Functional MRI (2): Data Processing
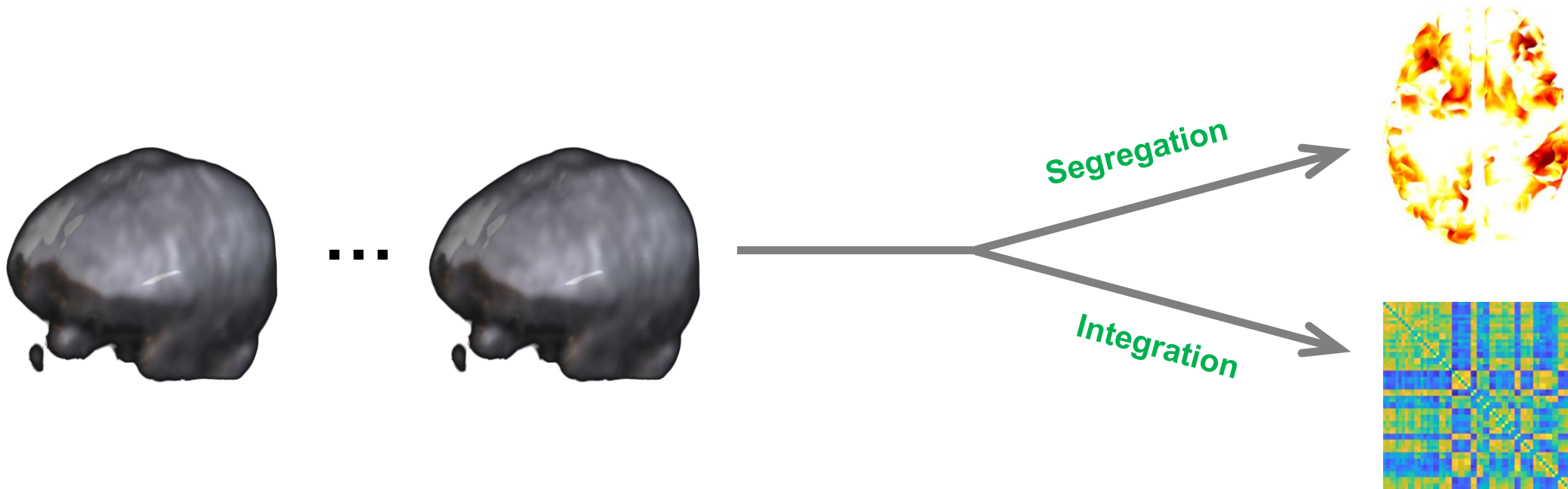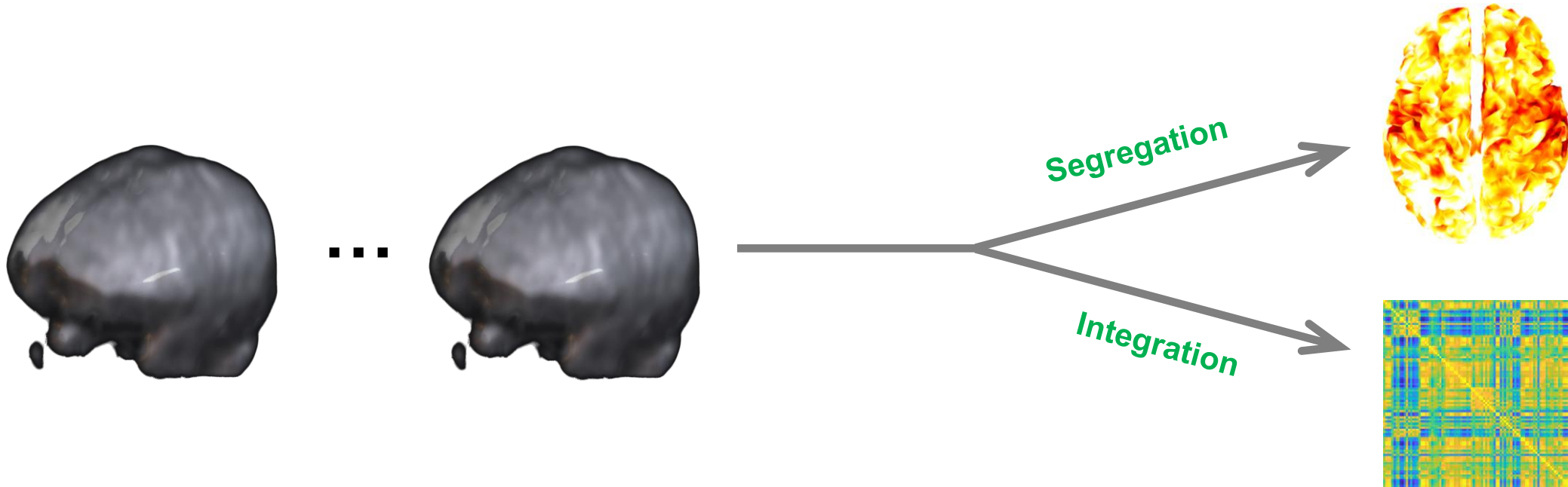
기능 자기공명영상 (2): 데이터 처리 방법

Brain Mapping with functional MRI (fMRI)

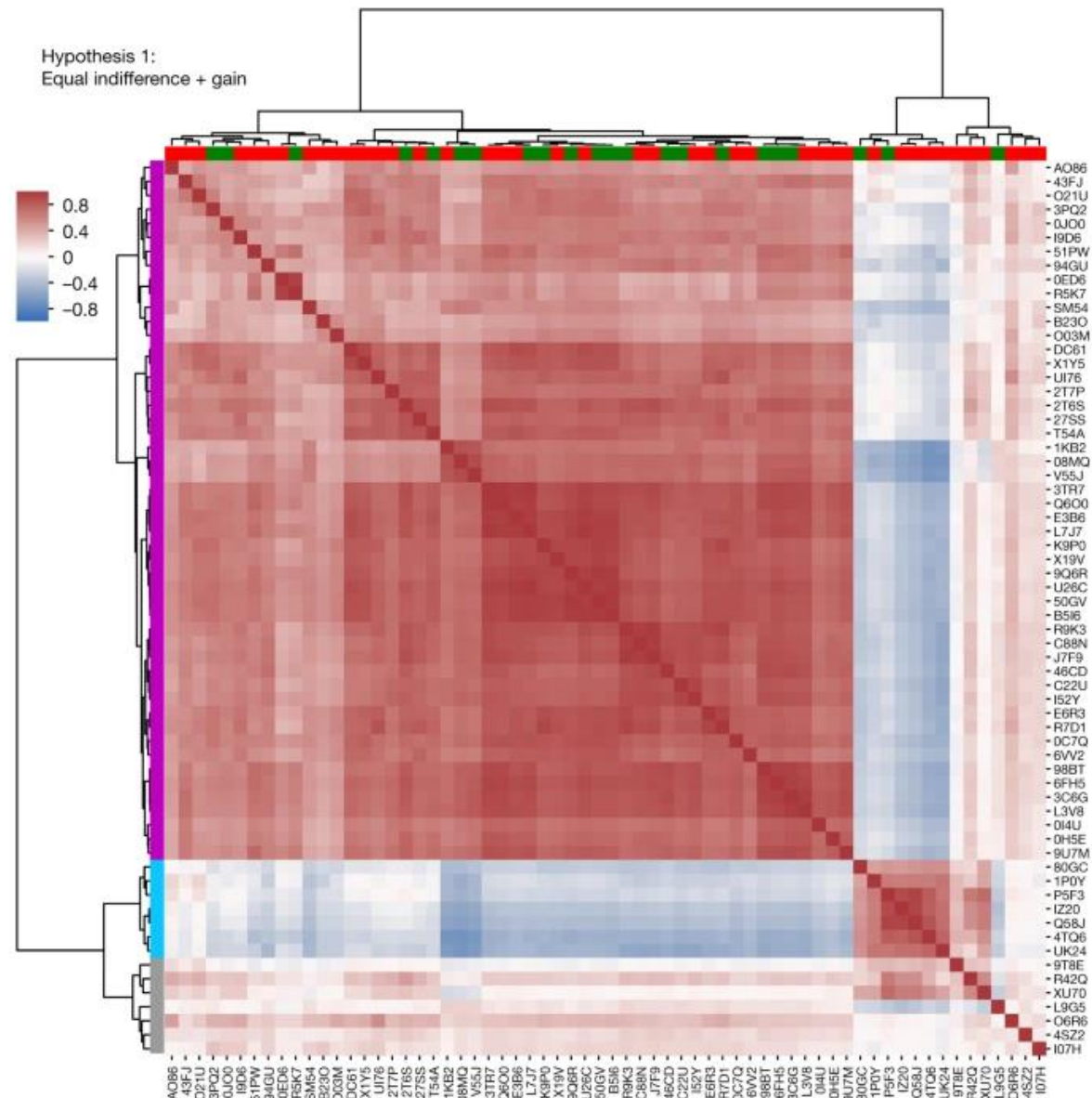- Task-based fMRI

- Resting state fMRI

Segregation

Integration

Analytical Variability in fMRI

- Variability of reported results [Botvinik-Nezer et al, 2020]
  - Resulted from different analysis pipelines
  - As strong factors, spatial smoothness, software package used, and methods of multiple test correction

Hypothesis 1:
Equal indifference + gain

[Botvinik-Nezer et al, 2020]

**Analytical variability in whole brain statistical results**

Preprocessing

- Numerous steps to clean and standardise fMRI data before modelling and statistical analysis based on the extraction of signals that are faithful to underlying neuronal activity
  - Identifies nuisance (non-neuronal) sources of variability and reduces their effect on fMRI data
  - Addresses particular imaging artifacts and the anatomical localisation of signals

- After preprocessing, it is assumed that fMRI signals are anatomically localised in terms of coordinates
  - Correction for unwanted variation
    - Difference in slice timing
    - Head motion
    - Inhomogeneity (small local inhomogeneities in the magnetic field based on differences in magnetic susceptibility between adjacent tissues or materials (such as air and brain tissue))-induced distortion
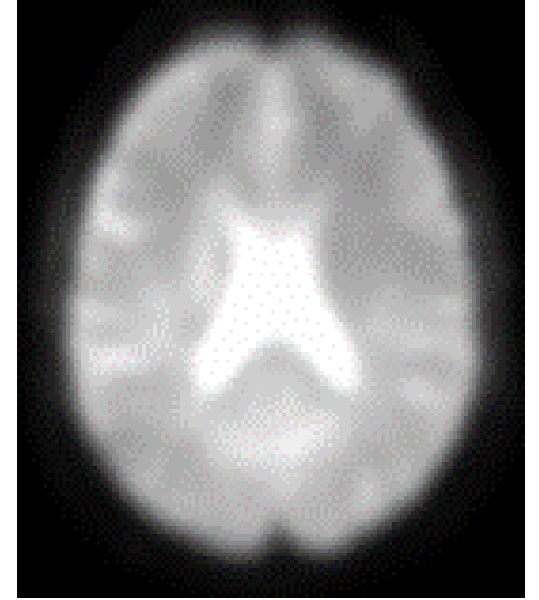 - Normalisation
  - Smoothing

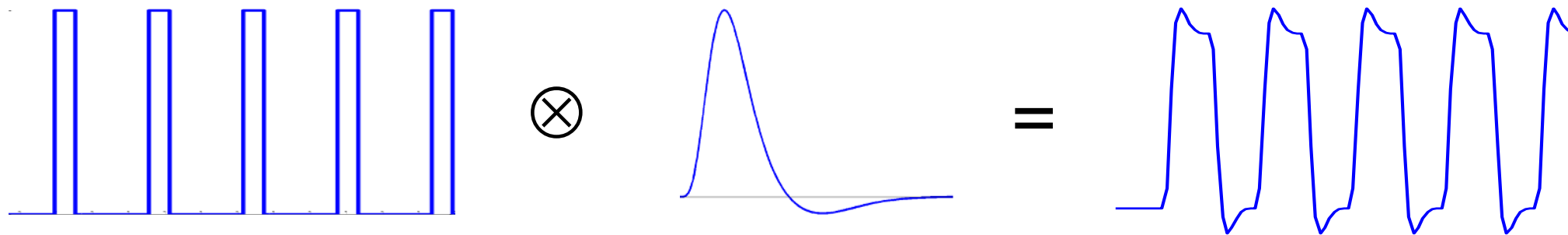**Frame-wise displacement**
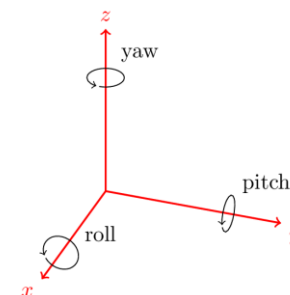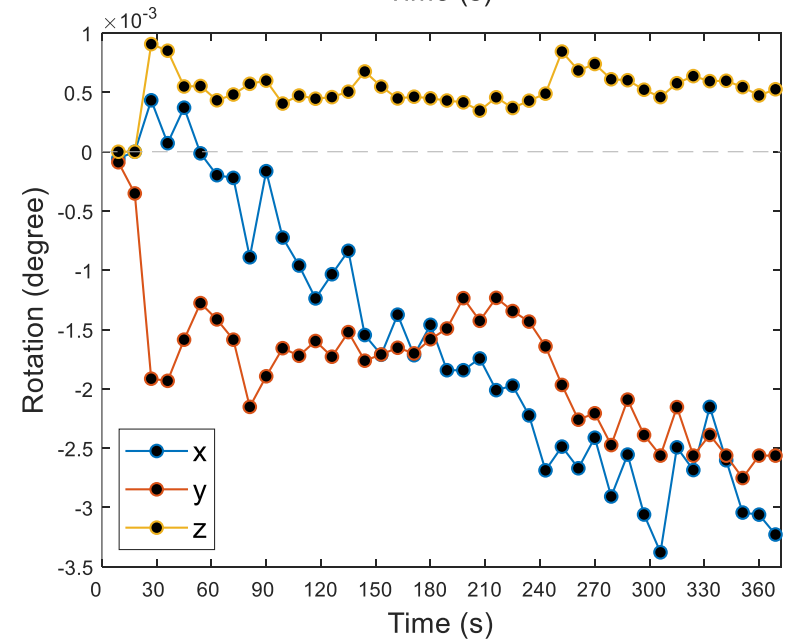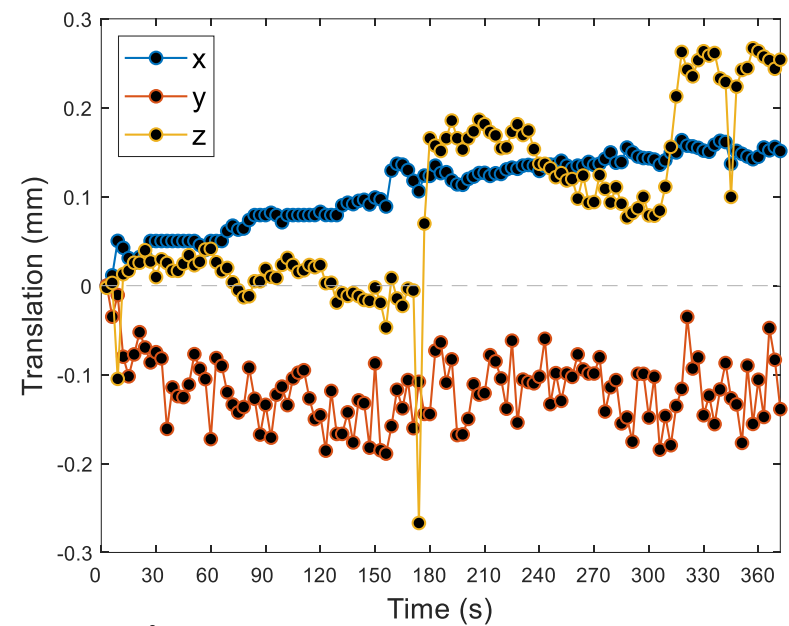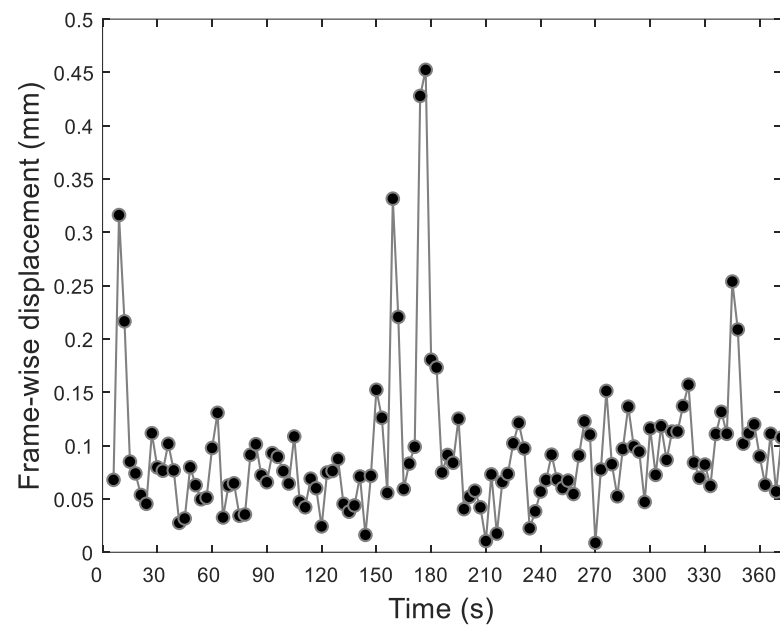
Estimated head motion
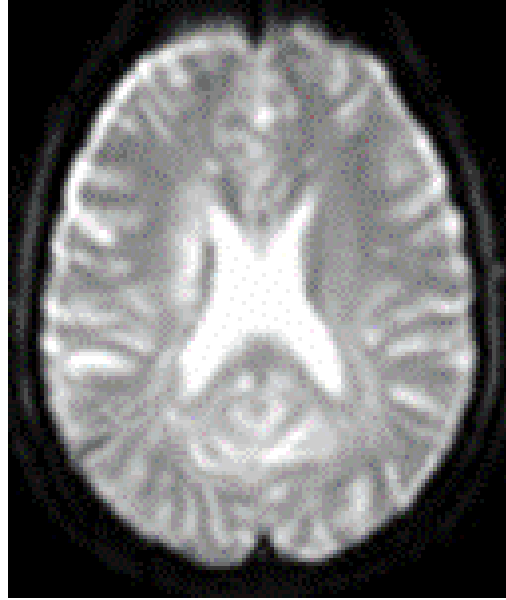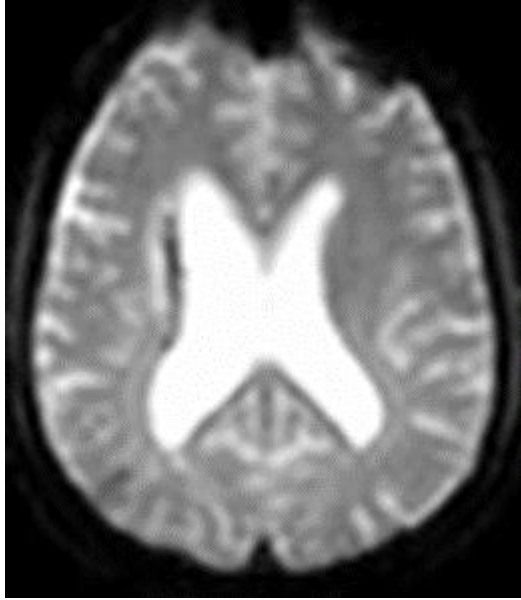
Normalisation

Smoothing

Normalisation and smoothing

Task-based fMRI: Segregation Analysis

- Mass univariate statistical analysis
- General linear model: $\boldsymbol{y} = \boldsymbol{X\beta} + \boldsymbol{e}$
  - Observed fMRI time series ~ predicted fMRI time series + nuisance variables + error
  - $\boldsymbol{y}$: observed fMRI time series
  - $\boldsymbol{X}$: design matrix
  - $\boldsymbol{\beta}$: parameter estimate
  - $\boldsymbol{e}$: error
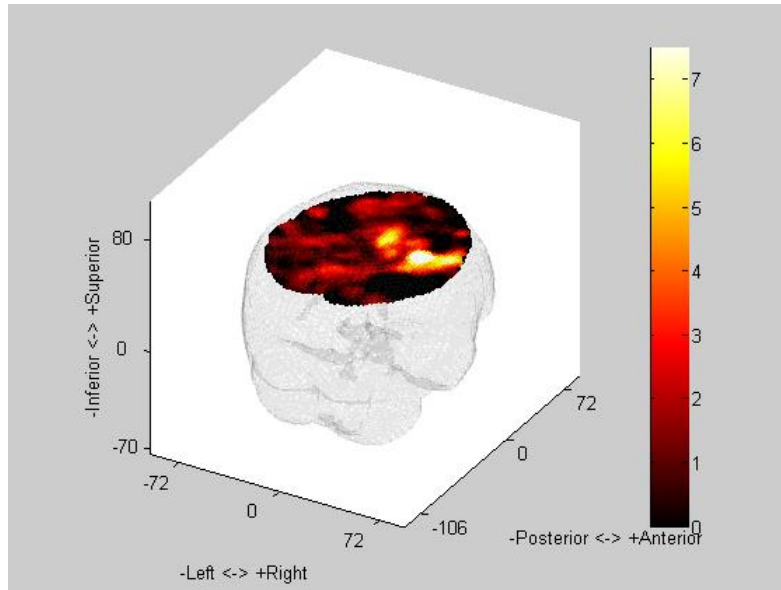
Predicting fMRI time series
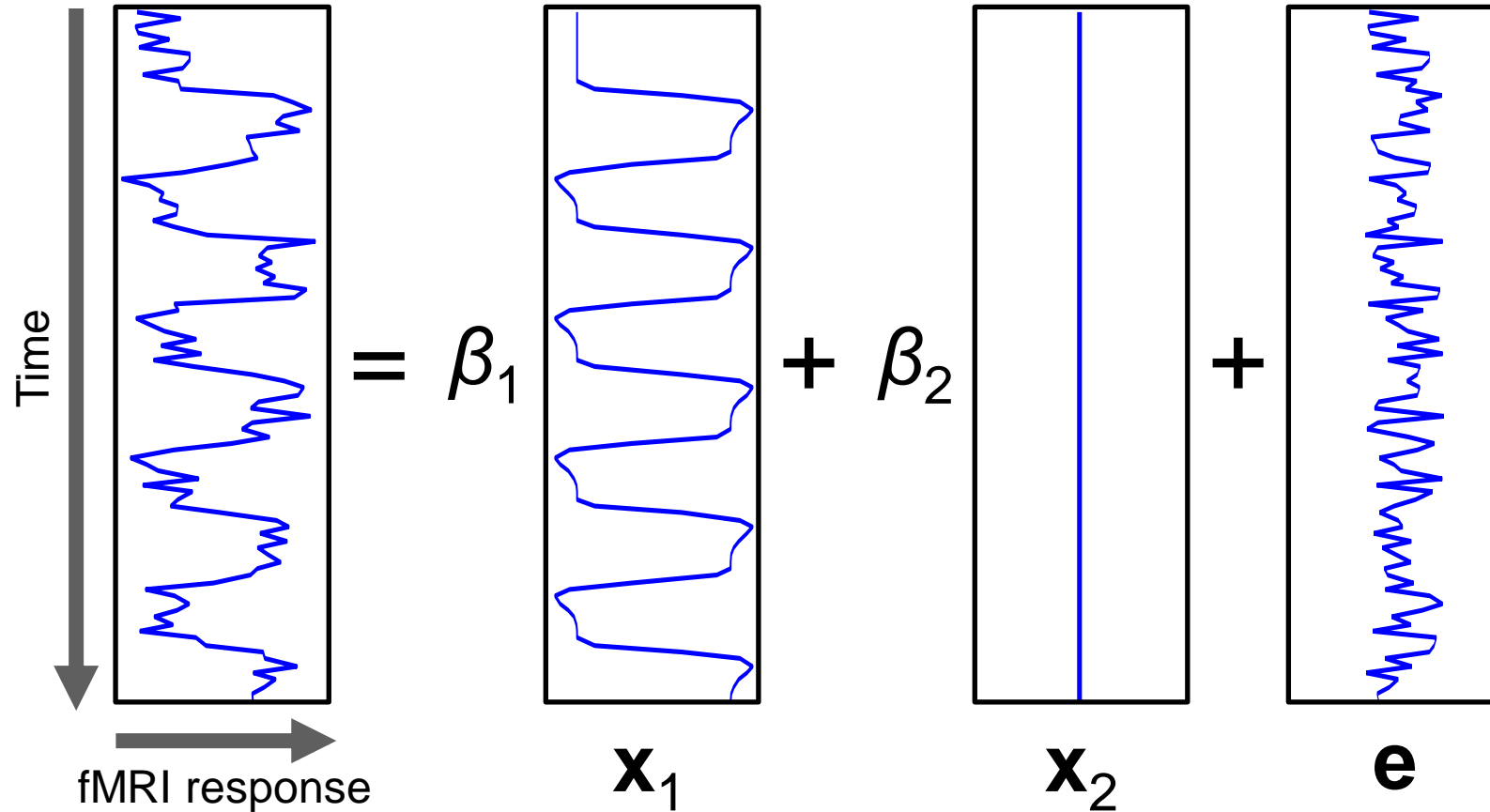
$$y = X\beta + e = x_1\beta_1 + x_2\beta_2 + e$$

General linear model for functional segregation analysis in task-based fMRI
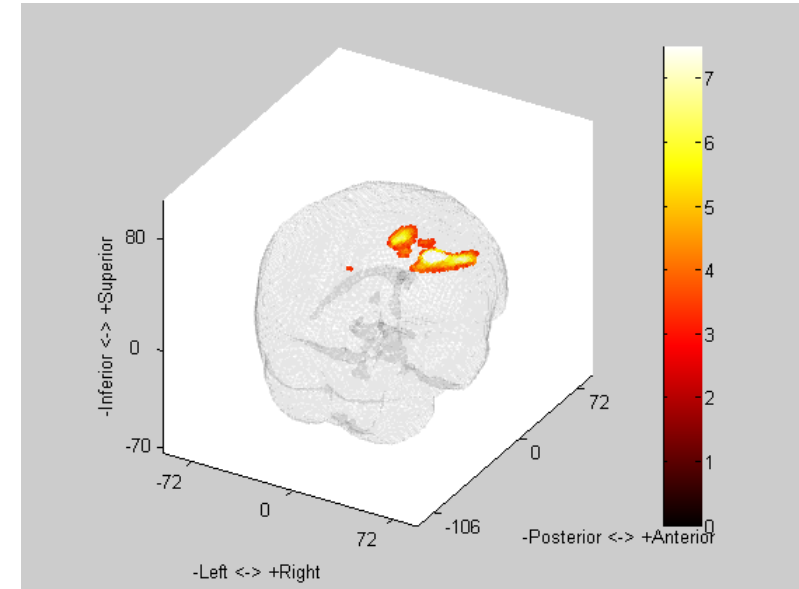
- Search of local brain activity
  - By statistical inferences under the null-hypothesis that predicted fMRI time series are no closer to observed fMRI time series than expected by chance
  - Requires correction for multiple tests

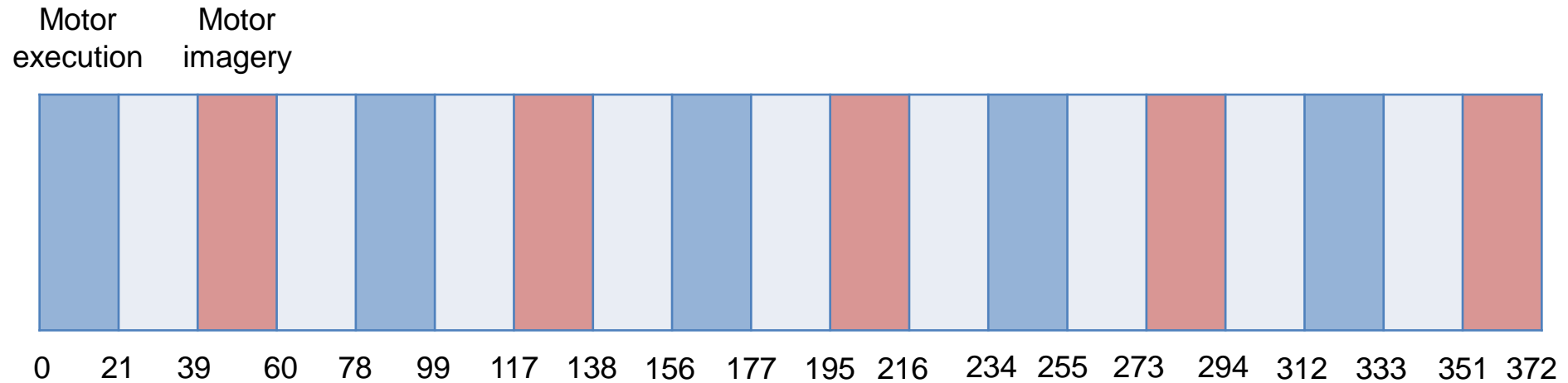**_t_ map**

Thresholded _t_ map

Thresholding
at a significance level

$$t = \frac{c^T \hat{\beta}}{\sqrt{\text{var}(e)\, c^T (X^T X)^{-1} c}}$$

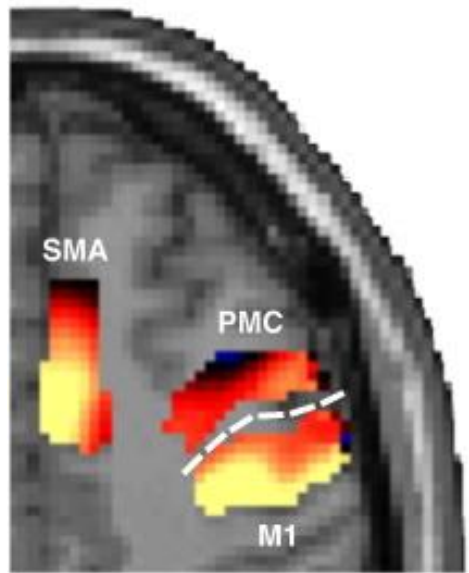**Search for local brain activity by statistical inferences**

[Task-based fMRI: Segregation Analysis]

Motor execution   Motor imagery

0   21   39   60   78   99   117   138   156   177   195   216   234   255   273   294   312   333   351   372
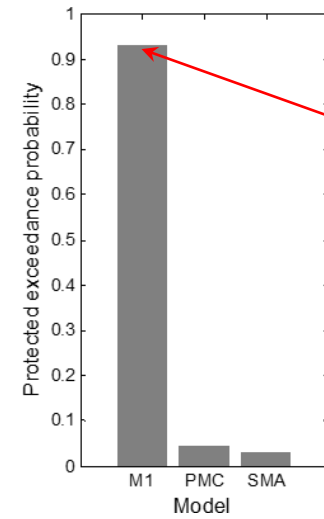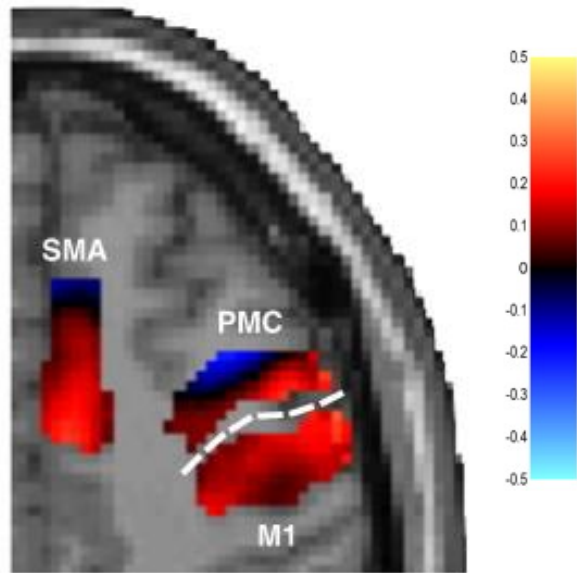
– 124 scans (372 seconds)

– Tasks

  • Motor execution

  • Motor imagery

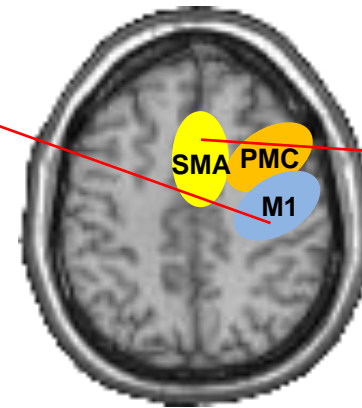Executed movement of hand grasping — SMA, PMC, M1
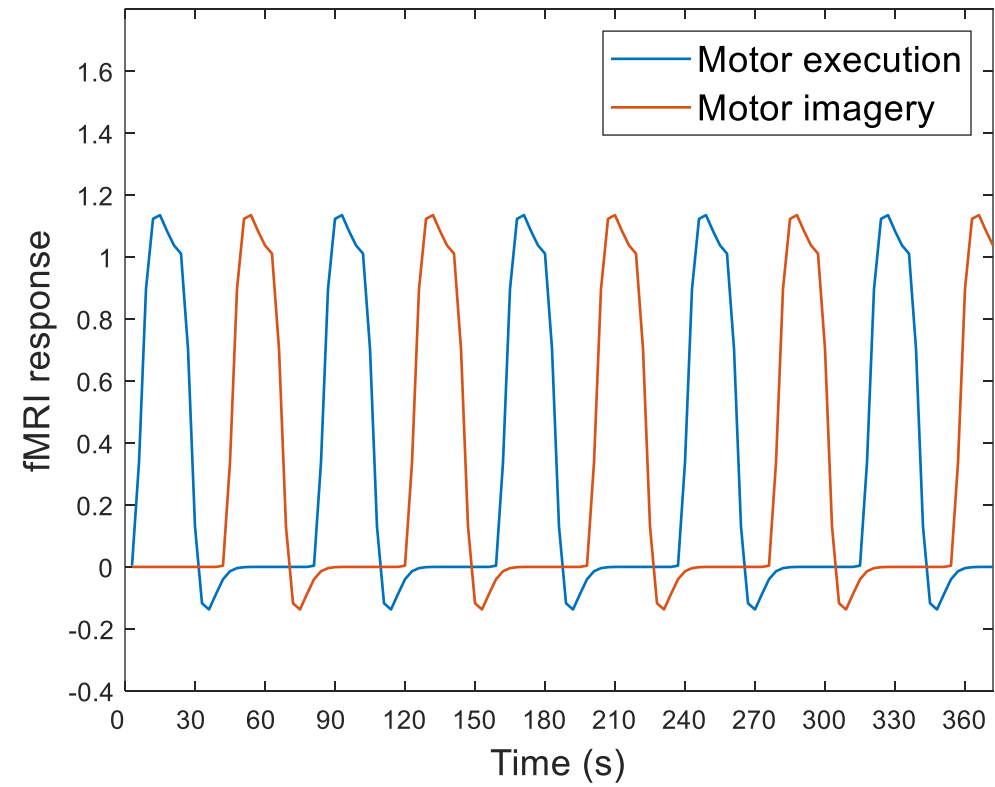
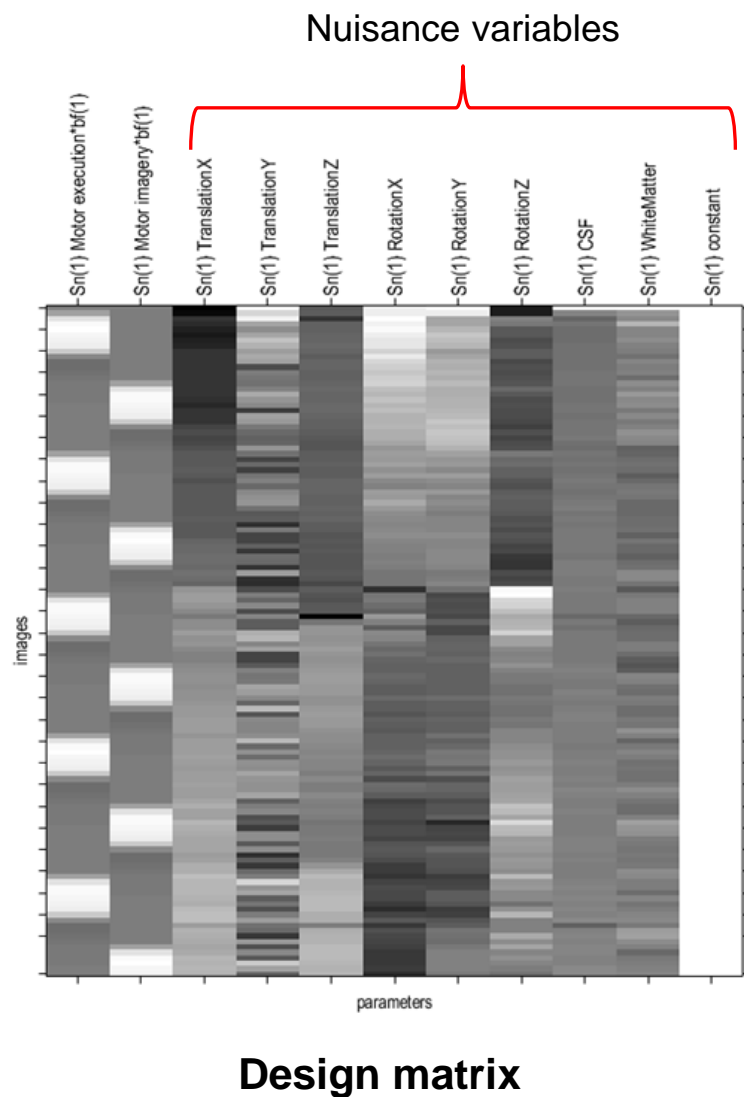Imagined movement of hand grasping — SMA, PMC, M1
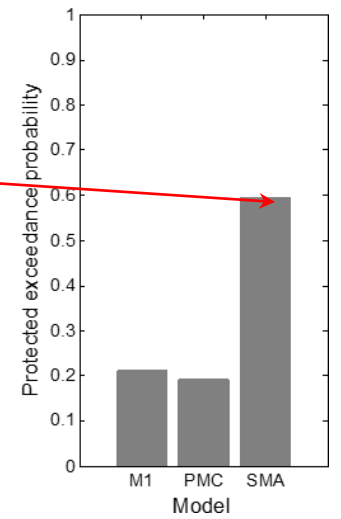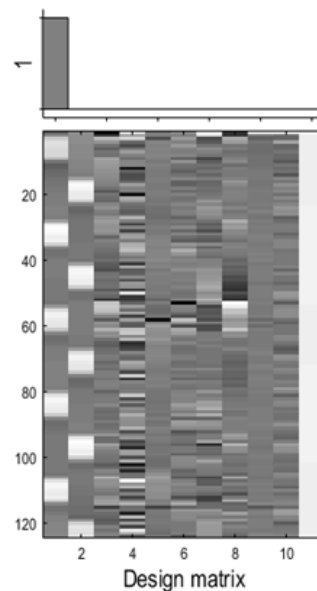
Motor execution

Motor imagery
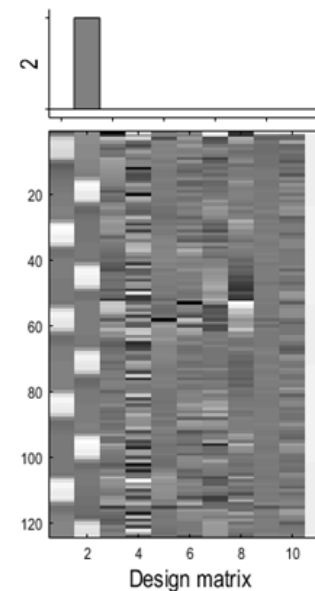
[Park et al., 2015]

Motor execution vs. motor imagery

Predicted fMRI time series

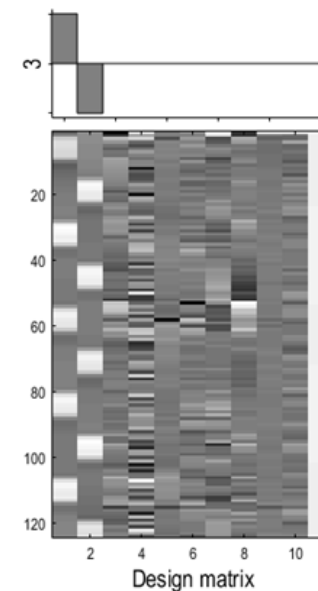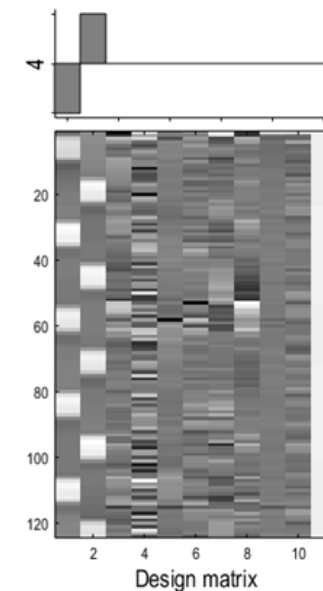Nuisance variables

Design matrix

Execution

Imagery
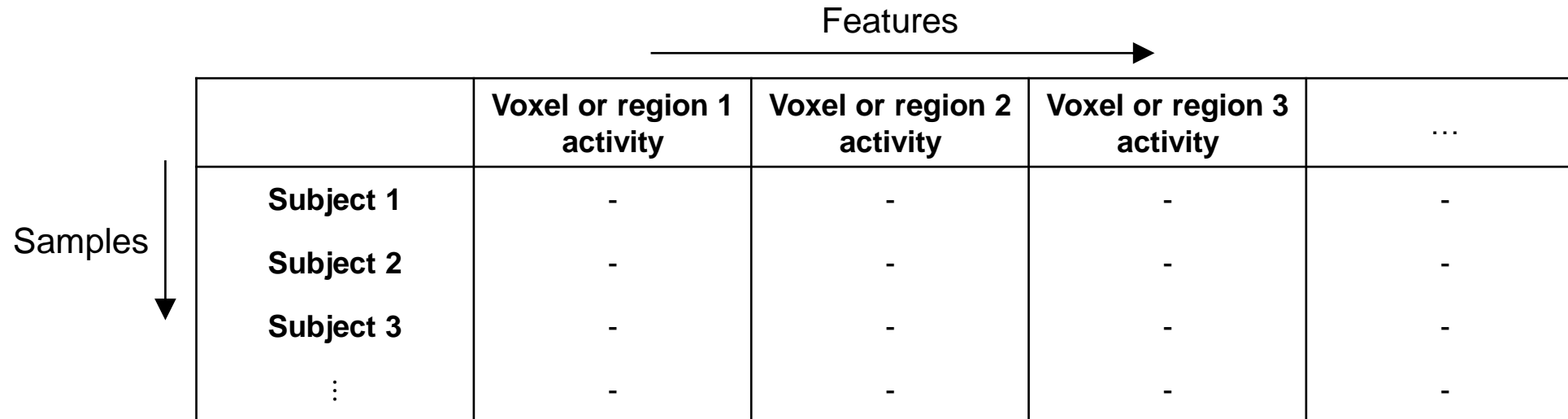
Execution > Imagery

Execution < Imagery

Activity during a task

Activity difference between tasks

- Input to machine learning models
  - Table of voxel-wise or region-wise activity values

<div align="center">Features →</div>

	Voxel or region 1 activity	Voxel or region 2 activity	Voxel or region 3 activity	…
Subject 1	-	-	-	-
Subject 2	-	-	-	-
Subject 3	-	-	-	-
⋮	-	-	-	-

Samples ↓

  - Brain activity map

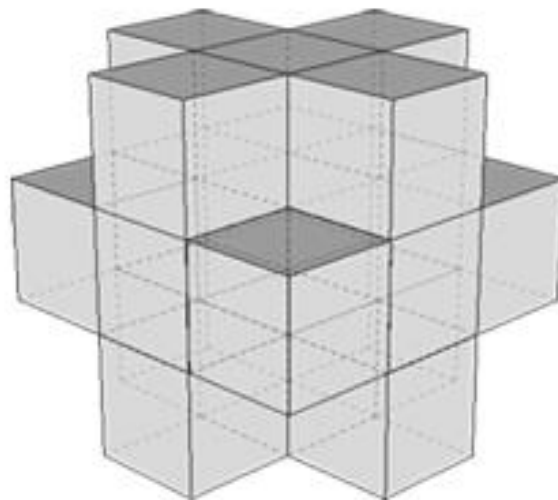# Resting State fMRI: Segregation Analysis

- # Regional homogeneity [Zang et al., 2004]

  – Synchronization of time series between a given voxel and its neighbours

    - Neighbours: K nearest neighbours

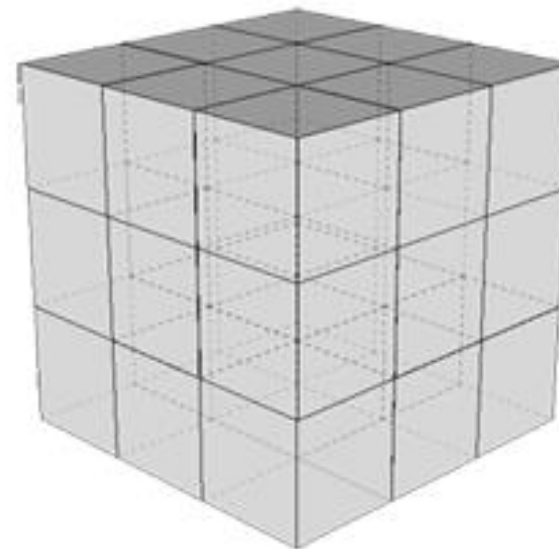   - Synchronization: Kendall's coefficient of concordance (KCC)

$$\text{KCC} = \frac{\sum_{i=1}^{n} R_i^2 - n(\overline{R})^2}{\frac{1}{12}K^2(n^3 - n)} = 12\frac{\sum_{i=1}^{n}(\overline{R}_i)^2}{(n^3 - n)} - 3\frac{(n+1)}{(n-1)}$$
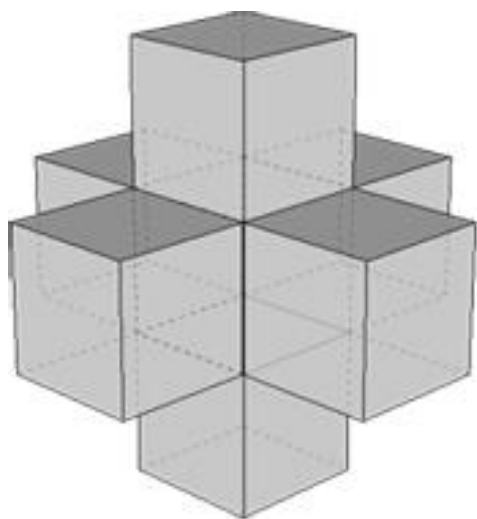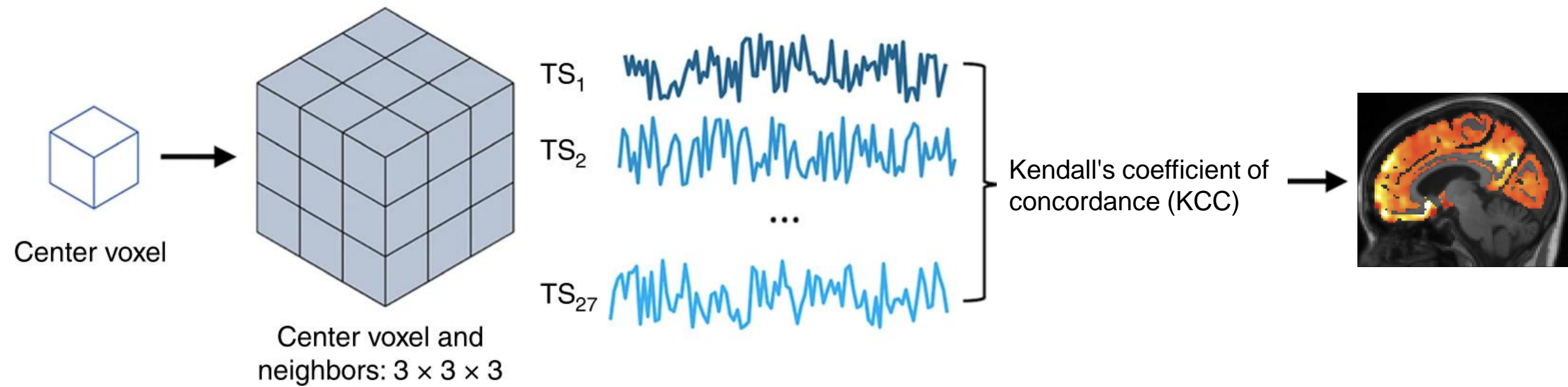
Faces
(7 voxels)

Faces + Edges
(19 voxels)

Faces + Edges + Corners
(27 voxels)

[https://fcp-indi.github.io/docs/latest/user/reho]

Different definitions of nearest neighbours

– Based on the hypothesis that intrinsic brain activity is manifested by clusters of voxels rather than single voxels

– Requires no pre-defined voxel or region

– Provides information about the local activity of regions throughout the brain

Center voxel

Center voxel and neighbors: $3 \times 3 \times 3$

TS_1

TS_2

TS_{27}

Kendall's coefficient of concordance (KCC)

[Harrison et al., 2019]

Regional homogeneity

- Seed-based correlation [Biswal et al., 1995]
  - Synchronization of time series between a seed and all other voxels in the brain
    - Seed: pre-defined voxel or region
    - Synchronization: statistical association, particularly correlation
  - Based on the hypothesis that brain regions with similar activity patterns are likely to be communicating and sharing information
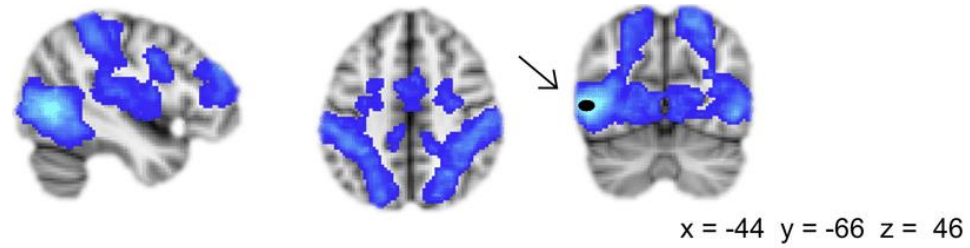 - Often used to explore a set of brain regions that share similar patterns of activity

Representative fMRI time series

fMRI time seirs from multiple voxels
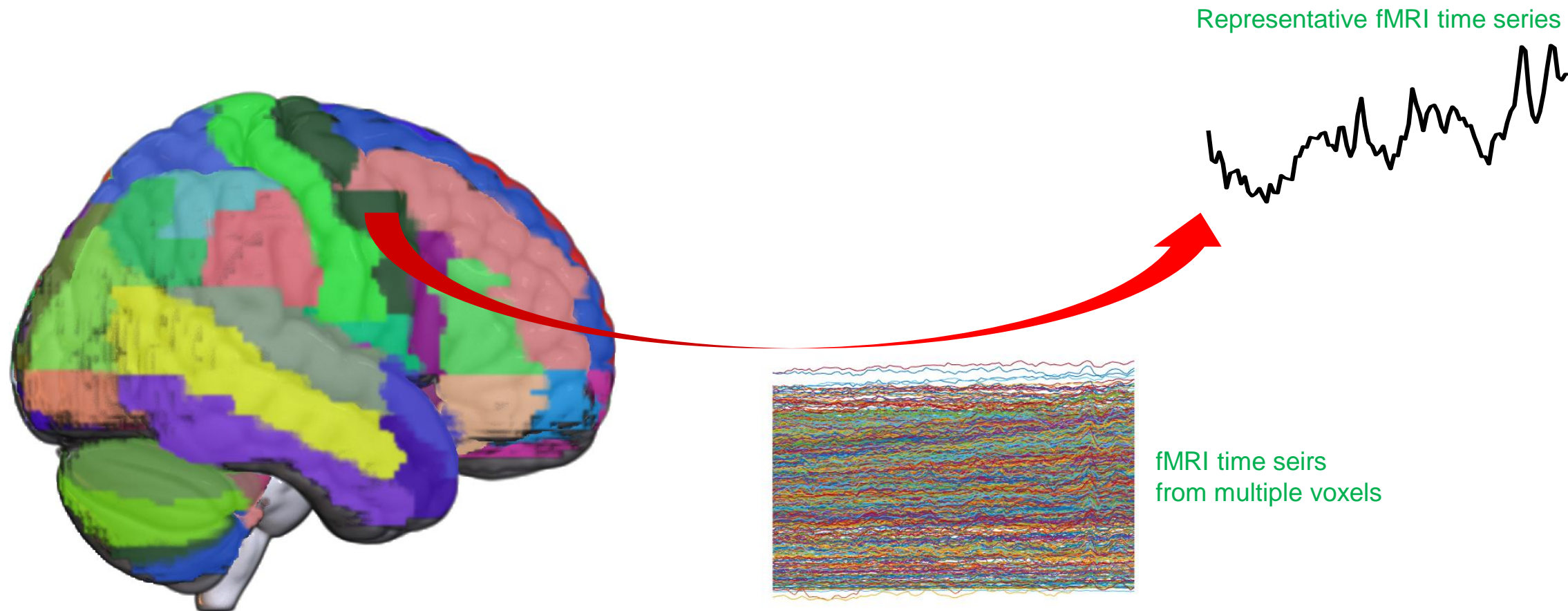
Extracting fMRI time series from the seed (primary motor cortex)
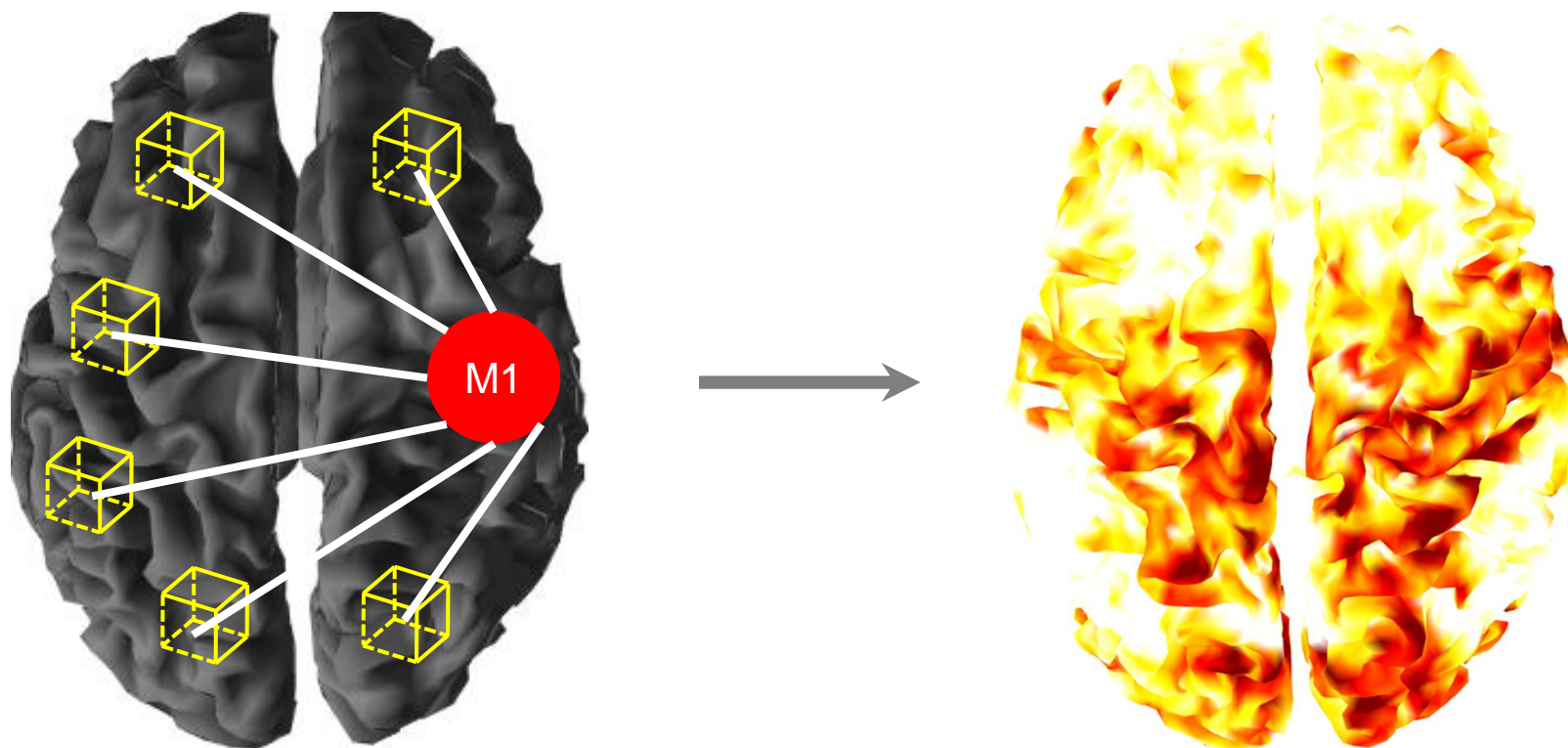
Seed-based correlation for the primary motor cortex

Left middle temporal gyrus
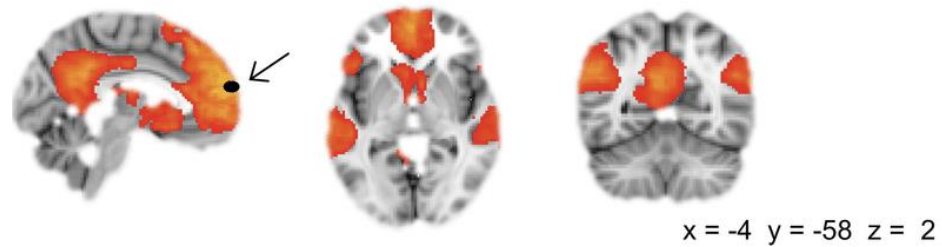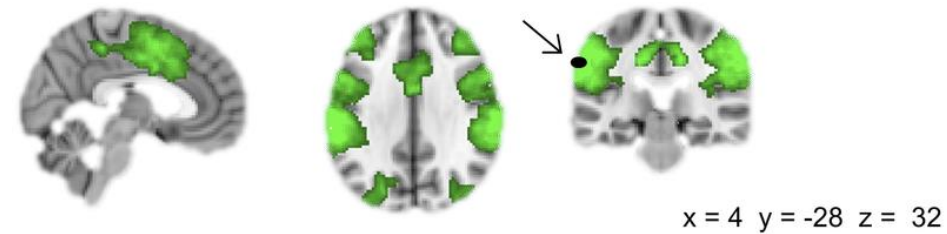
x = -44 y = -66 z = 46

Right middle temporal gyrus

x = -52 y = -64 z = 22

Left medial frontal gyrus

x = -4 y = -58 z = 2

Left supramarginal gyrus

x = 4 y = -28 z = 32
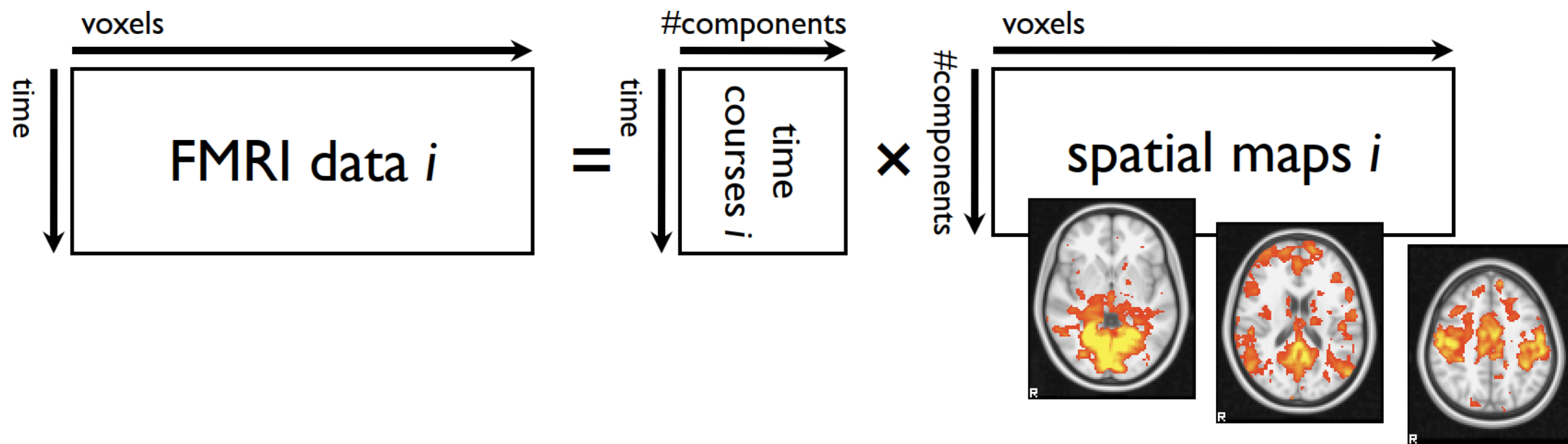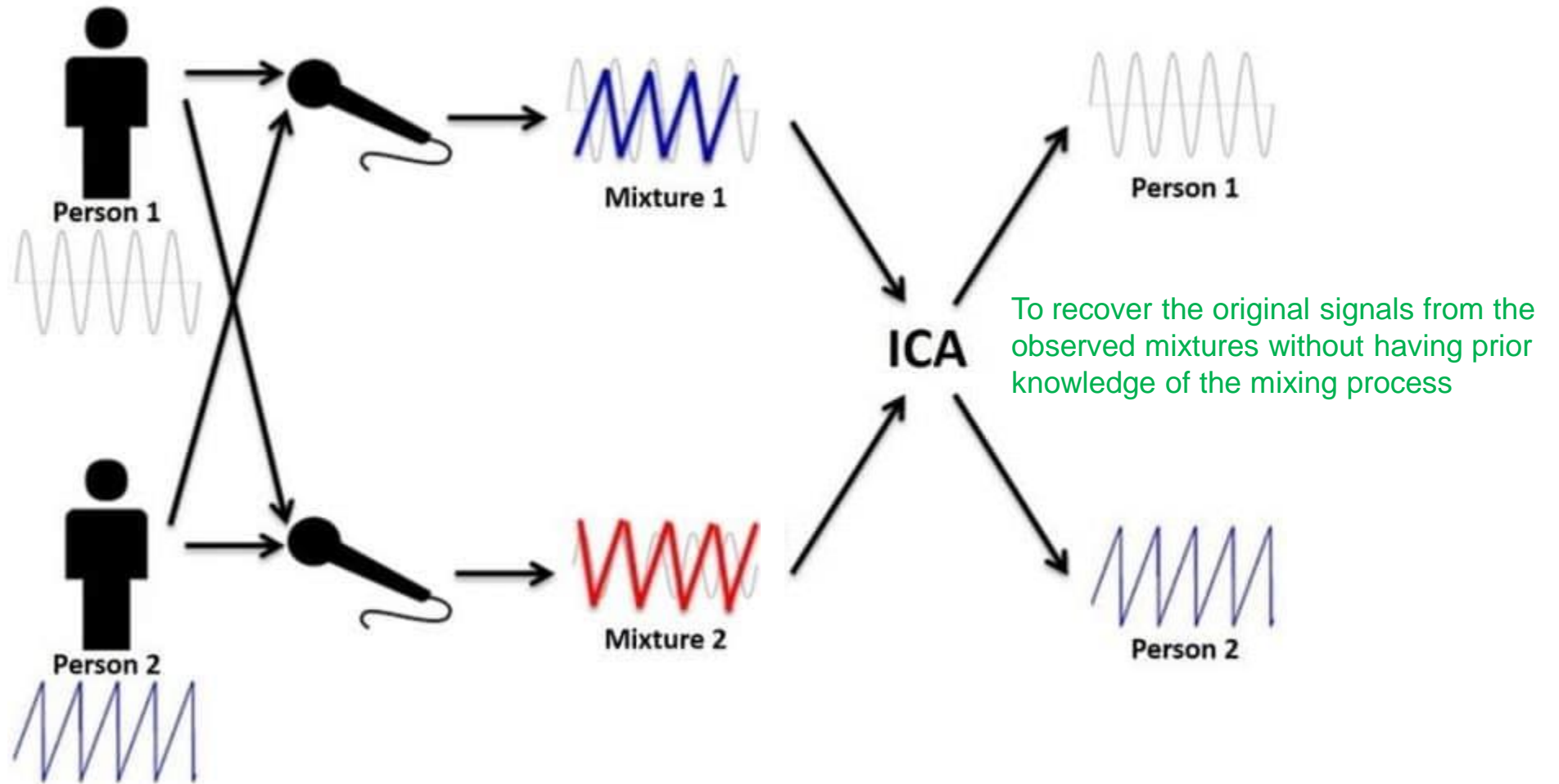
[Cousijn et al., 2014]

Time series synchronization explored by correlation with different seeds
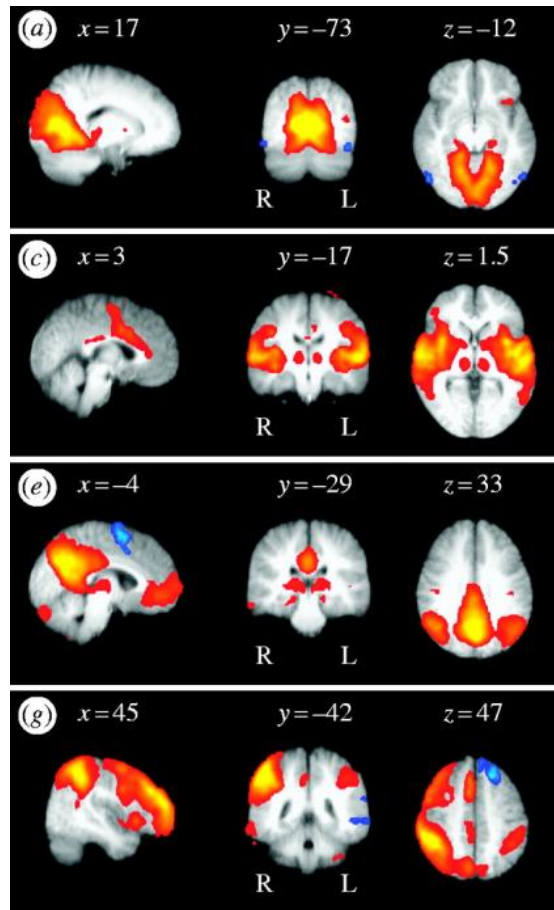
- Independent component
  - Statistical source or factor that independent component analysis (ICA) aims to extract from multivariate data
    - Spatial map and its time course separated from fMRI data
  - Based on the hypothesis that the observed data are linear mixtures of the unknown independent components

To recover the original signals from the observed mixtures without having prior knowledge of the mixing process

Independent component analysis for the cocktail party problem

(a) x=17 y=−73 z=−12 — Medial visual cortical areas
(b) x=−13 y=−61 z=6 — Lateral visual cortical areas
(c) x=3 y=−17 z=1.5 — Auditory system
(d) x=1 y=−21 z=51 — Sensory–motor system
(e) x=−4 y=−29 z=33 — Visuo-spatial system
(f) x=5 y=6 z=27 — Executive control
(g) x=45 y=−42 z=47 — Right dorsal visual stream
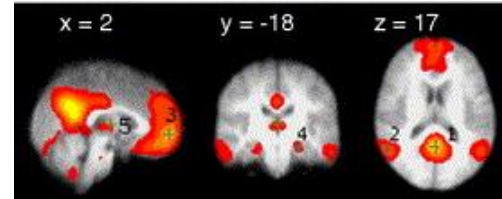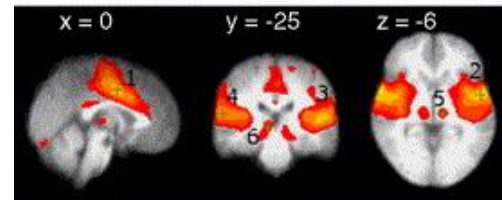(h) x=−45 y=−42 z=47 — Left dorsal visual stream
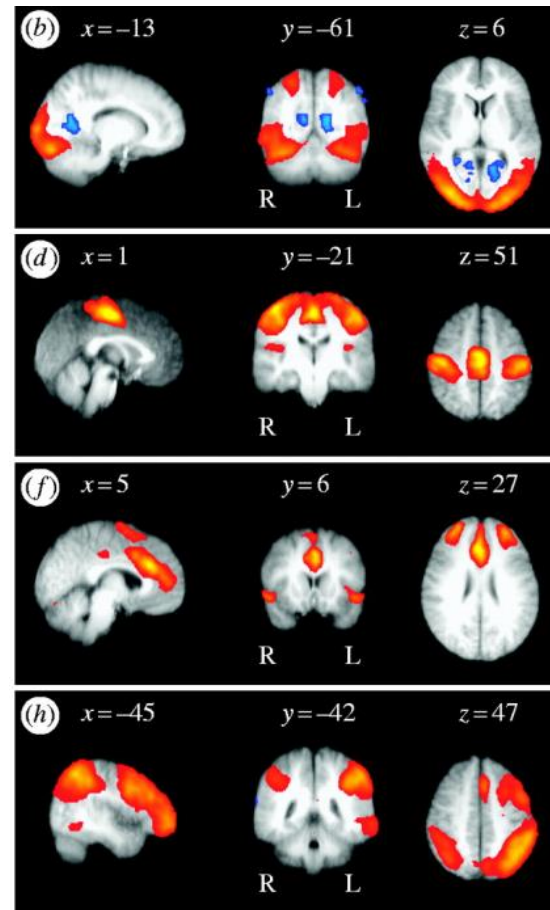
[Beckmann et al., 2005]

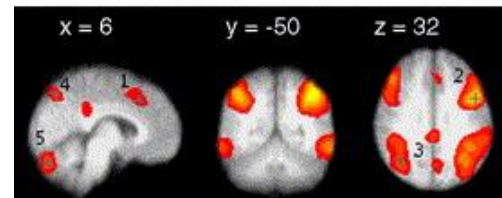**Time series synchronization explored by independent component analysis (1)**
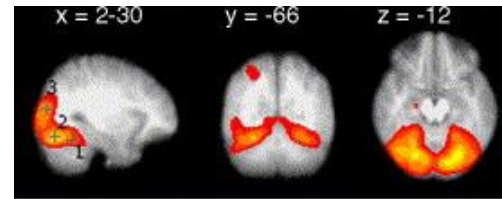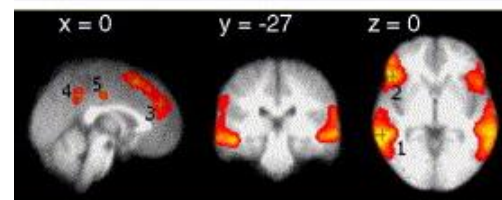
Visual cortical areas

Visuospatial and executive system
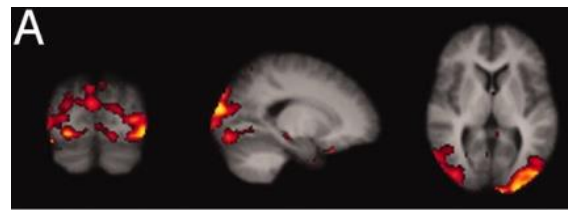
Sensory and auditory system

Dorsal pathway
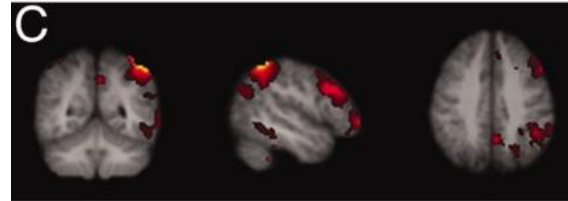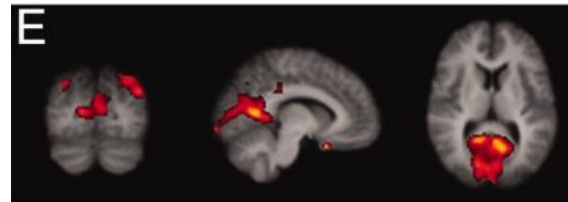
Ventral pathway

Time series synchronization explored by independent component analysis (2)

A — Lateral visual areas

B — Default-mode network

C — Memory function (left)

D — Memory function (right)

E — Medial visual areas

F — Motor and sensory network
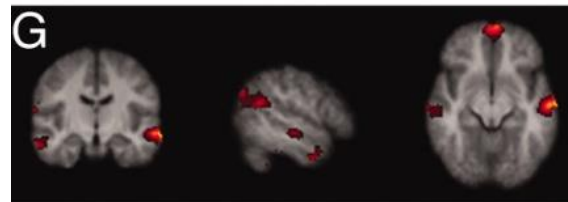
G — Occipitotemporal pathway (ventral stream)
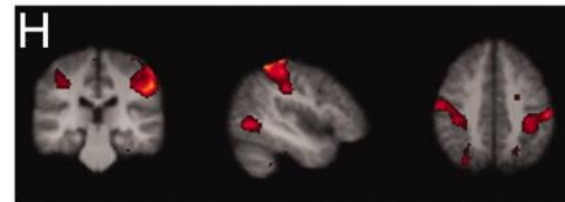
H — Superior parietal cortex

I — Auditory cortex
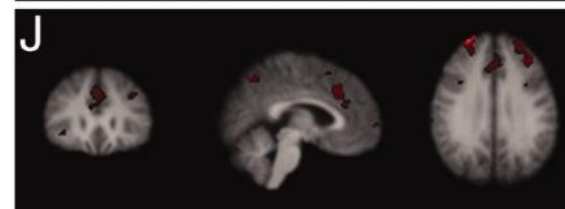
J — Executive control and working memory function

[Damoiseaux et al., 2006]

Time series synchronization explored by independent component analysis (3)

(a) IC 2 (-4, -52, 1) — Medial occipital cortices

(b) IC 10 (-46, -10, 13) — Bilateral temporal cortices and ACC

(c) IC 11 (5, -58, 22) — PCC, ACC, and bilateral inferior parietal cortex (default-mode network)

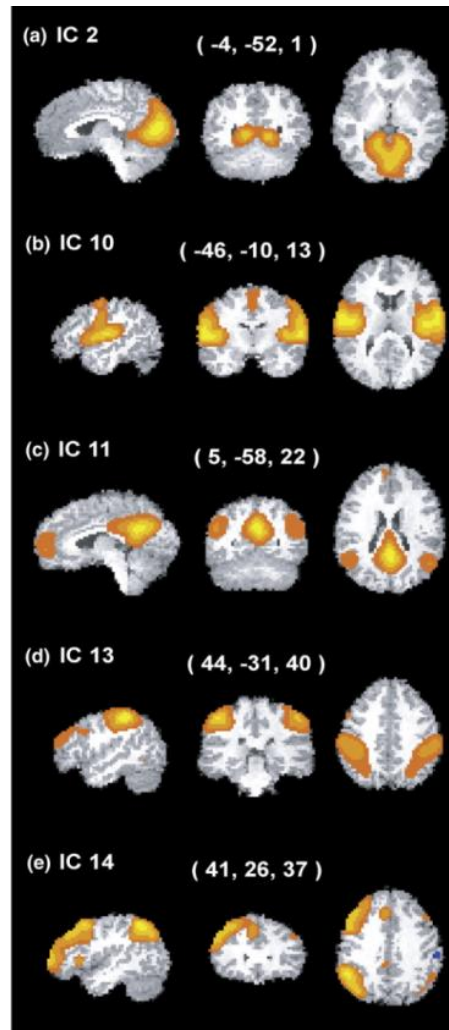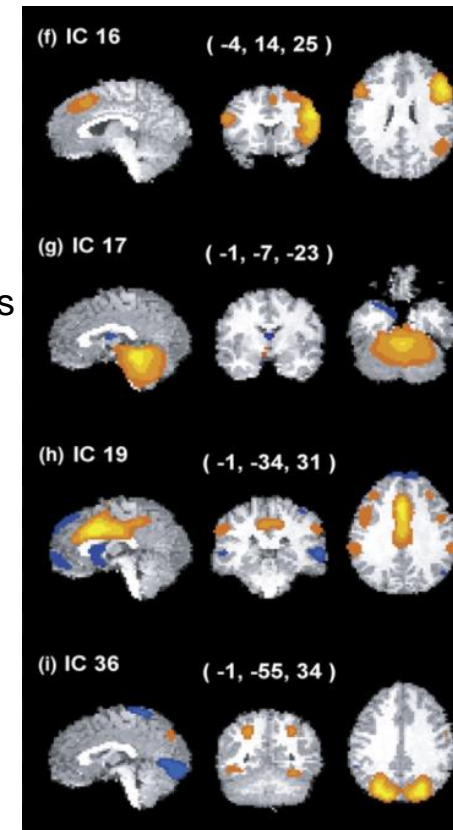(d) IC 13 (44, -31, 40) — Bilateral motor regions

(e) IC 14 (41, 26, 37) — Right medial and lateral frontal cortices and parietal cortex

(f) IC 16 (-4, 14, 25) — Left medial and lateral frontal cortices and parietal cortex

(g) IC 17 (-1, -7, -23) — Cerebellum

(h) IC 19 (-1, -34, 31) — Medial frontal/ACC, bilateral DLPFC, bilateral temporal cortex and striatum

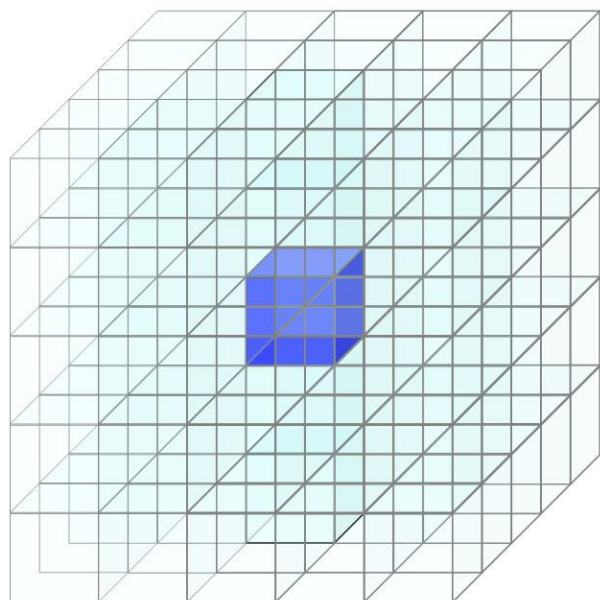(i) IC 36 (-1, -55, 34) — Bilateral lateral occipital cortices

[Chen et al., 2008]

Time series synchronization explored by independent component analysis (4)

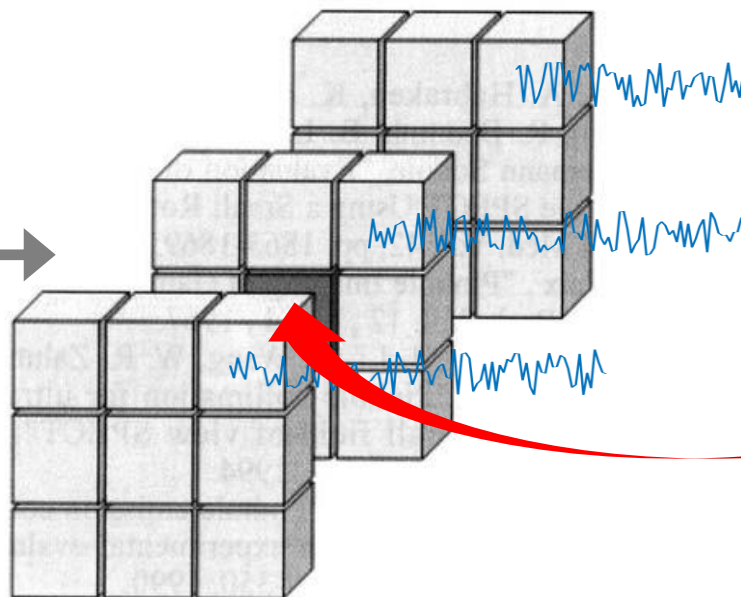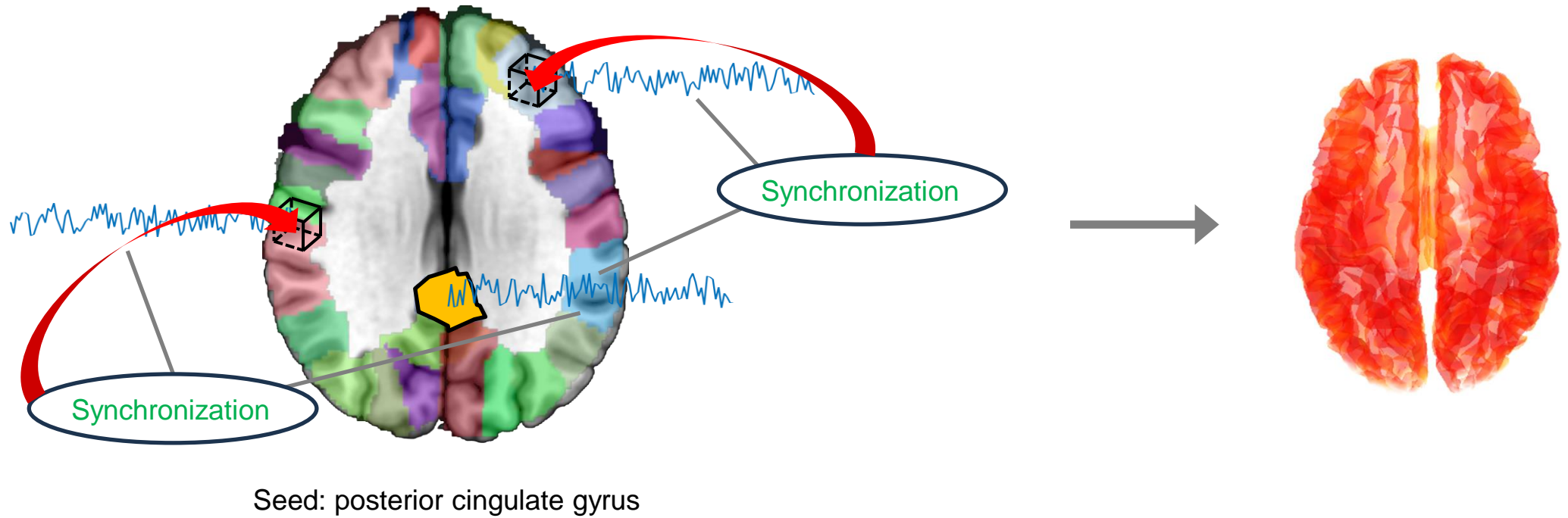# [Resting State fMRI: Segregation Analysis]

– 100 scans (200 seconds)

Centre voxel

Nearest neighbours

Synchronization

Regional homogeneity

Seed: posterior cingulate gyrus

**Correlation with the posterior cingulate gyrus: default mode network**

- Input to machine learning models
  - Table of voxel-wise or region-wise synchronization (regional homogeneity, seed-based correlation, or independent component) values

Features →

	Voxel or region 1 synchronization	Voxel or region 2 synchronization	Voxel or region 3 synchronization	…
Subject 1	-	-	-	-
Subject 2	-	-	-	-
Subject 3	-	-	-	-
⋮	-	-	-	-

Samples ↓

  - Time series synchronization (regional homogeneity, seed-based correlation, or independent component) map
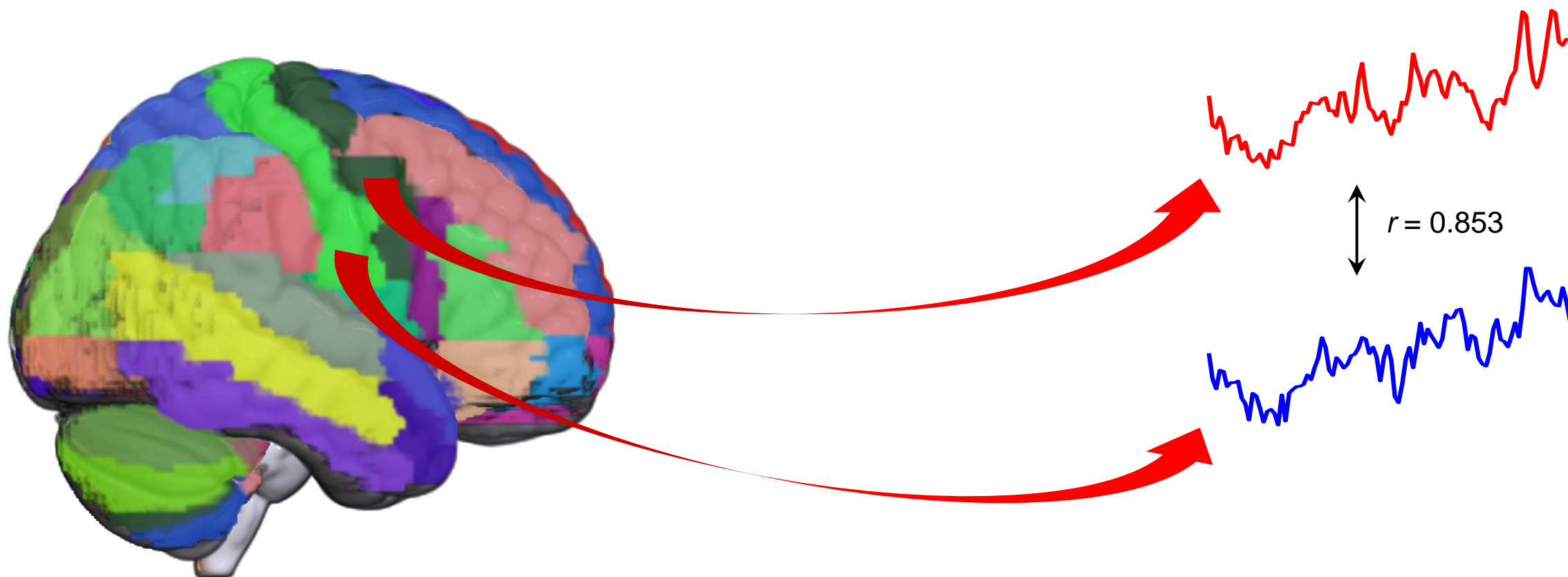
Resting State fMRI: Integration Analysis

- Network
  - Set of nodes and edges
    - Nodes: pre-defined regions
    - Edges: connectivity (correlation or causality) between regions
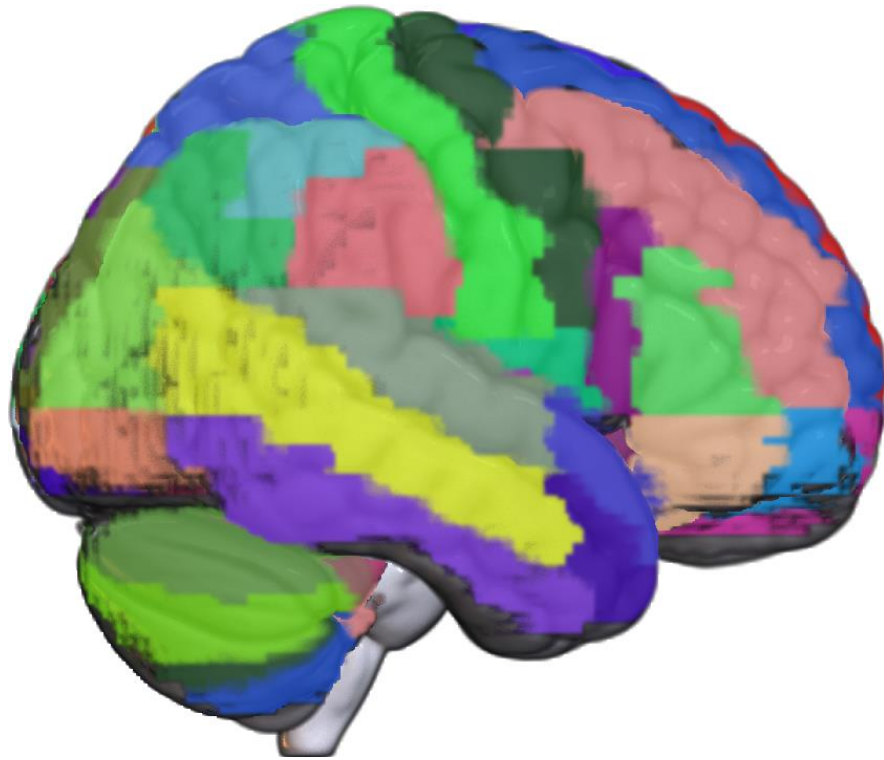
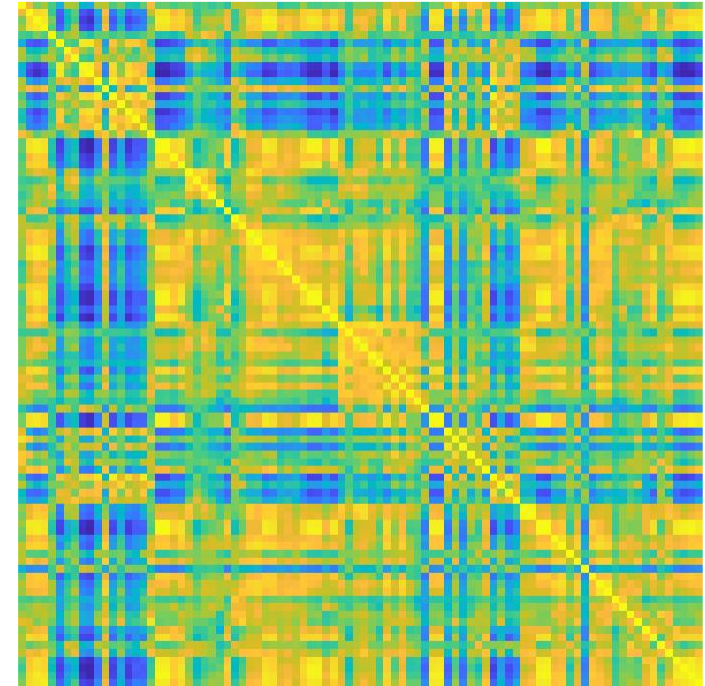structural connectivity　　functional connectivity　　effective connectivity
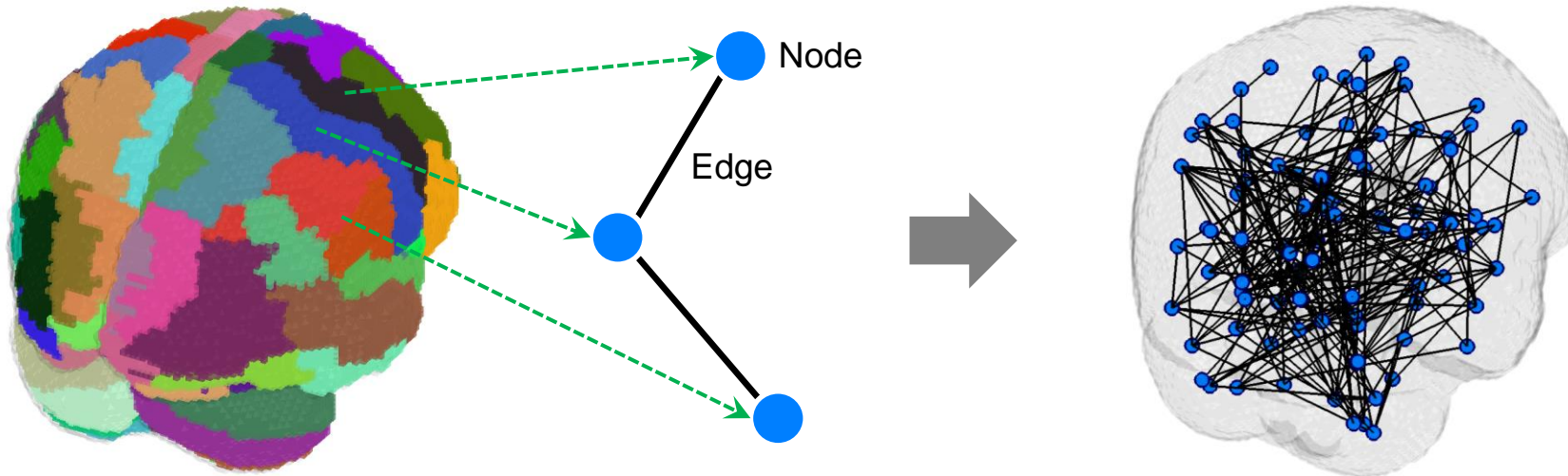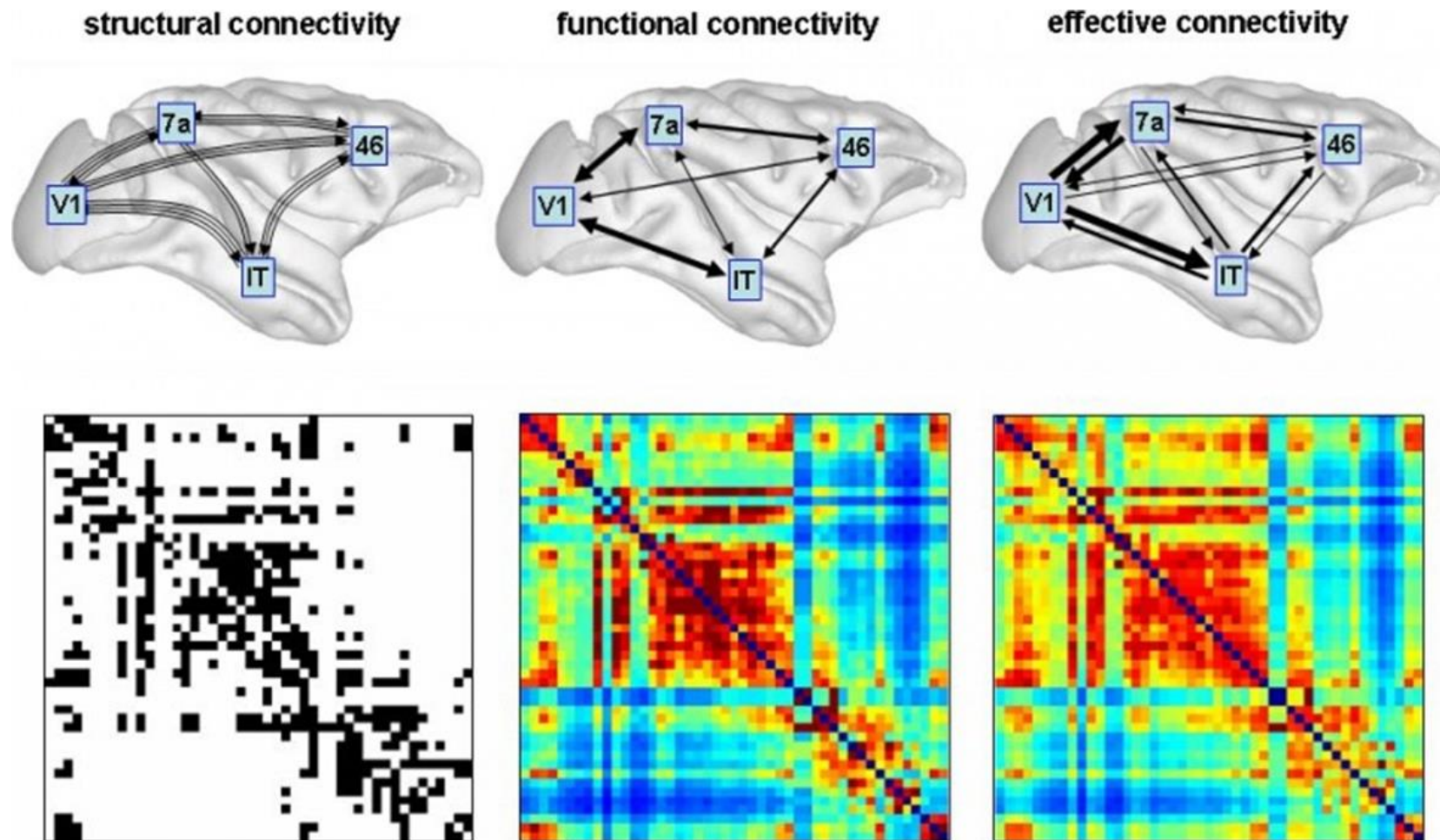
[Honey et al., 2007]

Modes of brain connectivity

Pair-wise correlation of time series

r = 0.853

Time series correlation

Functional network or connectome

- Input to machine learning models
  - Table of region-to-region connectivity (correlation or causality) values

Features →

	Brain regions 1 – 2 connectivity	Brain regions 1 – 3 connectivity	Brain regions 1 – 4 connectivity	…
Subject 1	-	-	-	-
Subject 2	-	-	-	-
Subject 3	-	-	-	-
⋮	-	-	-	-

Samples ↓

  - Functional network map