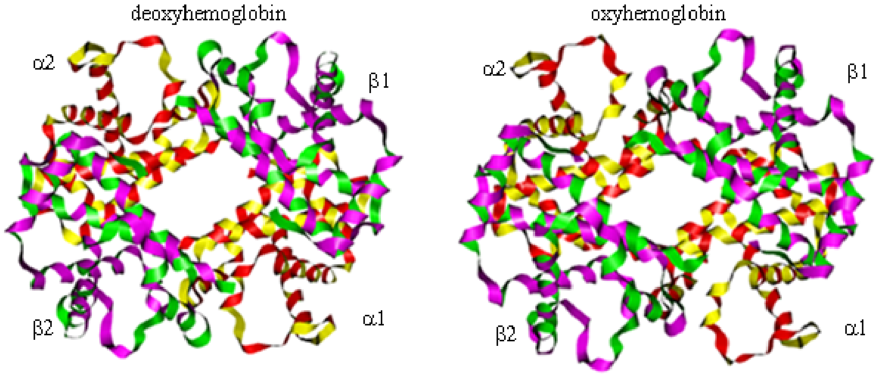
Vandenberghe, S., Moskal, P., & Karp, J. S. (2020). State of the art in total body PET. *EJNMMI physics*, *7*, 1-33.

Functional Magnetic Resonance Imaging (fMRI)

- Principle is similar as for MRI
- Exploits the magnetic properties of the blood pigment (hemoglobin) of the blood cells
- Hemoglobin transports oxygen in blood
- Hemoglobin with oxygen (HbO_2) and no oxygen (Hb)



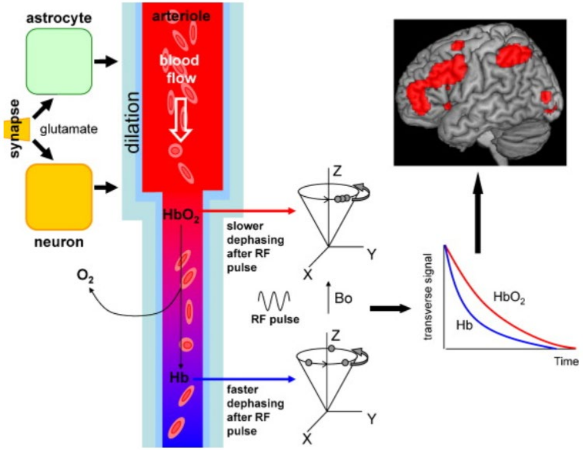
https://www.cell.com/pictureshow/erythrocytes

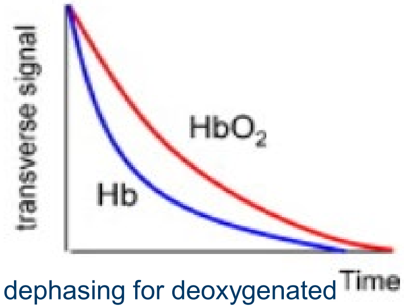


Meiyappan, S., Raghavan, R., Viswanathan, R., Yu, Y., & Lawton, W. (1999). Proteinmorphosis: A mechanical model for protein conformational changes. In *Biocomputing'99* (pp. 341-353).

Functional Magnetic Resonance Imaging (fMRI)

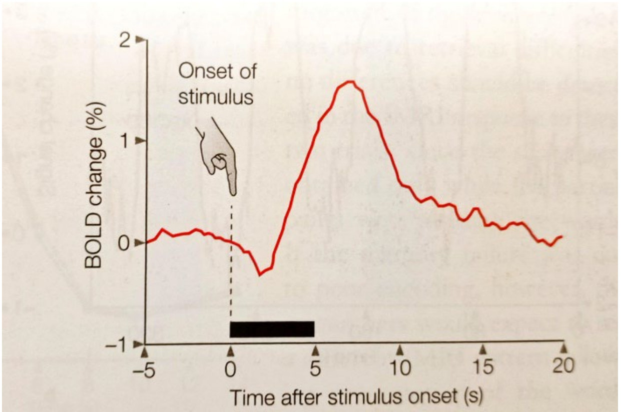
- Deoxygenated hemoglobin is paramagnetic oxygenated not
- Higher T2 value for oxygenated hemoglobin (transverse magnetization)
- Typical BOLD response:
    - Step 1) energy consumption (Hb)
    - Step 2) new oxygenated blood arrives (HbO_2)





Faster dephasing for deoxygenated hemoglobin, magnetic field inhomogeneities because of paramagnetic properties

Harris, J. J., Reynell, C., & Attwell, D. (2011). The physiology of developmental changes in BOLD functional imaging signals. *Developmental cognitive neuroscience*, *1*(3), 199-216.



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Functional Magnetic Resonance Imaging (fMRI): Limitations

- Advantage: Has a good spatial resolution (~1mm)
- Disadvantages: Metabolic Signal (blood oxygenation), bad temporal resolution
- -> difficult to do experiments with fast occurring stimuli such as speech
- Some approaches exist to use fMRI for research on language processing -> it is necessary to carefully consider the limitations of that technique

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DATA DESCRIPTOR

A natural language fMRI dataset for voxelwise encoding models

Amanda LeBel[1], Lauren Wagner[2], Shailee Jain[3], Aneesh Adhikari-Desai[3,4], Bhavin Gupta[3], Allyson Morgenthal[4], Jerry Tang[3], Lixiang Xu[5] & Alexander G. Huth[3,4]

articles

Neurophysiological investigation of the basis of the fMRI signal

Nikos K. Logothetis, Jon Pauls, Mark Augath, Torsten Trinath & Axel Oeltermann

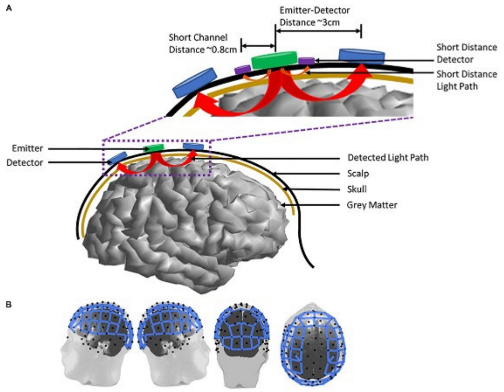
Max Planck Institute for Biological Cybernetics, Spemannstrasse 38, 72076 Tuebingen, Germany

Control experiments:

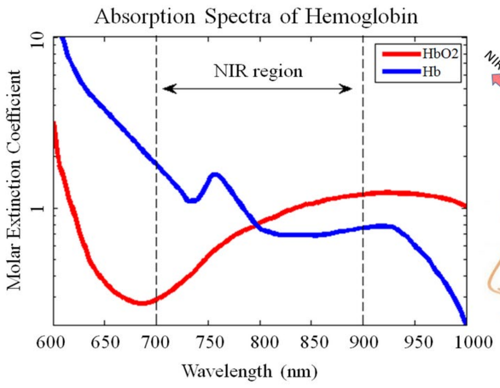
- Combined Intracranial recordings and fMRI
- fMRI reflects well the overall activity of the neurons
- Low-passed filtered version of it

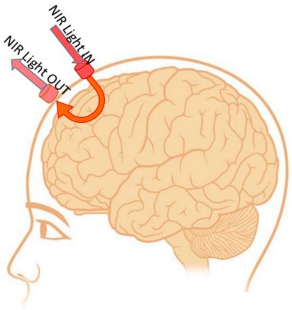
Functional Near Infrared Spectroscopy (fNIRS):

- Measures also the fraction of oxygenated and deoxygenated hemoglobin -> not via magnetic properties
- Infrared emitter shines near infrared light (700 nm-900nm) through the skull which is refracted at brain
- Skull and skin is transparent for this wavelengths
- Light is absorbed by hemoglobin depending on oxygenation



Chen, W. L., Wagner, J., Heugel, N., Sugar, J., Lee, Y. W., Conant, L., ... & Whelan, H. T. (2020). Functional near-infrared spectroscopy and its clinical application in the field of neuroscience: advances and future directions. *Frontiers in neuroscience*, *14*, 724.





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Conclusion

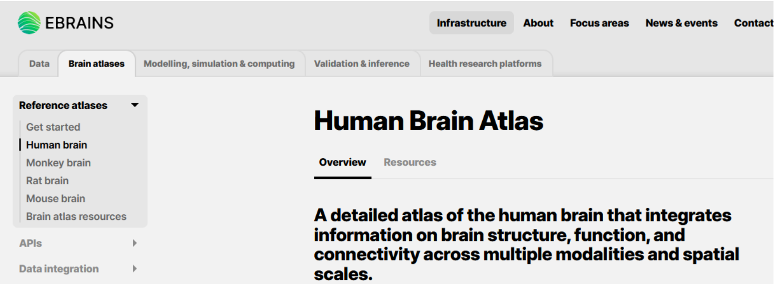
Feature	EEG	MEG	ECoG	Intracortical Recording	fMRI	fNIRS	PET
Activity type	Electrical	Magnetic	Electrical	Electrical	Metabolic	Metabolic	Metabolic
Measurement type	Direct	Direct	Direct	Direct	Indirect	Indirect	Indirect
Invasiveness	Non-invasive	Non-invasive	Invasive	Invasive	Non-invasive	Non-invasive	Invasive
Portability	Yes	No	Yes	Yes	No	Yes	No
Temporal resolution	~ 0.05 s	~ 0.05 s	~ 0.003 s	~ 0.003 s	~ 1 s	~ 1 s	1–2 min
Spatial resolution	~ 10 mm	~ 5 mm	~ 1 mm	~ 0.5 mm (LFP) ~ 0.1 mm (MUA) ~ 0.05 mm (SUA)	~ 1 mm	~ 5 mm	~ 4 mm
BCI applicability	Acceptable spatio-temporal resolution with high-density electrodes	Mobility constraint	Unfavorable for healthy BCI users	Unfavorable for healthy BCI users	Slow and mobility constraint	Slow, but mobile and a potential alternative to fMRI	Limited potentiality

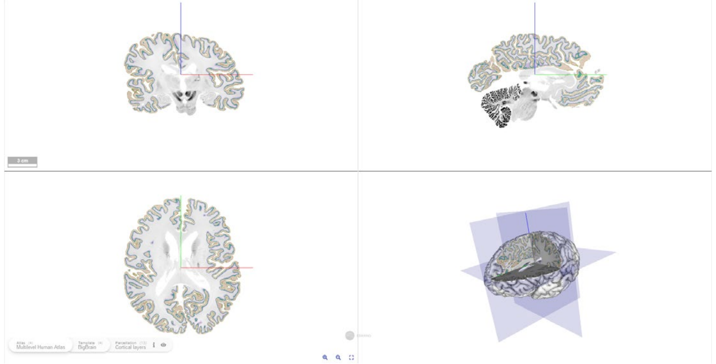
EEG, electroencephalography; MEG, magnetoencephalography; ECoG, electrocorticography; fMRI, functional magnetic resonance imaging; fNIRS, functional near infrared spectroscopy; PET, positron emission tomography.

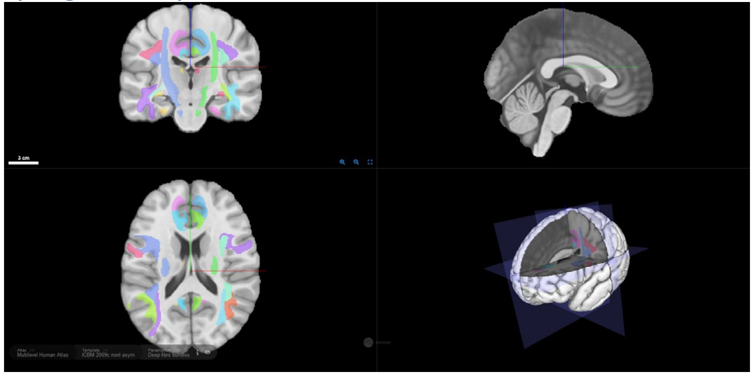
Saha, S., Mamun, K. A., Ahmed, K., Mostafa, R., Naik, G. R., Darvishi, S., ... & Baumert, M. (2021). Progress in brain computer interface: Challenges and opportunities. *Frontiers in Systems Neuroscience*, *15*, 578875.

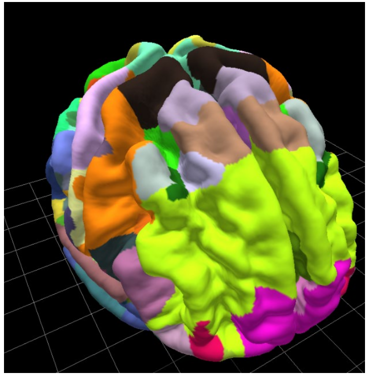
Essence of many different imaging techniques to from an open Brain Atlas

- Human Brain Project: EU Flagship Initiative -> brings together heterogeneous neuroscience data from different imaging techniques
- Provide information of cyto-architectonics and different neuroimaging techniques (e.g. DTI)









https://www.humanbrainproject.eu/en/science-development/focus-areas/brain-atlases/

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