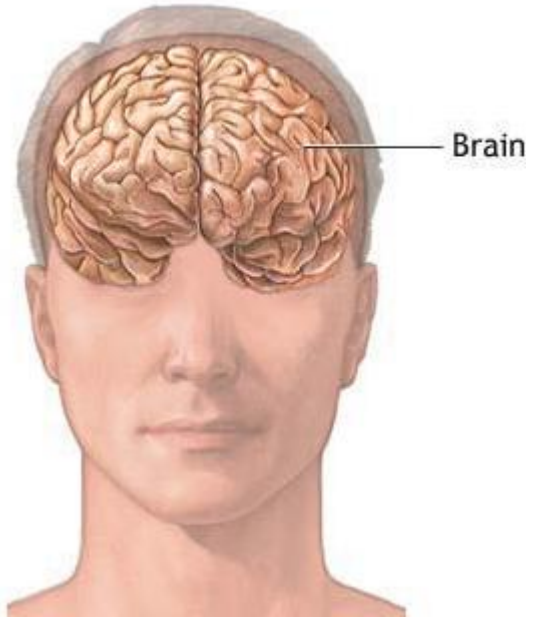
Medical/Bio Research Topics Ⅰ: Week 02 (11 March 2025)

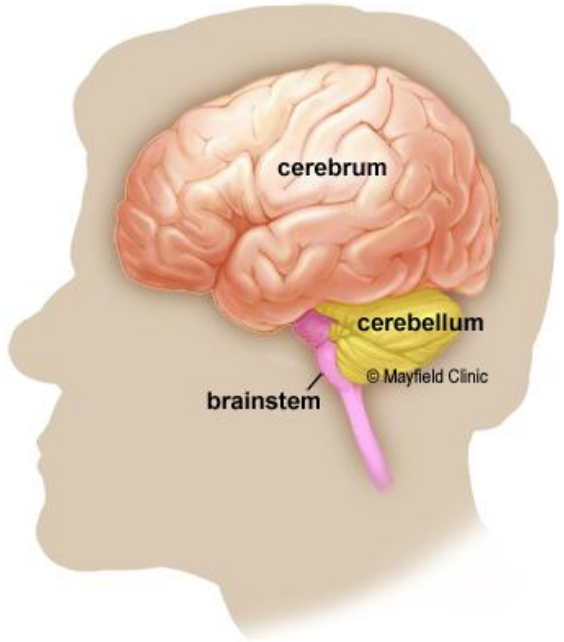
Introduction to Brain Imaging

뇌영상 소개

Brain

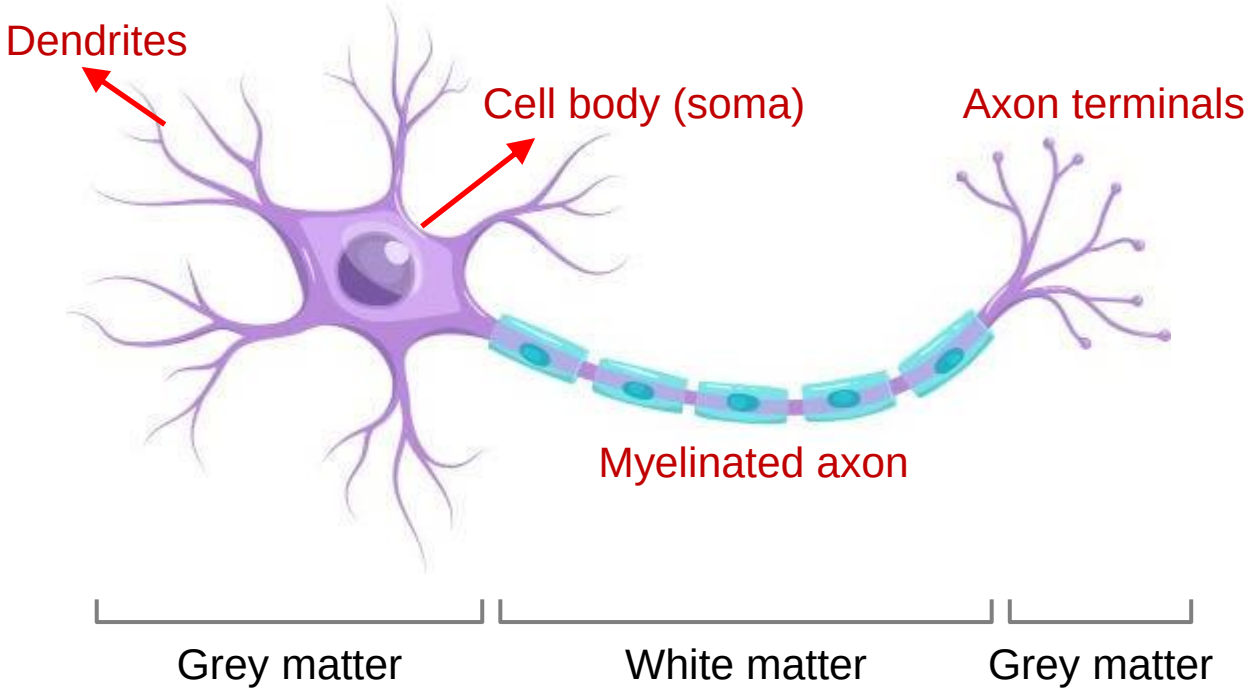
- Centre of the nervous system located in the head

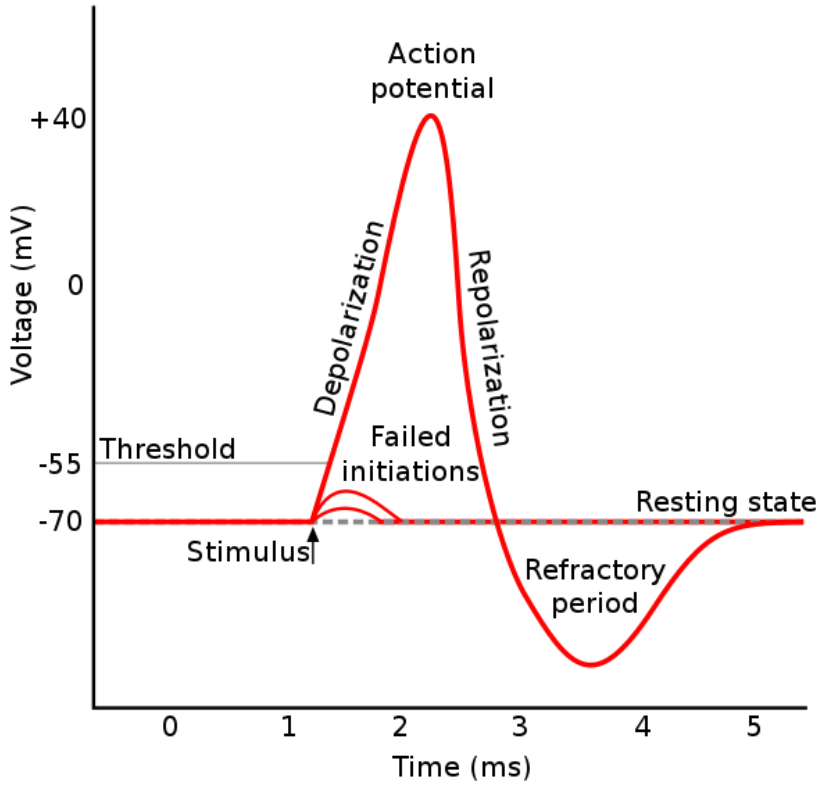




[https://medlineplus.gov/ency/imagepages/8738.htm;
https://mayfieldclinic.com/pe-anatbrain.htm]

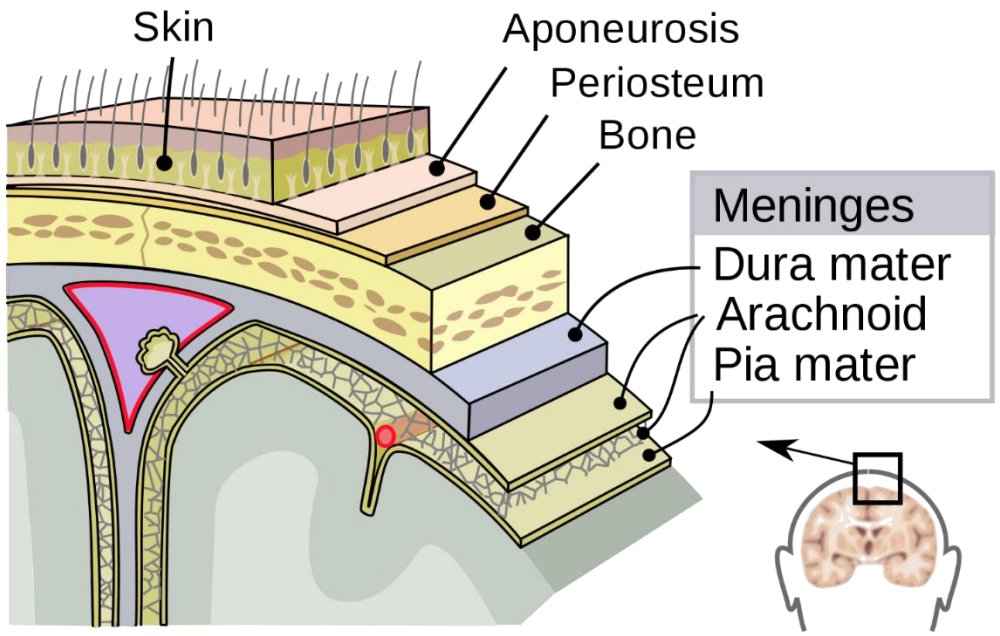
- Composed of tens of billions of neurons
  - Interconnected neurons communicate with each other by axons

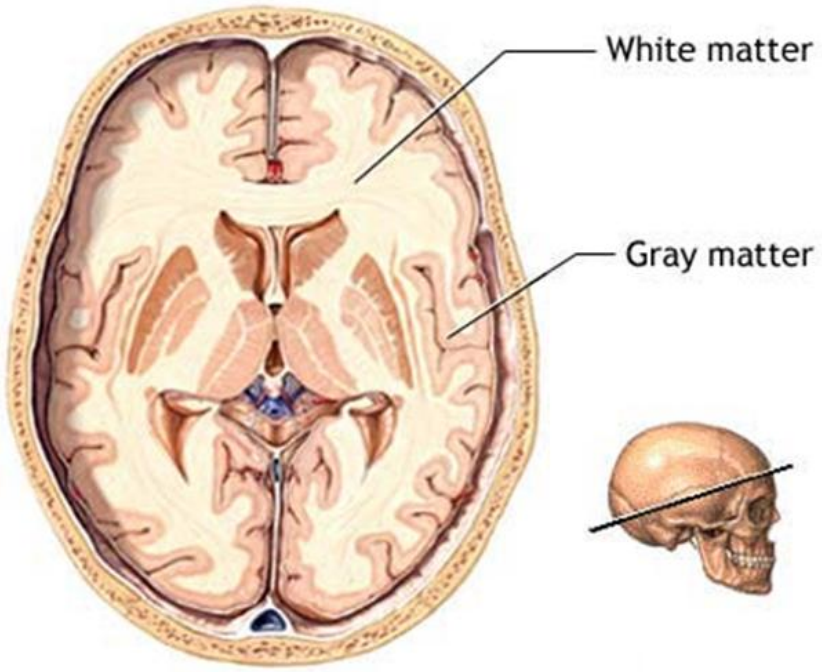




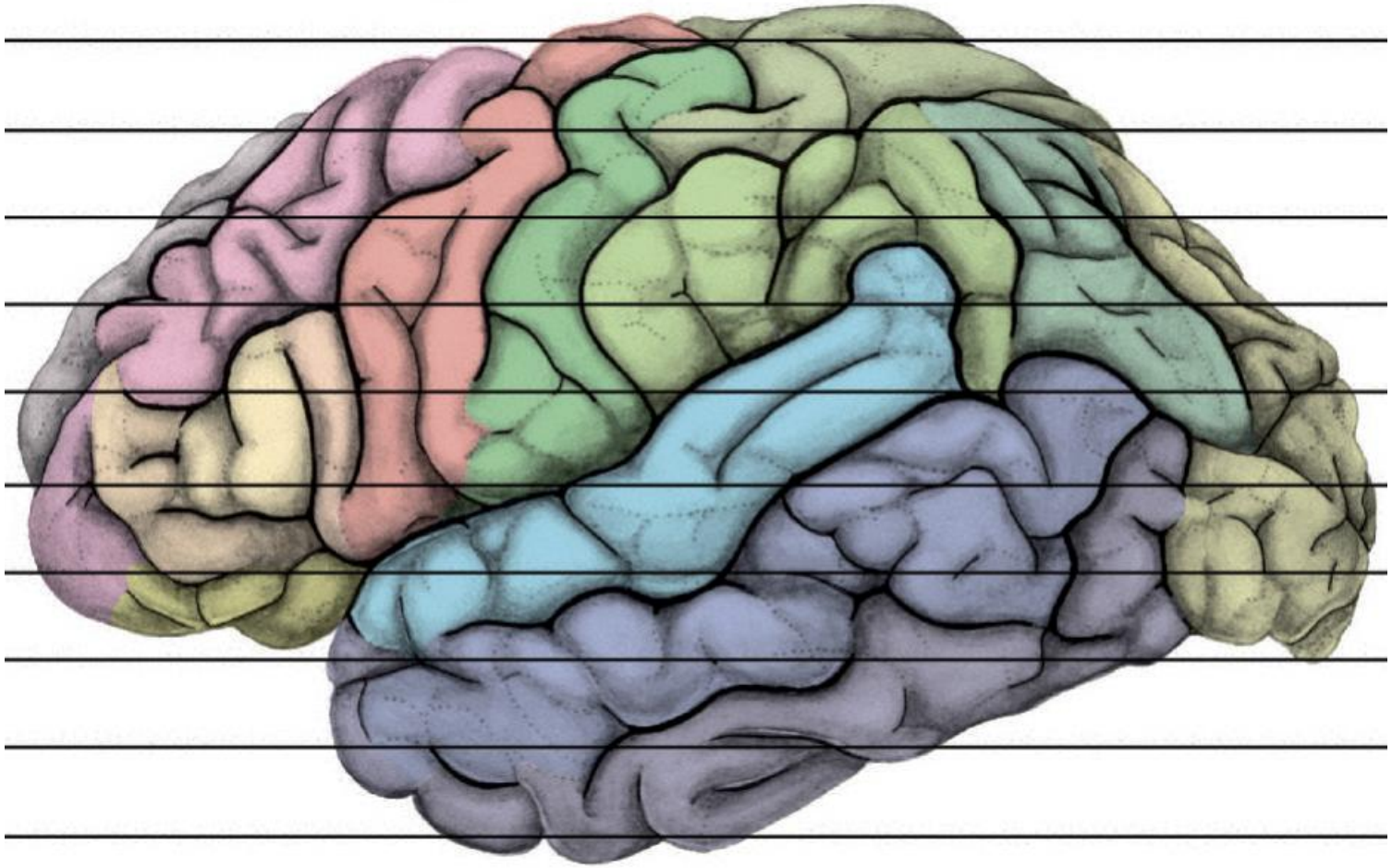
[https://en.wikipedia.org/wiki/Action_potential]

- Anatomy of the brain





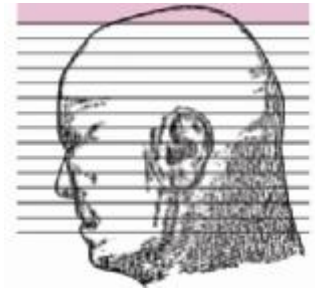
[https://www.physio-pedia.com/Meninge; https://medlineplus.gov/ency/imagepages/18117.htm]

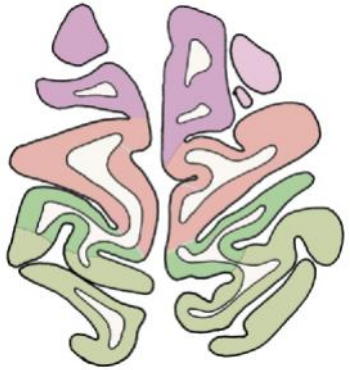


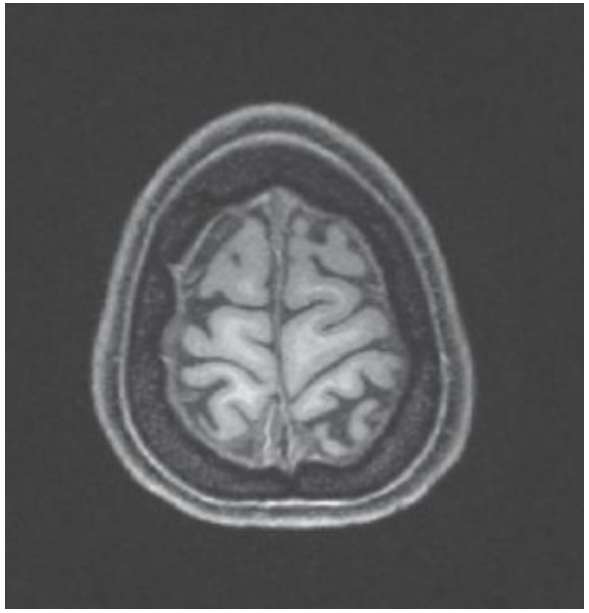
[Mai et al., 2015]

Horizontal (Transverse) Slices of the Brain

Slice 1

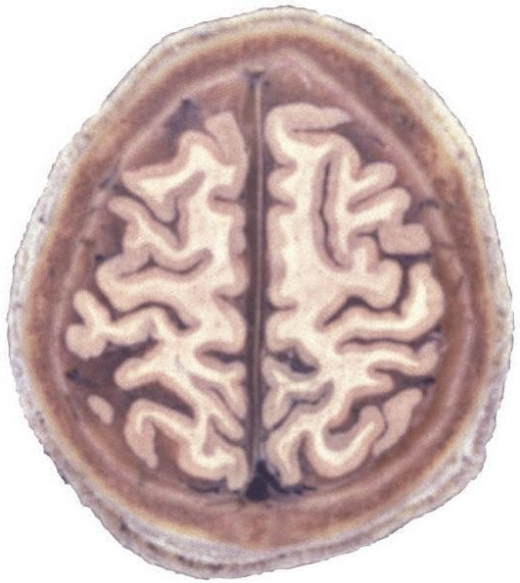


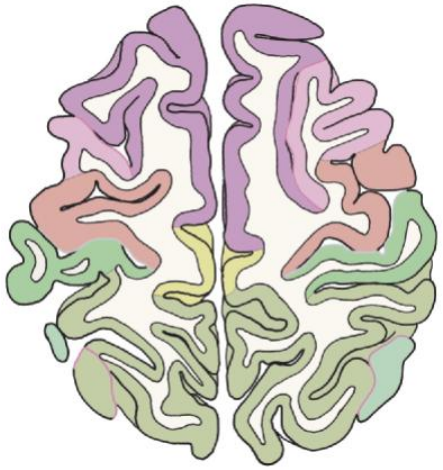


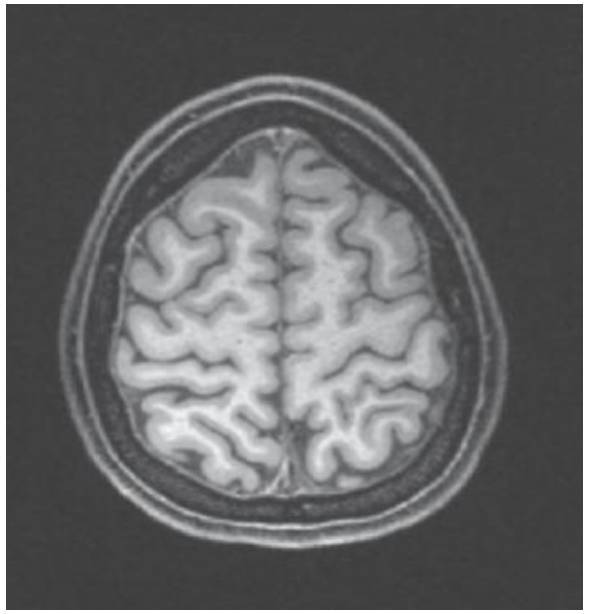


[Mai et al., 2015]

Slice 2

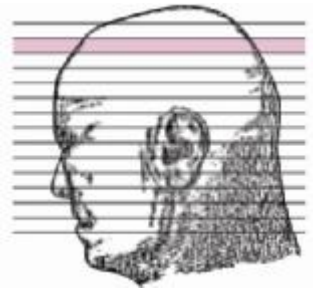


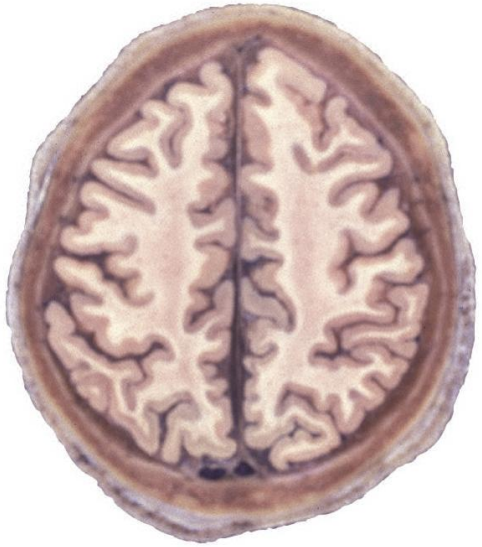


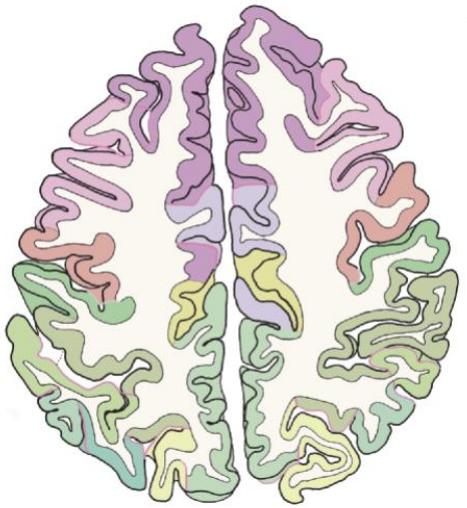


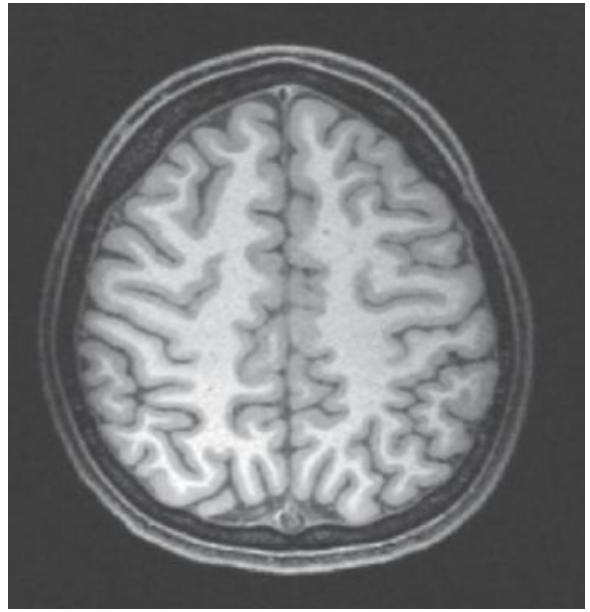
[Mai et al., 2015]

Slice 3



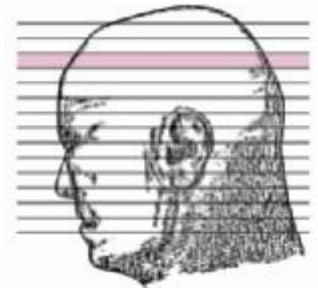


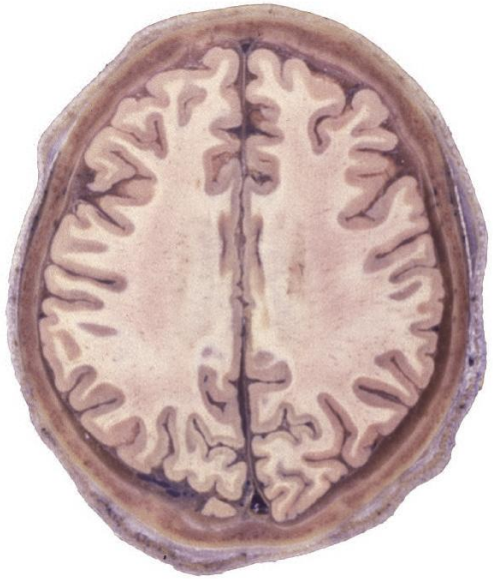


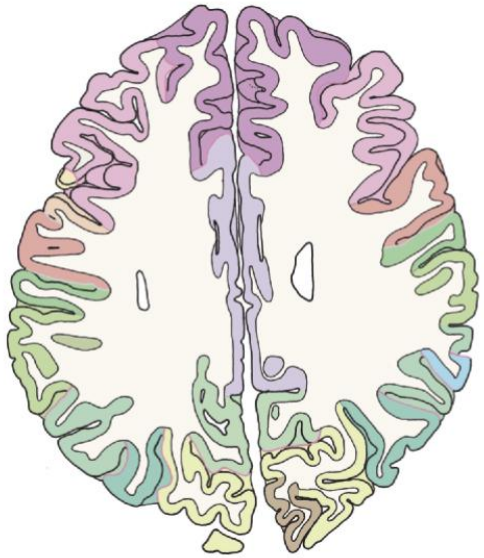


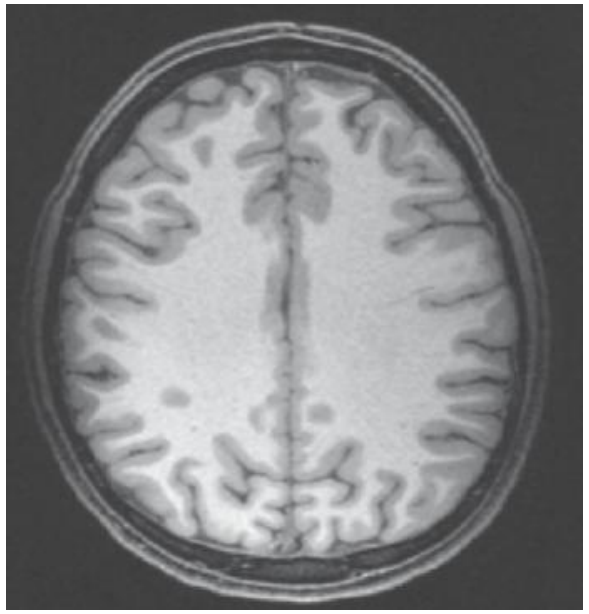
[Mai et al., 2015]

Slice 4



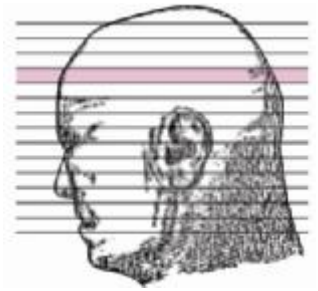


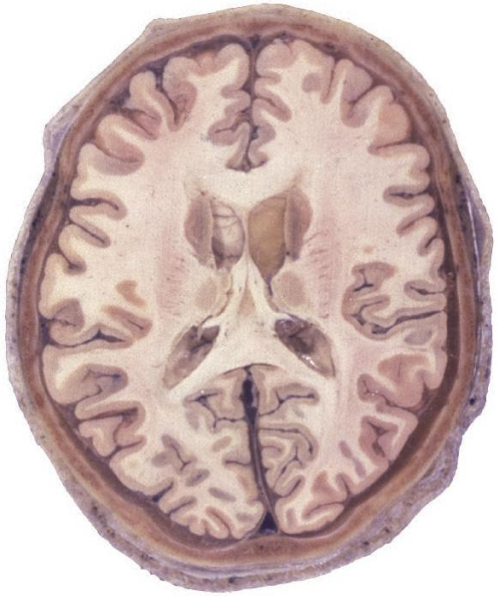


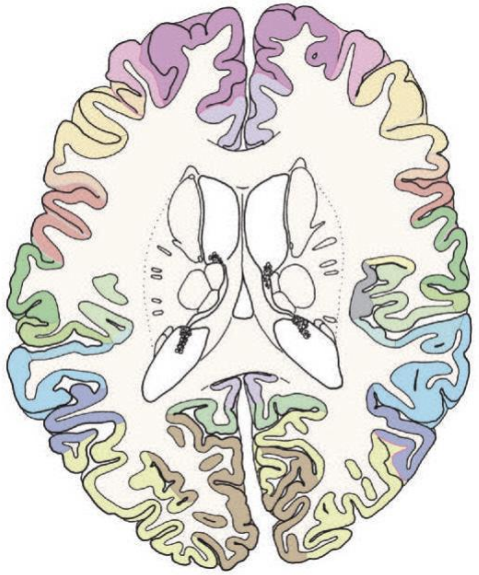


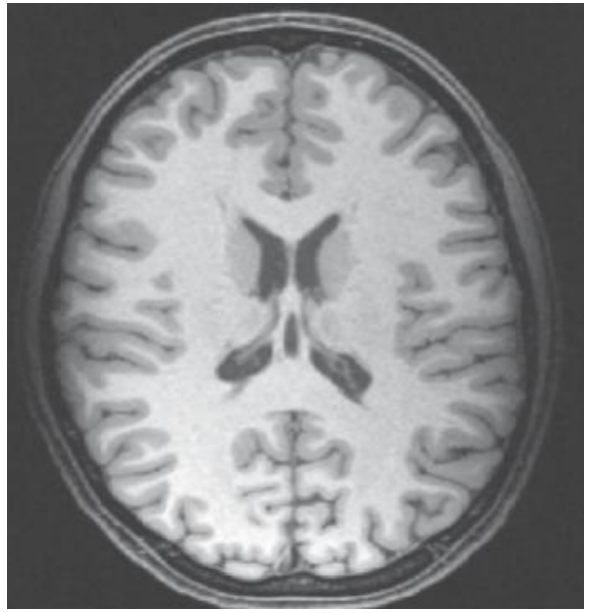
[Mai et al., 2015]

Slice 5



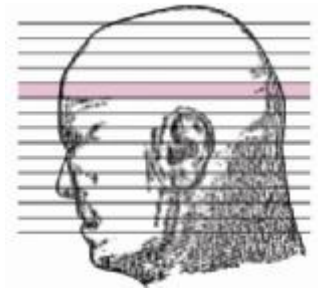


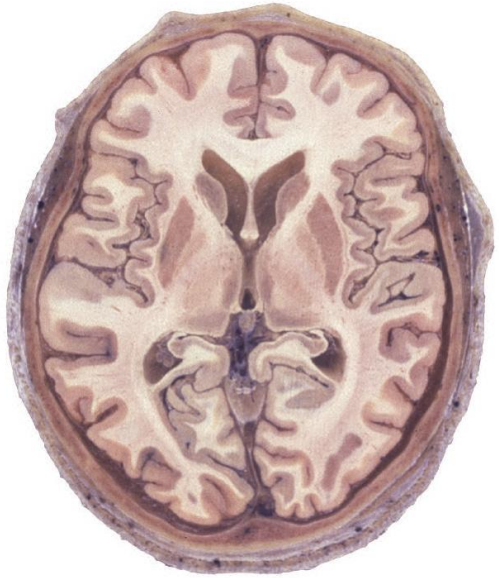


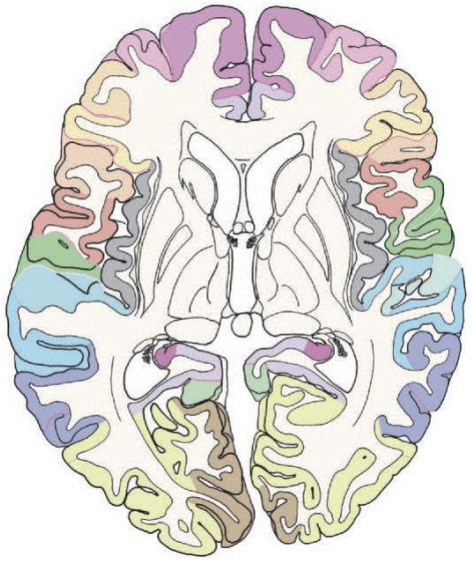


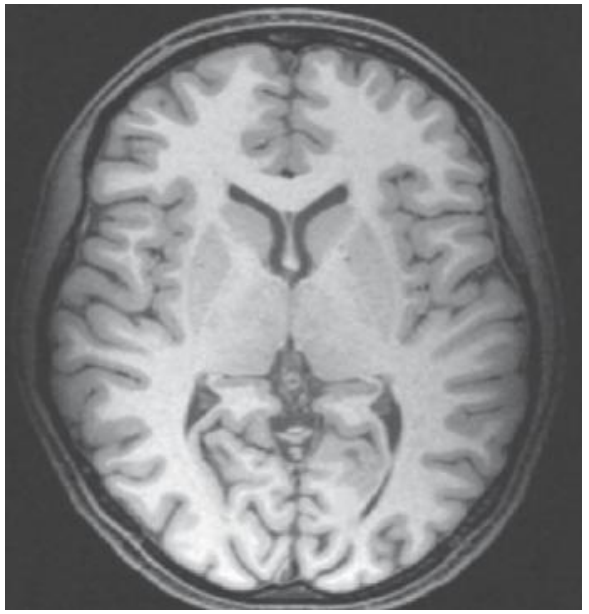
[Mai et al., 2015]

Slice 6



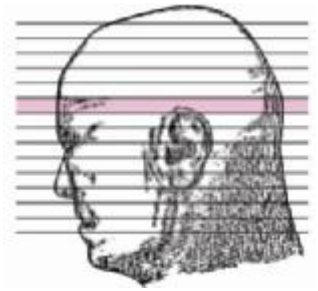


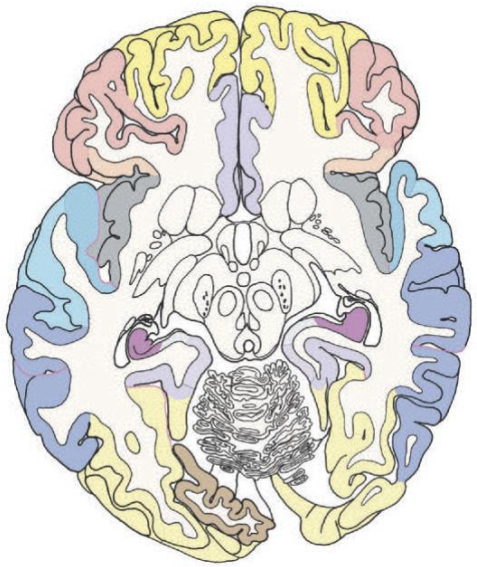


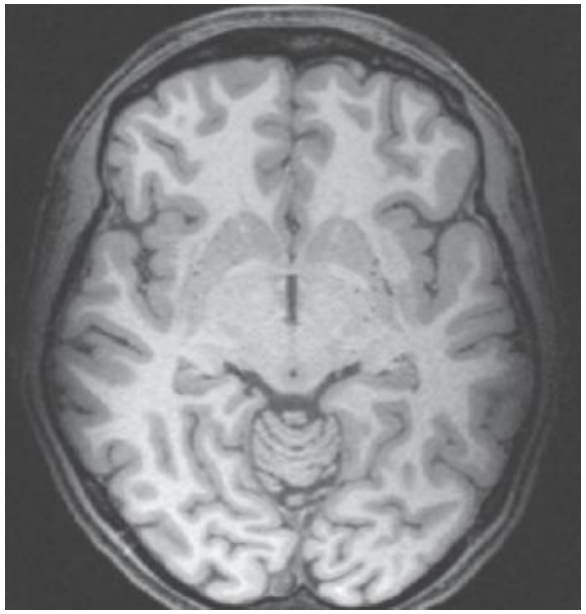


[Mai et al., 2015]

Slice 7

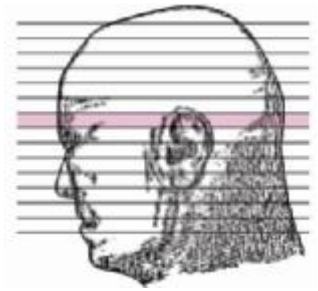


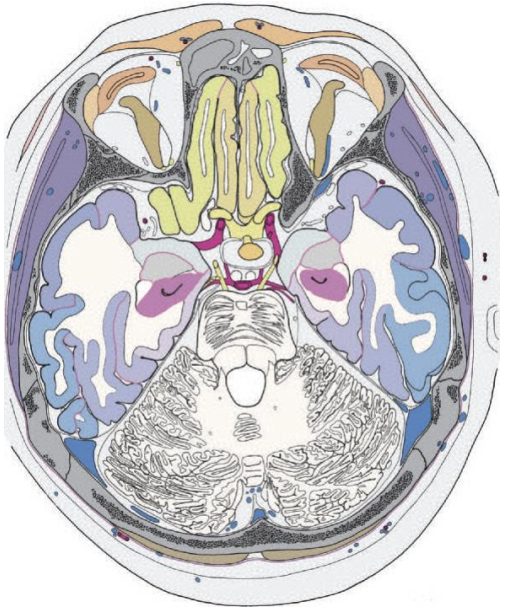


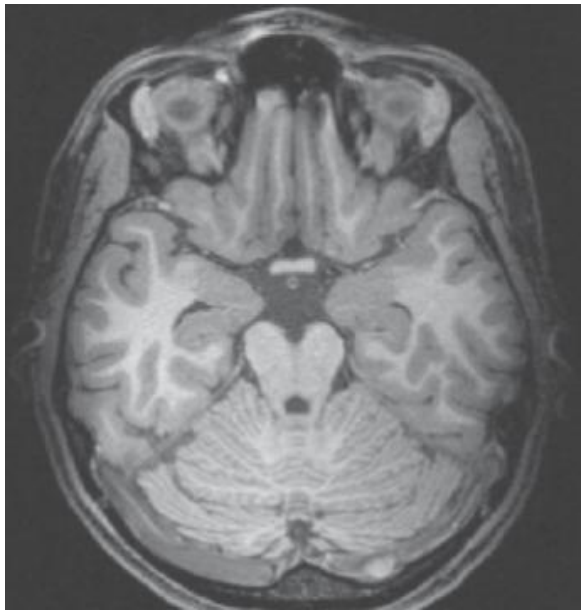


[Mai et al., 2015]

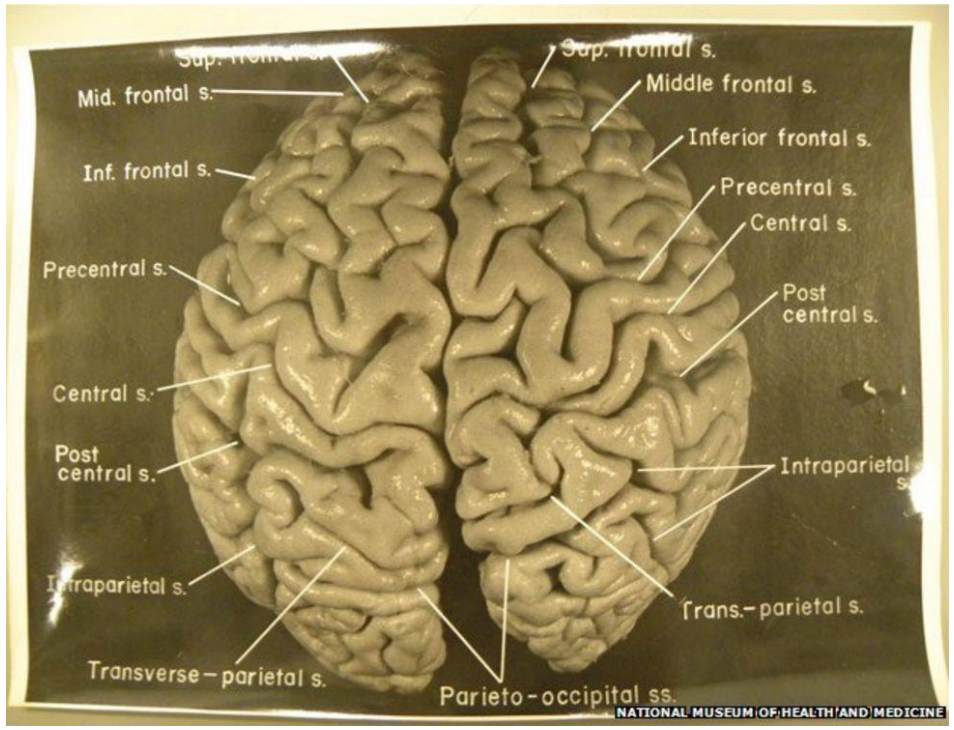
Slice 8

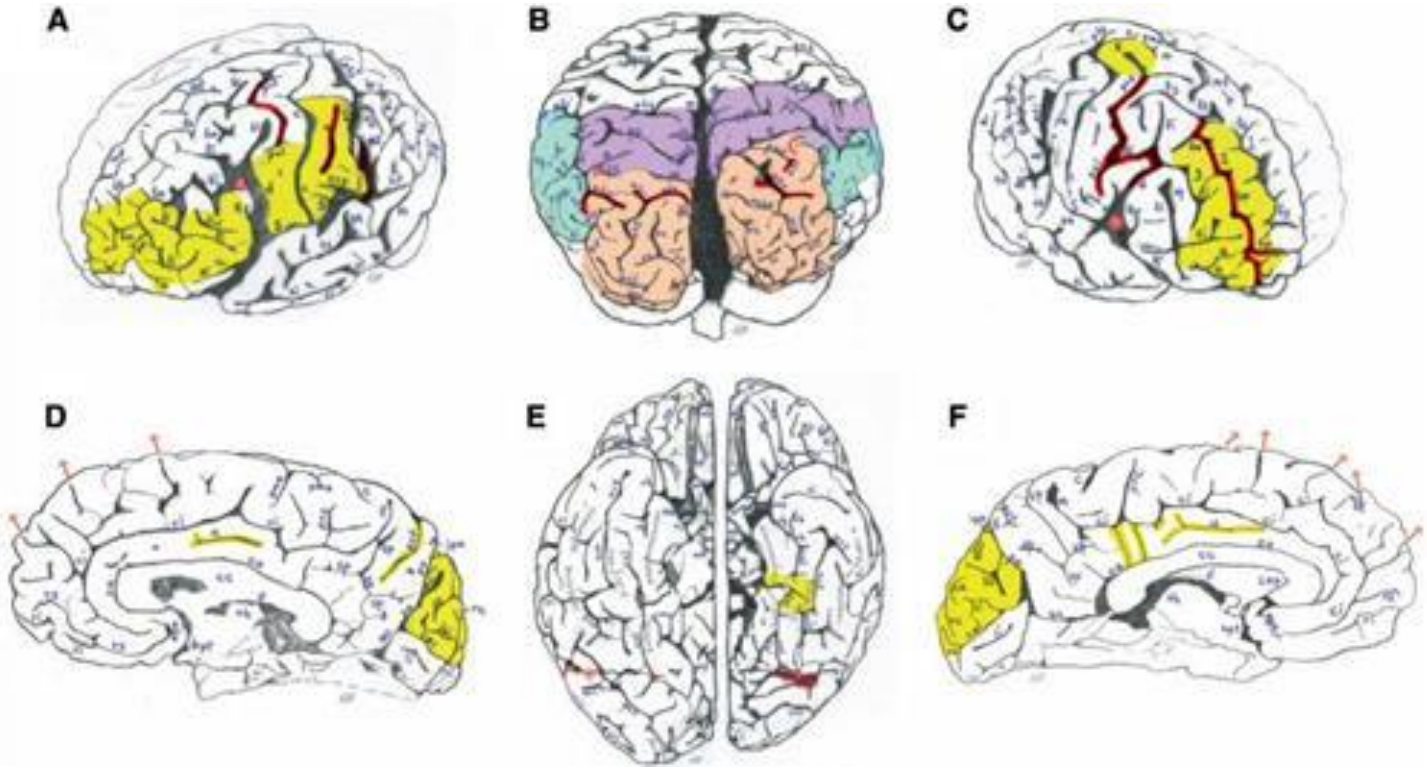






[Mai et al., 2015]



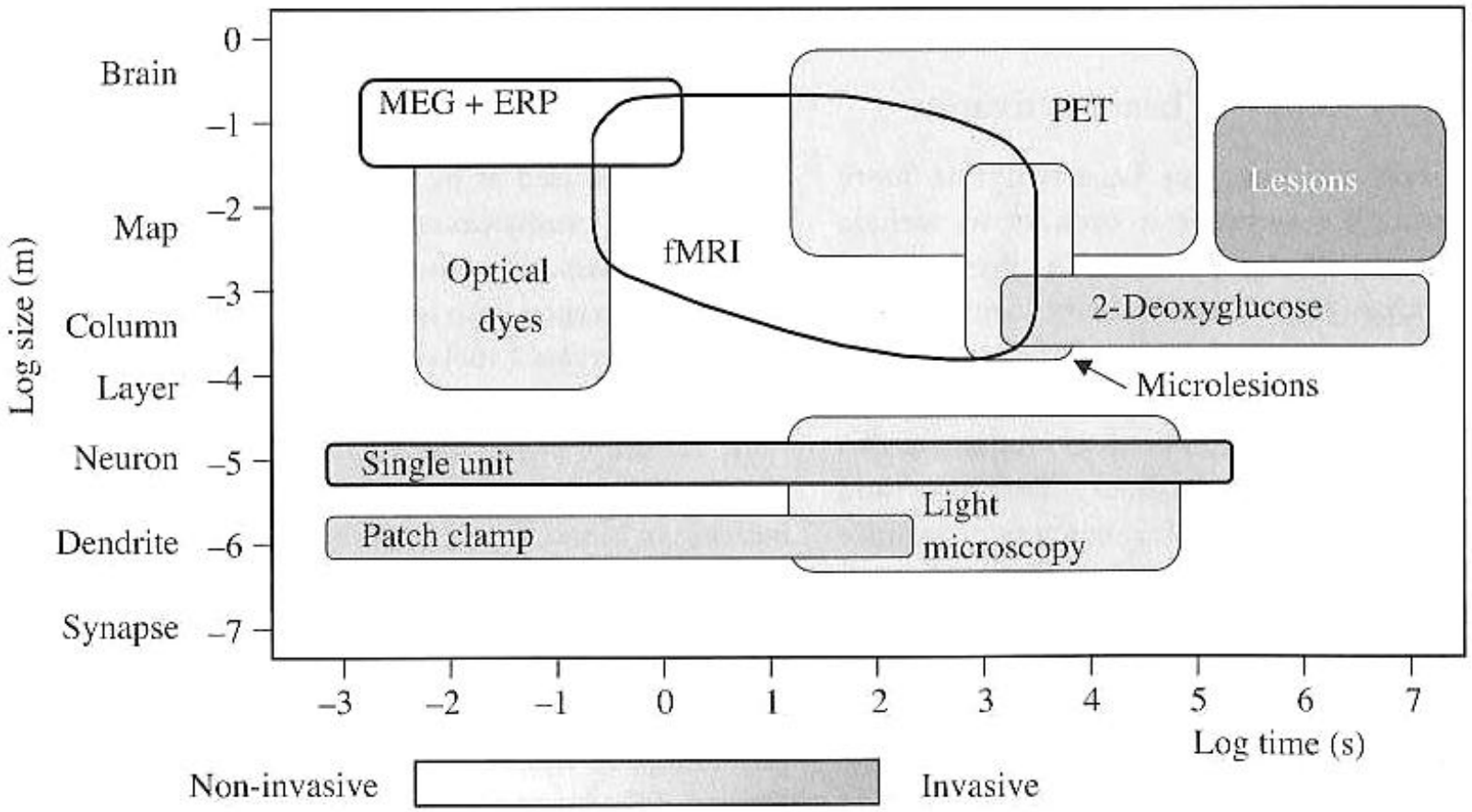


[Falk et al., 2019]

Unusual Features of Einstein's Brain

Brain Imaging

- Various quantitative techniques for imaging the structure or function of the brain
  - Computed tomography (CT)
  - Magnetic resonance imaging (MRI)
    - Structural MRI (sMRI)
    - Diffusion-weighted MRI (dMRI)
    - Functional MRI (fMRI)
  - Positron emission tomography (PET)



[Churchland and Sejnowski, 1988]

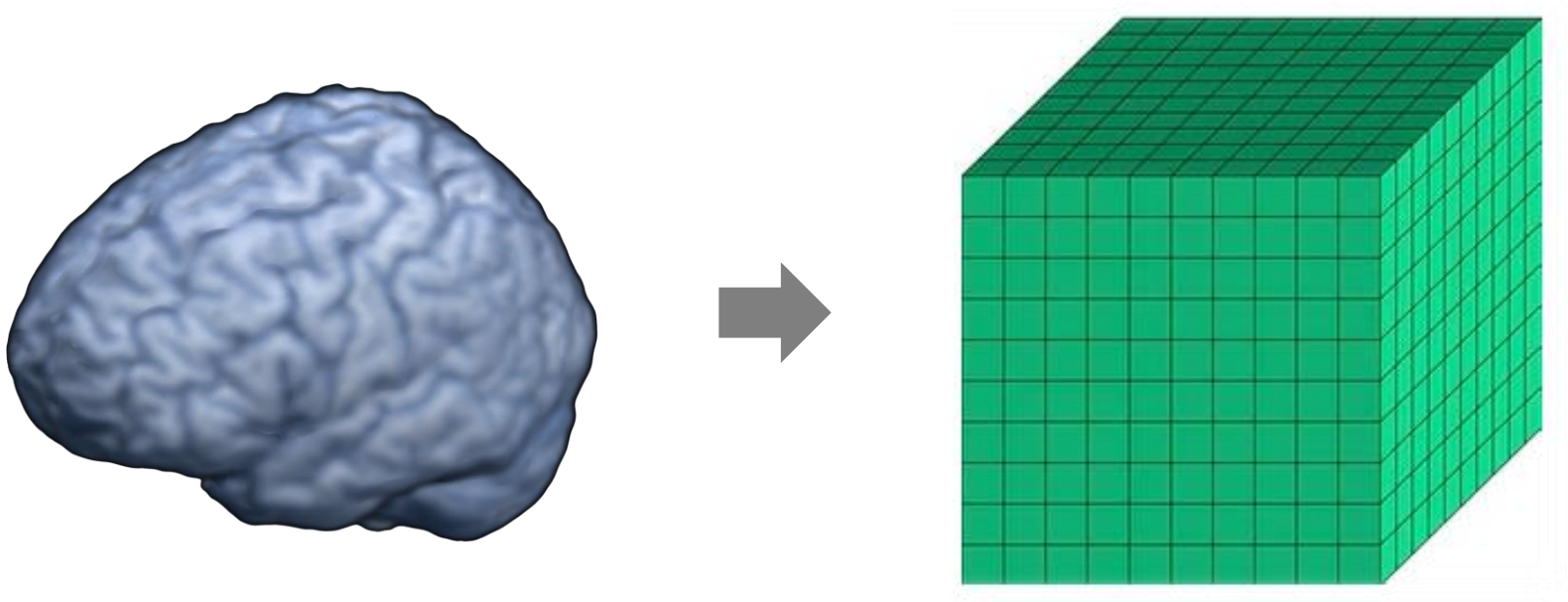
Spatial and Temporal Resolutions of Neuroscience Methods

Brain Imaging Data

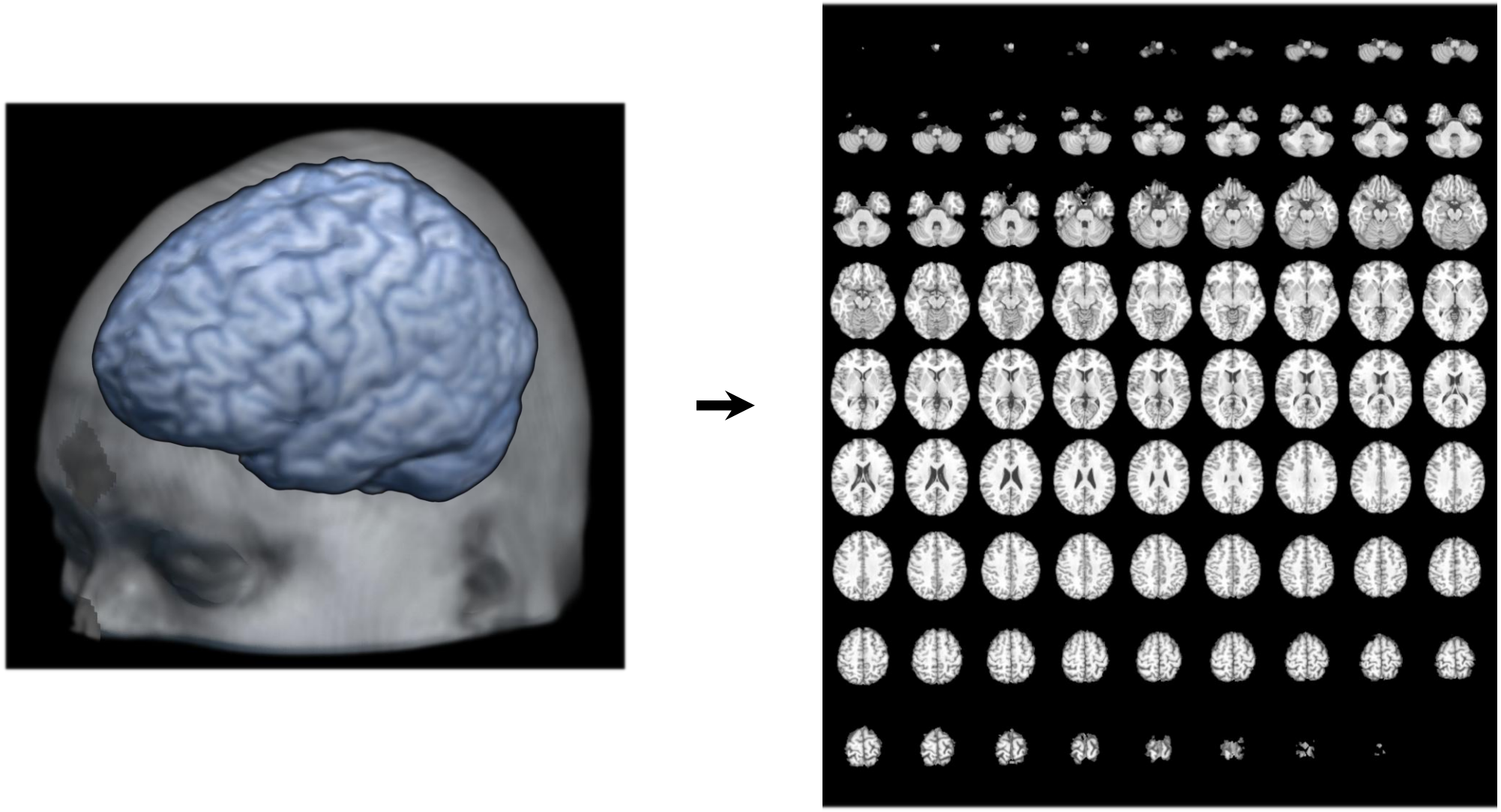
- Volumetric description of the brain as a 3D array

[Larobina and Murino, 2014]

  - Representation of the structure or function of the brain in the form of an array of voxels
  - Discrete representation resulting from a sampling/reconstruction process that maps numerical values to positions of the space



Brain Volumetric Data as a 3D Array



Brain Volume as a Series of Slices in a Stack

Image File Format

- Provides a standardized way to store the information describing an image in a computer file [Larobina and Murino, 2014]
  - How image data are organized inside an image file
  - How image data should be interpreted by a software for the correct loading and visualization

- Basic concepts common to all image file formats
  - Voxel depth: number of bits used to encode the information of each voxel
    - Integer, real number, or complex number in different bits
  - Photometric interpretation: how image data should be interpreted for the correct image display as a monochrome or color image
    - Samples per voxel: number of channels
    - MRI data has a gray scale photometric interpretation

- Metadata: Information that describe an image
  - Typically stored at the beginning of the file as a header
  - Contains at least image matrix dimensions, spatial resolution, voxel depth, and photometric interpretation
  - Enables a software to recognize and correctly open an image in a supported file format
  - Tool to annotate and exploit image-related information for clinical and research purposes
- Image data: Section where numerical values of voxels are stored
  - Usually stored as integers or floating-point numbers using the minimum number of bytes required to represent values according to a designated data type

- Image file size = header size + image data size
  - Metadata and image data may be contained in a single file or in separate files
- Major file formats currently used in brain imaging
  - Intended to standardize images generated by diagnostic modalities
    - Digital Imaging and Communications in Medicine (DICOM)
  - Aimed to facilitate and strengthen post-processing analysis
    - Neuroimaging Informatics Technology Initiative (NIfTI)

Format	Header	Extension	Data types
Analyze	Fixed-length: 348 byte binary format	.img and .hdr	Unsigned integer (8-bit), signed integer (16-, 32-bit), float (32-, 64-bit), complex (64-bit)
Nifti	Fixed-length: 352 byte binary format[a] (348 byte in the case of data stored as .img and .hdr)	.nii	Signed and unsigned integer (from 8- to 64-bit), float (from 32- to 128-bit), complex (from 64- to 256-bit)
Minc	Extensible binary format	.mnc	Signed and unsigned integer (from 8- to 32-bit), float (32-, 64-bit), complex (32-, 64-bit)
Dicom	Variable length binary format	.dcm	Signed and unsigned integer, (8-, 16-bit; 32-bit only allowed for radiotherapy dose), float not supported

[Larobina and Murino, 2014]

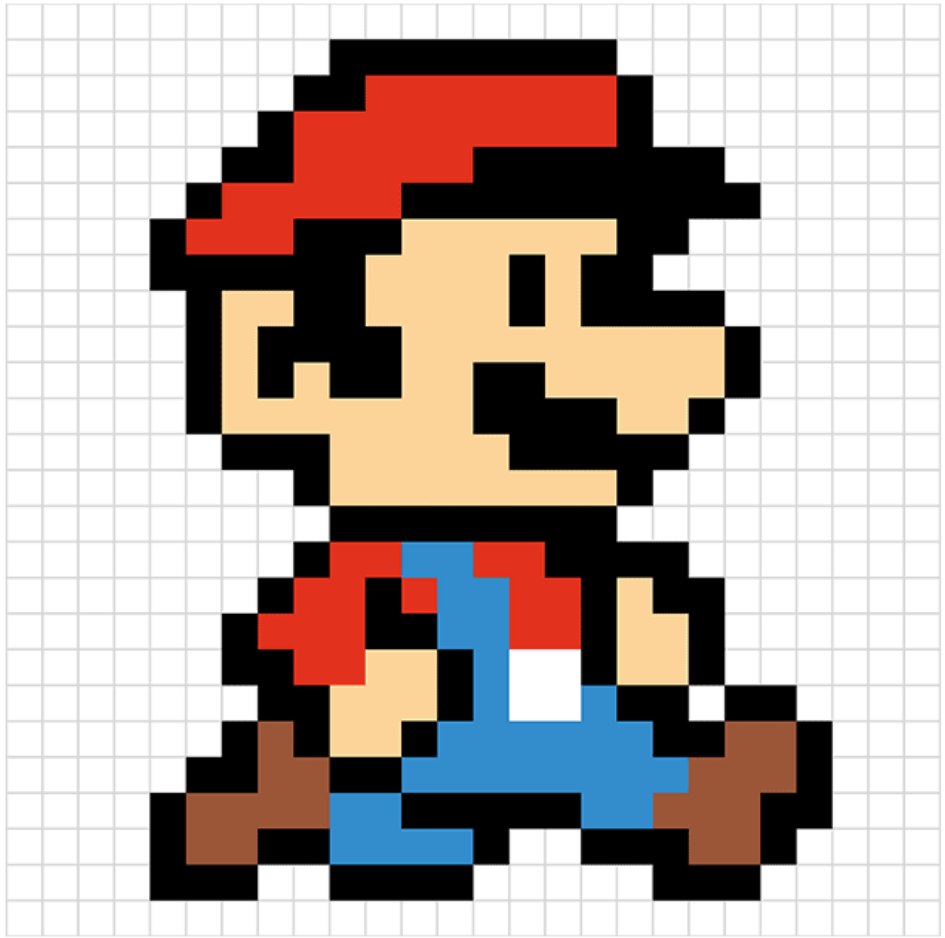
Characteristics of Image File Formats

- DICOM
  - Origin and development
    - Developed by the National Electrical Manufacturers Association (NEMA) and the American College of Radiology (ACR)
    - First introduced in 1985 as ACR/NEMA 1.0
  - Version evolution
    - DICOM 3.0 (1993) - First official DICOM standard
    - Continuous updates and supplements added over time
    - Current version is DICOM 2023b (as of 2023)
  - Primary uses
    - Standard format for medical imaging
    - Includes a network protocol for image transmission

- NIfTI
  - Origin and development
    - Developed by the Data Format Working Group (DFWG)
    - Created to address limitations in the ANALYZE 7.5 format
    - First released in 2003
  - Version evolution
    - NIfTI-1 (2003) - Initial release
    - NIfTI-2 (2011) - Extended to support larger image dimensions
  - Primary uses
    - Specifically designed for neuroimaging research
    - Supports both single-file (.nii) and dual-file (.hdr/.img) formats

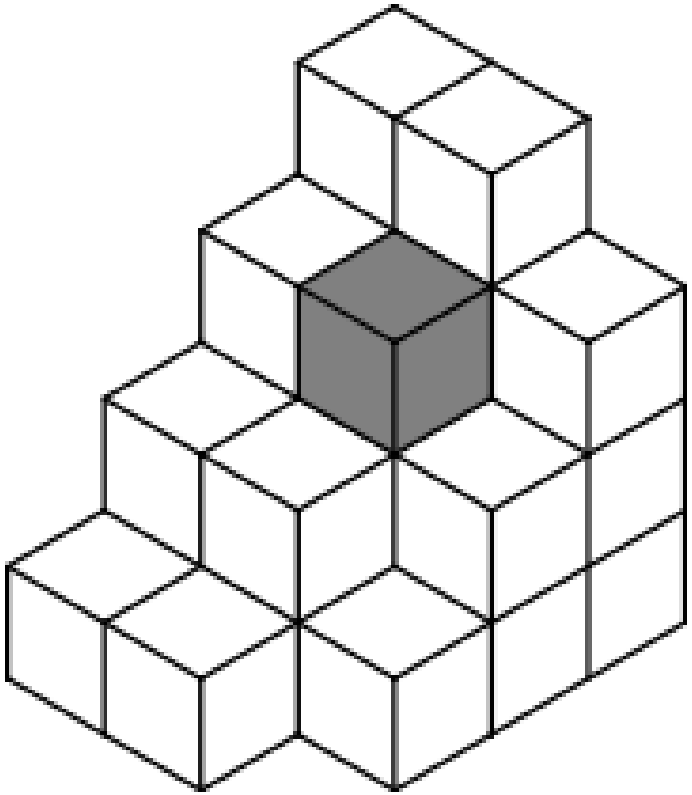
Voxel

- Volume element or volumetric pixel
  - Analogous to a pixel in 2D space
  - Smallest volumetric unit in 3D space



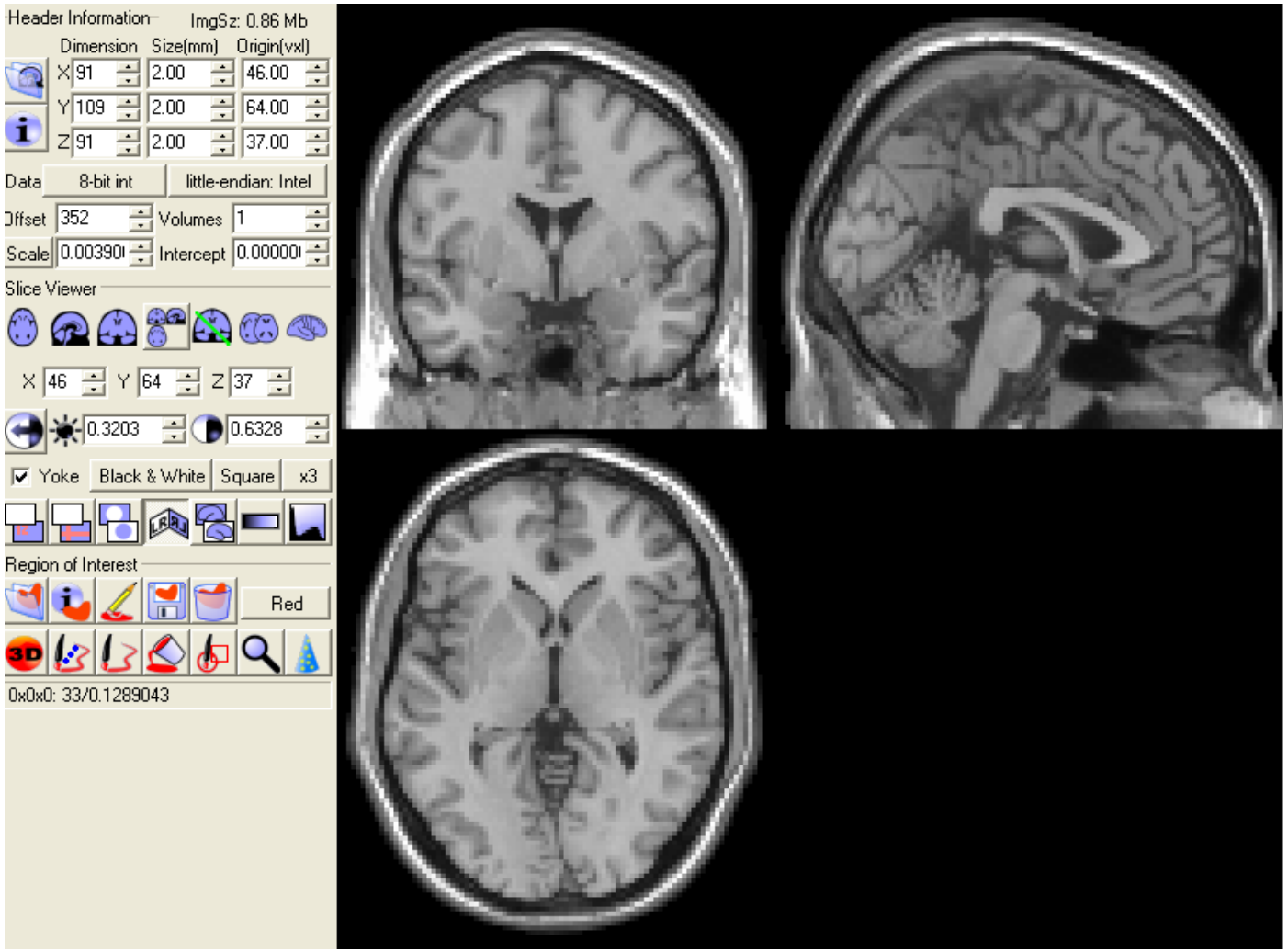
[https://easydrawingguides.com/how-to-draw-mario-pixel-art/]

2D Raster Image Composed of Pixels



[https://en.wikipedia.org/wiki/Voxel]

Voxels Representing Regularly Sampled Spaces

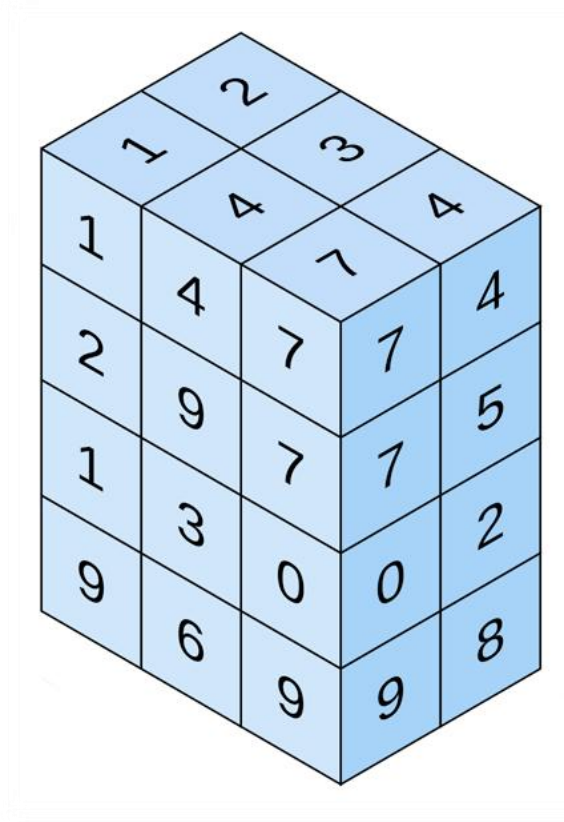


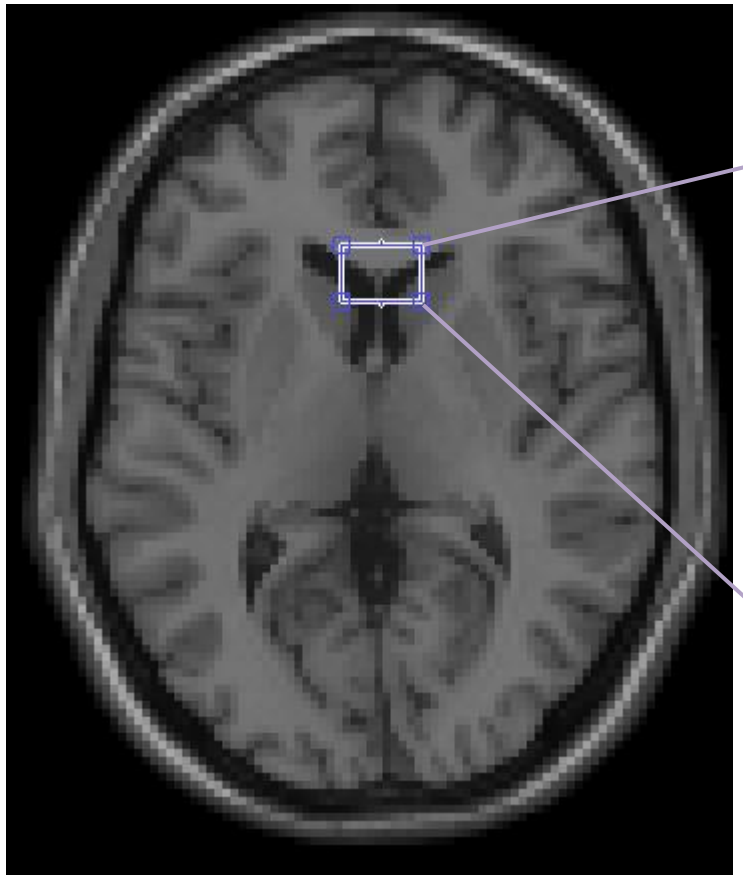
Dimensions: 91 × 109 × 91
Voxel depth: 8-bit integer
Voxel size: 2 mm × 2 mm × 2 mm
Origin: [46, 64, 37]

File size:
Header = 352 B
Image data = 91 × 109 × 91 × 8 bits
Total = 352 B + 902,629 B
= 902,981 B
= 0.86 MB

MRI Image Composed of Voxels

- Represents a value on a regular grid in 3D space
  - Sub-volume box with a constant value inside

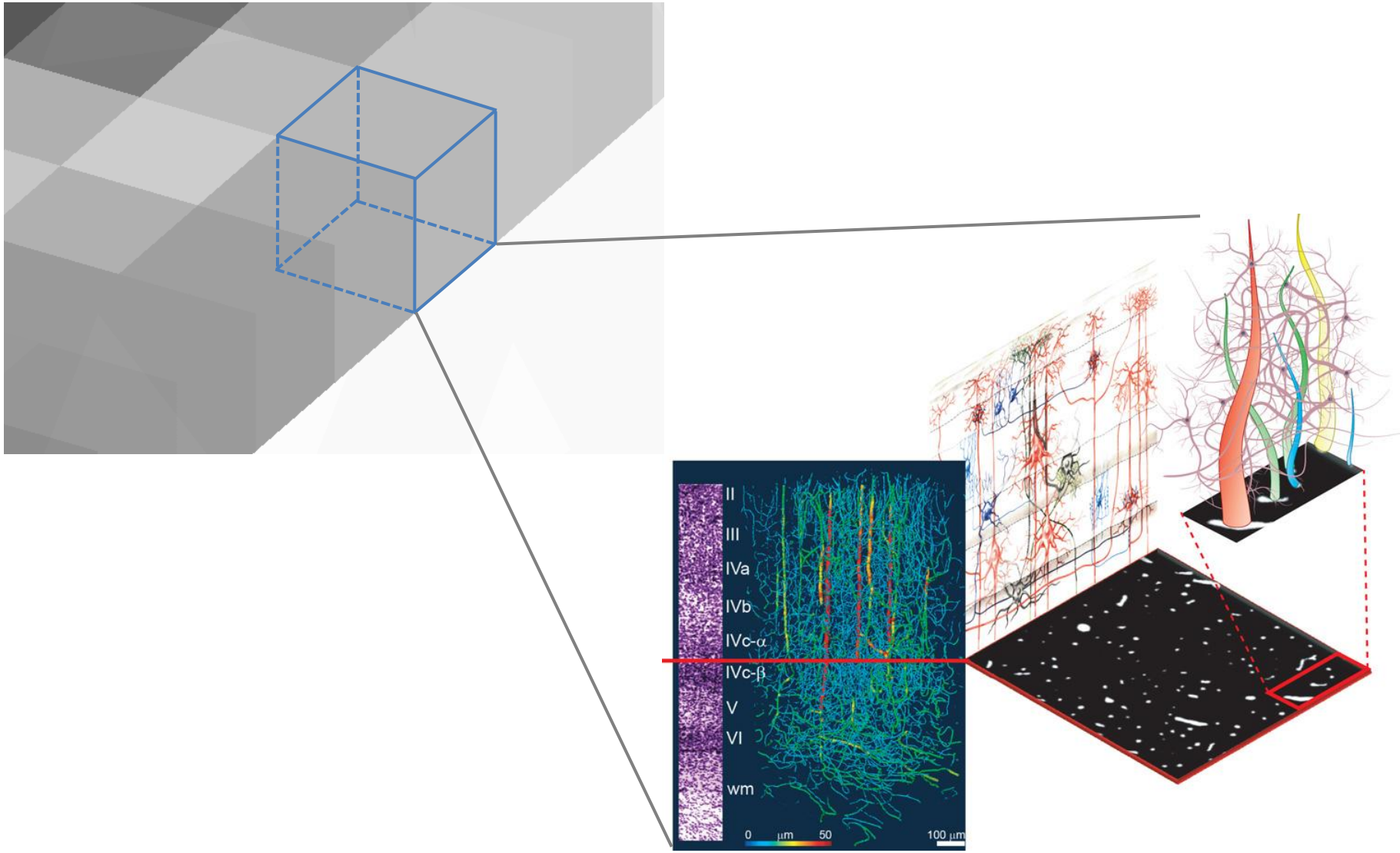




0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
0.41	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.44
0.16	0.28	0.40	0.45	0.45	0.43	0.43	0.41	0.29	0.15
0.12	0.12	0.17	0.33	0.29	0.37	0.24	0.13	0.12	0.13
0.12	0.11	0.12	0.15	0.31	0.18	0.11	0.11	0.17	0.31
0.18	0.12	0.11	0.11	0.27	0.11	0.11	0.14	0.31	0.33
0.32	0.12	0.11	0.11	0.22	0.11	0.11	0.24	0.32	0.33

Voxels Representing Values

- Typical fMRI voxel [Logothetis, 2008]
  - In-plane resolution: 2×2 mm^2 to 4×4 mm^2
  - Slice thickness: 3 mm to 7 mm
  - Occupied by:
    - Vessels for less than 3% of the volume
    - Neural elements for the rest
  - Contains:
    - 5.5 million neurons
    - 2.2 - 5.5 $\times 10^{10}$ synapses
    - 22 km of dendrites
    - 220 km of axons



[Logothetis, 2008]

Neural and Vascular Contents within a Voxel

MRI Coordinate System

- Reference frame in a 3D space that assigns *x*, *y*, and *z* coordinates to anatomical regions [https://www.fieldtriptoolbox.org/faq/coordsys/]
  - What is the definition of the origin, *i.e.* [0, 0, 0]?
  - In which directions are the *X*-, *Y*- and *Z*-axis pointing?
  - In what units are coordinates expressed?
  - Is the geometry scaled to some template or atlas, or does it still match the individual's brain size?

system	units	orientation	origin	scaling	notes
ACPC	mm	RAS	anterior commissure	native, i.e., not normalized to a template	
Allen Institute	mm	RAS	Bregma point		
Analyze	mm	LAS		native	
BTi/4D	m	ALS	between the ears	native	
CTF MRI	mm	ALS	between the ears	native	voxel order can be arbitrary
CTF gradiometer	cm	ALS	between the ears	native	
CapTrak	mm	RAS	approximately between the ears		
Chieti ITAB	mm	RAS	between the ears	native	
DICOM	mm	LPS	centre of MRI gradient coil	native, see here	
EEGLAB	mm	ALS	between the ears	native	
FreeSurfer	mm	RAS	center of isotropic 1 mm 256x256x256 volume		
MNI	mm	RAS	anterior commissure	scaled to match averaged template	
NIfTI	mm	RAS		see here, search for "Orientation information".	
Neuromag/Elekta /Megin	m	RAS	between the ears	native	
Paxinos-Franklin	mm	RSP	Bregma point		
Scanner RAS (`scanras`)	mm	RAS	scanner origin	native	
Talairach-Tournoux	mm	RAS	anterior commissure	scaled to match atlas	
Yokogawa		ALS	center of device		

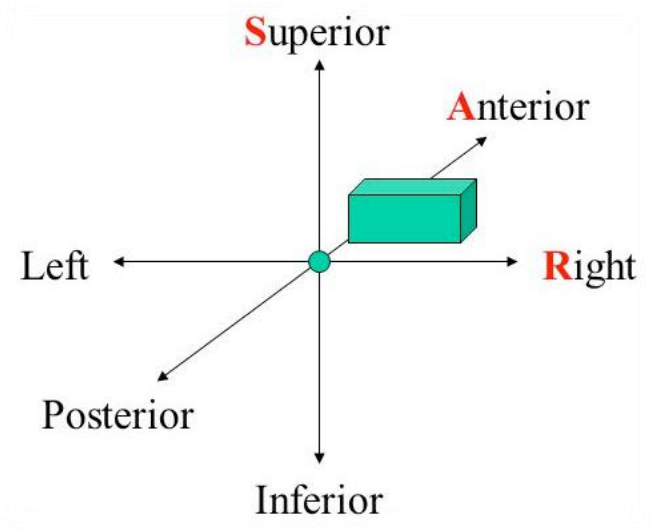
[https://www.fieldtriptoolbox.org/faq/coordsys/]

Different MRI Coordinate Systems

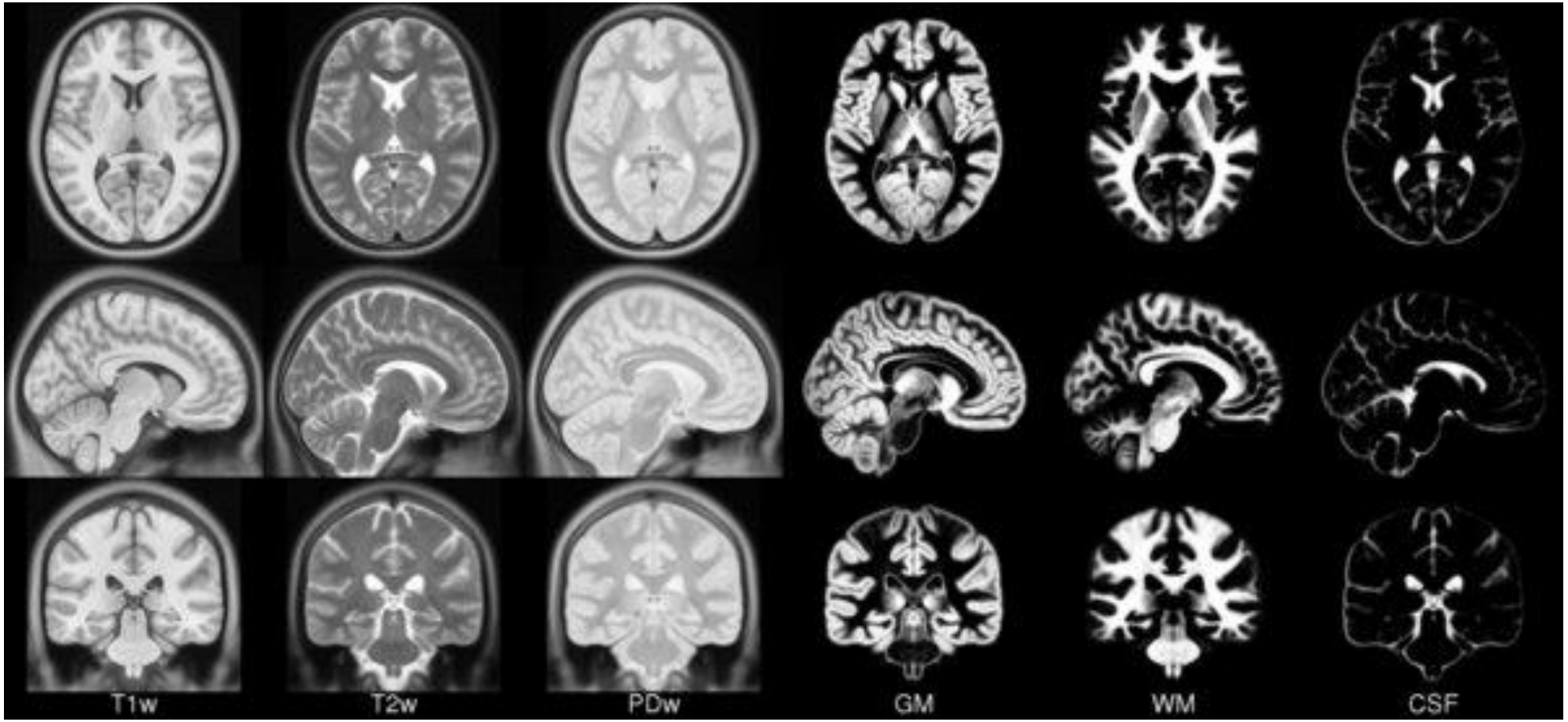
- Montreal Neurological Institute (MNI) coordinate system

[https://www.fieldtriptoolbox.org/faq/coordsys/]

  - The origin is the anterior commissure
  - The *X*-axis points from left to right
  - The *Y*-axis points from posterior to anterior
  - The *Z*-axis points from inferior to superior



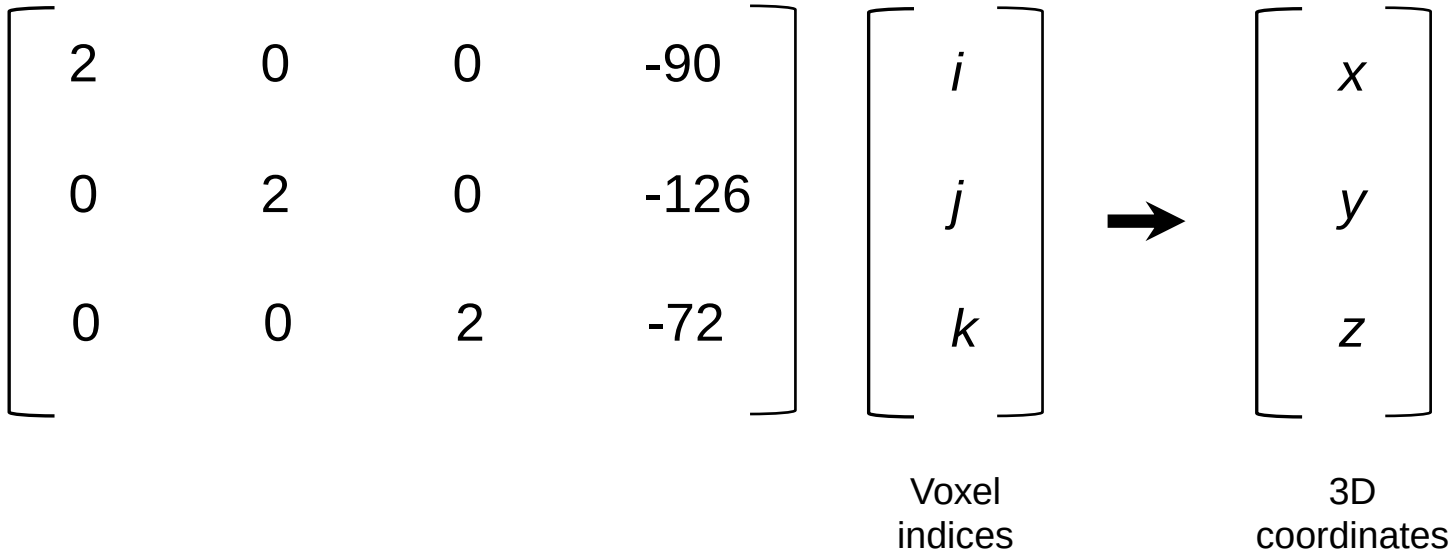
- Used if the geometry is spatially warped to the template brain
  - MNI152 Linear Template: Based on linearly coregistered 152 healthy brains
  - MNI152 Nonlinear Template, 6th Generation: Based on nonlinearly coregistered 152 healthy brains
  - MNI152 2009a/b/c Nonlinear Symmetric/Asymmetric Template: Based on nonlinearly coregistered 152 healthy brains with improved resolution and registration methods



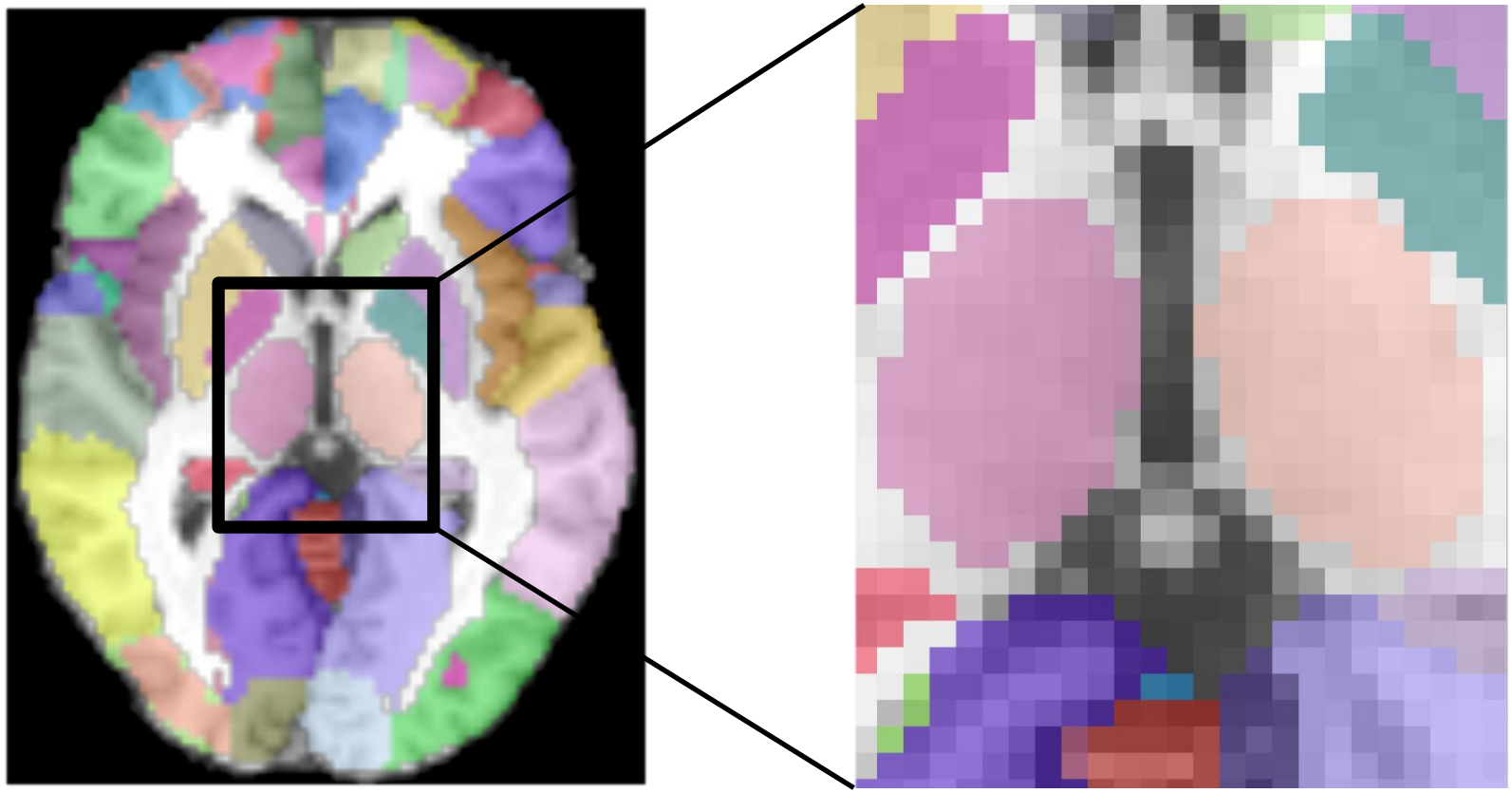
[https://www.bic.mni.mcgill.ca/ServicesAtlases/ICBM152NLin2009]

MNI152 2009c Nonlinear Asymmetric Template

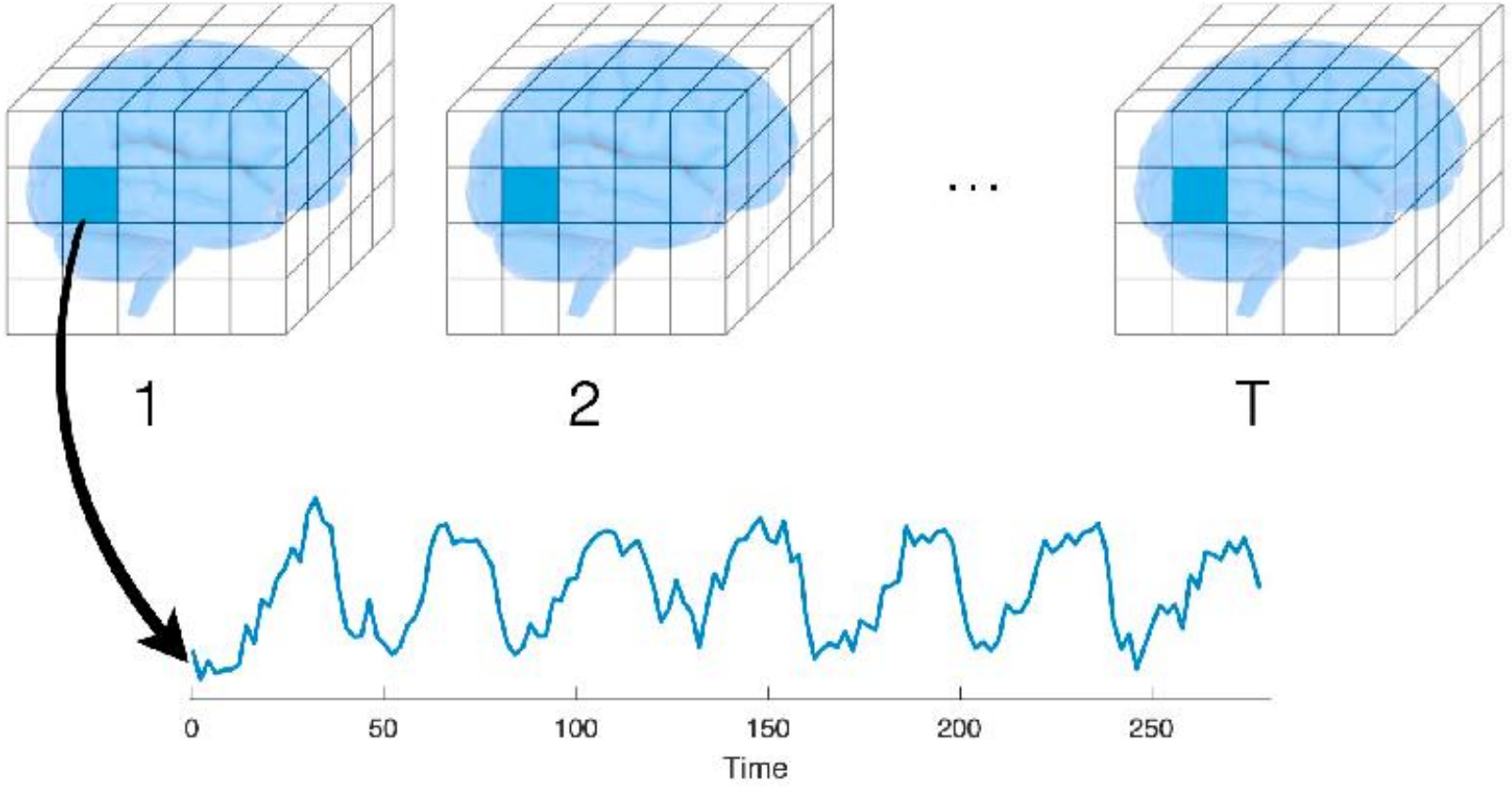
- Transformation matrix
  - Links array indices to 3D coordinates



- Applications of 3D coordinates in brain imaging
  - Identifying voxels within specific brain areas based on their 3D spatial coordinates

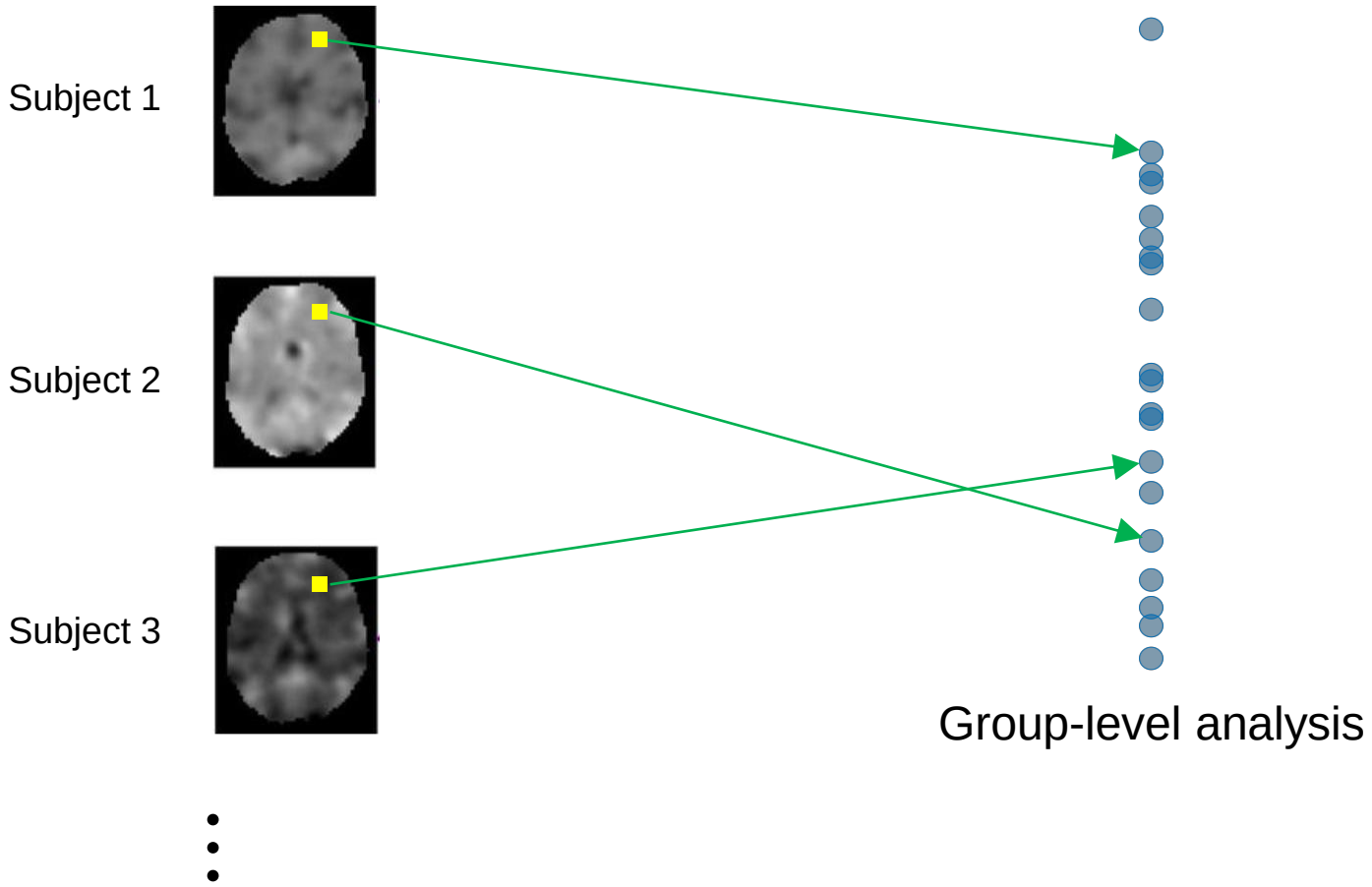


– Extracting voxel time series data from consistent 3D locations across multiple time points in a single subject's brain volumes



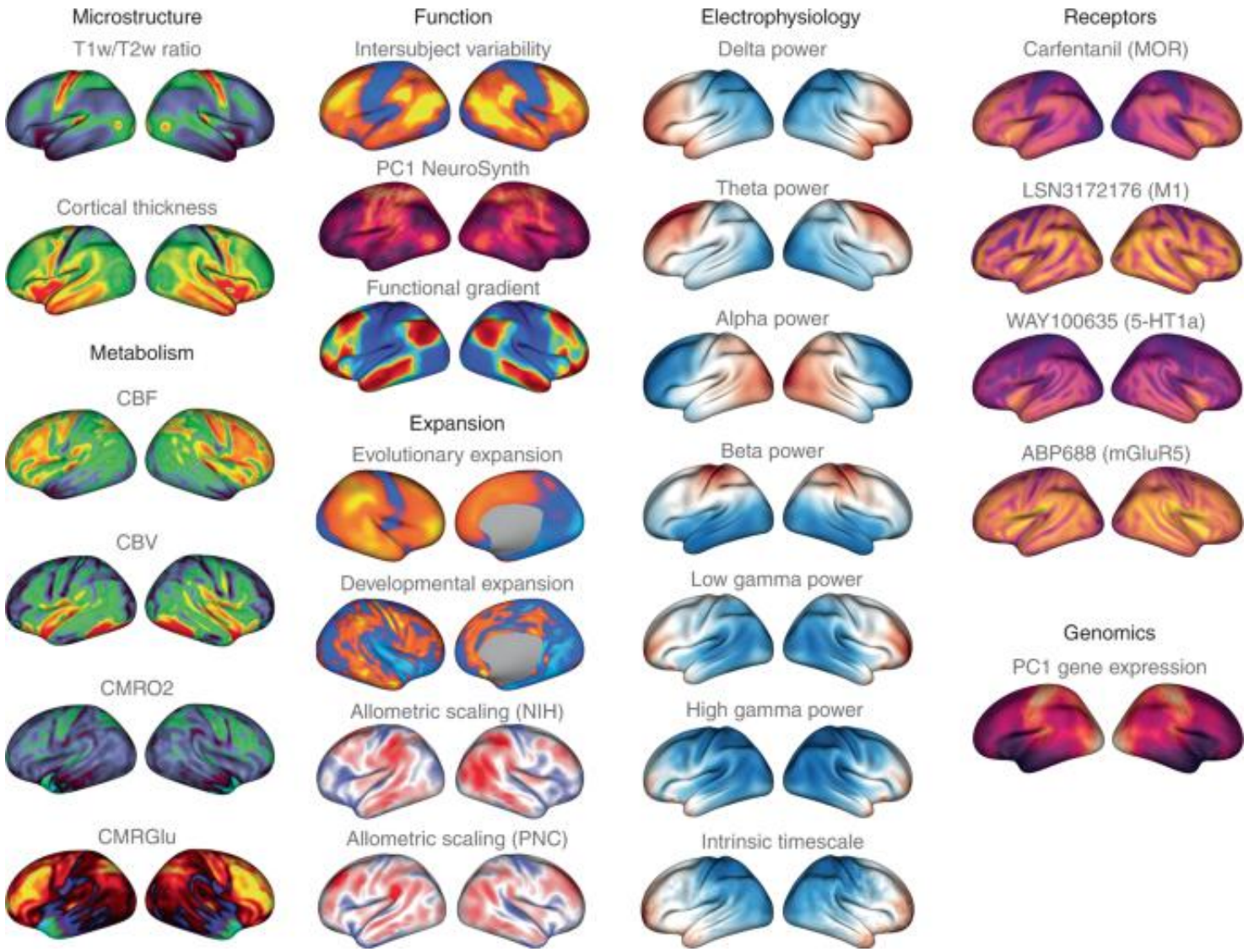
[Sidén, 2020]

– Acquiring voxel values from corresponding 3D coordinates across multiple subjects' brain volumes for group-level analyses



Brain Mapping

- Mapping of quantities or properties onto spatial representations of the brain [https://en.wikipedia.org/wiki/Brain_mapping]
  - All brain imaging is considered part of brain mapping
  - Conceived as a higher form of brain imaging
  - What the numerical value of a voxel expresses depends on imaging modality, acquisition protocol, reconstruction, and additional data processing or analysis



[Markello et al., 2022]

Brain Maps Obtained from the Published Literature