Principles of fMRI: How we measure brain function

Valentina Giunchiglia

v.giunchiglia20@imperial.ac.uk

@valegiunca

At the end of this lecture, you should know..

- What we can learn from studying brain function
- What fMRI is sensitive to
- What causes noise in fMRI data
- How fMRI data is preprocessed and modelled to gain insights into the human mind

How do we navigate the complexities of our world?

Complexity of the world

↓

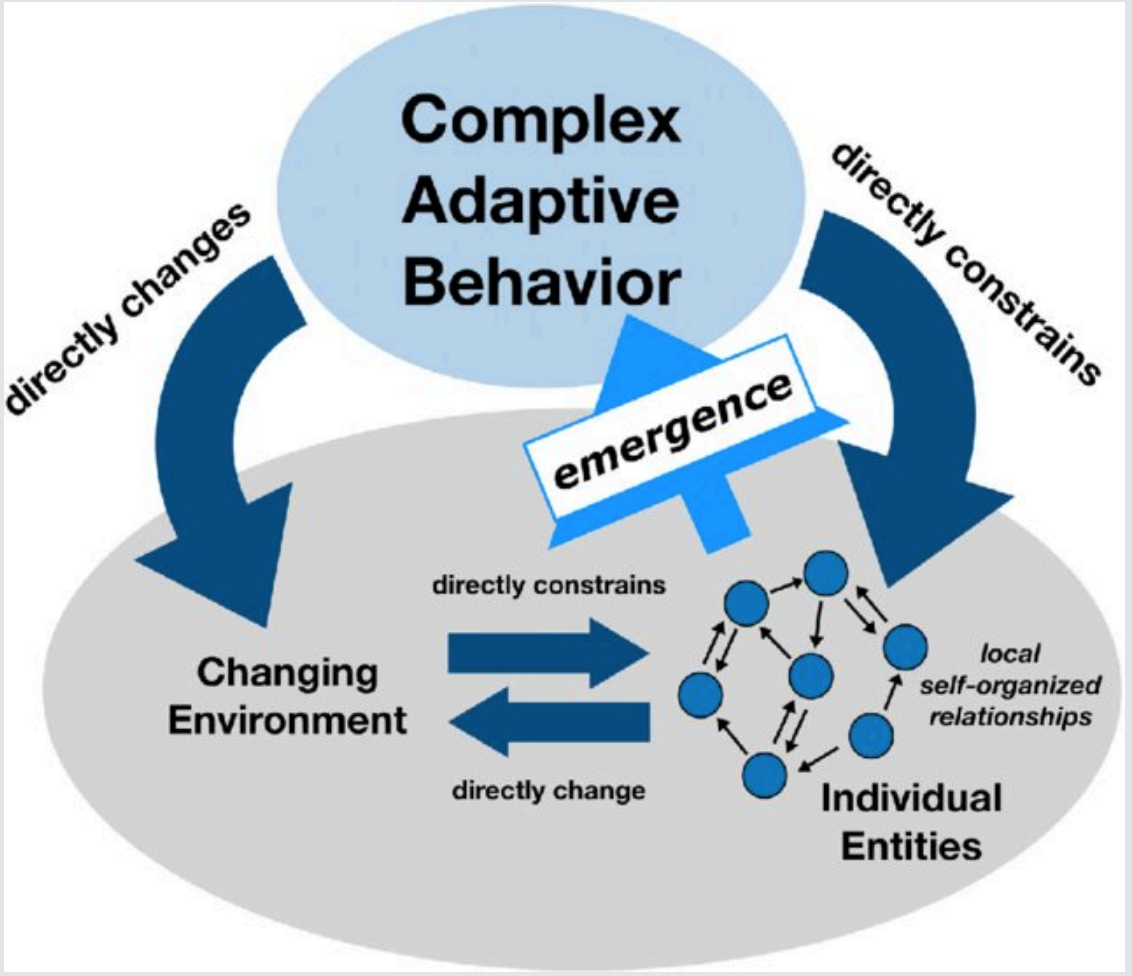
Complex cognitive processes to survive

↓

Complex adaptive behavior

↓

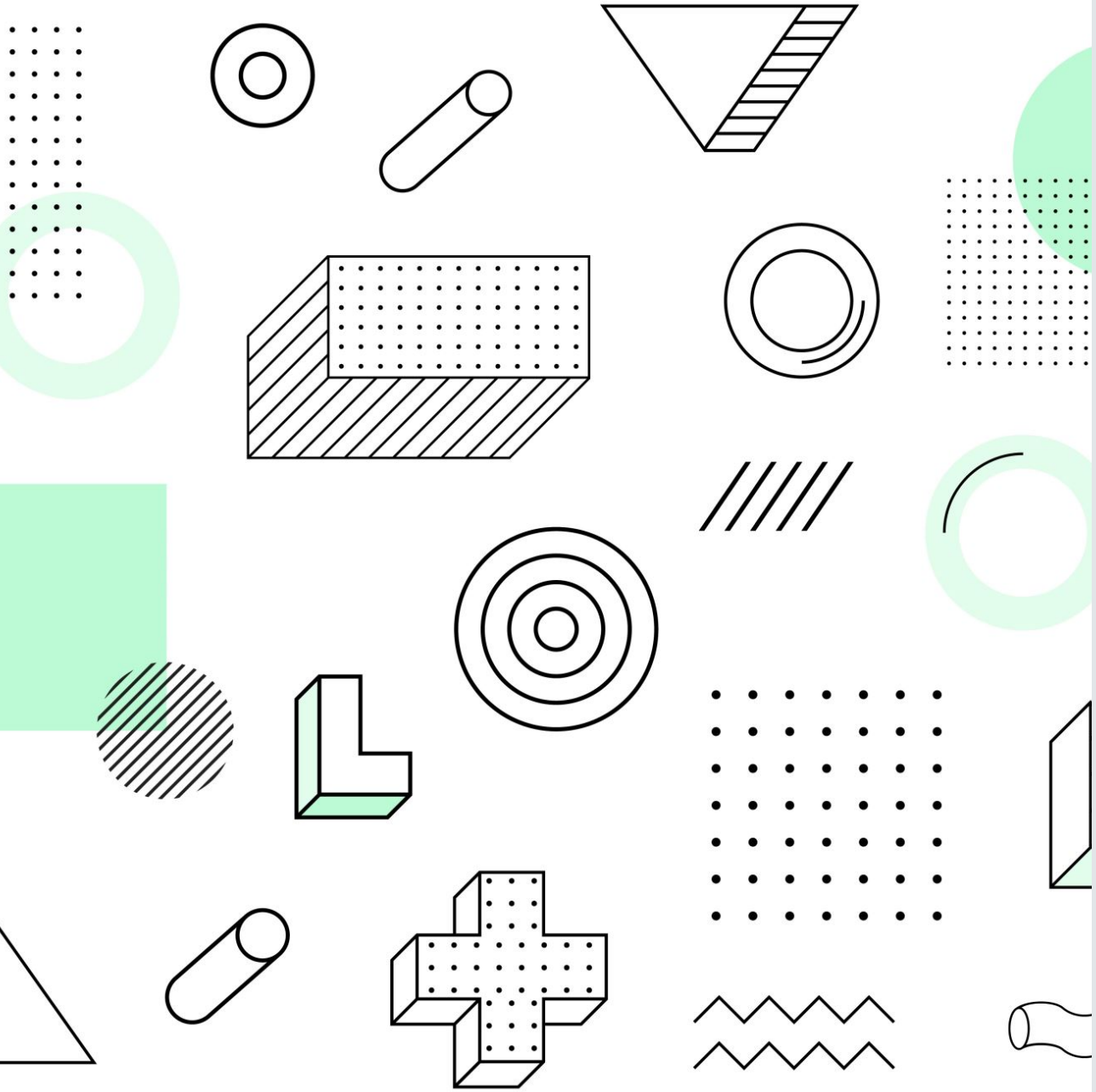
COGNITIVE NEUROSCIENCE



Chiovaro et al. 2020

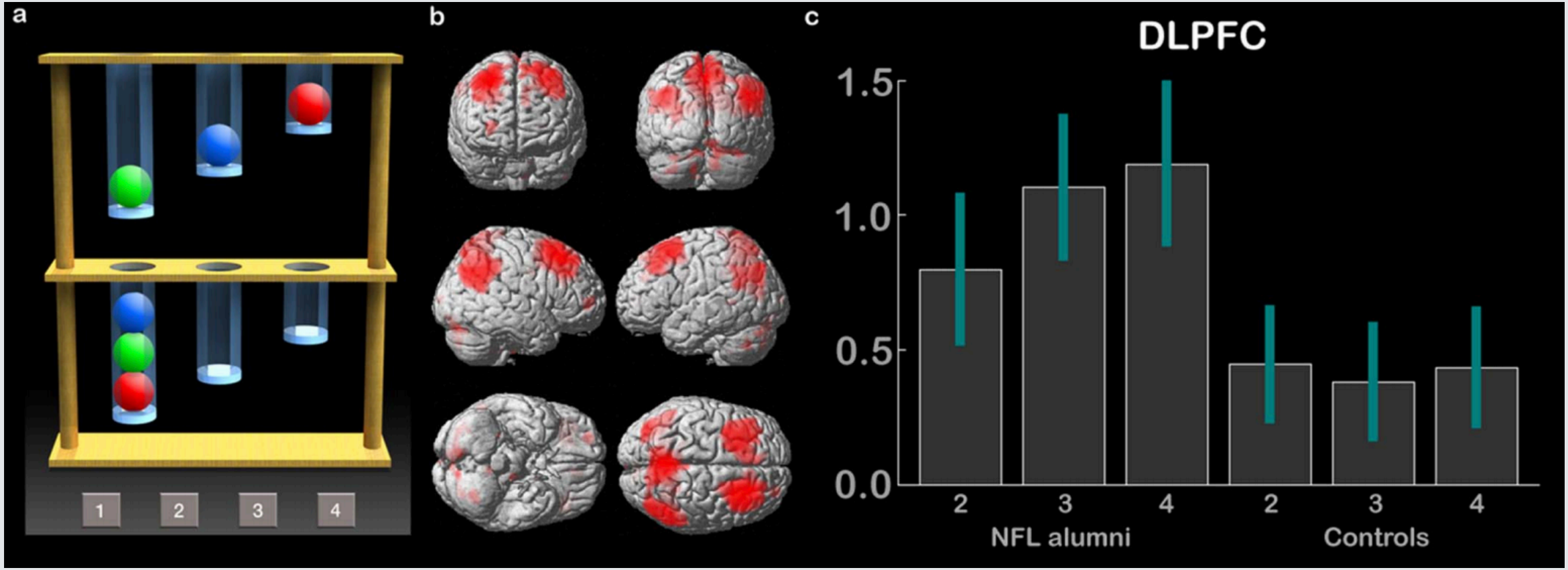
Investigating human behavior

Credit: Richard Daws



Using cognitive paradigms to investigate behaviour

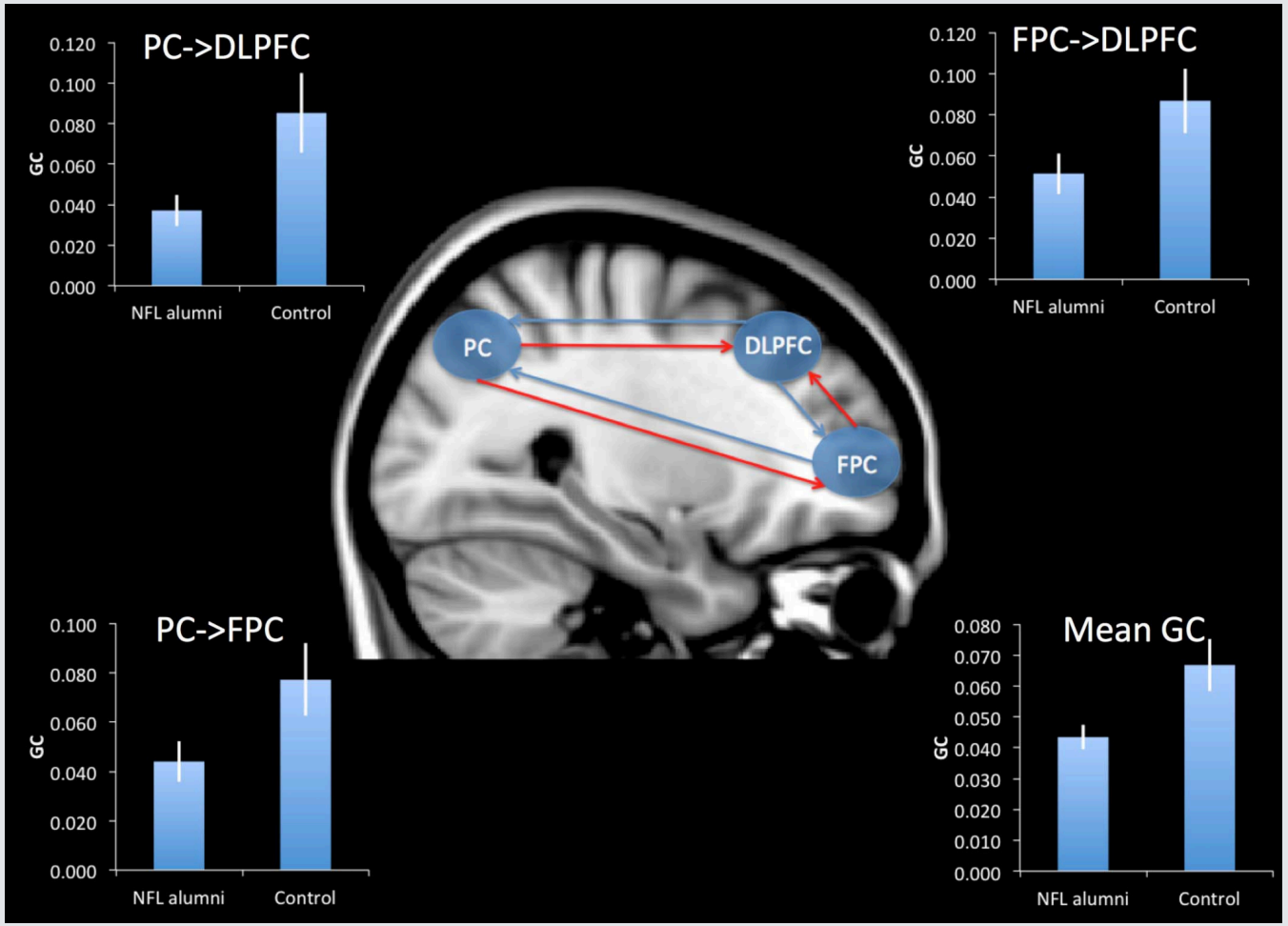
Spatial planning: retired American Football players



ROI analysis: Often used with *a priori* hypothesis or when contrasts (e.g. planning activation minus activation during counting) reveal regions with strong associations to a particular cognitive process

Hampshire et al., 2013

Spatial planning: Retired American Football players



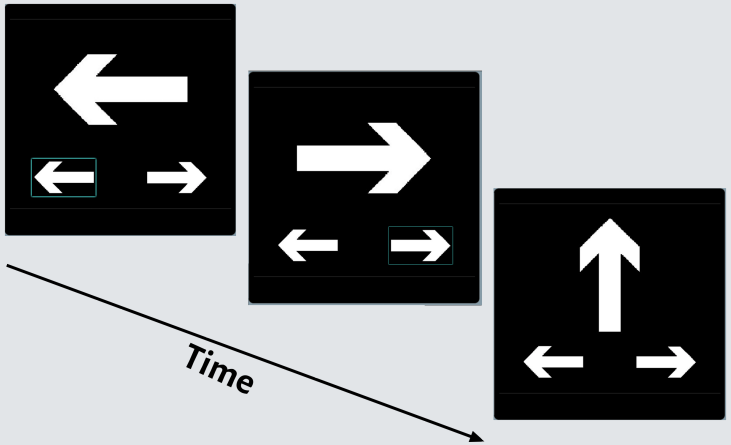
Hampshire et al., 2013

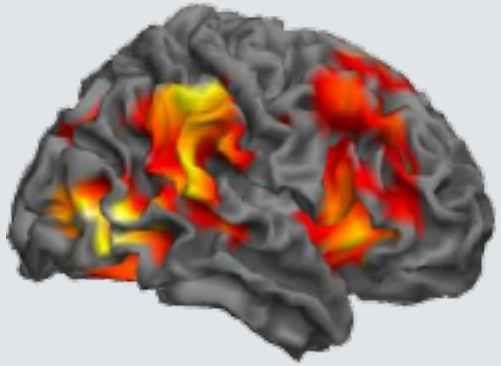
Affective connectivity

Measures level at which activation in one region is predicted by activations that occurred at earlier time points elsewhere in the brain

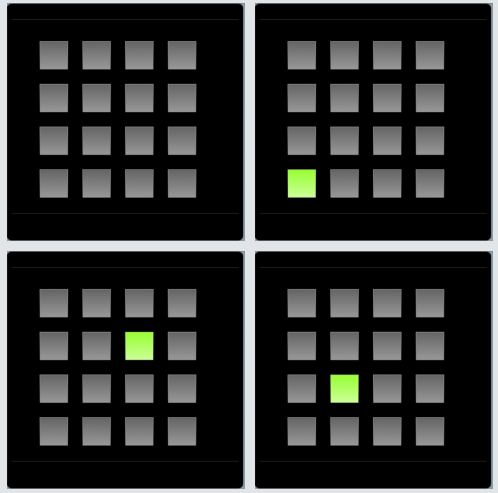
Different cognitive tasks can elicit different patterns of brain activation

Response inhibition

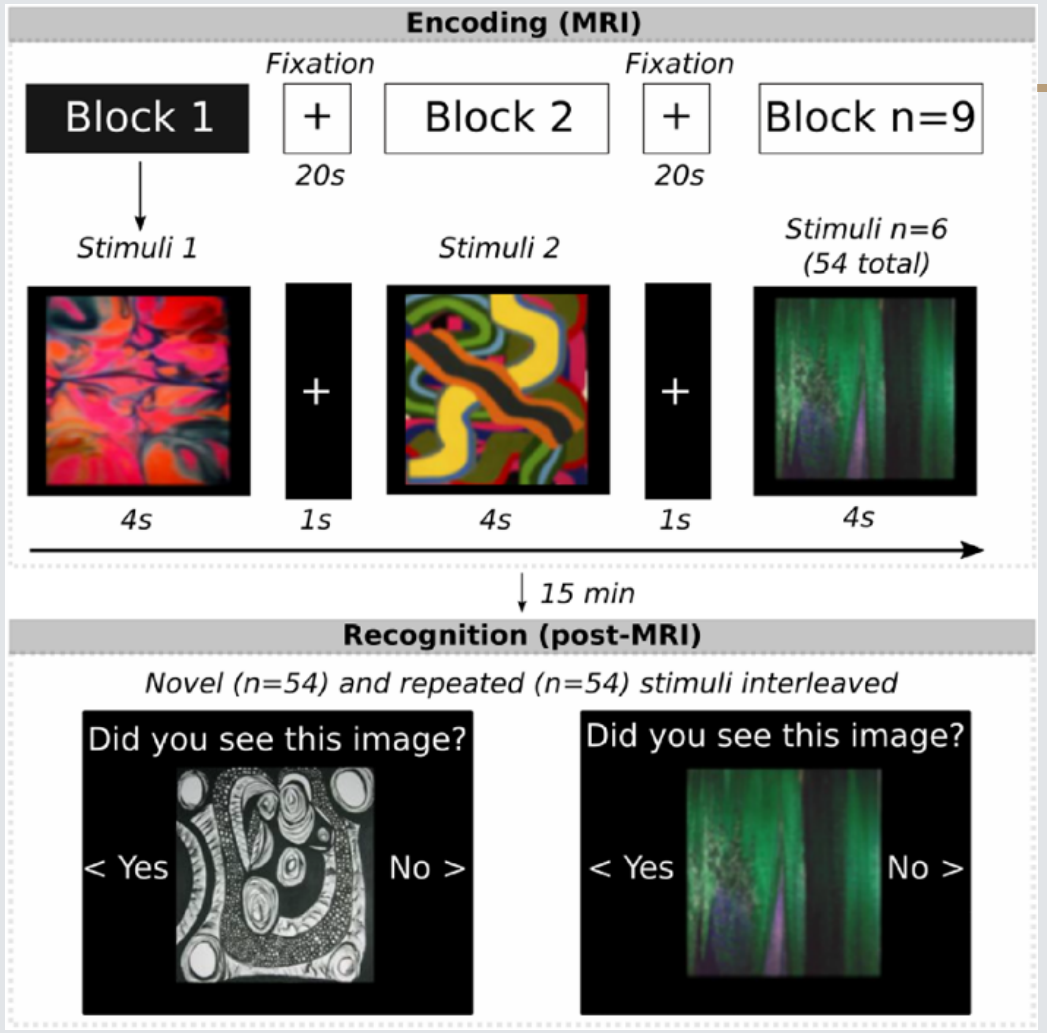


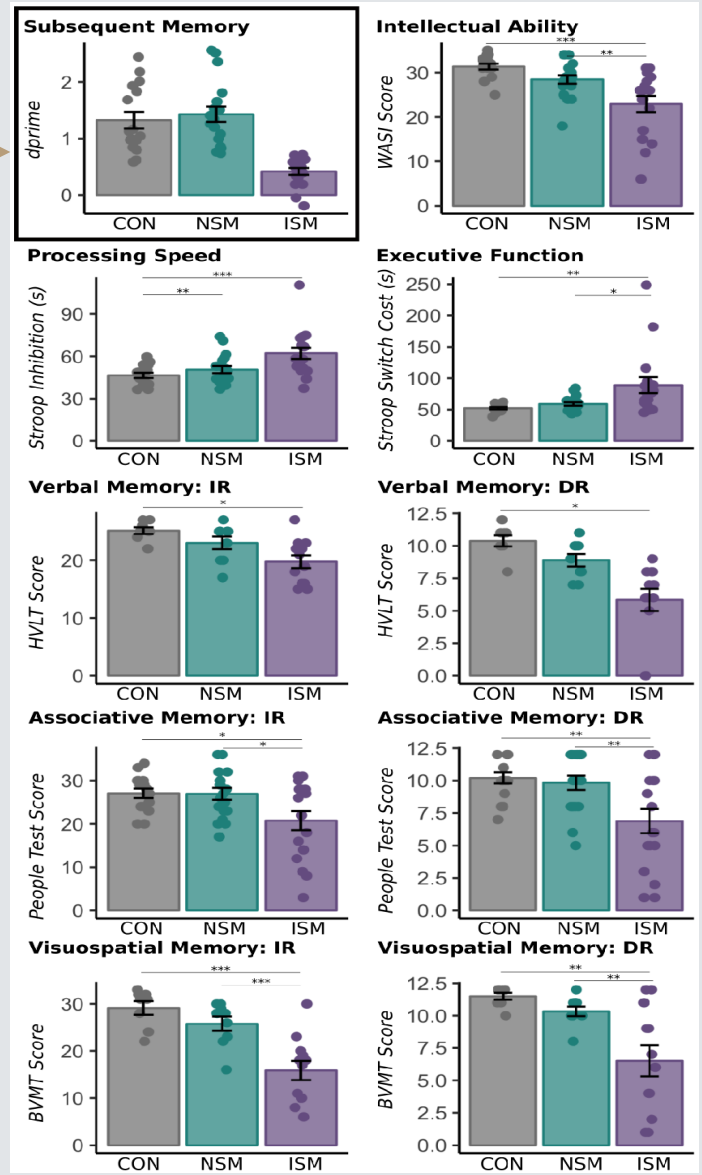


Visuospatial working memory



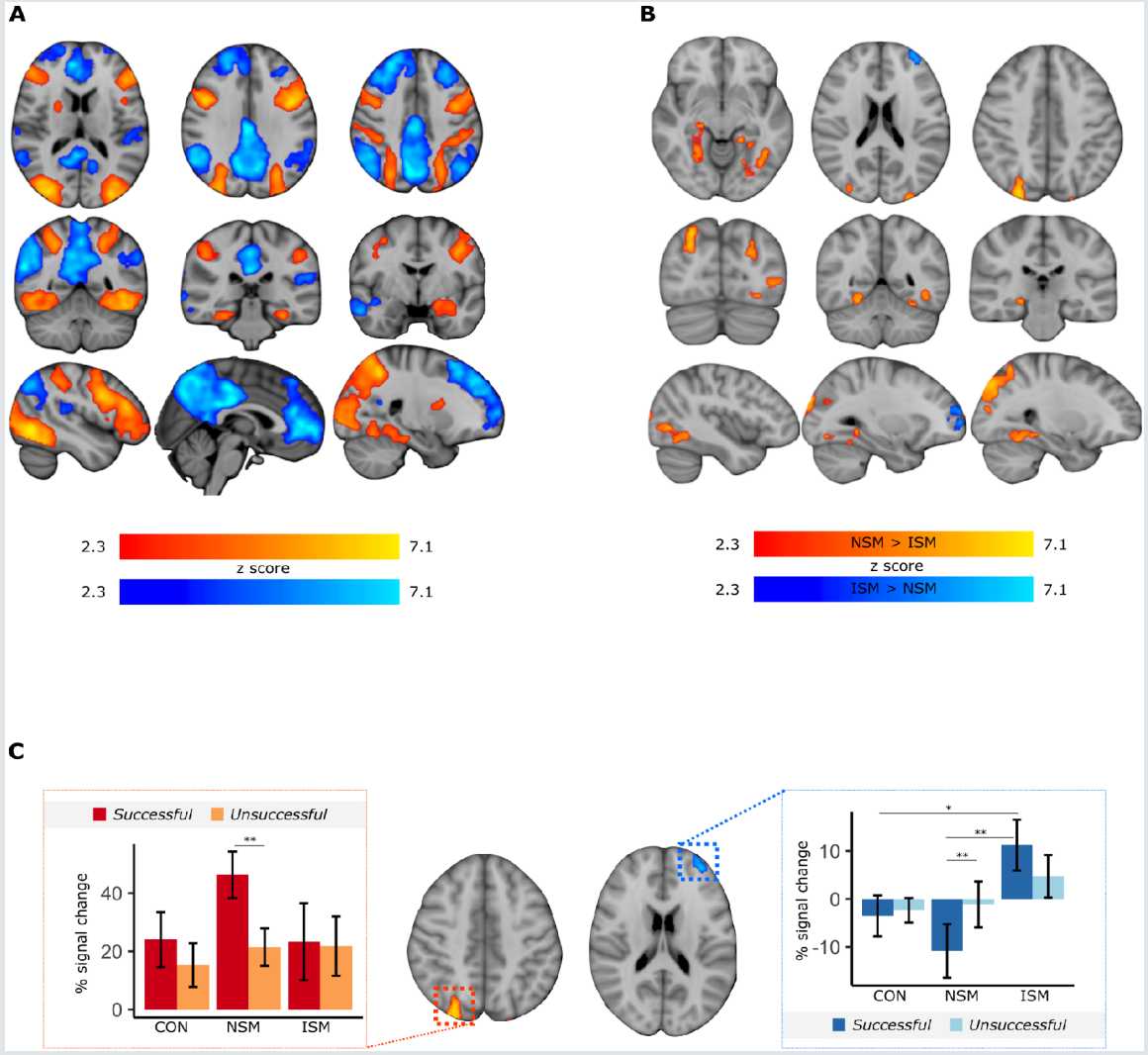
Investigating memory encoding in healthy and clinical populations





Mallas et al., 2020

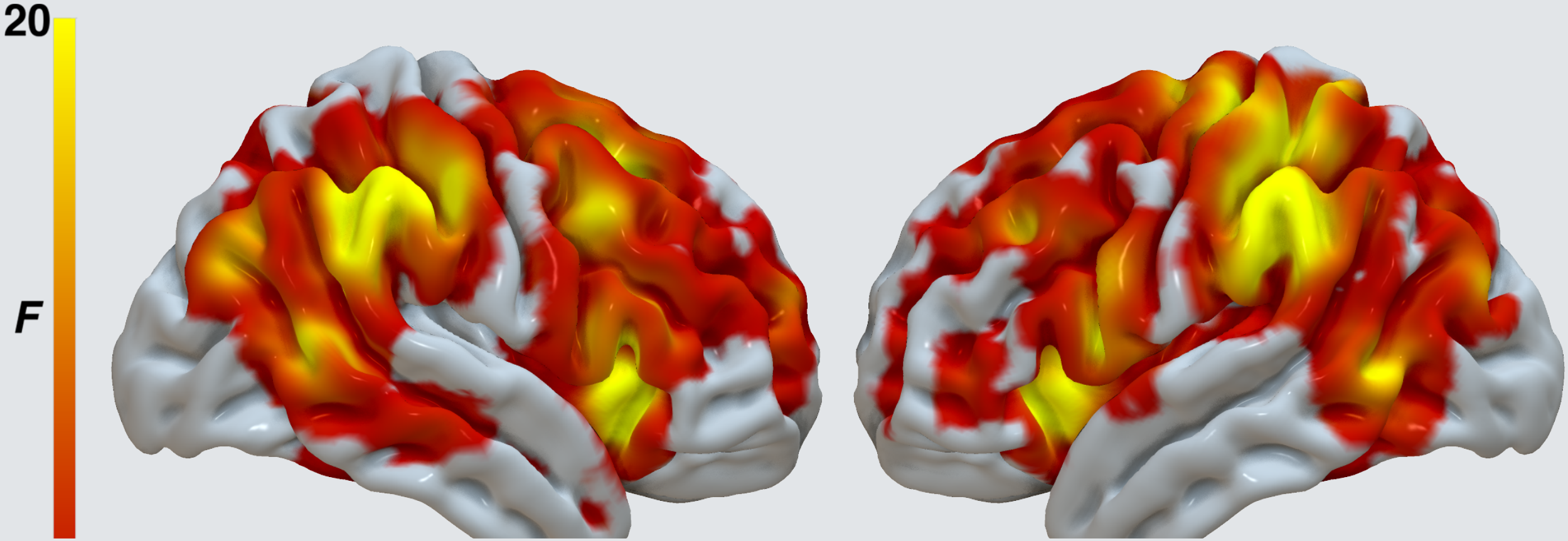
Investigating memory encoding in healthy and clinical populations



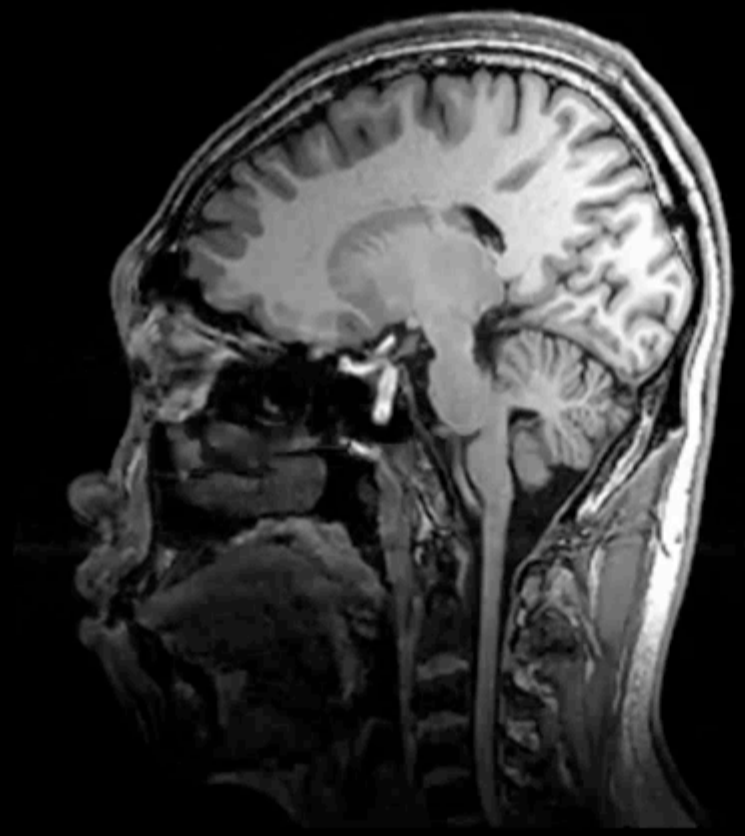
Bold activation and contrasts

Helps to Identify patterns of increased and decreased activation associated with successful and unsuccessful encoding

Mallas et al., 2020

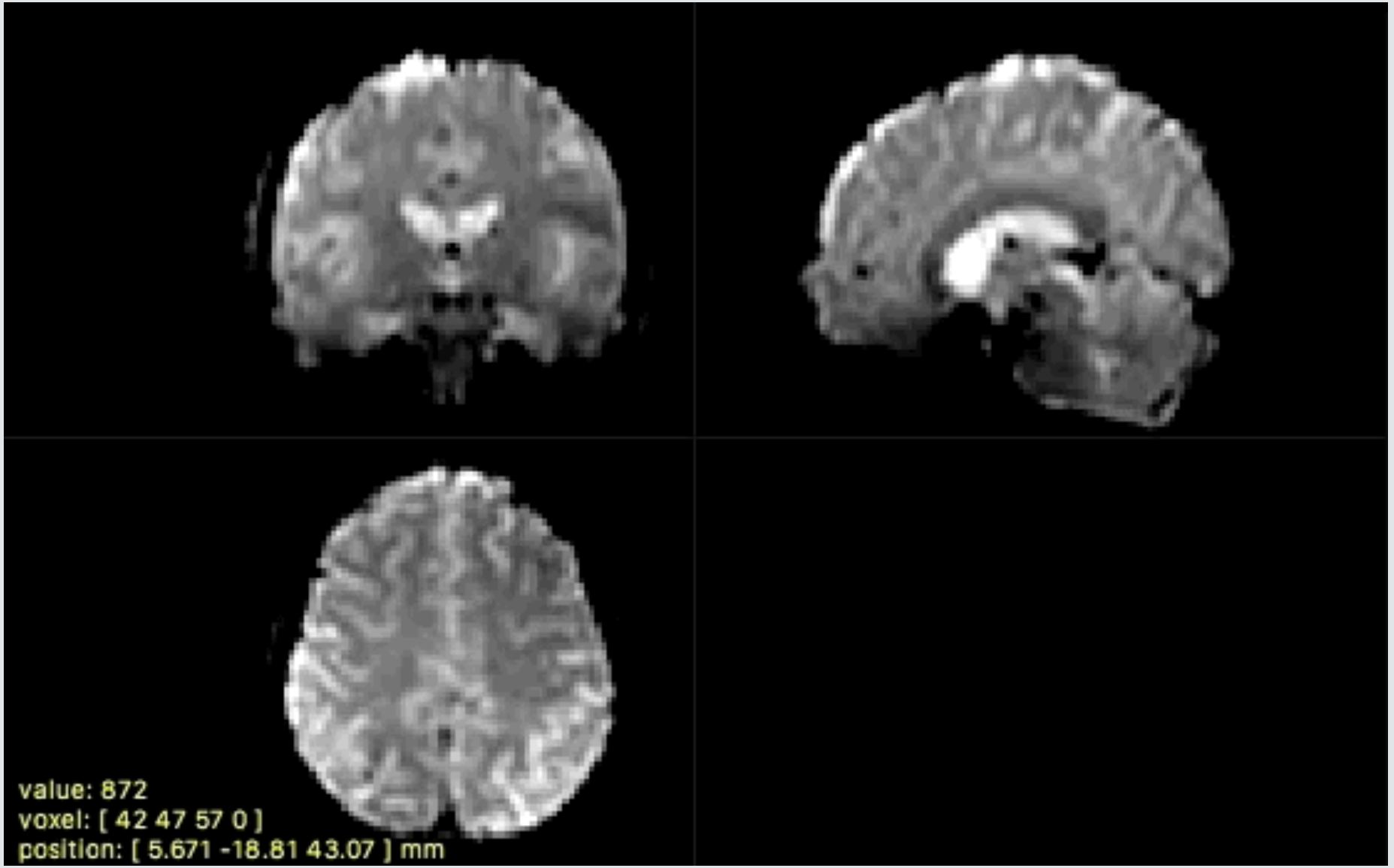


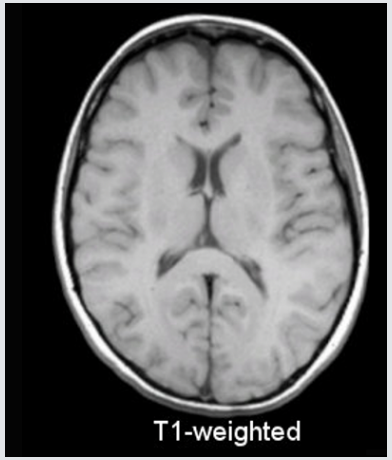
How do we get these brain activation maps?



- We take many images (slices) of the brain rapidly over the course of a task or period of rest (e.g. for resting-state fMRI)

- Specific acquisition parameters quantify properties associated with brain activation

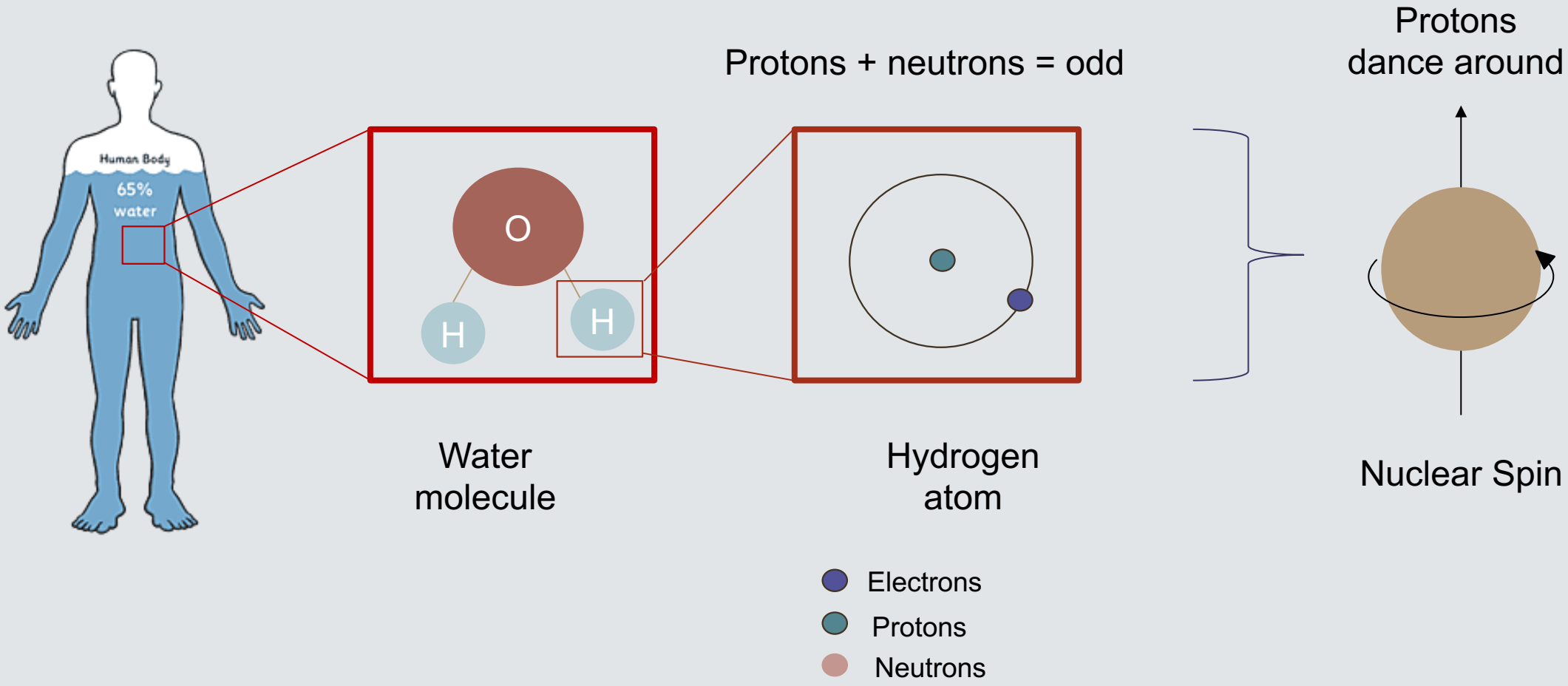




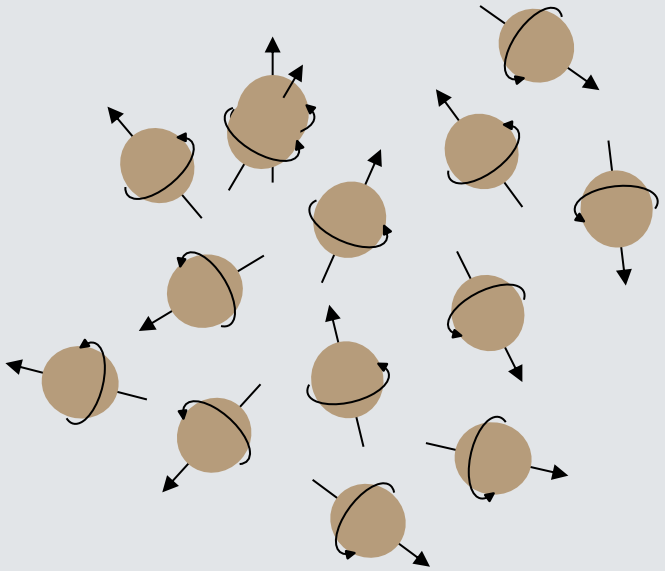
The spatial resolution of fMRI is lower than T1 due to the fact we acquire so many more images at such a fast rate (to provide dynamic/temporal information).

But what is it that fMRI measures?

The hydrogens of water have a nuclear spin

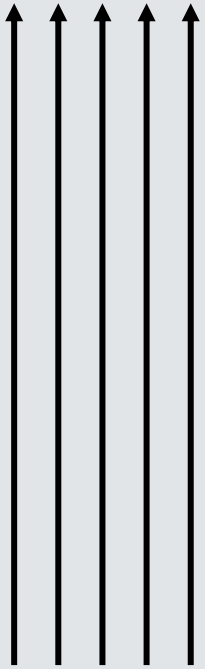


Protons align with the magnetic field

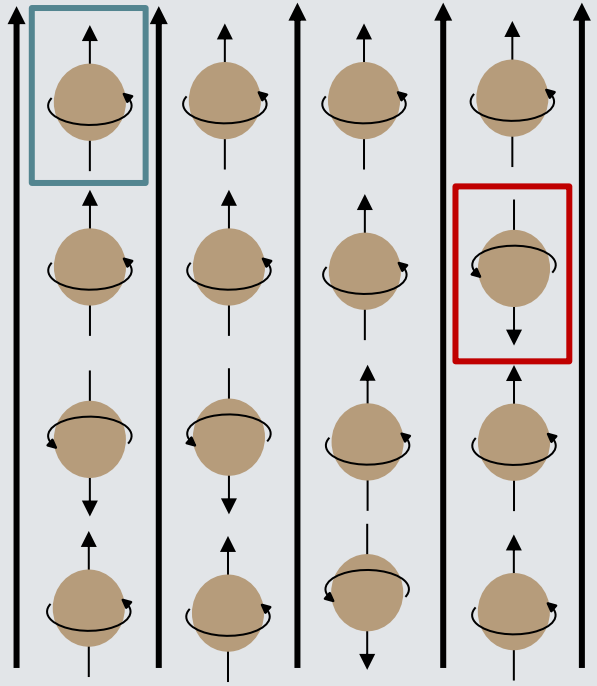


Random alignment of protons

+

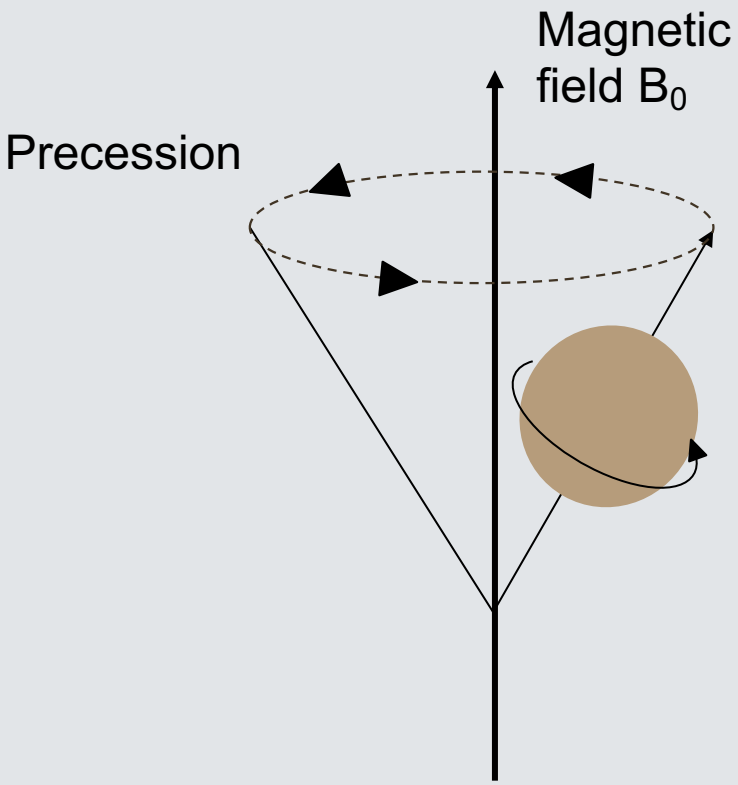


Magnetic field B_0

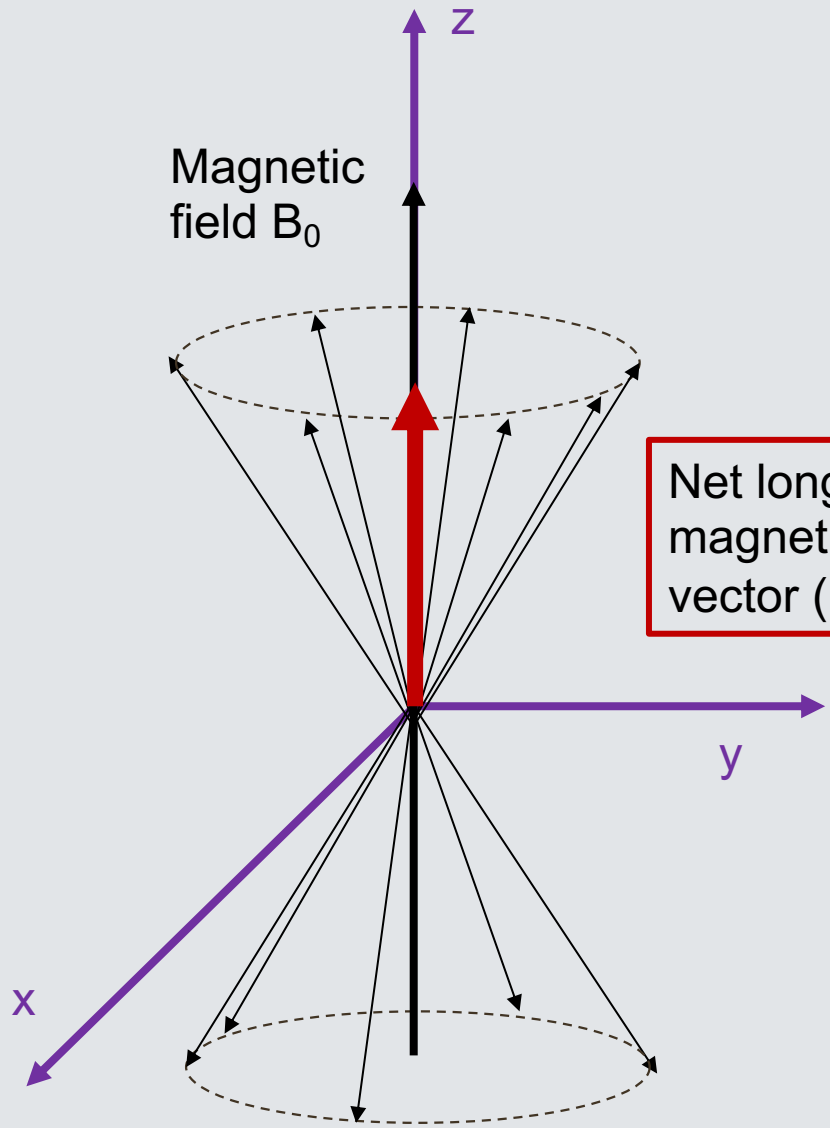


1. Parallel to the field: low energy
2. Antiparallel to the field: high energy

Precession of protons



Group of all protons



Resonance: radio frequency pulse gives energy to protons

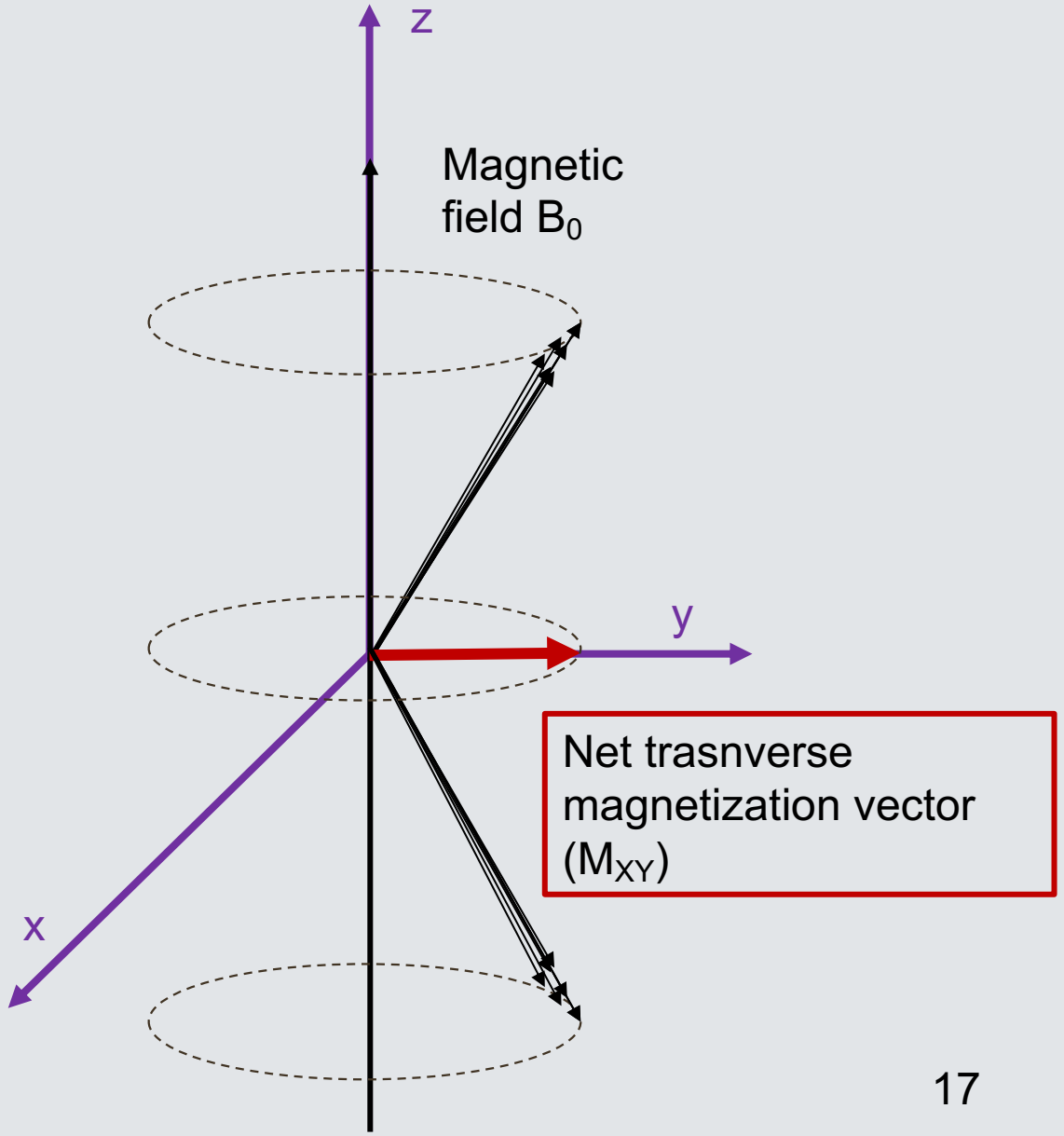
1

Protons moves from low energy to high energy state

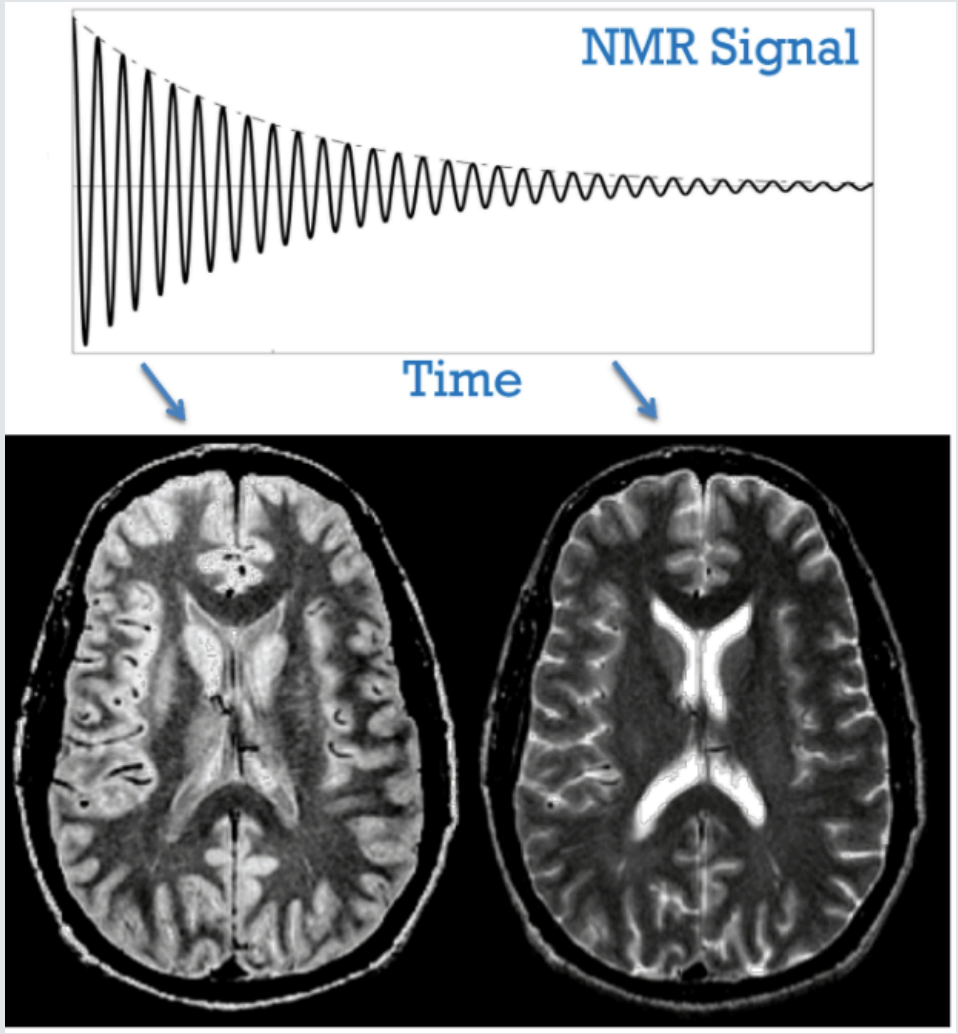
Parallel -> Antiparallel

2

Spinning of atoms becomes in phase



Relaxation: end of RF pulse leads ot energy release



End of RF pulse

↓

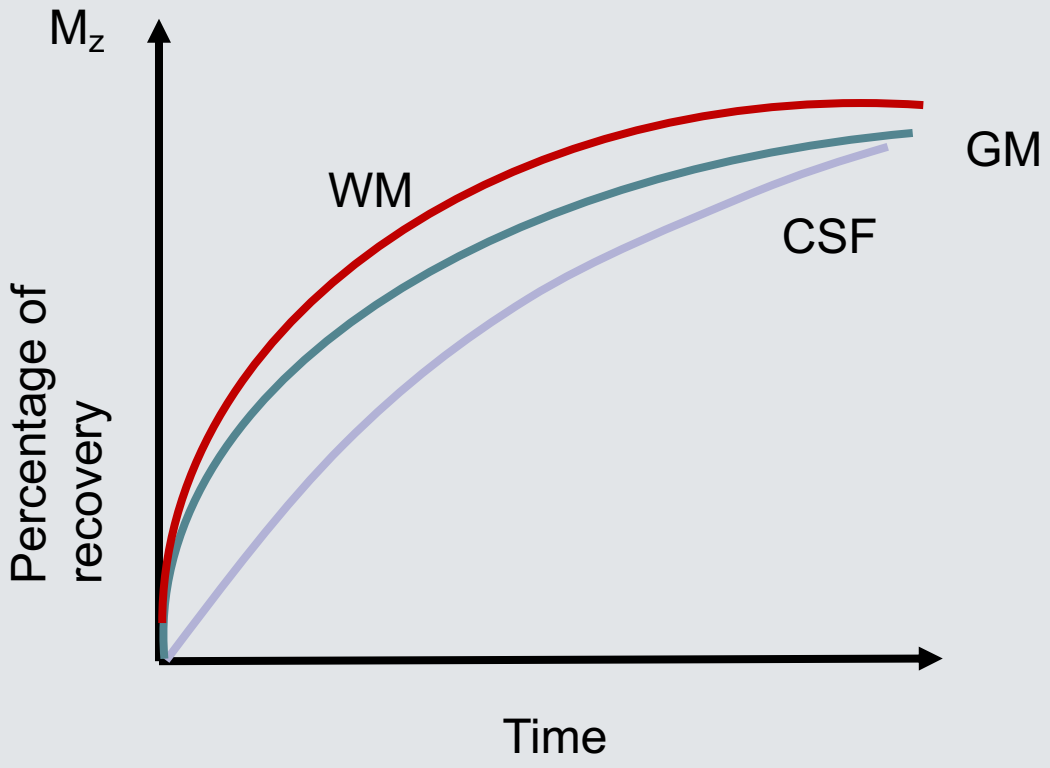
Detection of RF emission

↓

RF emission decays over time (relaxation) as a result of recovery and dephasing of protons

→ Decay different for each tissue leading to image contrast

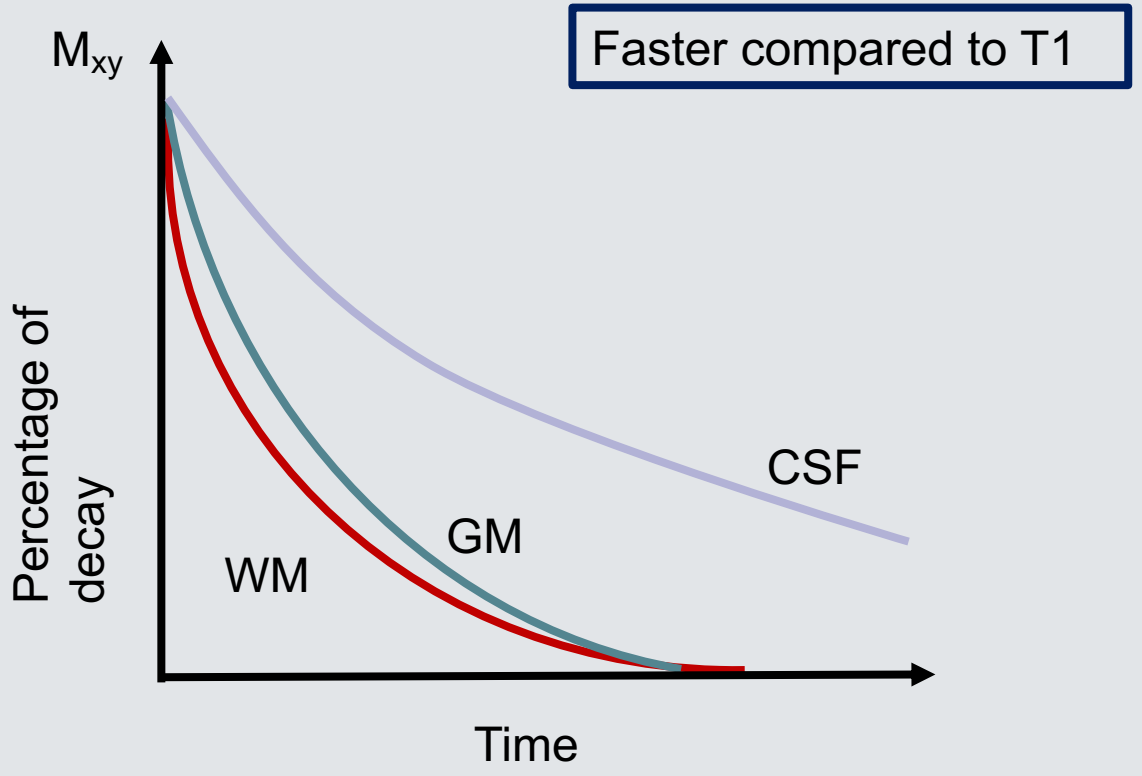
T1 or longitudinal relaxation



1

Protons move back to low energy state

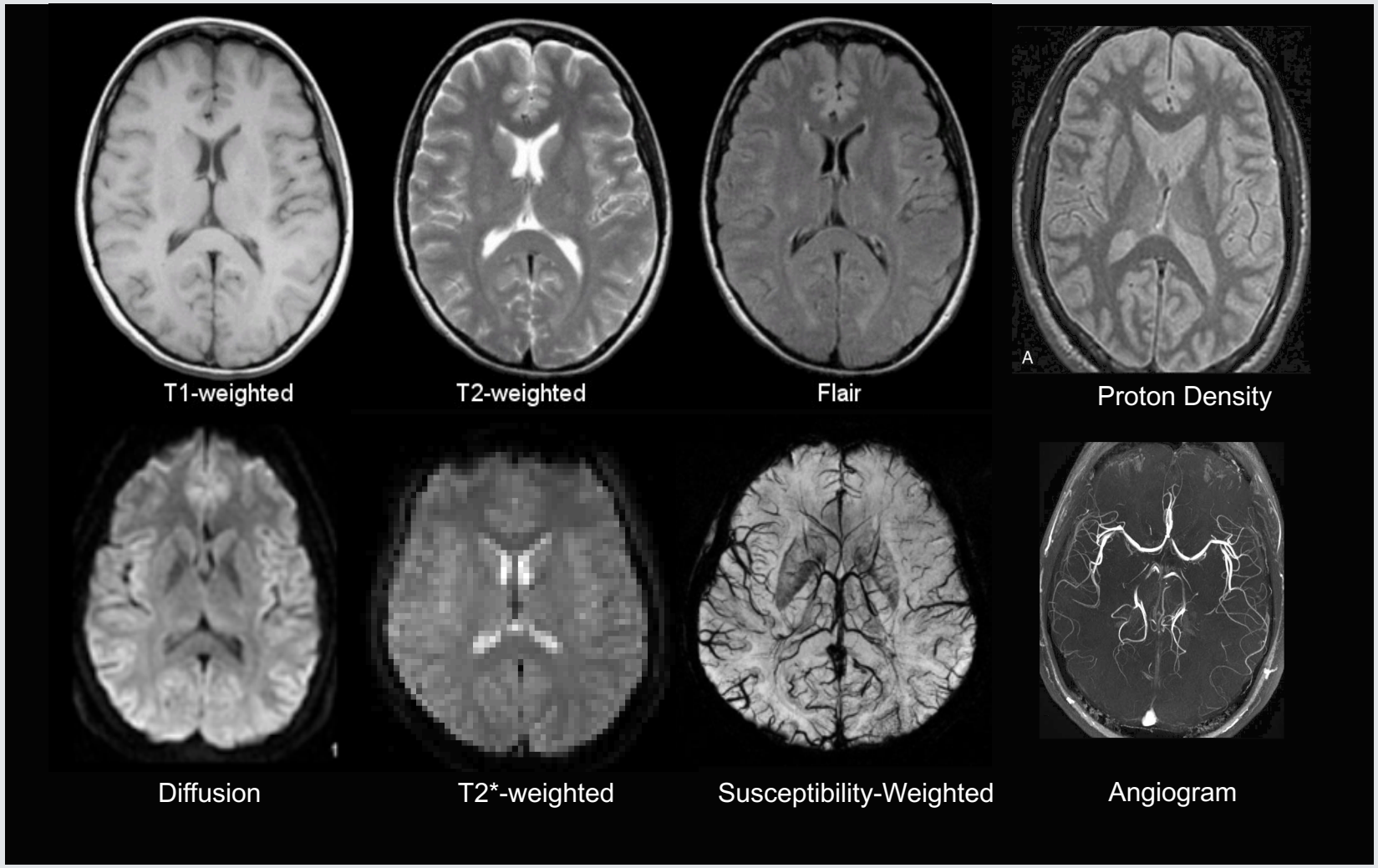
T2 or transverse relaxation



2

Protons go out of phase and the signal decays

How do you obtain different contrasts?

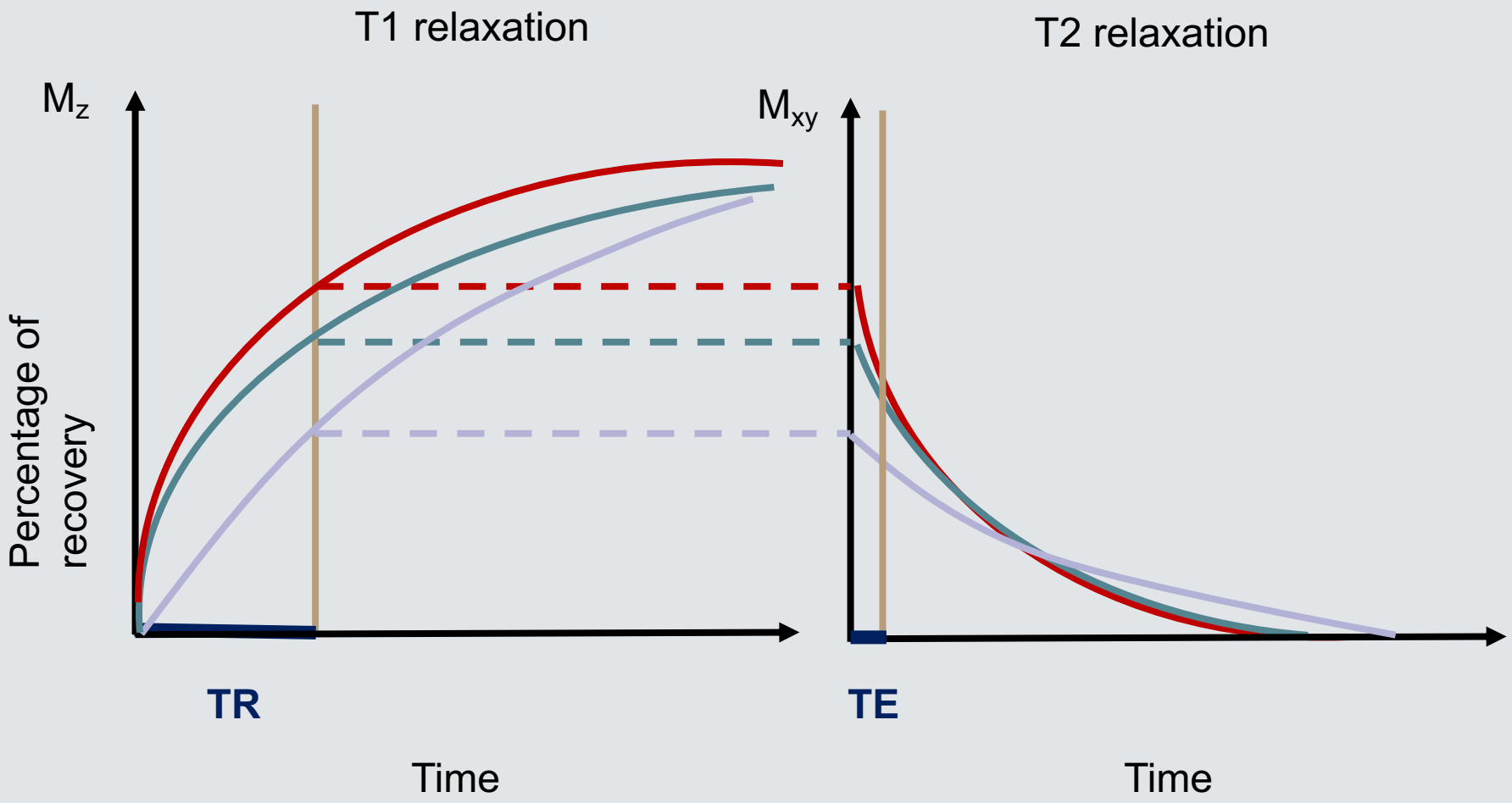


ACQUISITION PARAMETERS

REPETITION TIME: time between pulse sequences

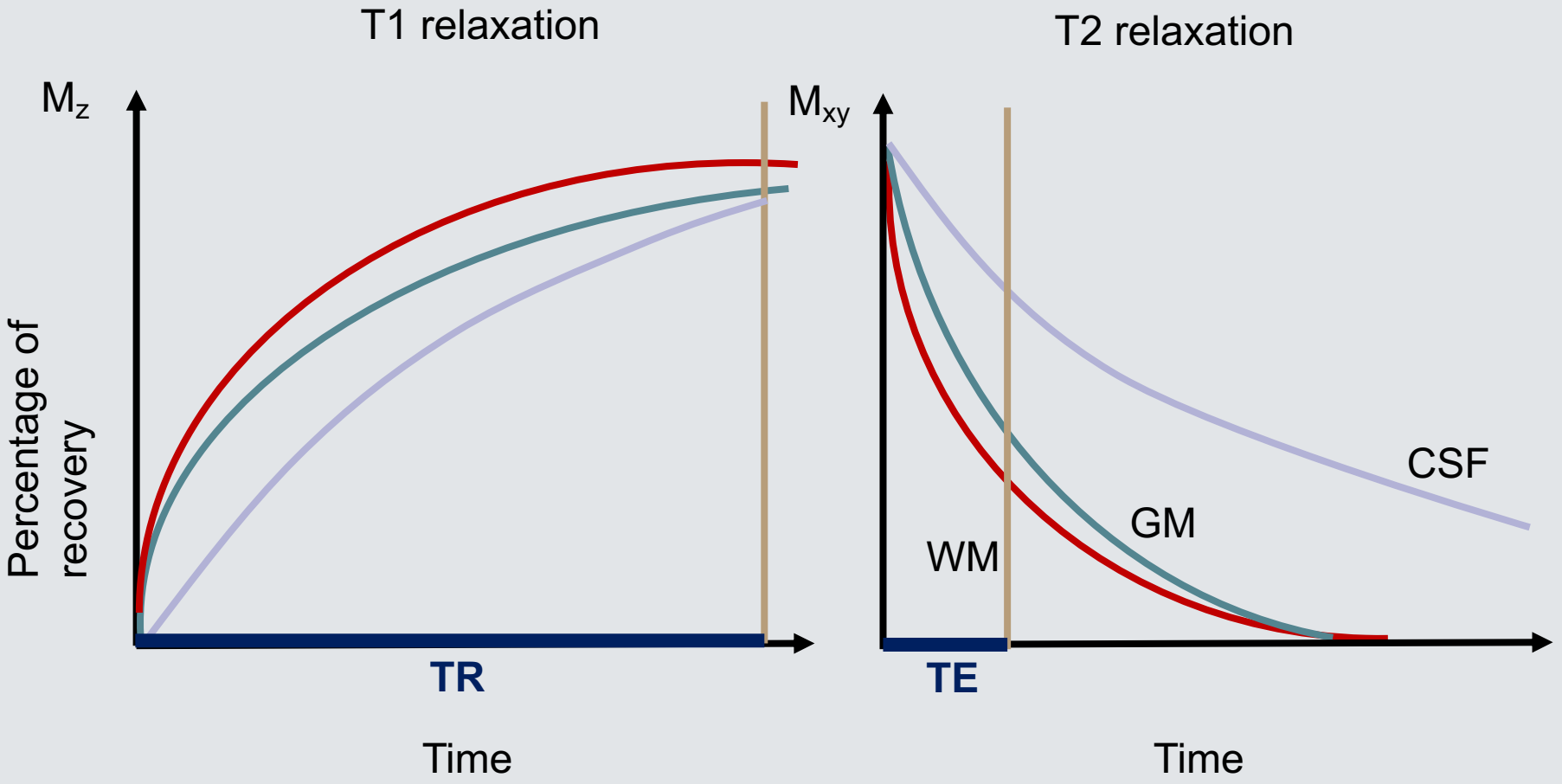
ECHO TIME: time between pulse sequence and measuremnt of peak of signal

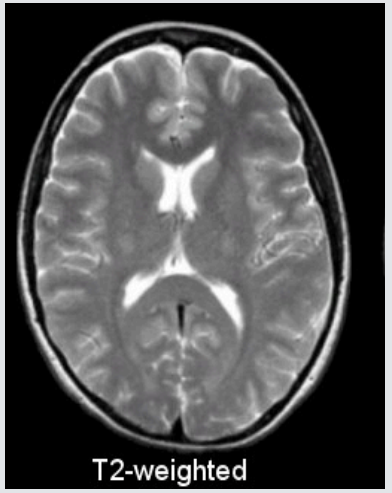
T1-weighted image



“SHORT” TR
“SHORT” TE

T2-weighted image



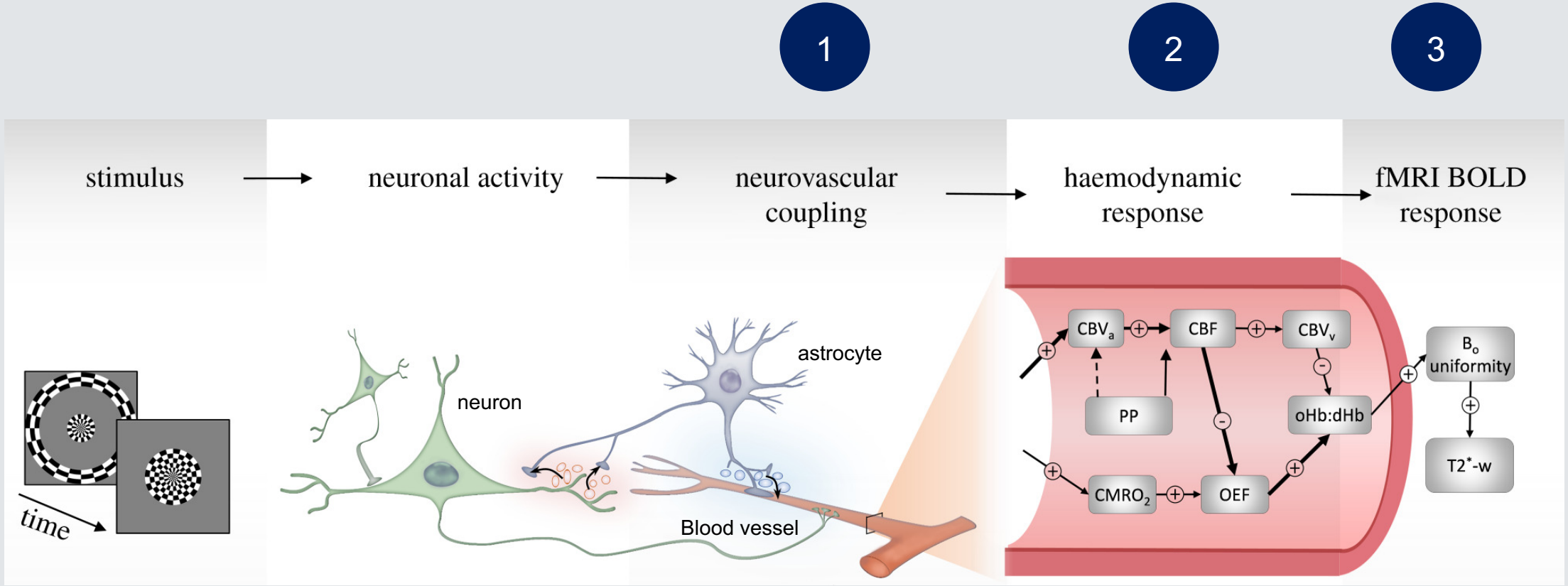


“LONG” TR
“LONG” TE

fMRI: T2* weighted image

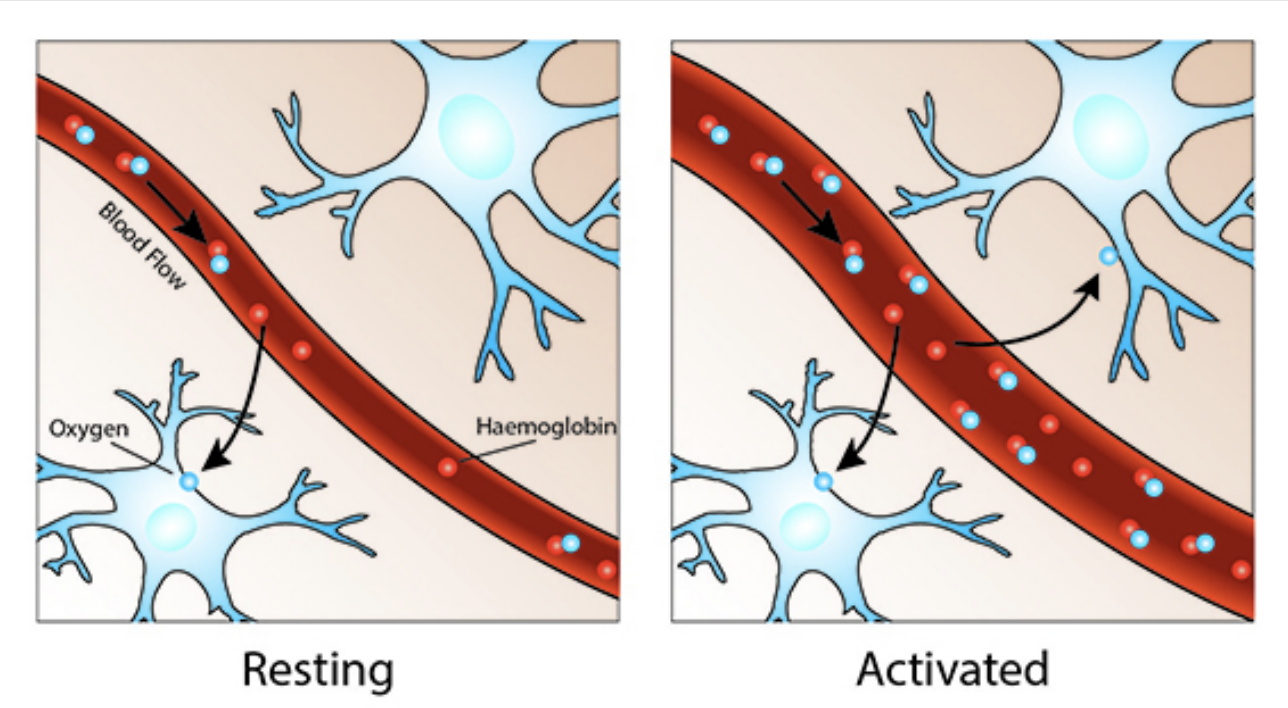
$$\frac{1}{T2^*} = \frac{1}{T2} + \frac{1}{T_{inhomogeneties}}$$

fMRI=Indirect measure of neuronal activity



Tsvetanov et al., 2020

1 Neurovascular coupling



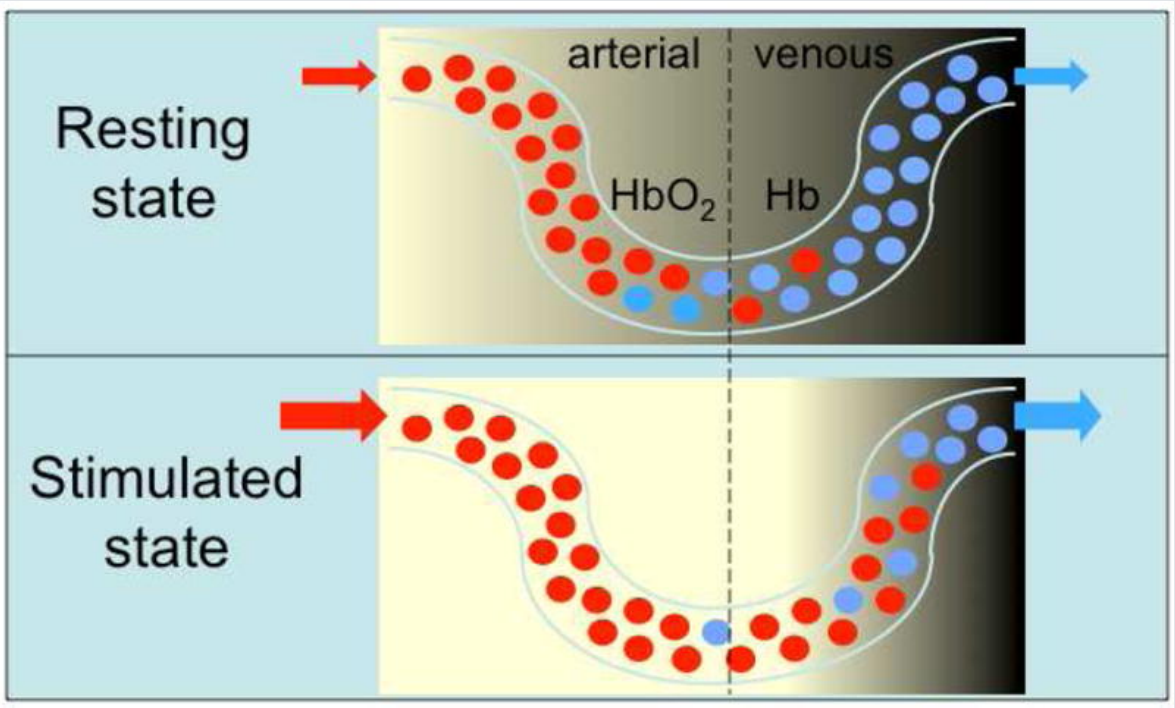
INCREASED BRAIN ACTIVITY

↑ Need of energy

↑ Use of oxygen

↑ Blood flow and vasodilation

2 Haemodynamic response



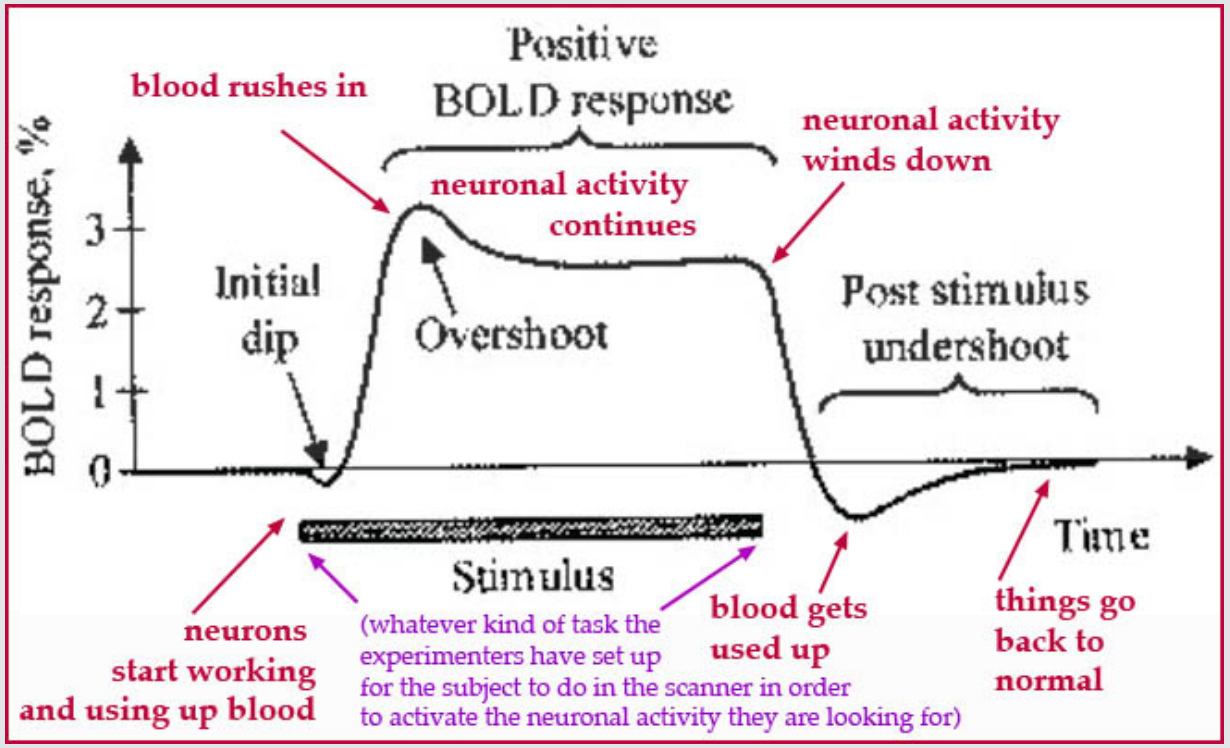
INCREASED BLOOD FLOW

Oxygenated blood (HbO_2)

Deoxygenated blood (Hb)

3

Blood **O**xygen **L**evel **D**ependent (BOLD) response

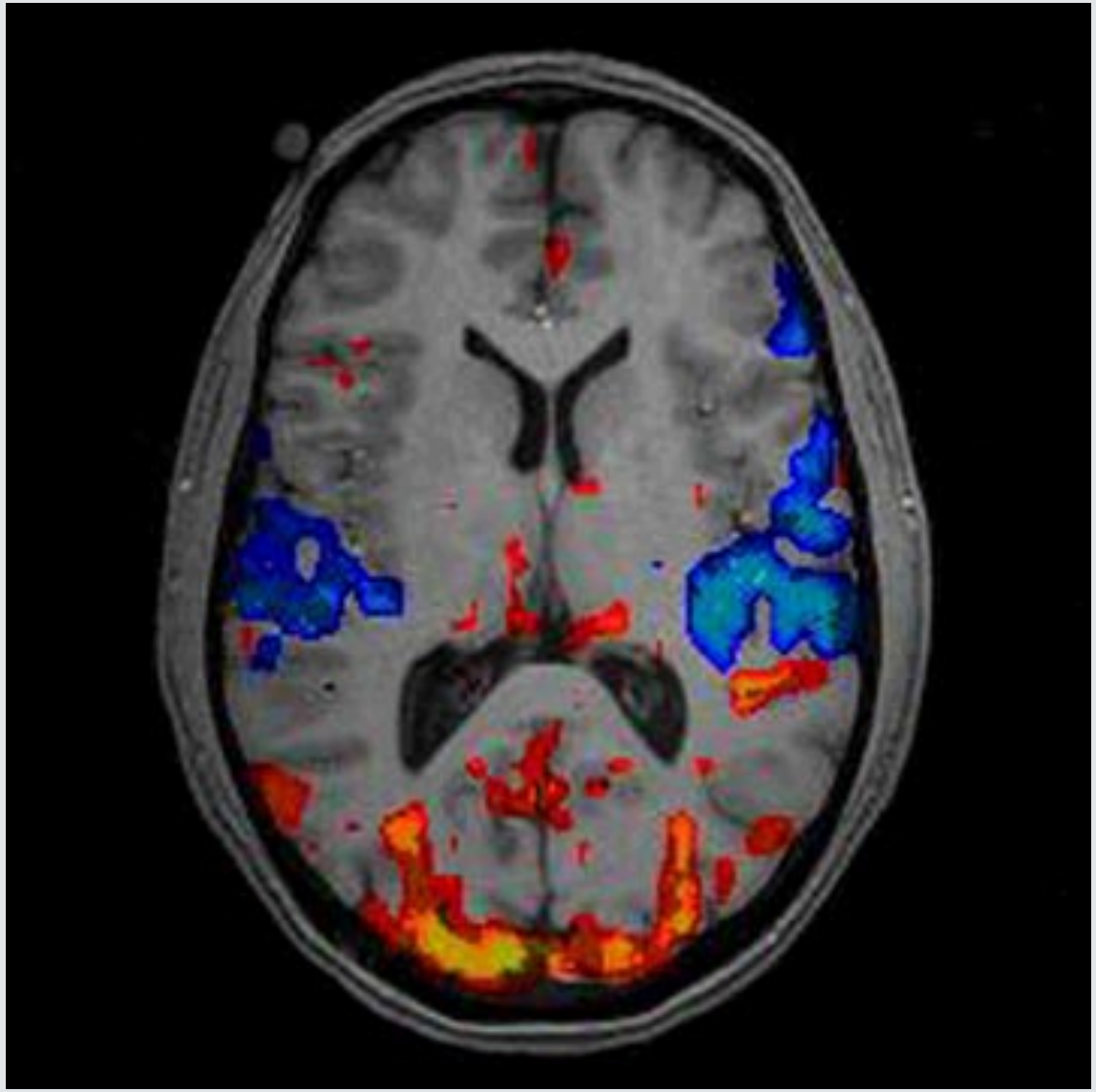


HbO_2
- *Diamagnetic*
- *No interaction*

Hb
- *Paramagnetic*
- *More interaction*

HbO_2 ↑ → Dephasing ↓ → T2* ↑ → **MRI signal** ↑

Hb ↑ → Dephasing ↑ → T2* ↓ → **MRI signal** ↓



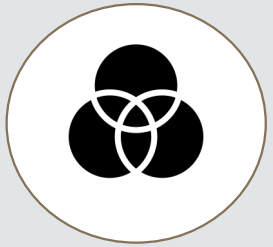
What are the sources of noise in fMRI measurement?

fMRI is very susceptible to noise, including:

Head motion

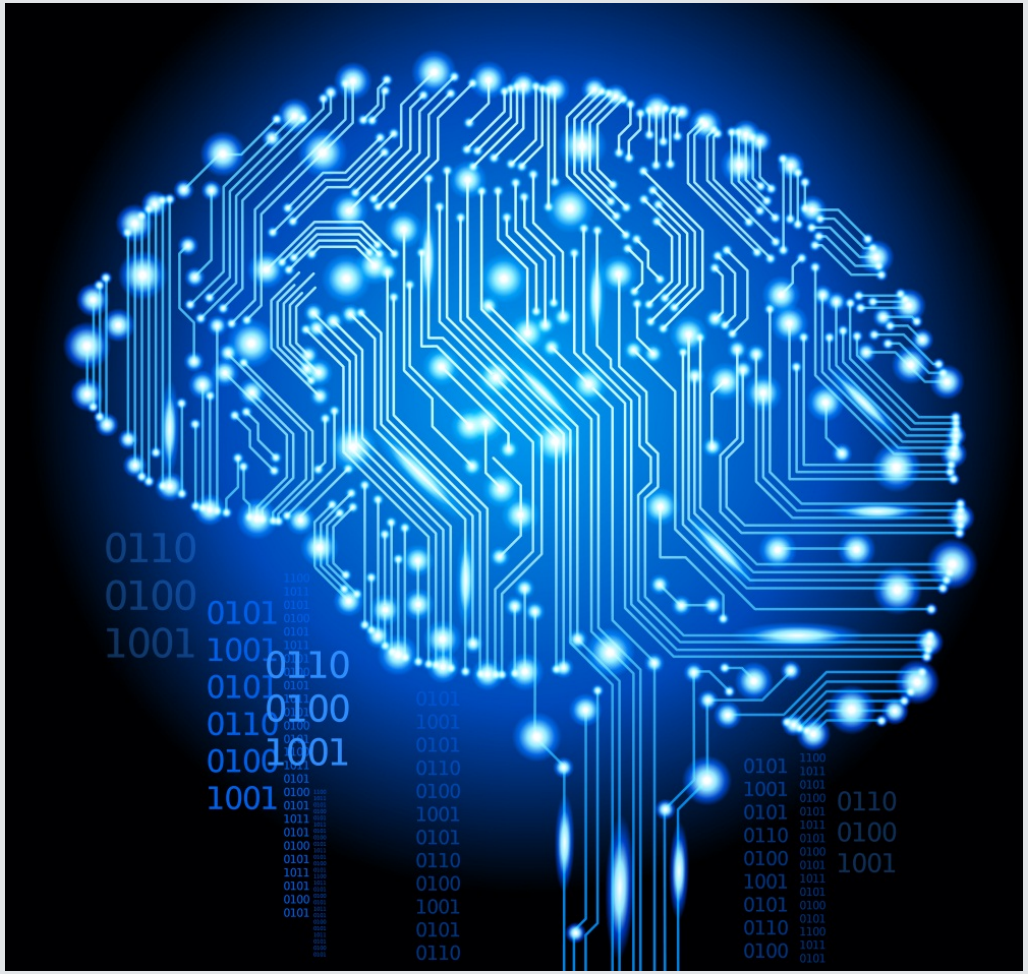
Signal drift (scanner heats up over time)

Heartbeat

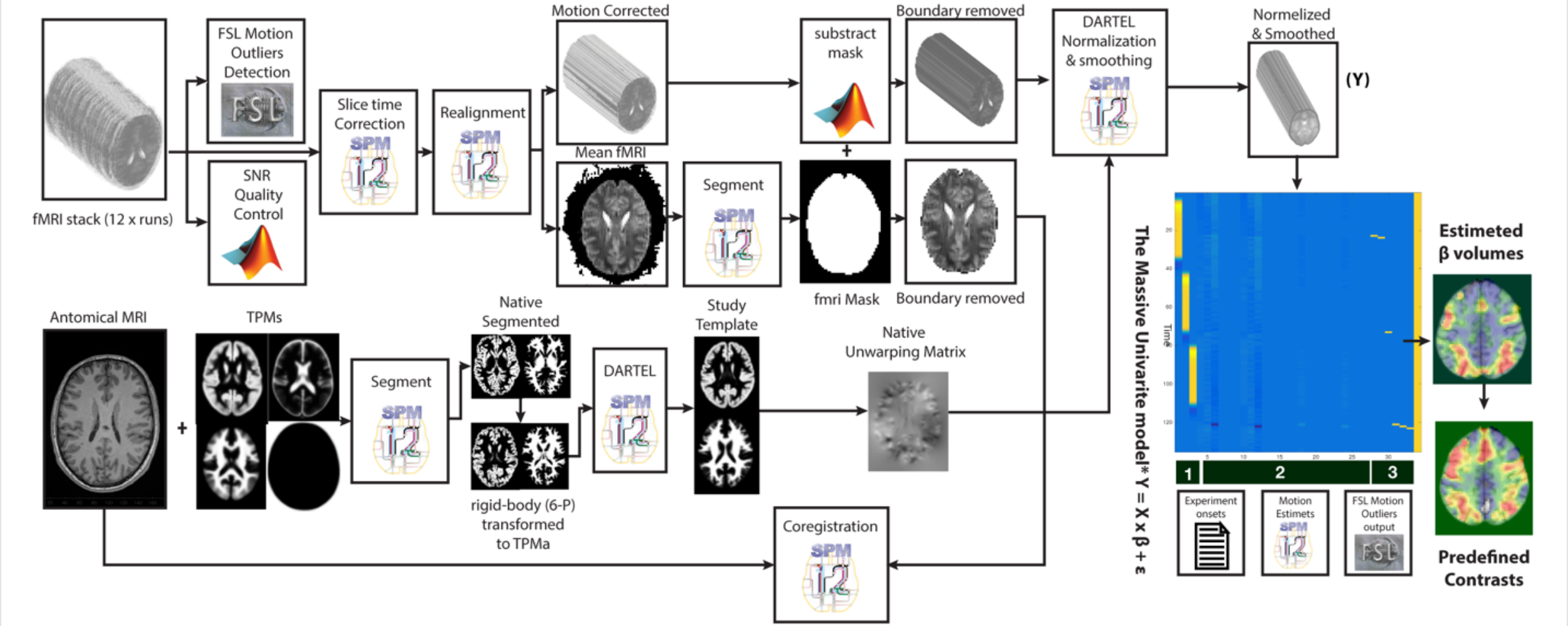


Partial volume effects

Participants falling asleep

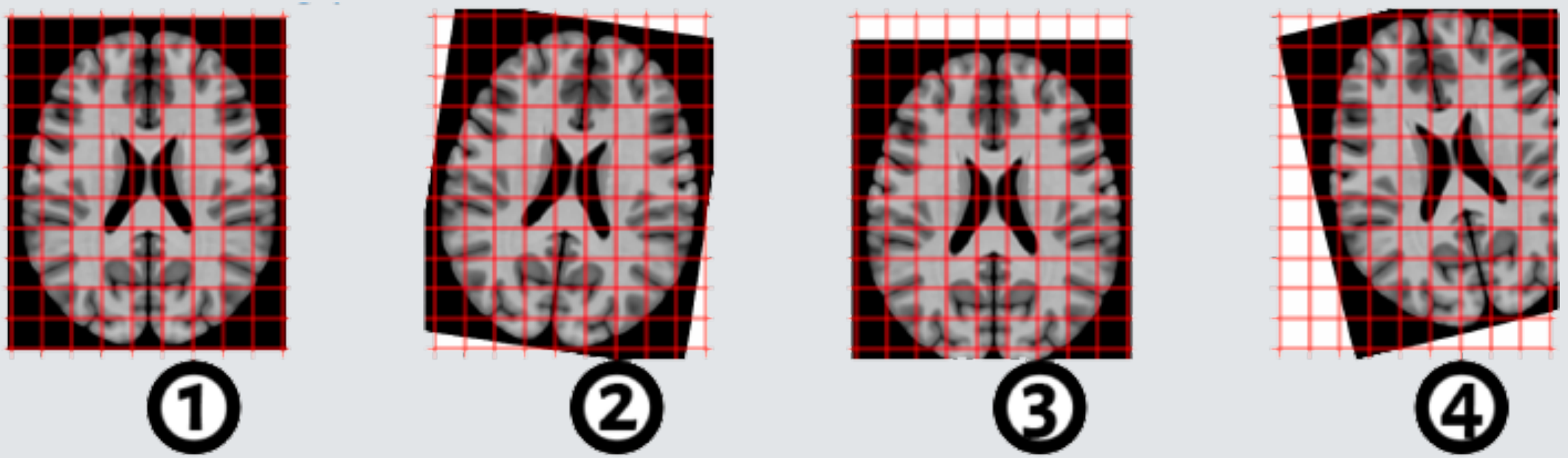


fMRI preprocessing



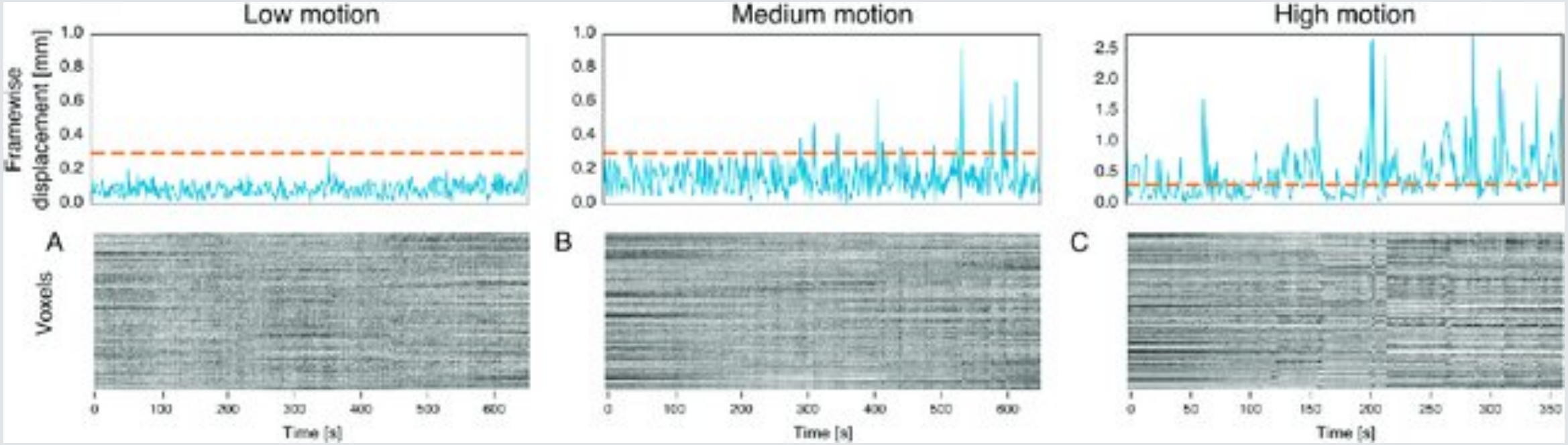
1. Motion correction
2. Slice time correction
3. Segmentation
4. Coregistration
5. Normalization
6. Smoothing

1 Motion causes misalignment



Rigid-body transform between time points:
(X,Y,Z) translations & rotations.

1 Motion influences voxels intensities



Include effect of head motion in the analysis

Further pre-processing steps…

2 **Slice time correction**

- Last slice collected at later timepoint compared to first slice
- ✗ Modelling of rapid events
- ✓ Sync interpolation

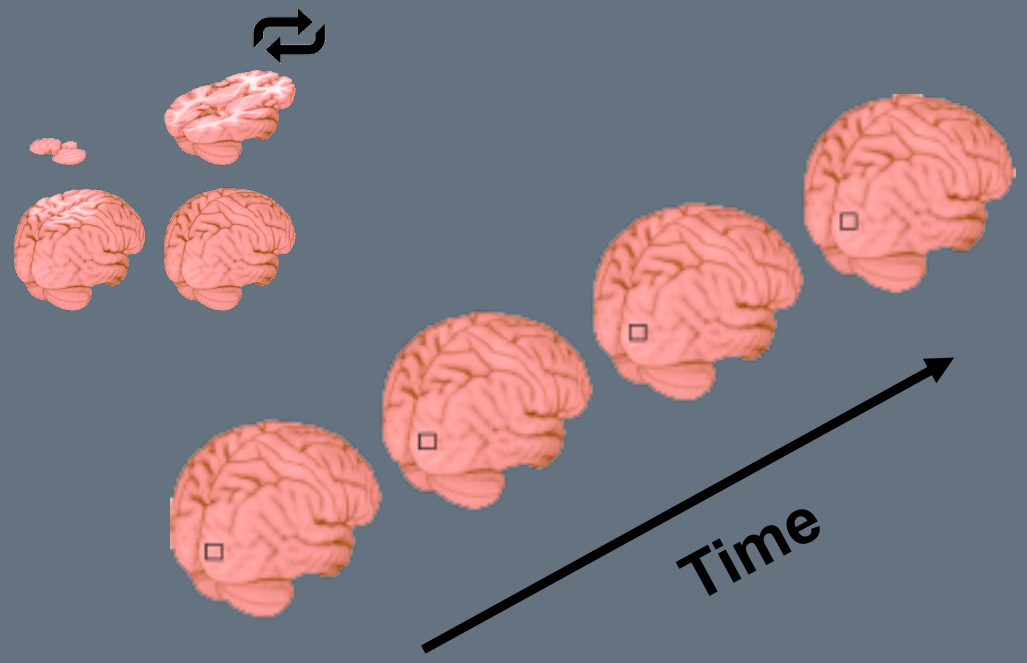
3 **Normalization**

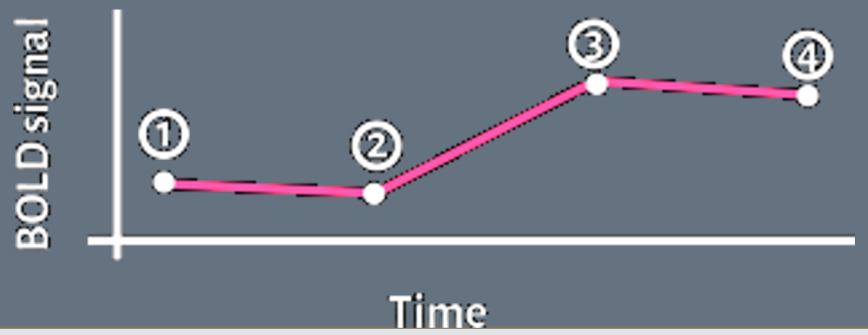
- Different brain shapes and sizes
- ✗ Group analysis and cross – studies comparison
- ✓ Registration to standard template

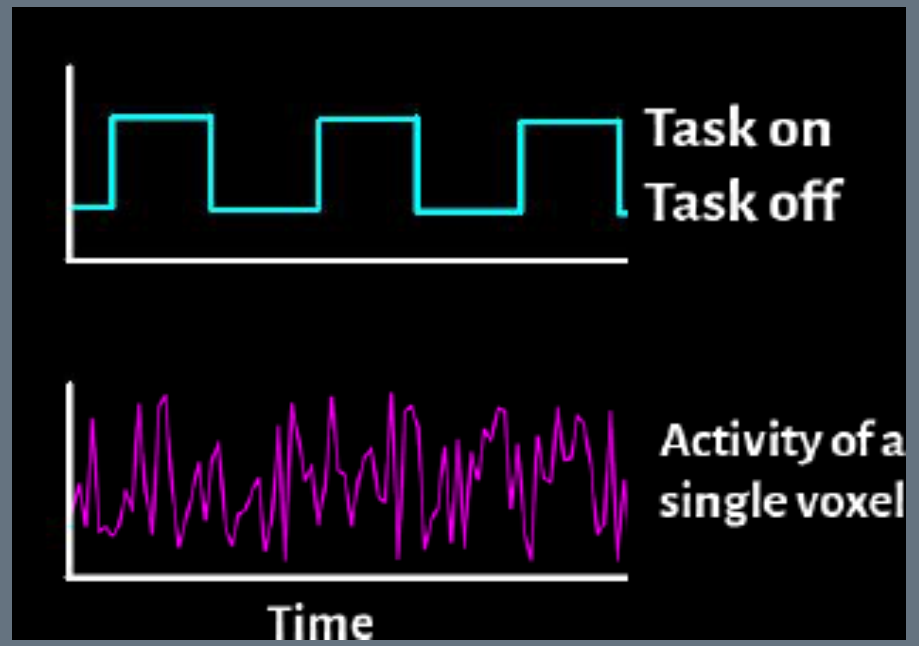
4 **Spatial smoothing**

- Noise in the image
- ✗ All steps in the analysis
- ✓ Spatial averaging for each voxel

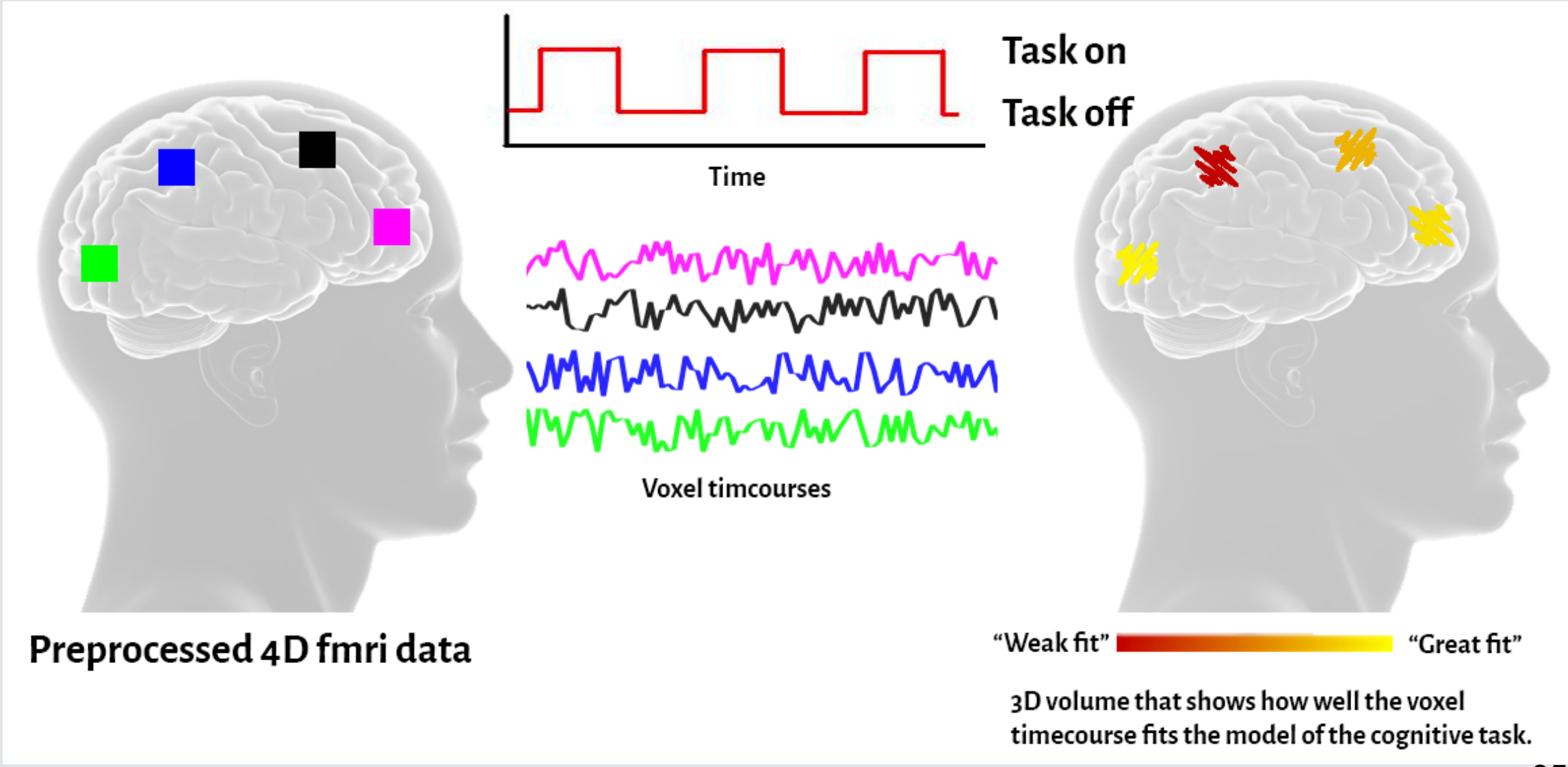
Voxel timeseries







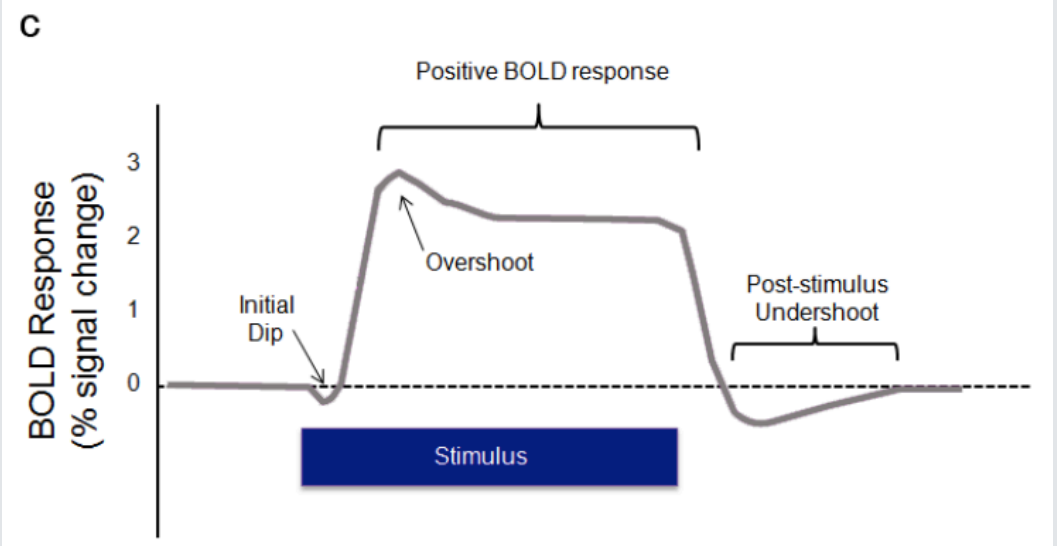
Which voxels show activation change?

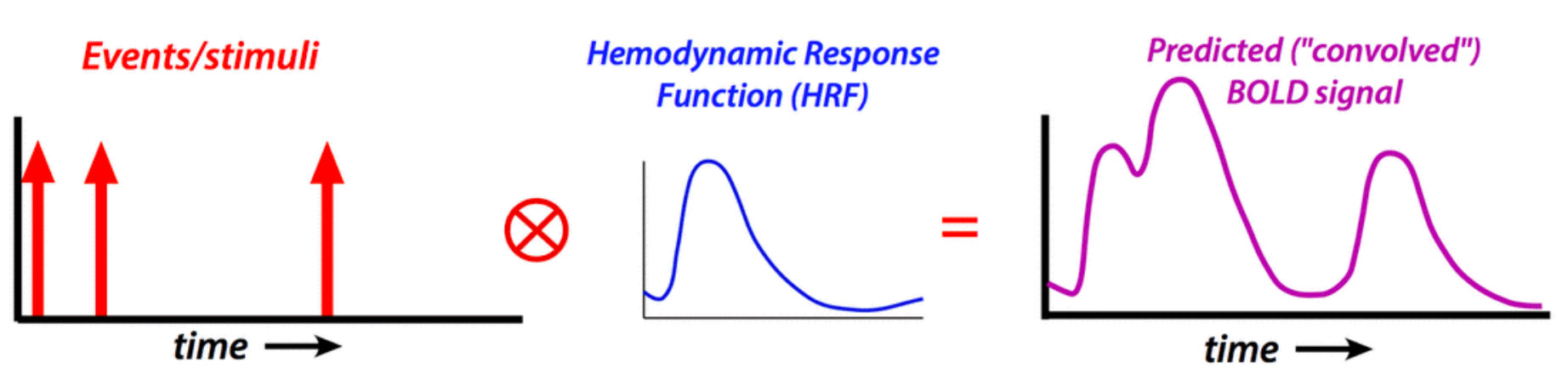


Credit: Richard Daws

Convolution

Inherent temporal lag between the changes in neuronal activity and the changes in the BOLD signal

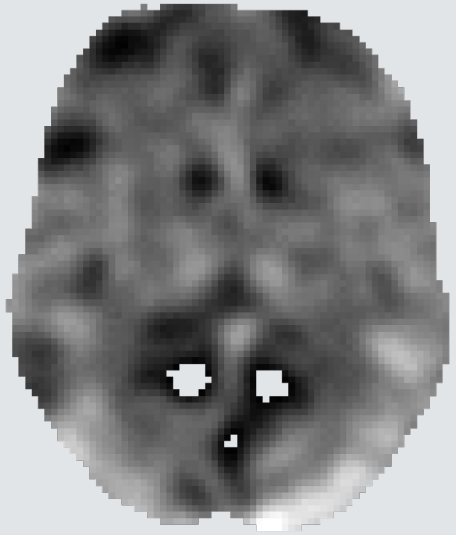




Experiment design

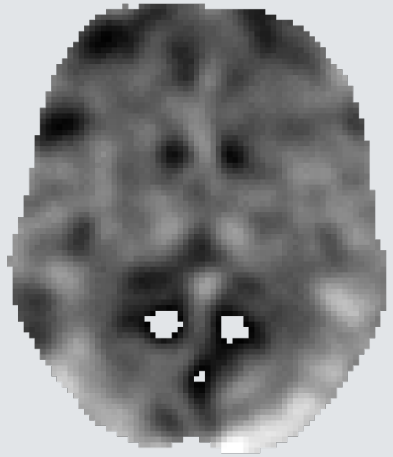
Mathematical representation of bold response

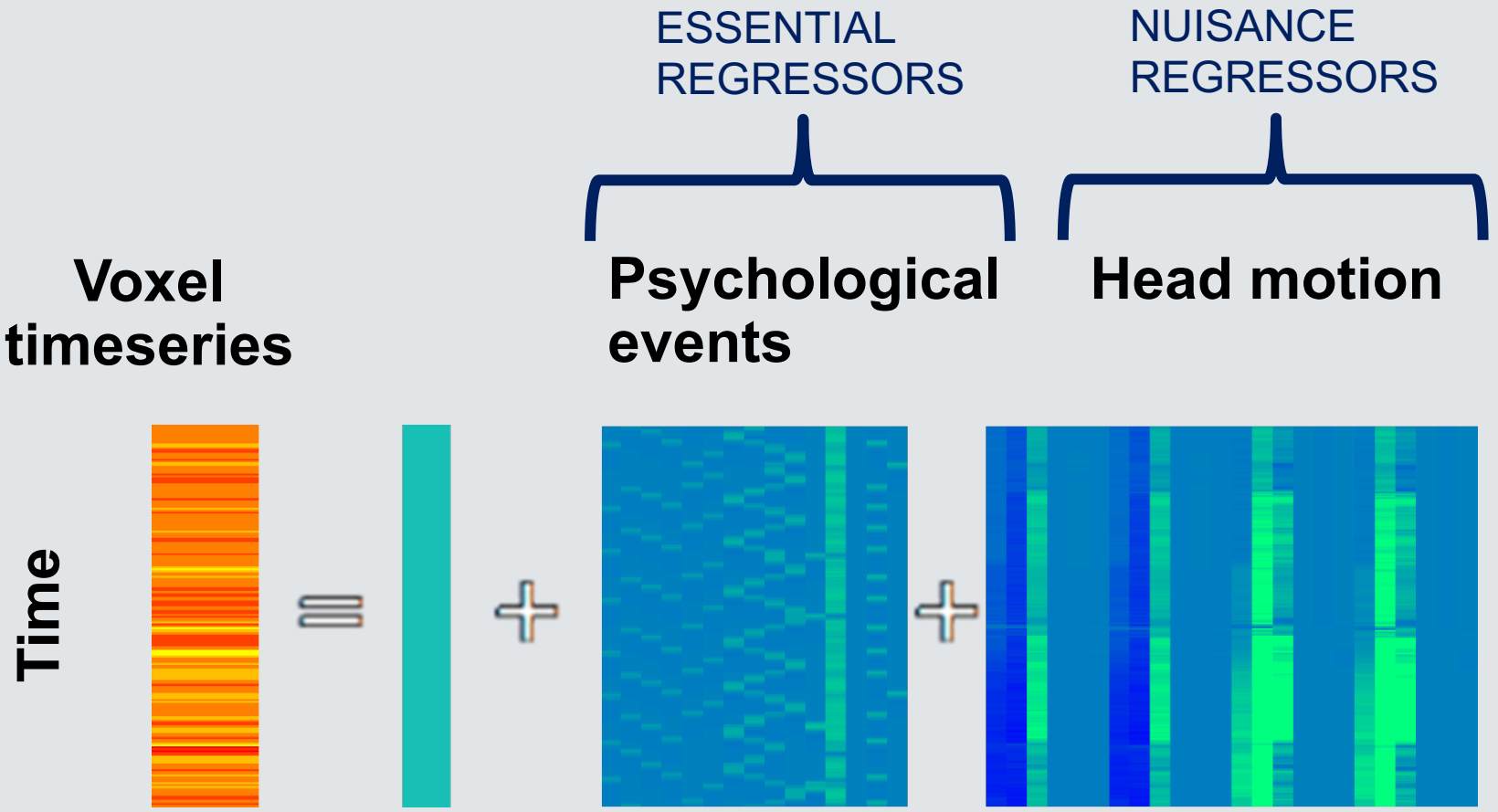
General Linear Modelling (GLM)



$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_N X_N + e$$

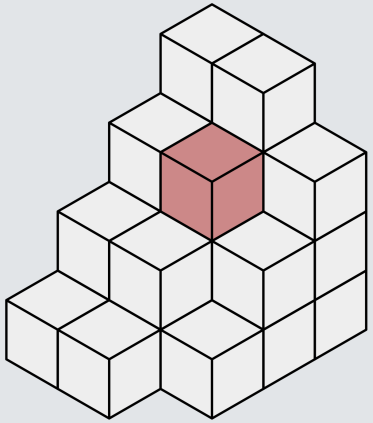
GLM



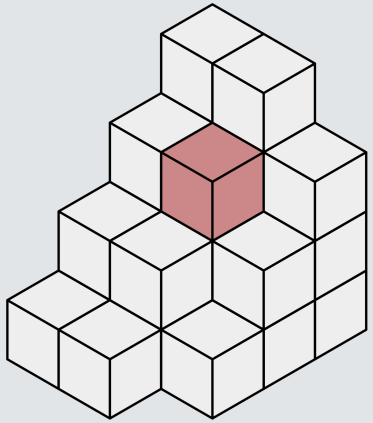


$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_N X_N + e$$

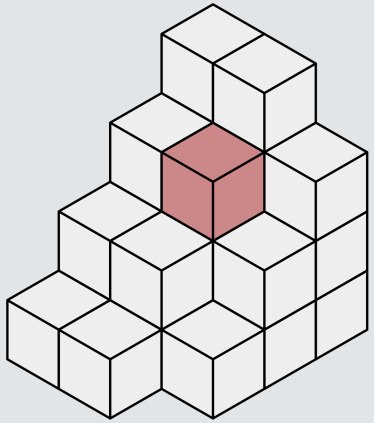
For each voxel…



BRAIN 1

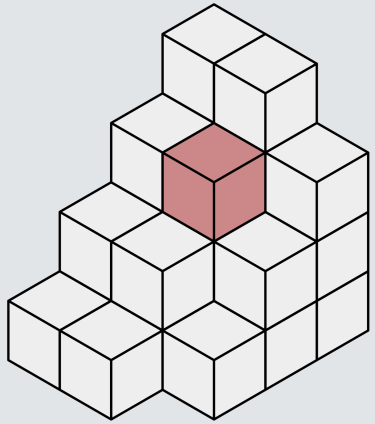


BRAIN 2

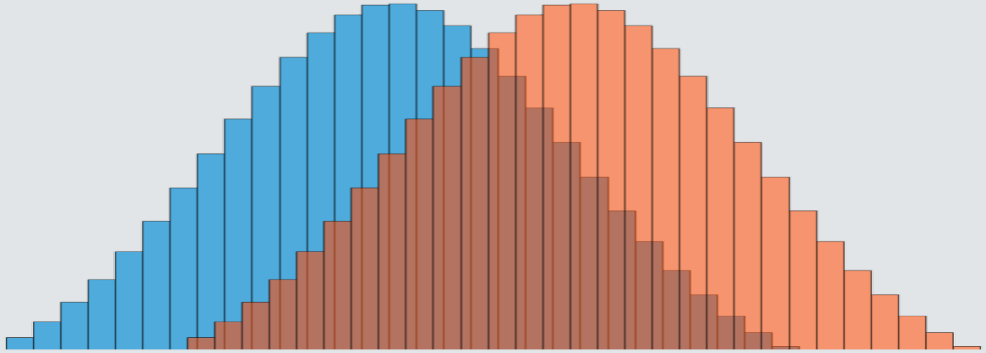


BRAIN 3

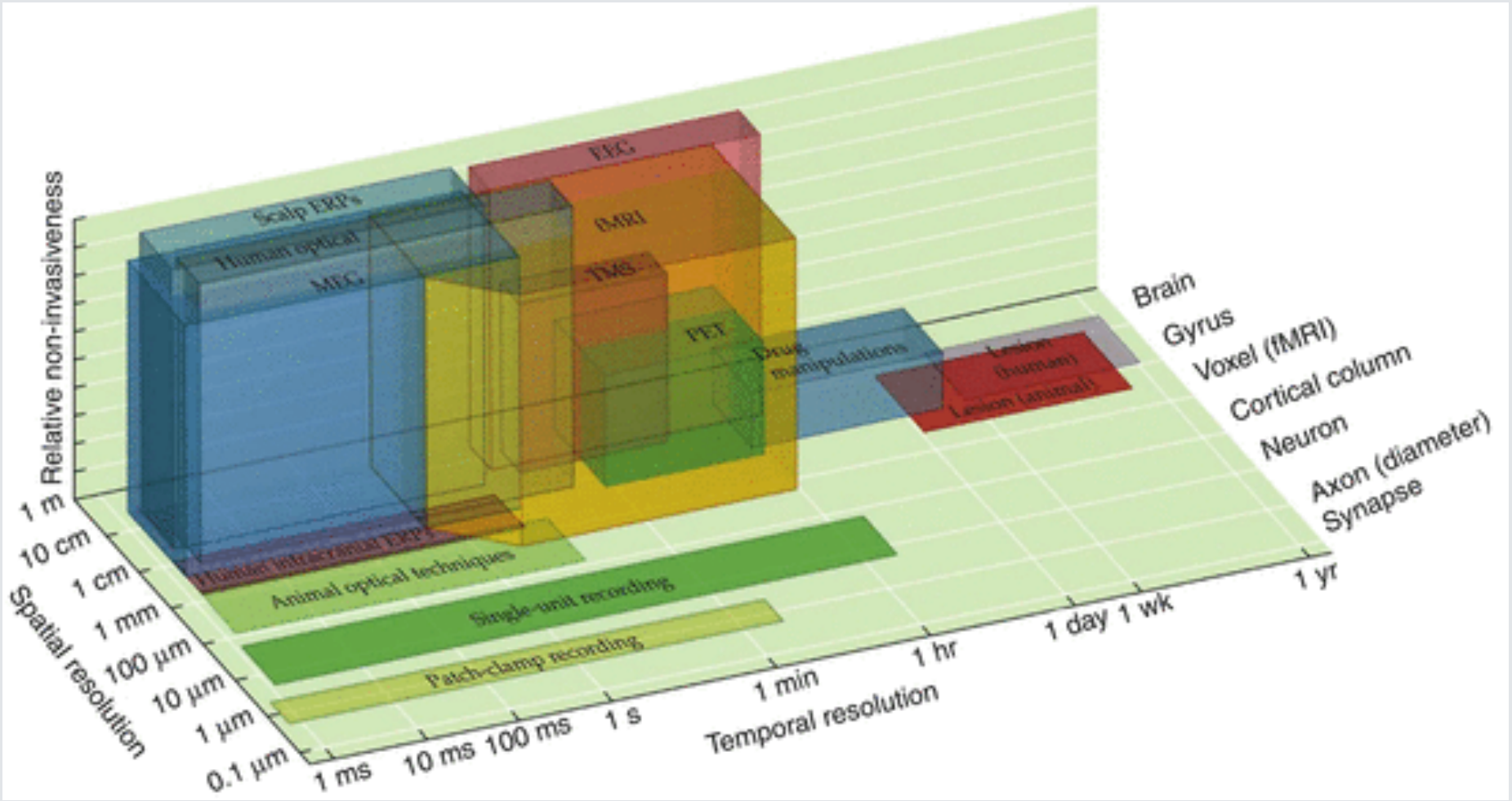
…



BRAIN N



How does fMRI compare to other neuroimaging?



+ Non-invasive

+ Demonstrate entire network of brain regions involved in a particular cognitive task

× Uses an indirect measure of neuronal activity

× Susceptible to many types of noise

Questions?

With thanks to Amy Jolly for help with the slides