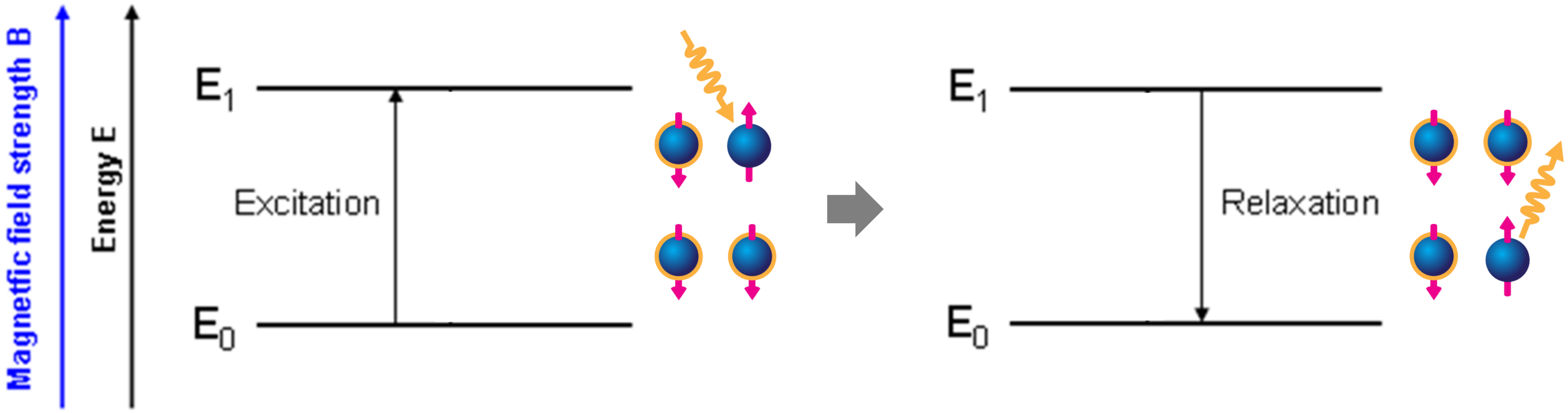
Medical/Bio Research Topics Ⅰ: Week 05 (1 April 2025)

Functional MRI (1): Basic Principles

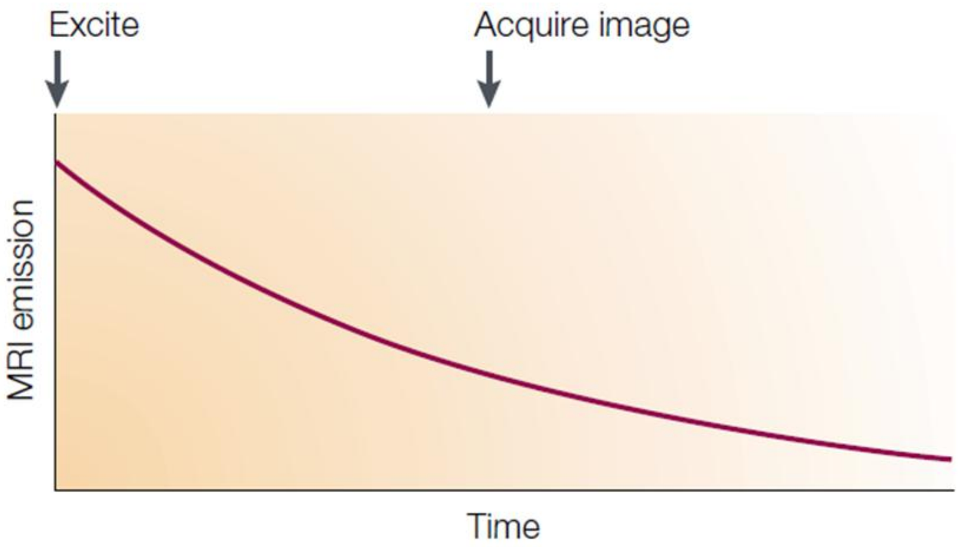
기능 자기공명영상 (1): 기본 원리

MRI Principles

- Medical application of nuclear magnetic resonance (NMR)
  - Generates different contrasts between tissues based on the relaxation properties of hydrogen nuclei therein

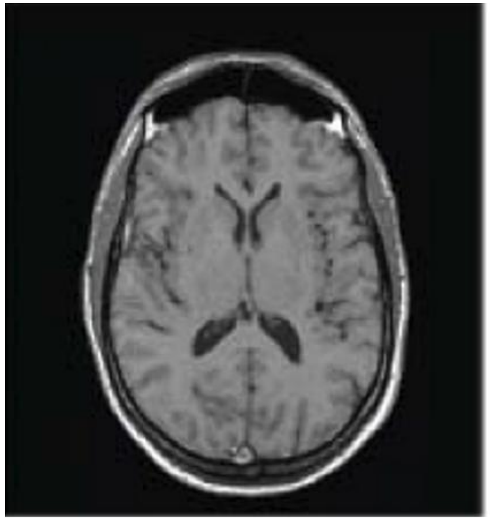


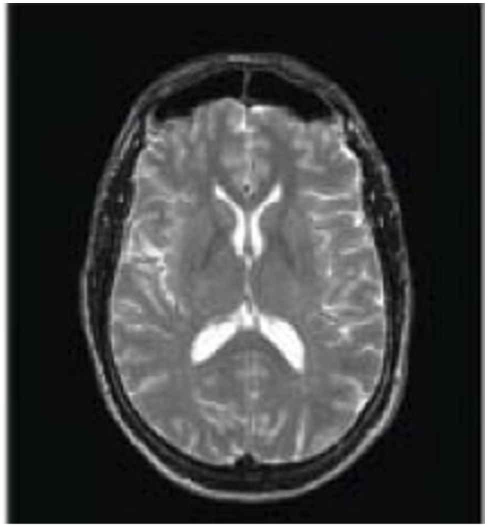
- Creates contrast between different structures
  - Due to differences in the time and amount of relaxation according to electromagnetic properties
  - For the T2-weighted contrast, faster relaxation results in a decrease in image intensity



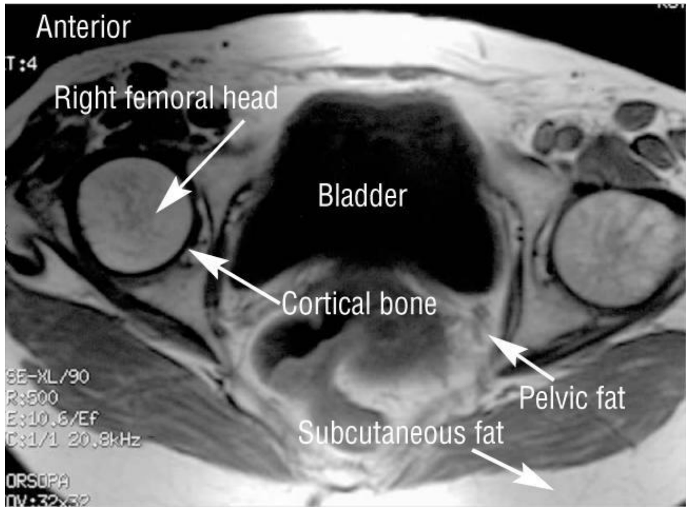
[Heeger and Ress, 2002]

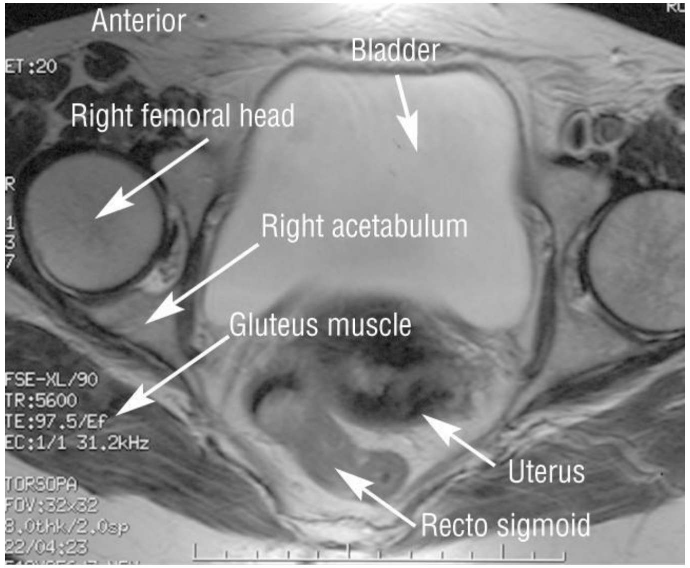
Brain





Pelvis





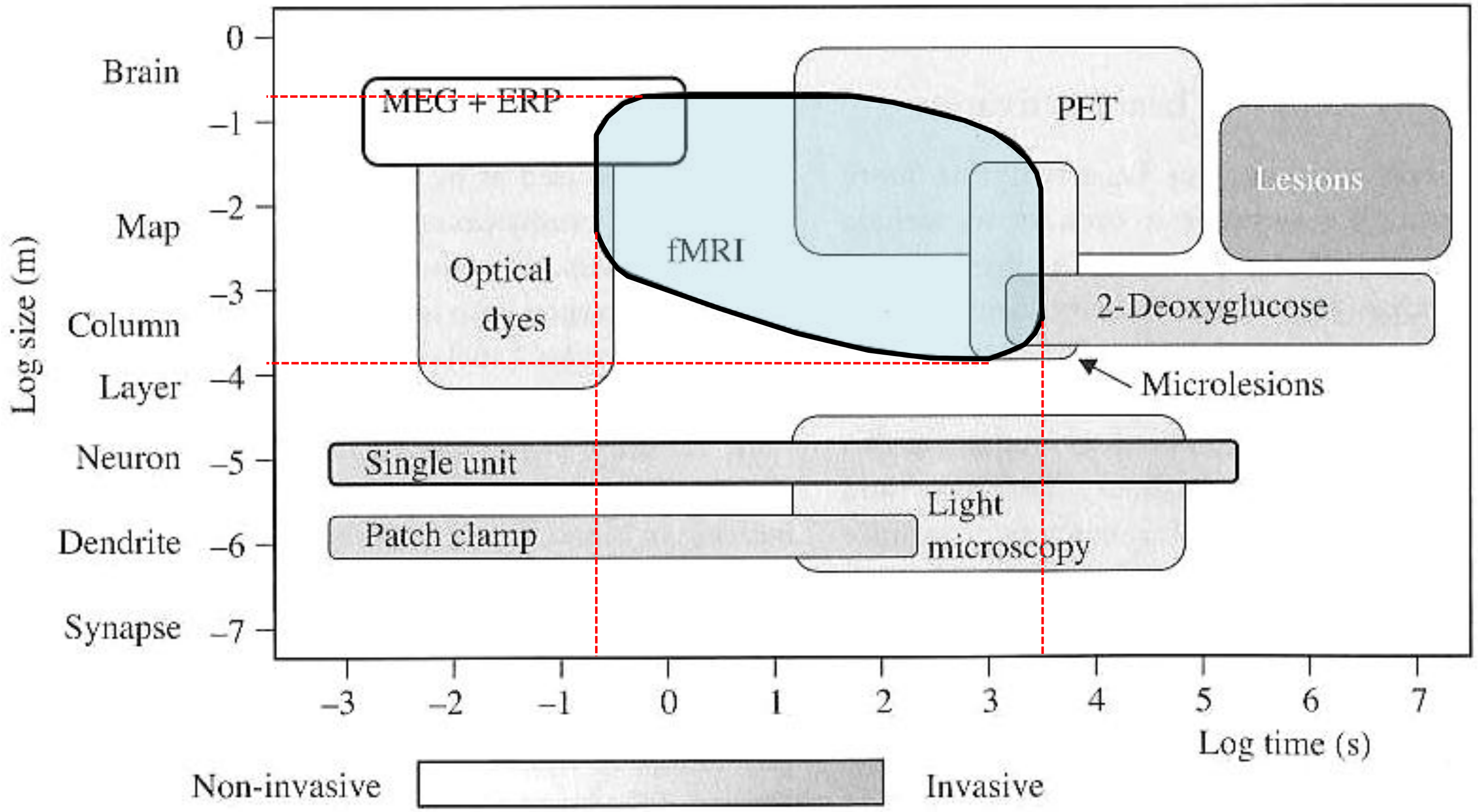
[https://radiologykey.com/mr-relaxation-theory-and-exchange-processes-in-the-presence-of-contrast-agents/; Berger, 2002]

T1-weighted vs T2-weighted MRI

Functional MRI (fMRI)

- MRI technique primarily for measuring brain activity indirectly through the coupling between hemodynamics (changes in blood flow, blood volume, and blood oxygenation) and neuronal activity
  - Creates a movie that non-invasively reveals details of events over time in the brain
- Applications of fMRI
  - Brain function analysis

- Spatially within millimeters
- Temporally within a window of a few seconds



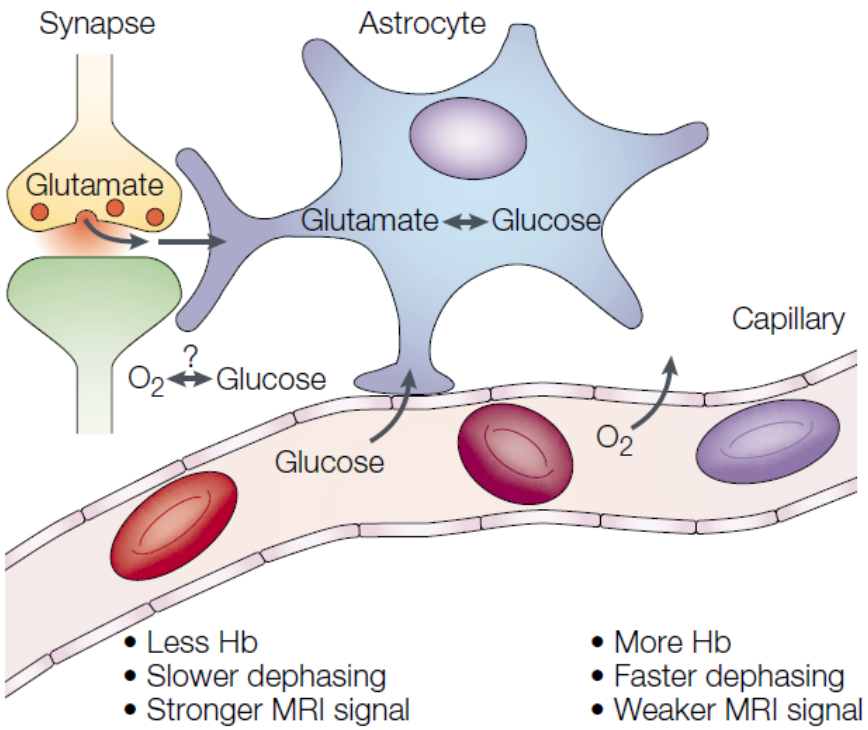
[Adapted from Churchland and Sejnowski, 1988]

fMRI in Comparison with Other Neuroscience Methods

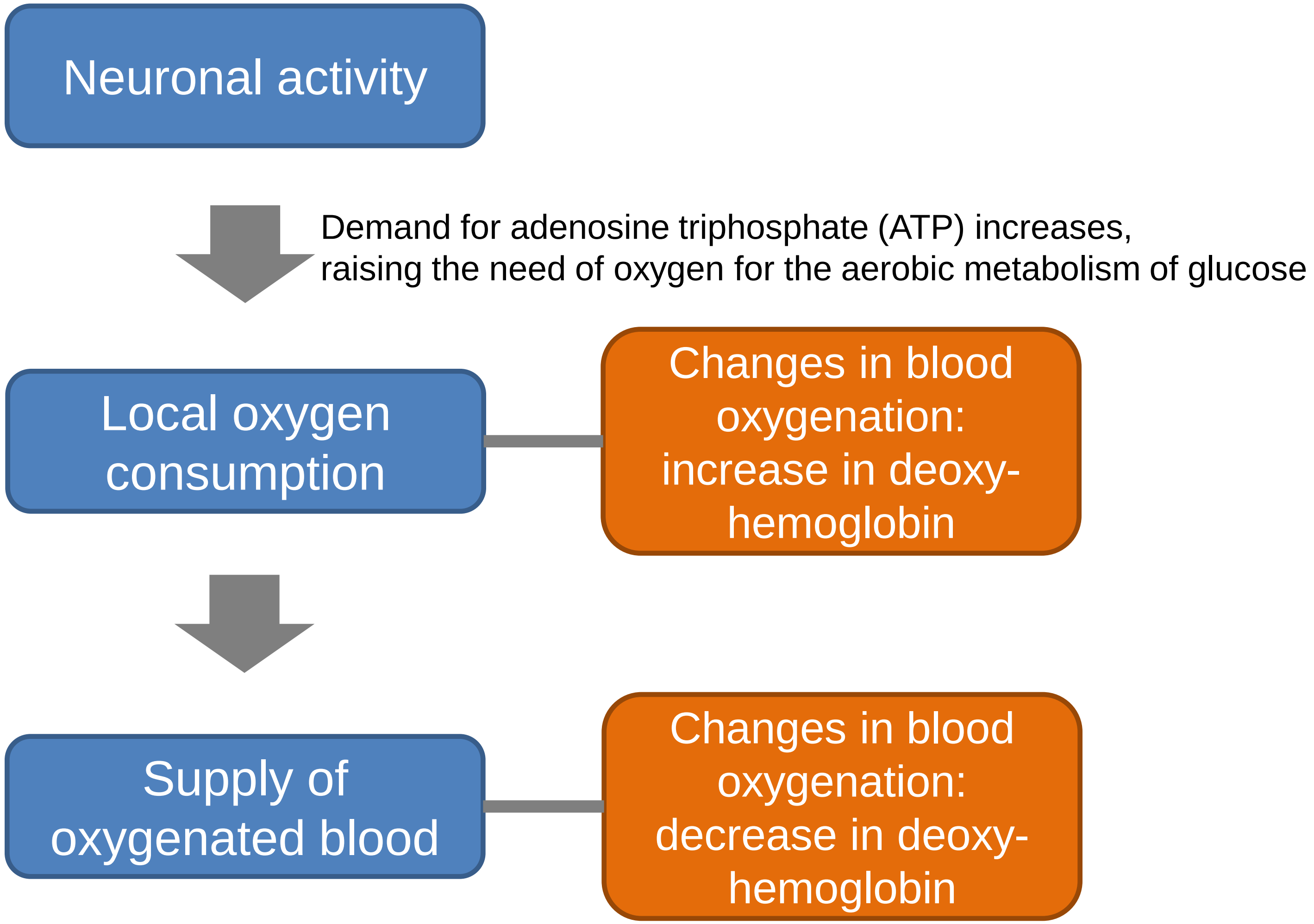
BOLD Contrast for fMRI

- Blood-oxygen-level dependent (BOLD) contrast
  – Exploits different electromagnetic properties between blood containing oxygen (oxyhemoglobin) and blood without oxygen (deoxyhemoglobin)
  – Deoxyhemoglobin (paramagnetic, thus faster relaxation) vs oxyhemoglobin (weakly diamagnetic)
    - Deoxyhemoglobin concentration ↑ ➜ image intensity ↓
    - Deoxyhemoglobin concentration ↓ ➜ image intensity ↑

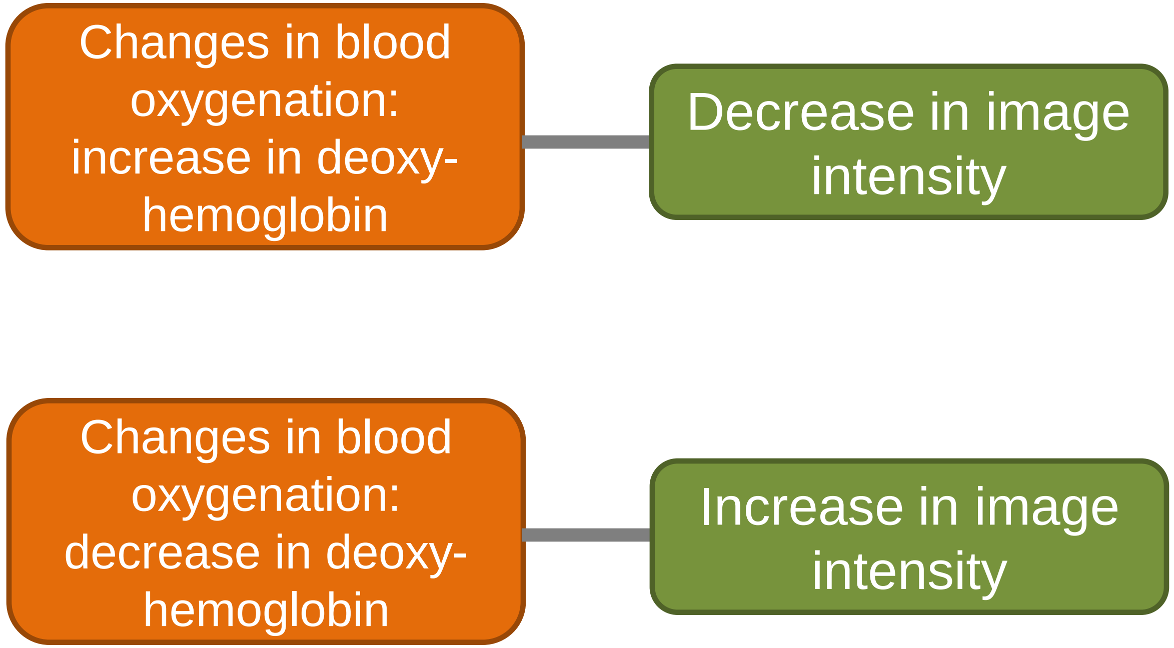
- Based on the assumption that the changing distribution of blood oxygenation in the brain correlates with neuronal activity



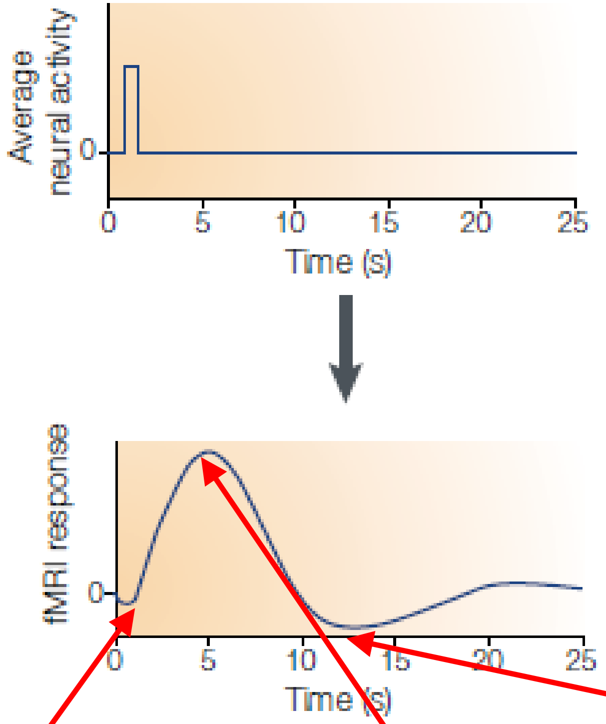
[Heeger and Ress, 2002]



Neuronal Activity →Blood Oxygenation Change



Blood Oxygenation Change → Image Intensity Change



	Phase 1	Phase 2	Phase 3
Hemodynamics	Consumption of local oxygen	Oversupply of oxygenated blood	Diminished oversupply of oxygenated blood
fMRI signal	Small decrease below baseline	Large increase above baseline	Decrease back to below baseline

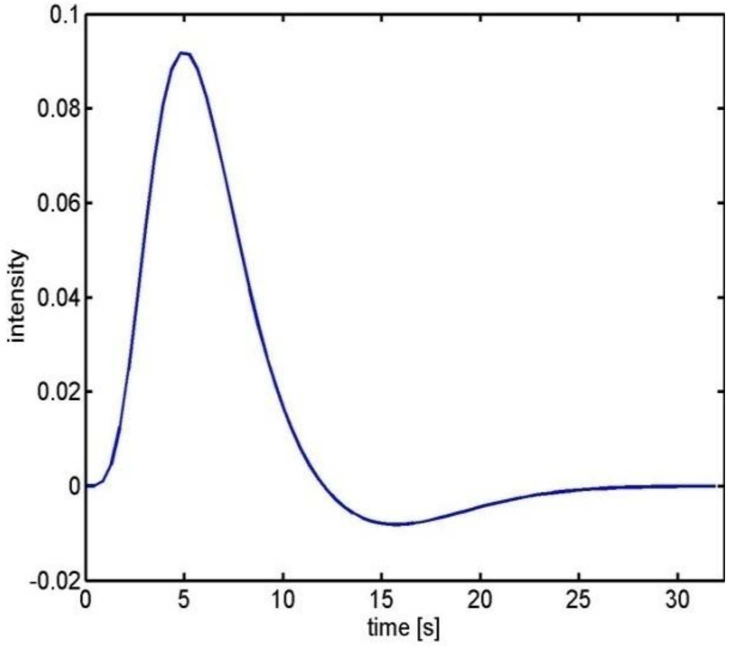
[Heeger and Ress, 2002]

Three Phases of a BOLD fMRI Response

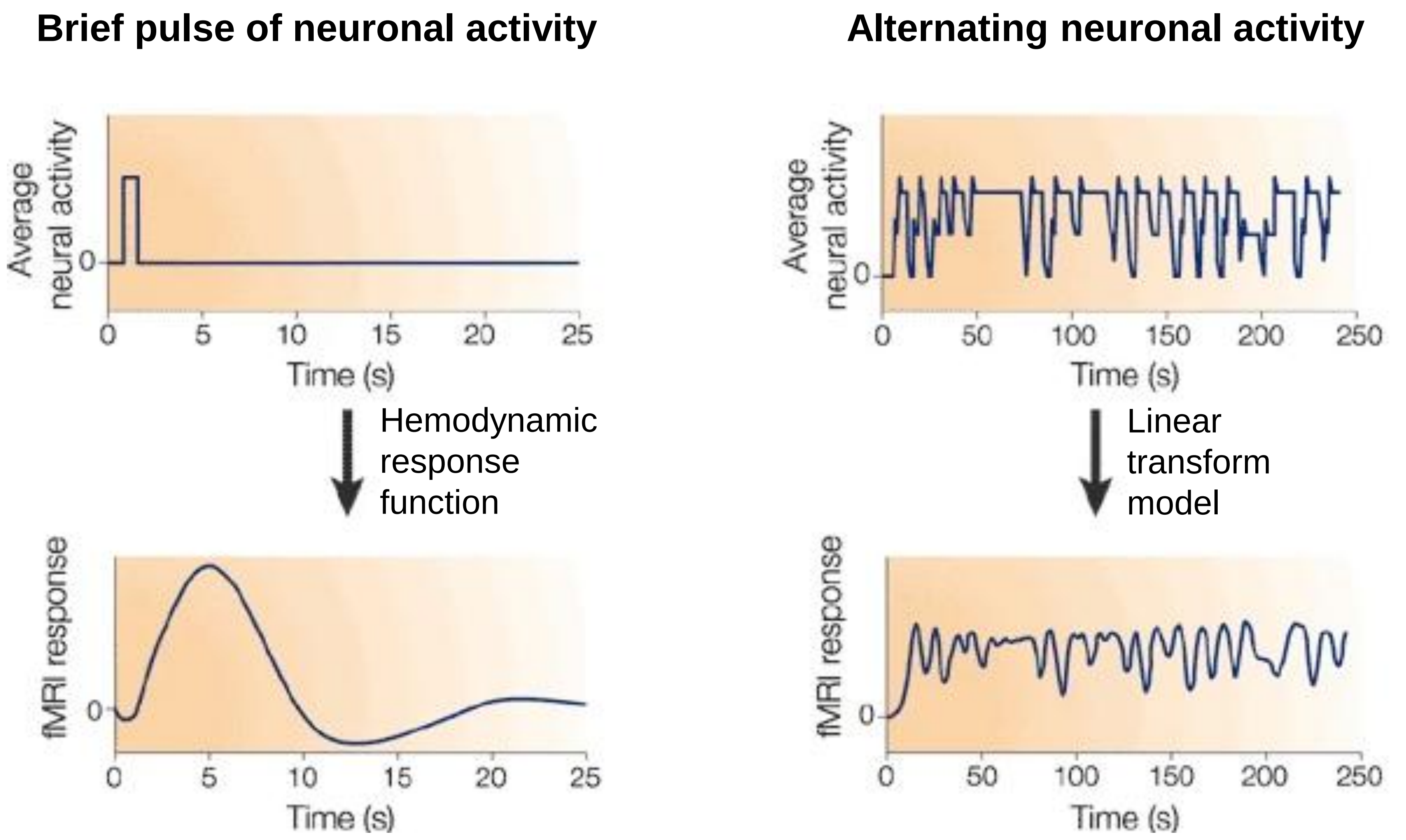
Hemodynamic Response Function

- Hypothetically characterizes the relationship between neuronal activity and an fMRI signal
  - Positive for excitatory neuronal activity
  - Much slower than underlying neuronal processes

- Models a gradual rise to peak (about 6 seconds), a long return to baseline (about 10 seconds), and a slight undershoot (about 10-15 seconds)
  - Mathematically represented by a mixture of gamma functions

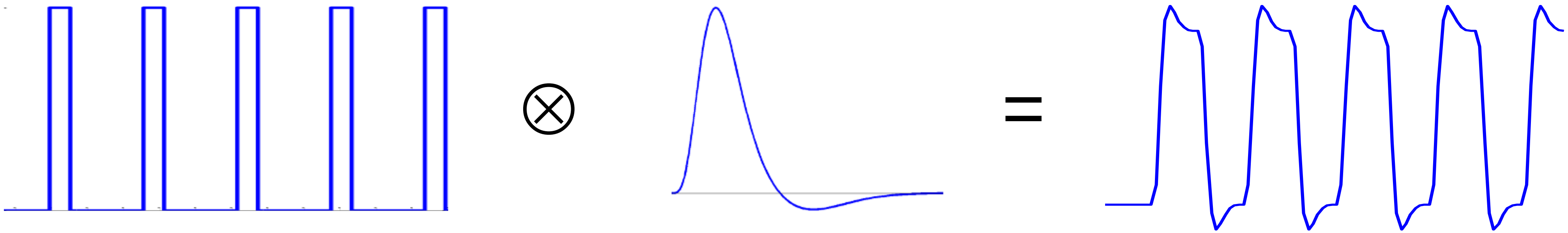


- Linear transform model
  - Predicts that an fMRI signal should sum over time
  - Enables to compute (using convolution) the time series of an fMRI signal, given a measured time series of neuronal activity
  - Simplifies the analysis and interpretation of fMRI data



[Heeger and Ress, 2002]

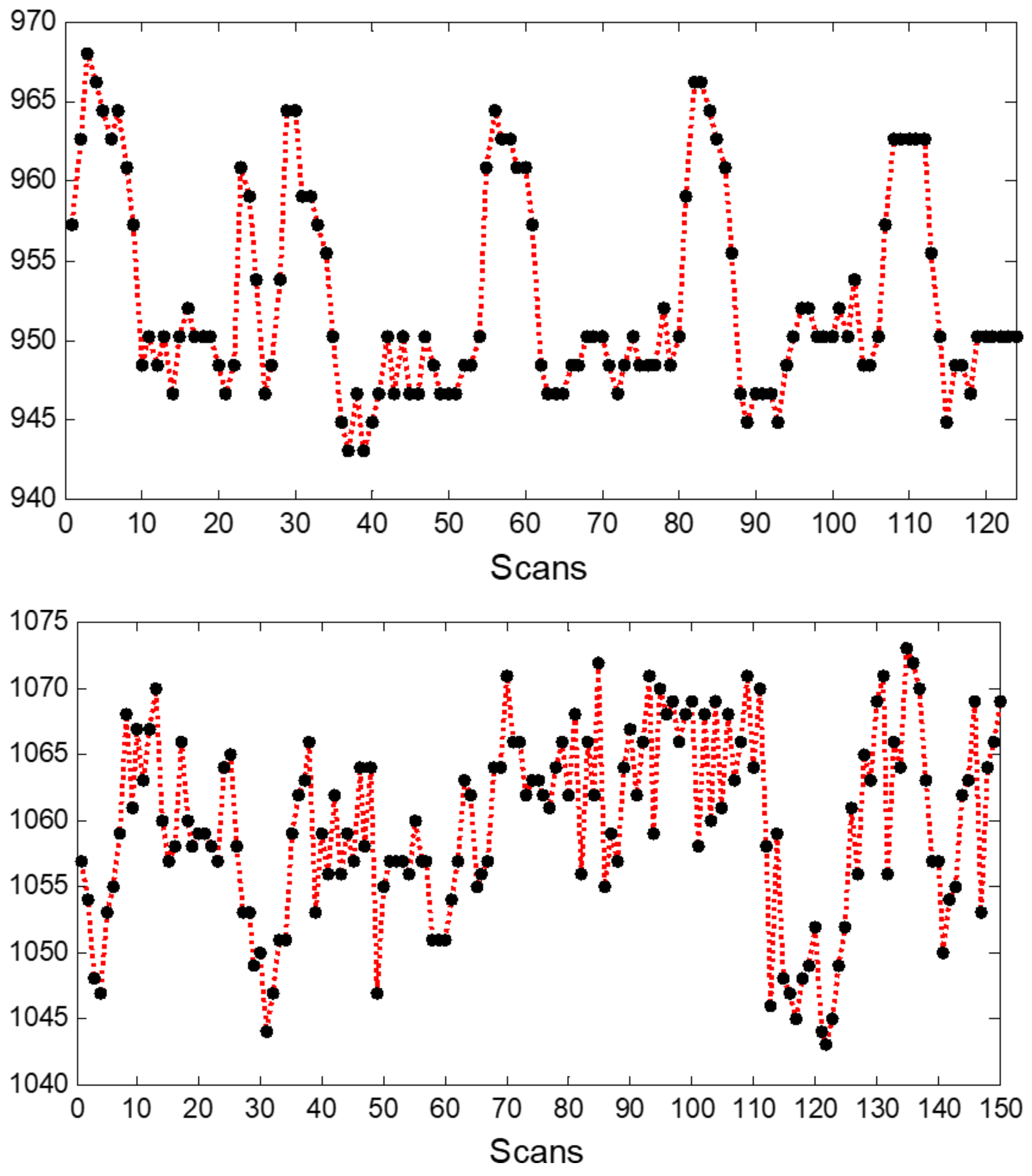
Prediction of a BOLD fMRI Response



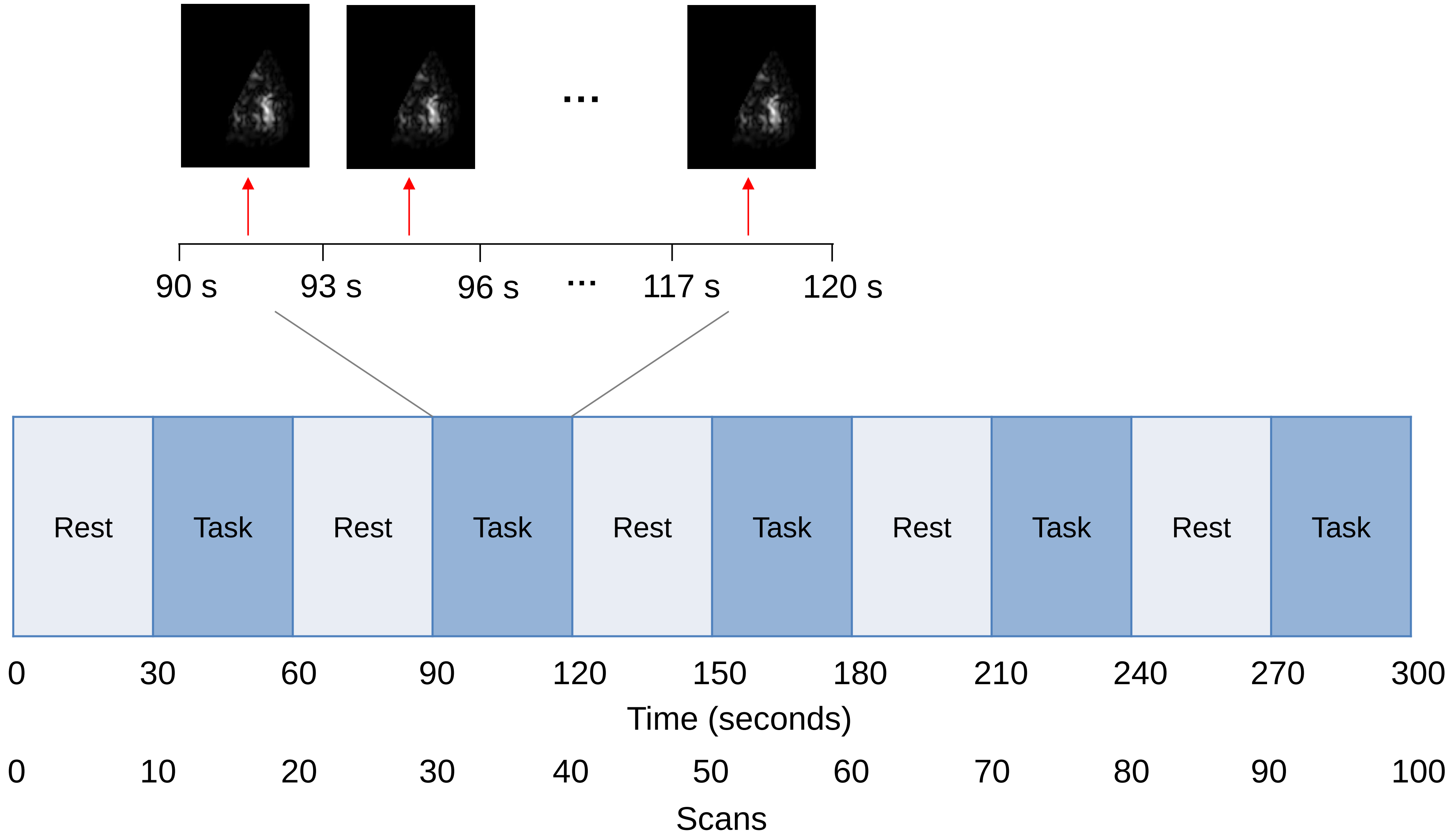
Linear Transform Model for Predicting fMRI Time Series

Experimental fMRI

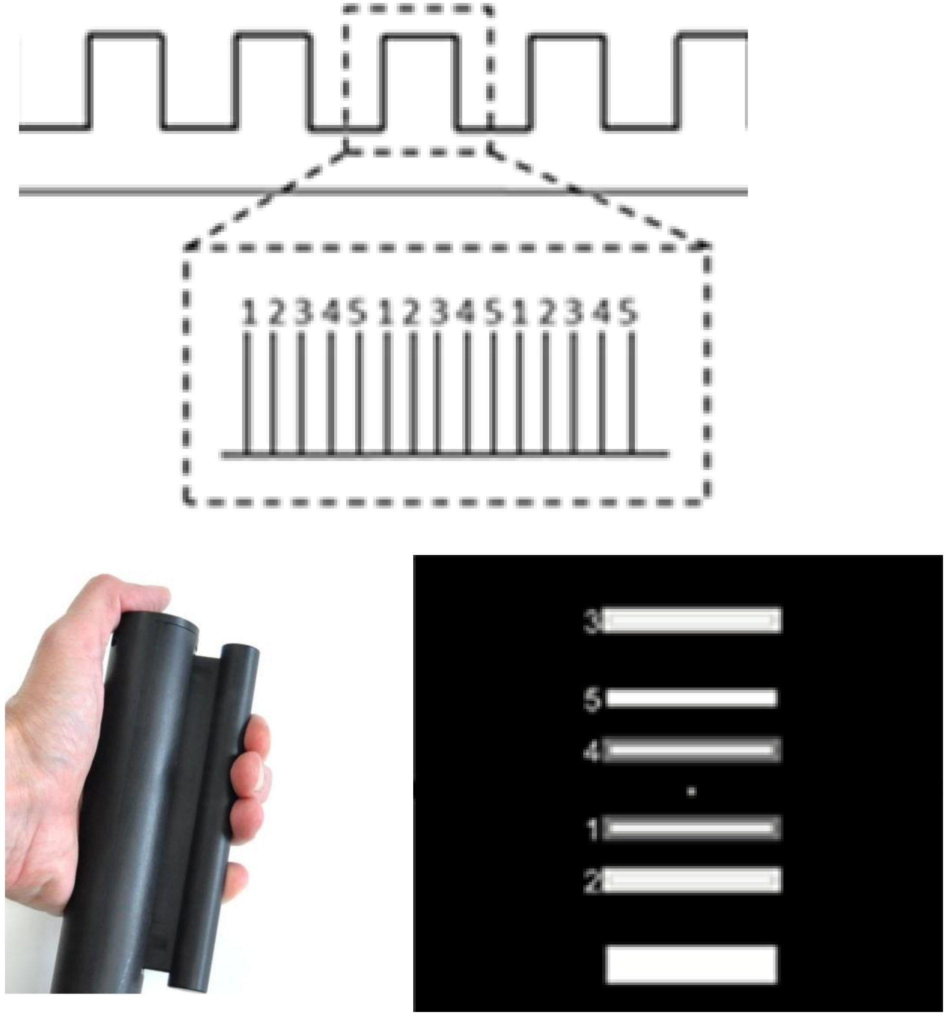
- Task-based fMRI
  - Given an overt task or external stimuli
  - The brain exhibits task-related activity
- Resting-state fMRI
  - With wakefulness maintained but structural thinking (e.g., counting) avoided
  - The brain exhibits spontaneous fluctuations in activity



Time Series from the Same Location for Task-based vs Resting-state fMRI

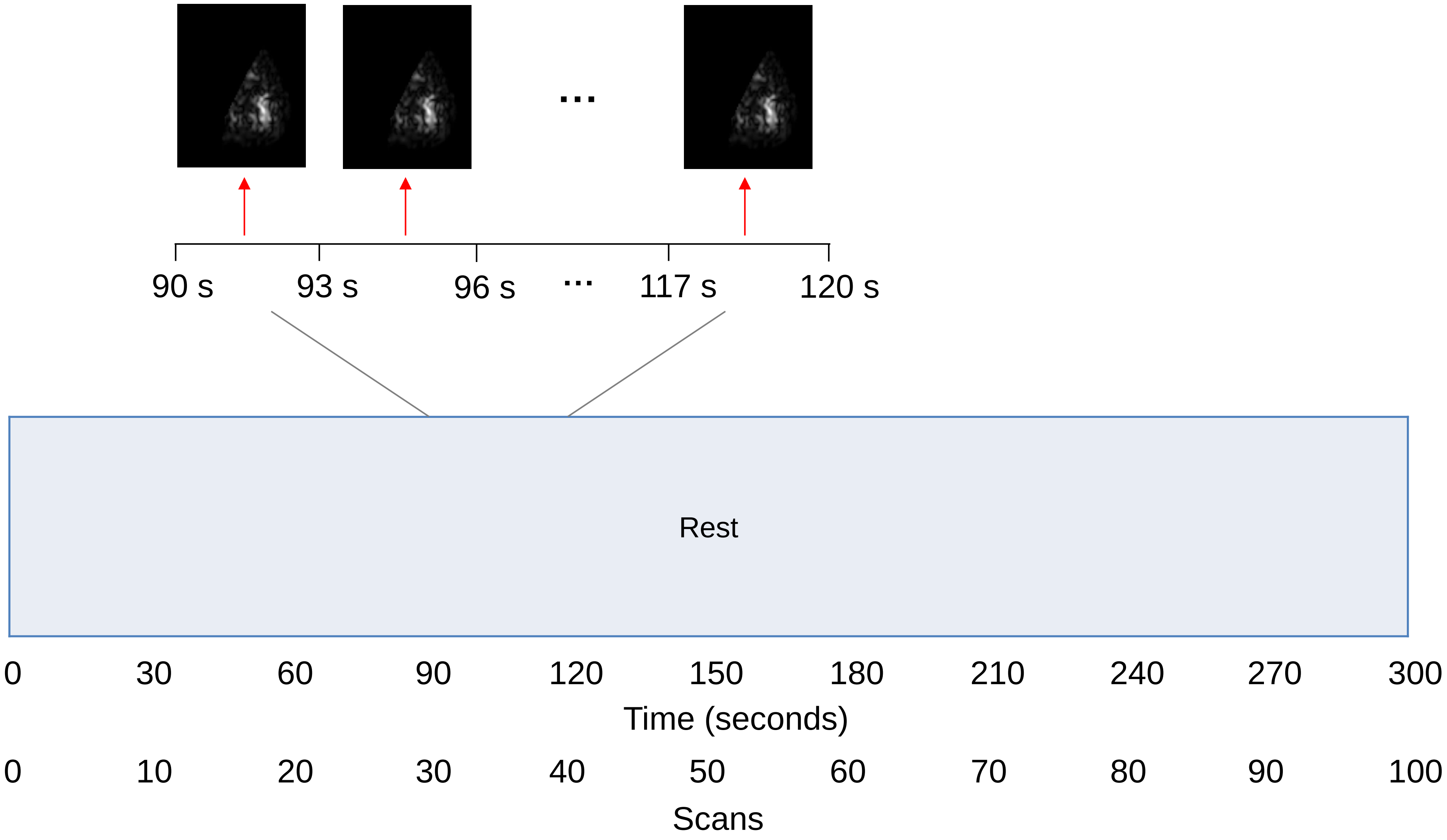


Example of Task-based fMRI



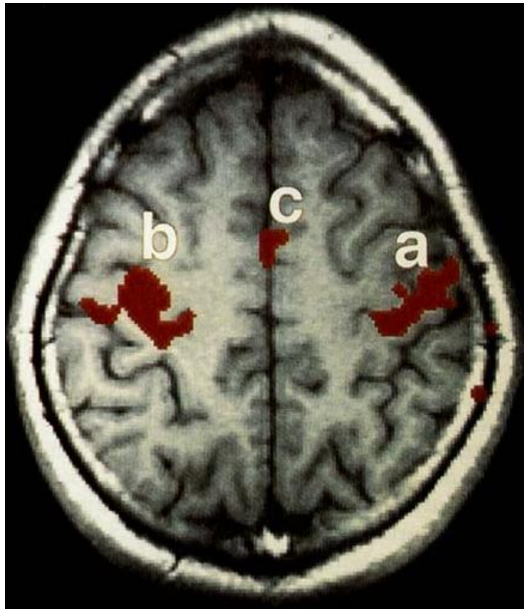
[Manon et al., 2023]

Sequential Hand Grip Task for fMRI



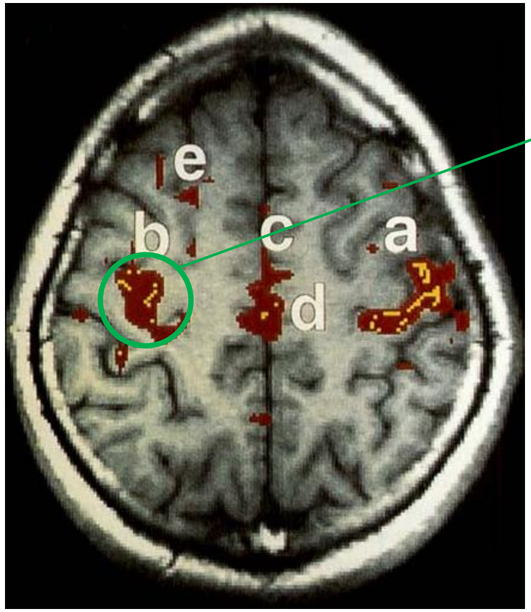
Example of Resting-state fMRI

Task-based fMRI

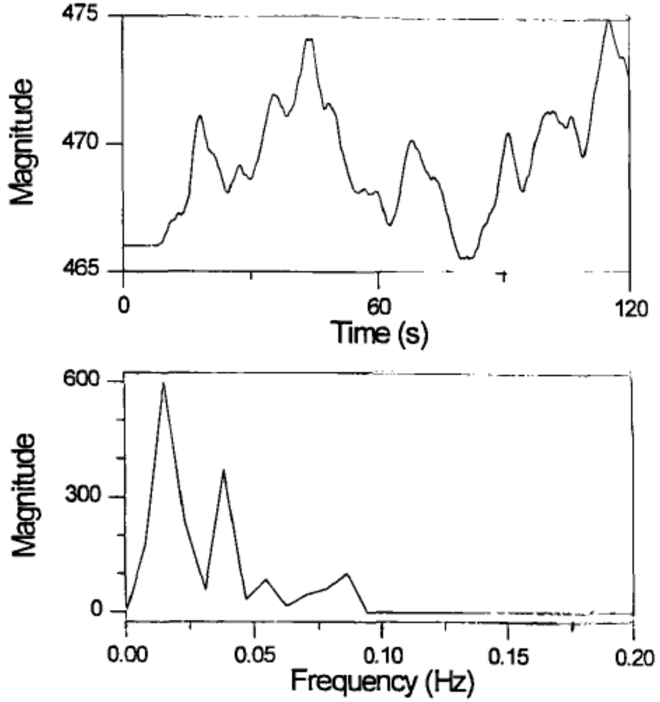


Finger movement-induced activation

Resting state fMRI

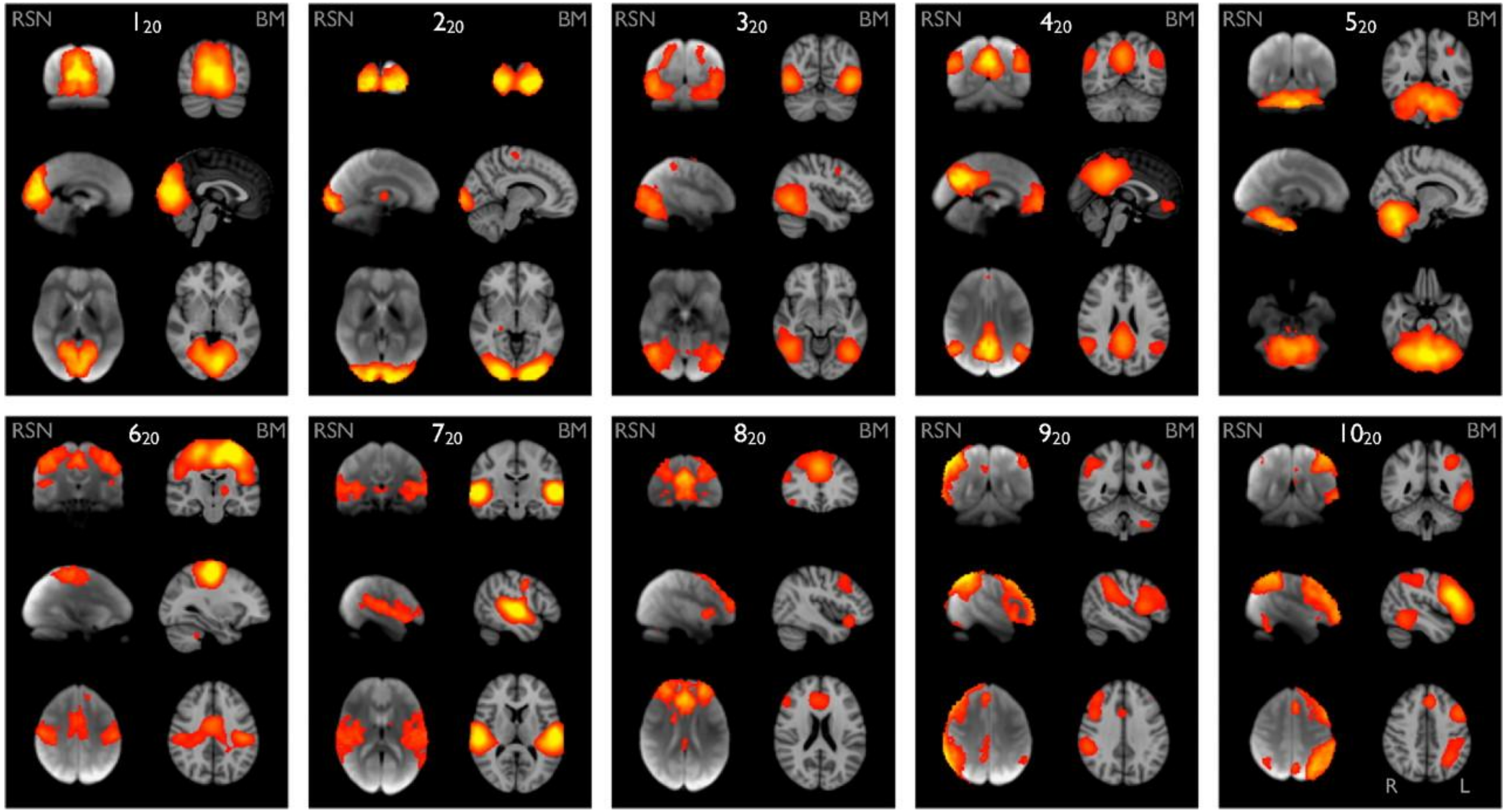


Correlation with the representative time series



[Biswal et al., 1995]

Correspondence between Task-based and Resting-state fMRI: Sensorimotor Network



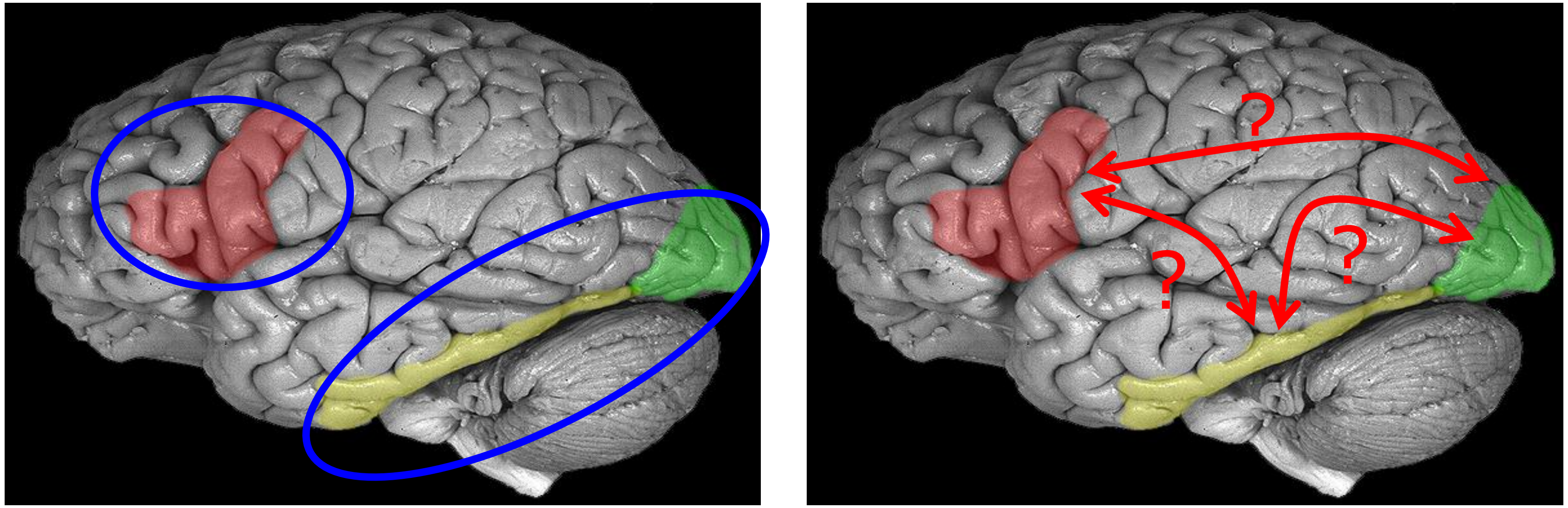
Resting-state fMRI   Task-based fMRI

[Smith et al., 2009]

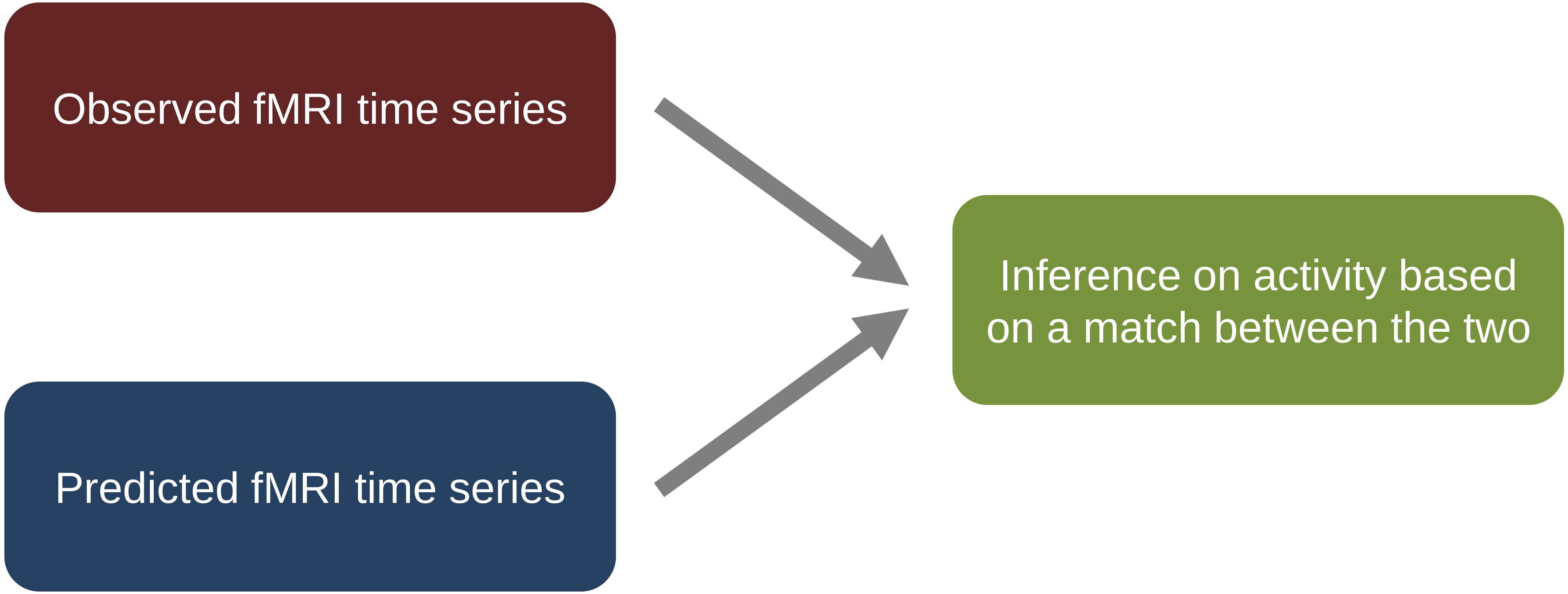
Correspondence between Task-based and Resting-state fMRI: 10 Brain Networks

Brain Function Analysis with fMRI

- Functional segregation vs. integration
  - Related to perspectives on how brain areas communicate and work together to process information



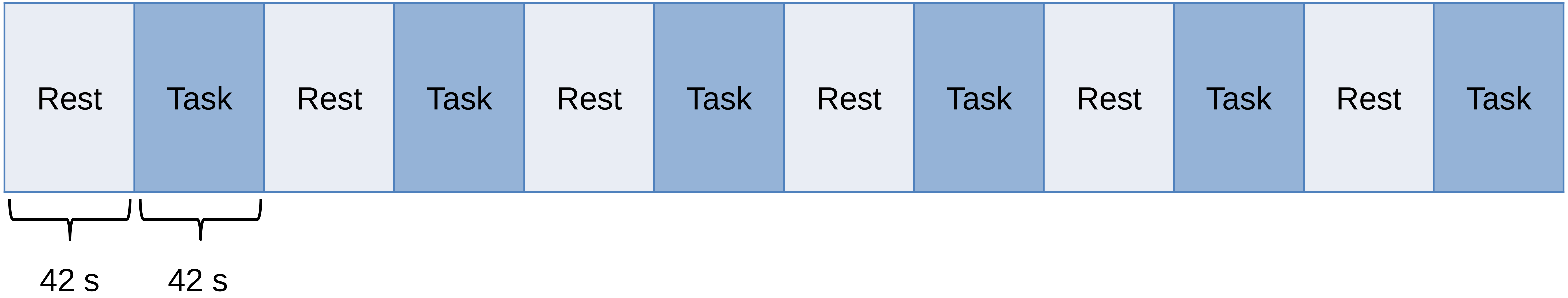
- Functional segregation
  - Specialization of different brain areas for different functions
    - Based on the idea that certain tasks or processes are localized to specific areas of the brain
  - In task-based fMRI:
    - Increased activity in specific brain areas during a task, as compared to a baseline, suggests those areas are specialized for the task
  - In resting-state fMRI:
    - Synchronized activity patterns in certain brain areas reveal functional specialization often in terms of specific brain networks (e.g., visual network, sensorimotor network)



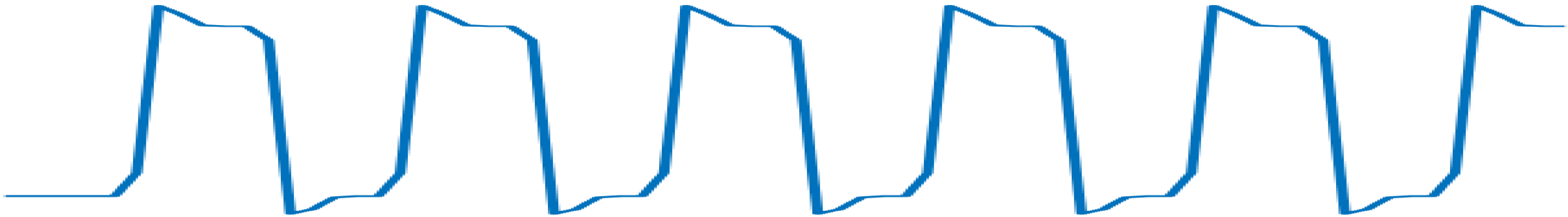
Functional Segregation Analysis in Task-based fMRI

Auditory stimulation task [https://www.fil.ion.ucl.ac.uk/spm/data/auditory/]

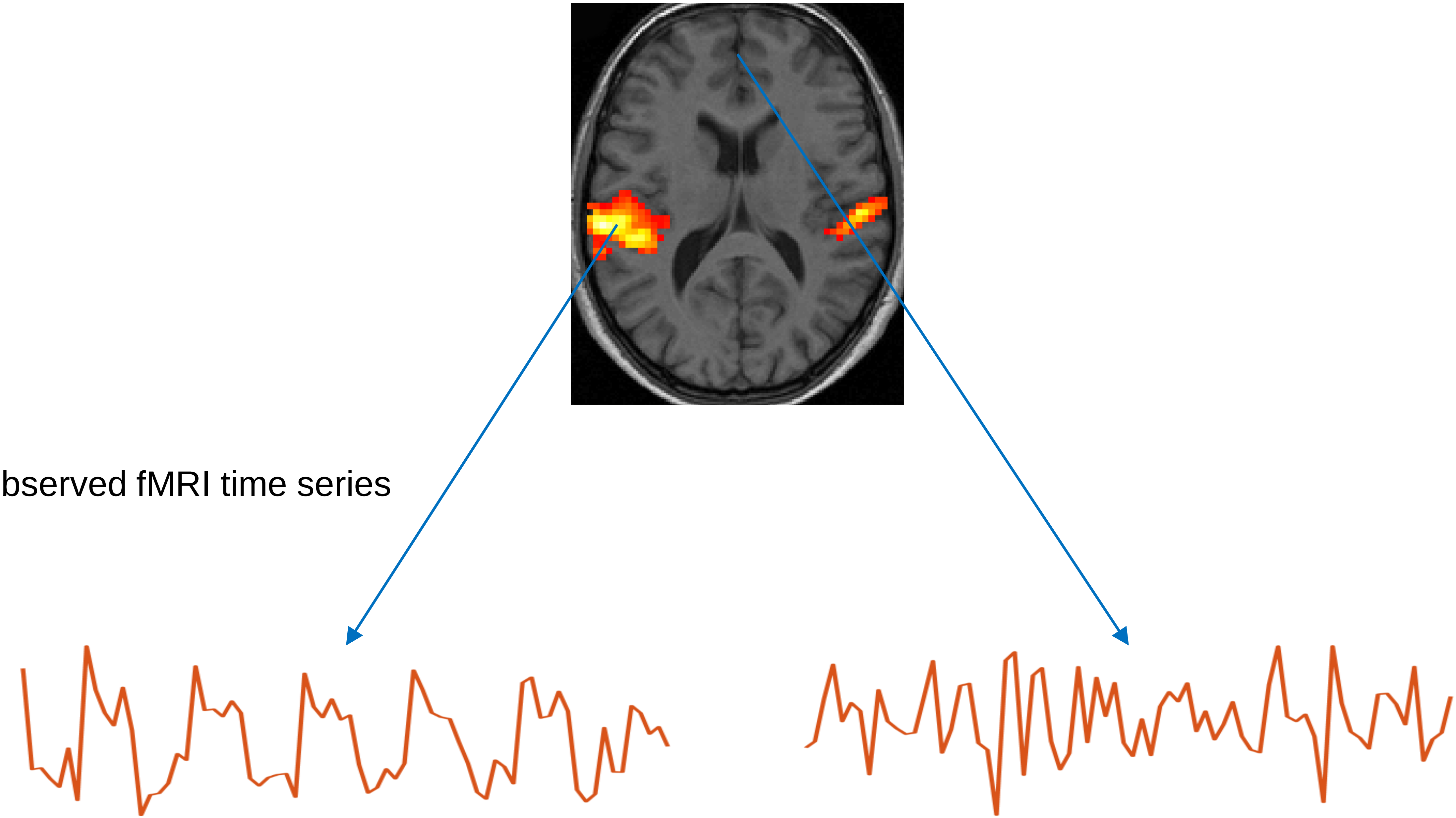
Bi-syllabic words presented binaurally at a rate of 60 per minute

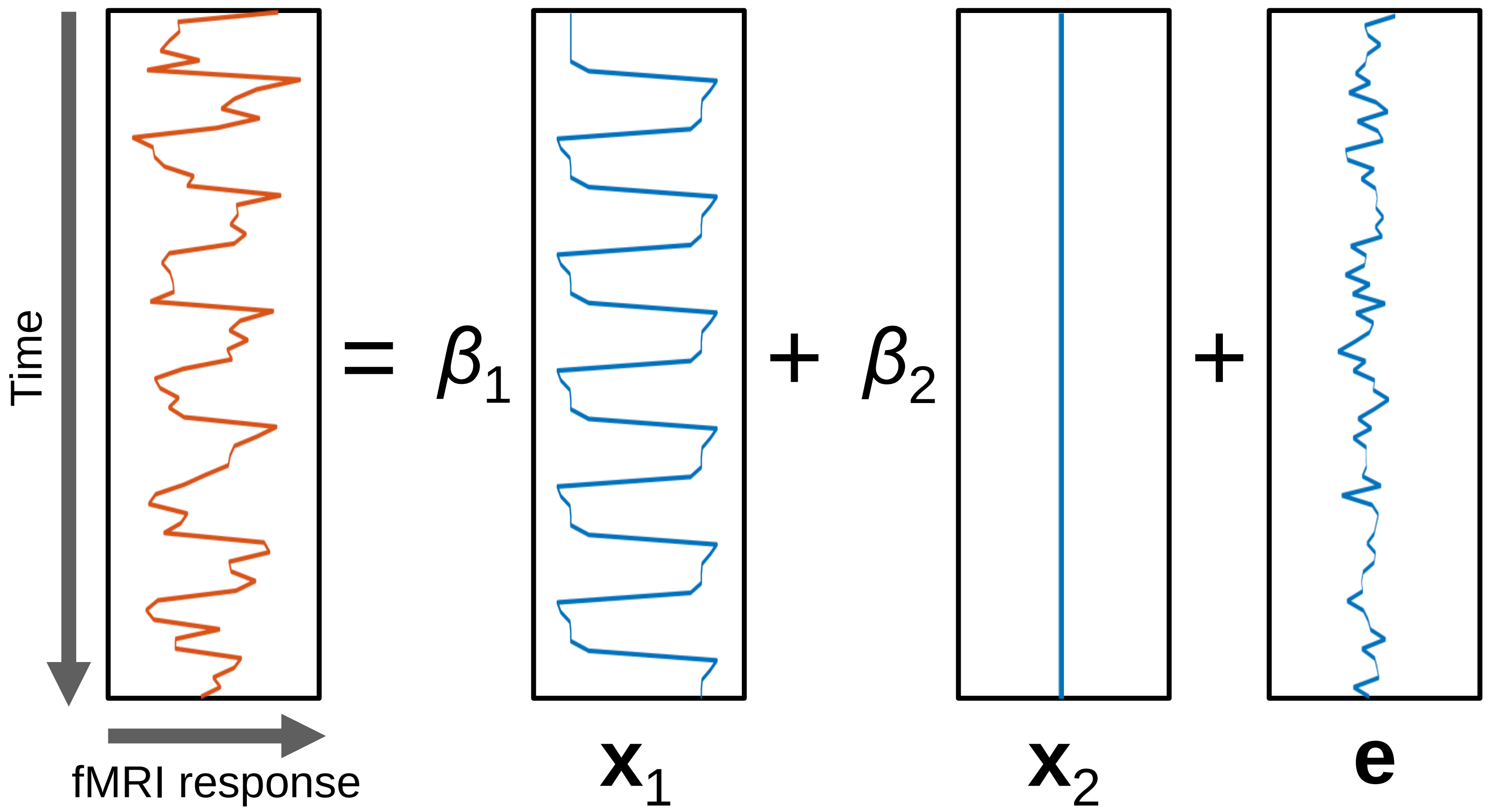


Predicted fMRI time series



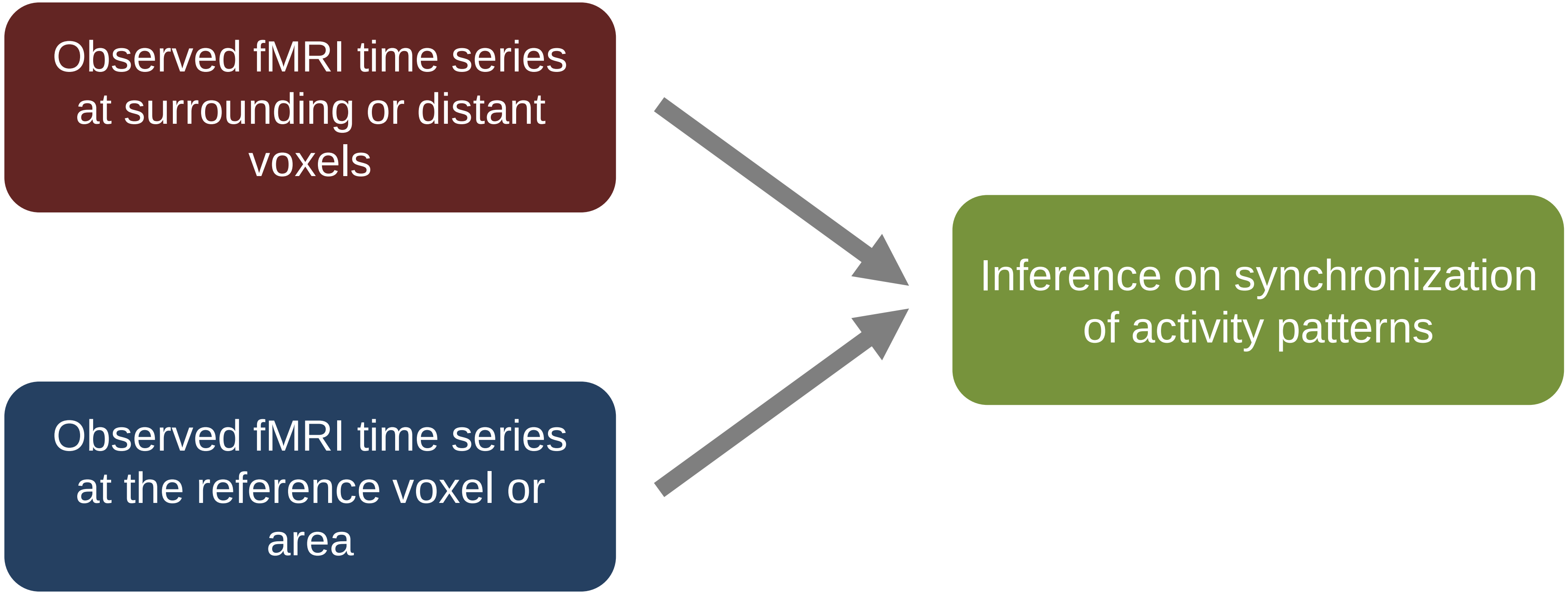
Observed fMRI time series



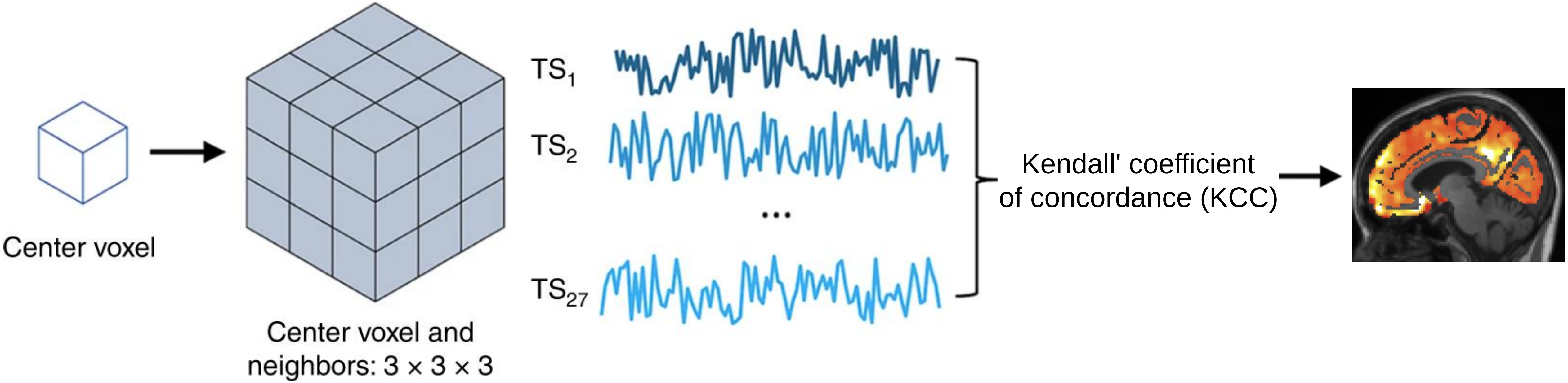


$$\boldsymbol{y} = \boldsymbol{X\beta} + \boldsymbol{e} = \boldsymbol{x}_1\boldsymbol{\beta}_1 + \boldsymbol{x}_2\boldsymbol{\beta}_2 + \boldsymbol{e}$$

General Linear Model for Functional Segregation Analysis in Task-based fMRI

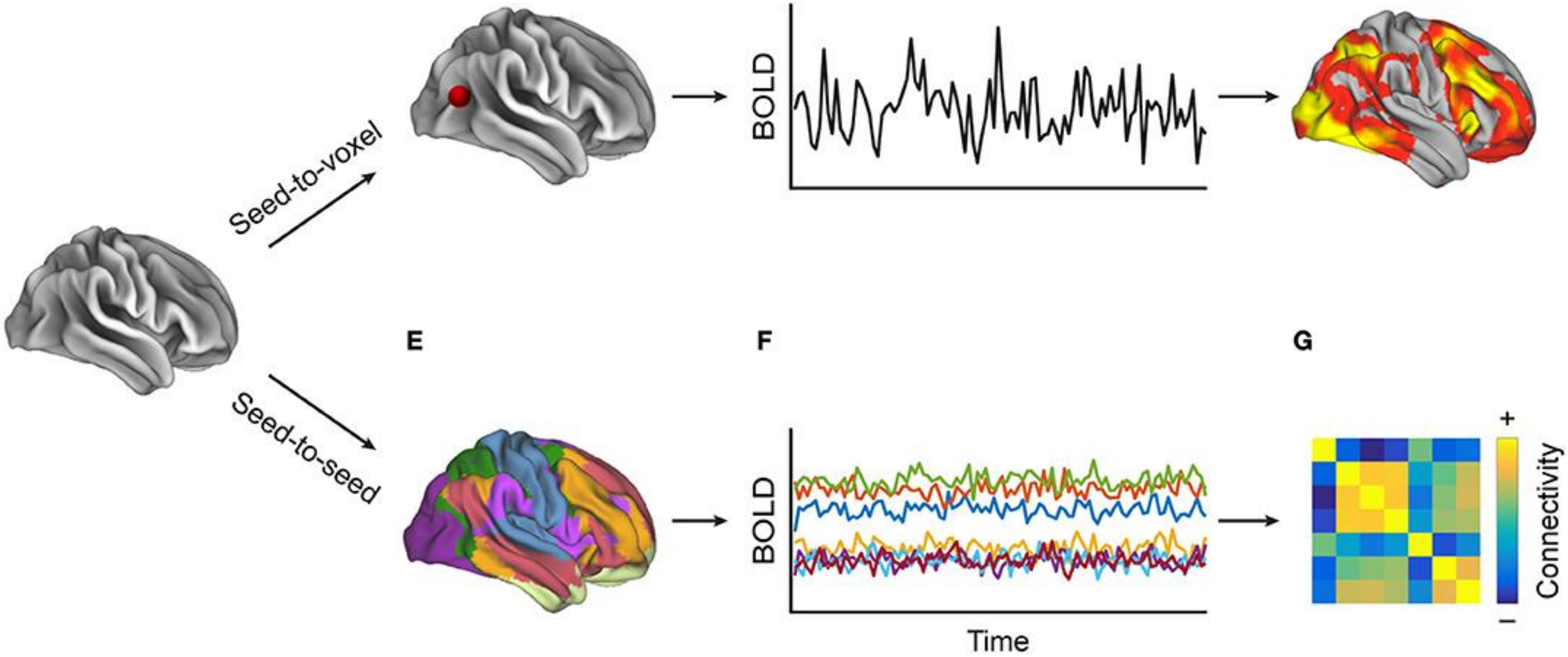


Functional Segregation Analysis in Resting-state fMRI



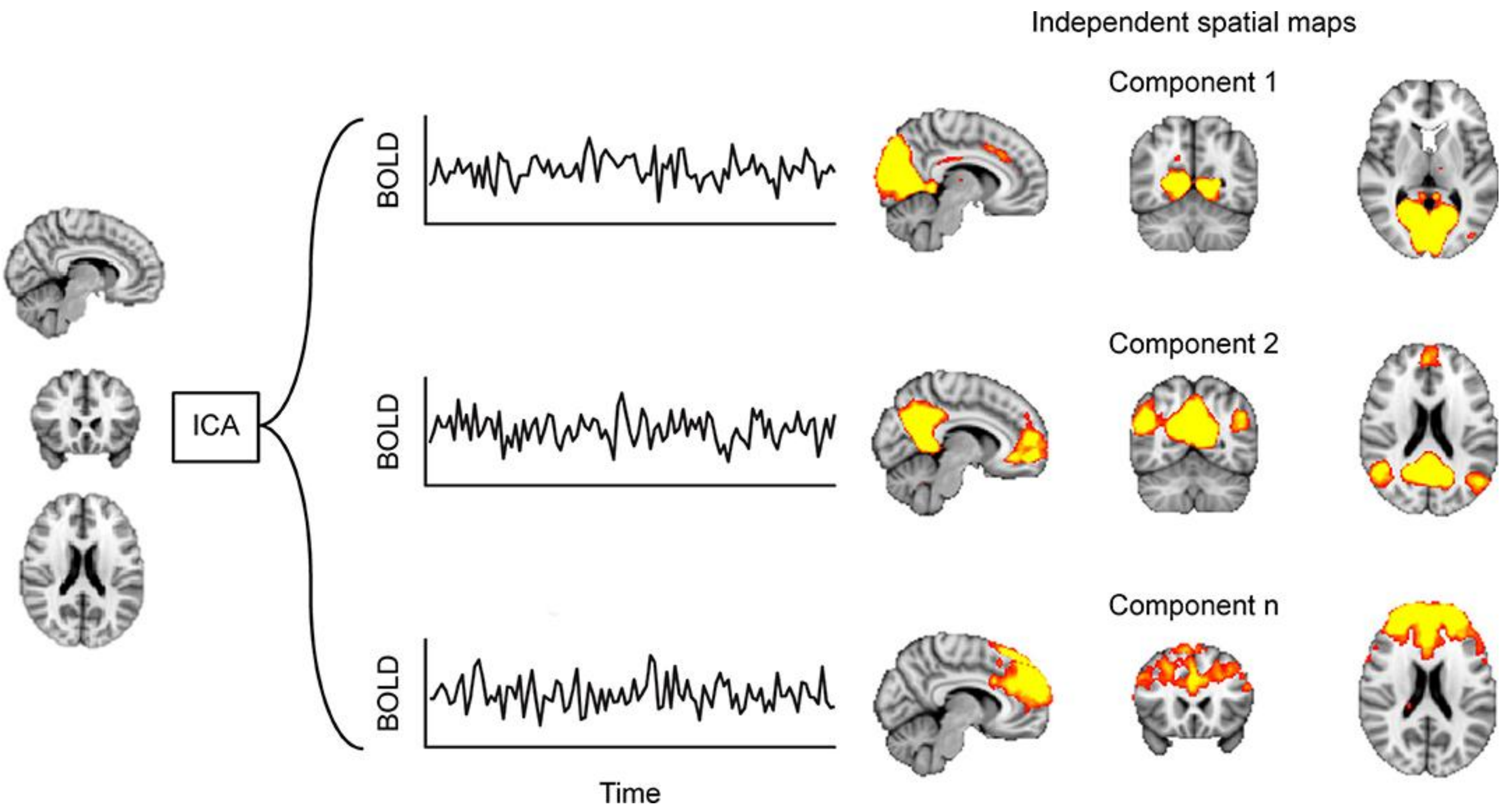
[Harrison et al., 2019]

Regional Homogeneity



[Tahedl et al., 2018]

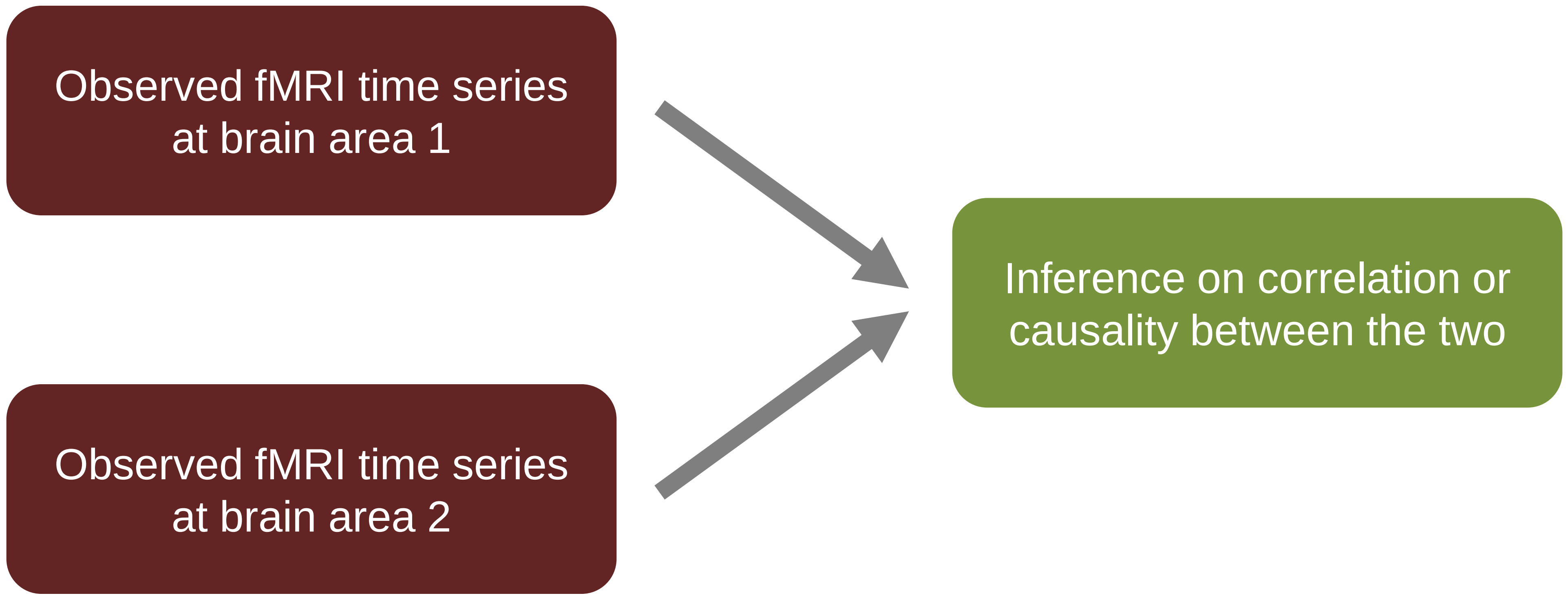
Functional Connectivity



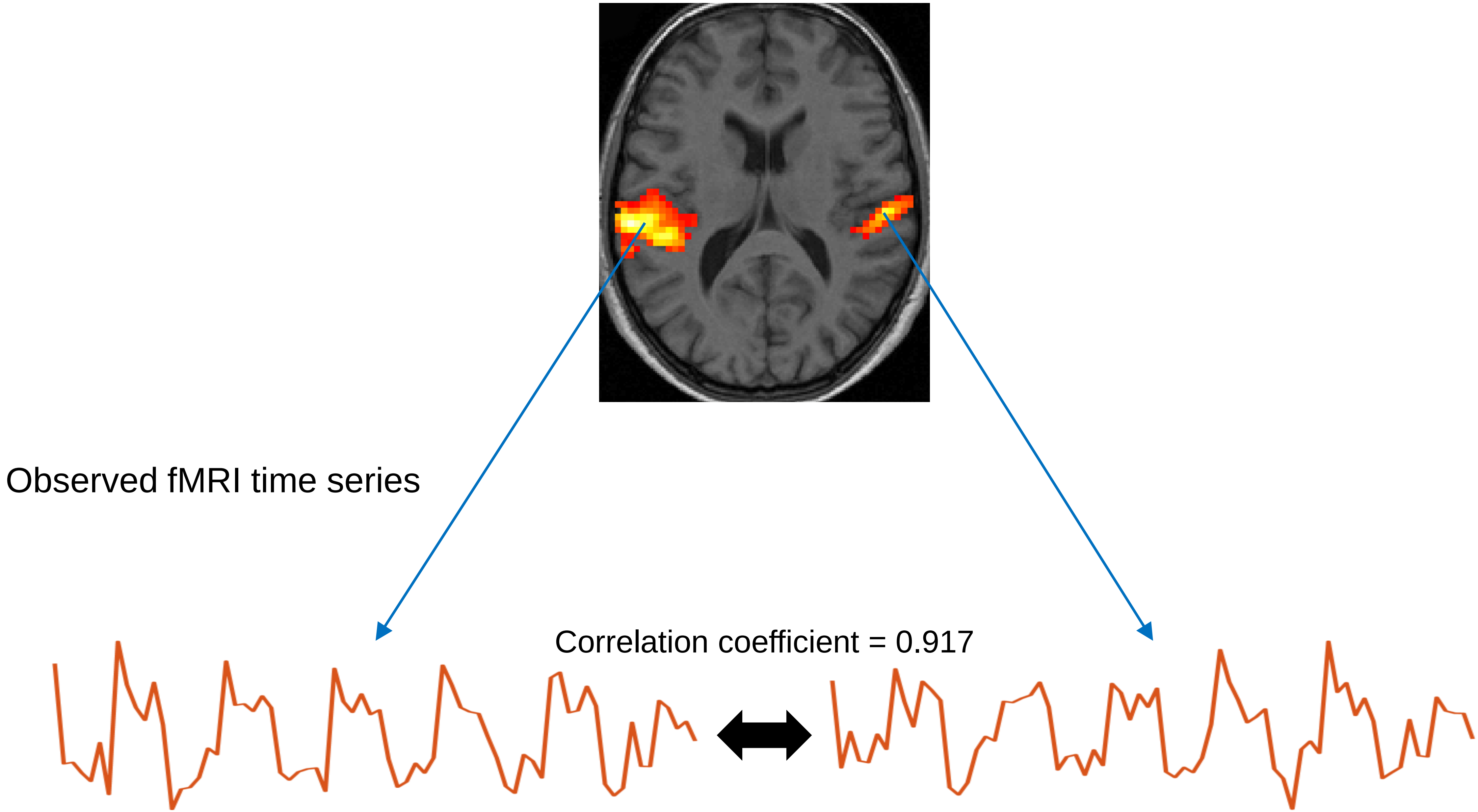
[Tahedl et al., 2018]

Independent Components

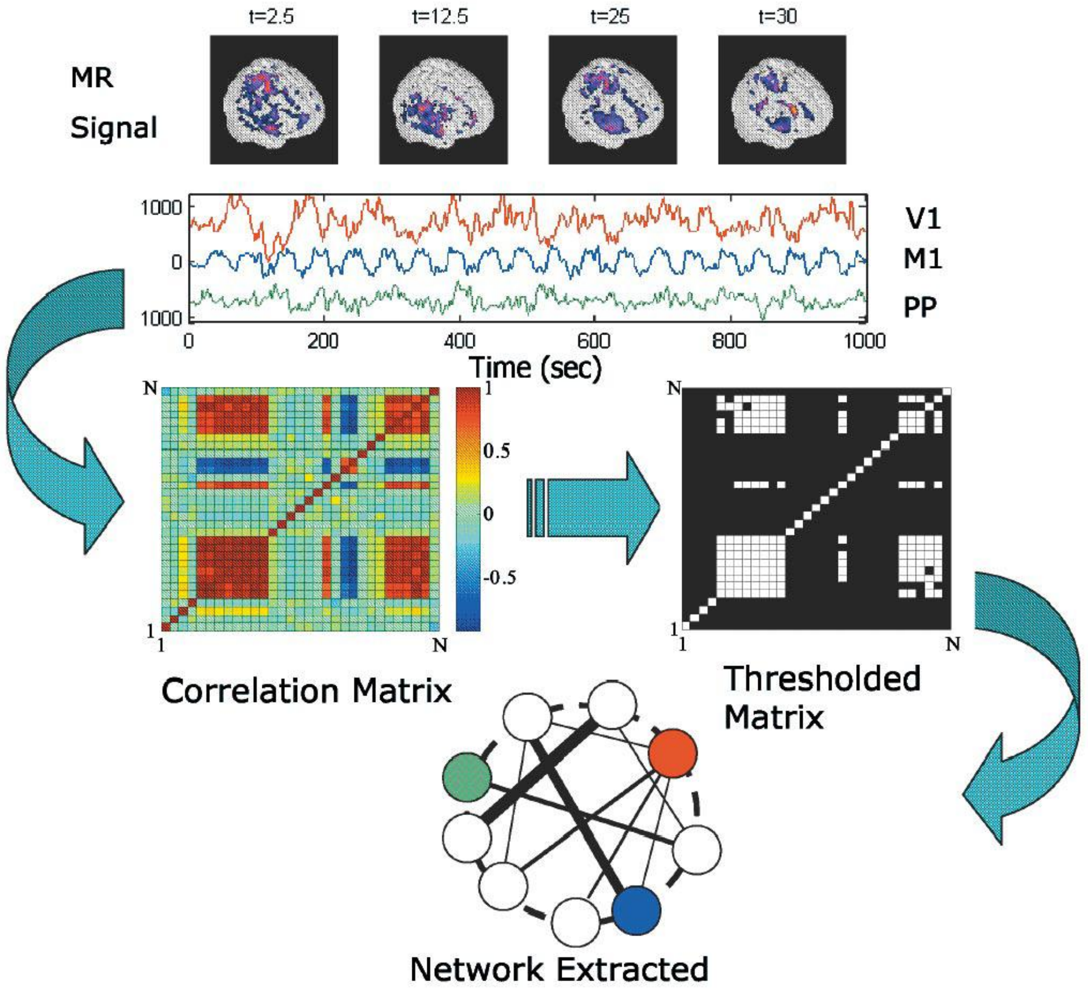
- Functional integration
  - Interaction between segregated brain areas for the integration of information across various parts of the brain
    - Based on the idea that certain tasks or processes are supported by the communication and coordination of different brain areas with each other
  - In task-based and resting state fMRI:
    - The association between time series of activity from different brain areas reveals networks of areas that work together
    - Graph-theoretical analysis enables to characterize the brain's network architecture, such as identifying hubs (key areas in the brain) and analyzing connection topology (global and local efficiency of information transfer within the brain)

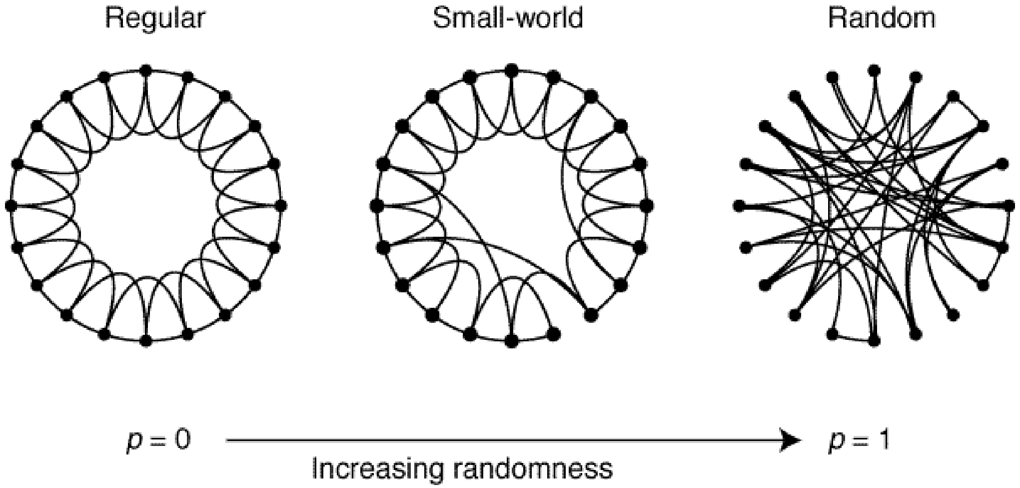


Functional Segregation Analysis in fMRI


Observed fMRI time series
Correlation coefficient = 0.917

- Correlation vs. causality
  - Correlation: statistical relationship between variables
    - Claims that, given a change in one variable, there is a corresponding change in another variable
    - Can be positive (both variables increase or decrease together), negative (one variable increases while the other decreases), or zero (no relationship)
    - Does not imply causation, but simply indicates that there is a relationship between the variables
  - Causality: cause-and-effect relationship between variables
    - Claims that a change in one variable directly brings about a change in another variable
    - Much stronger assertion than correlation, often involving controlled experiments or analyses

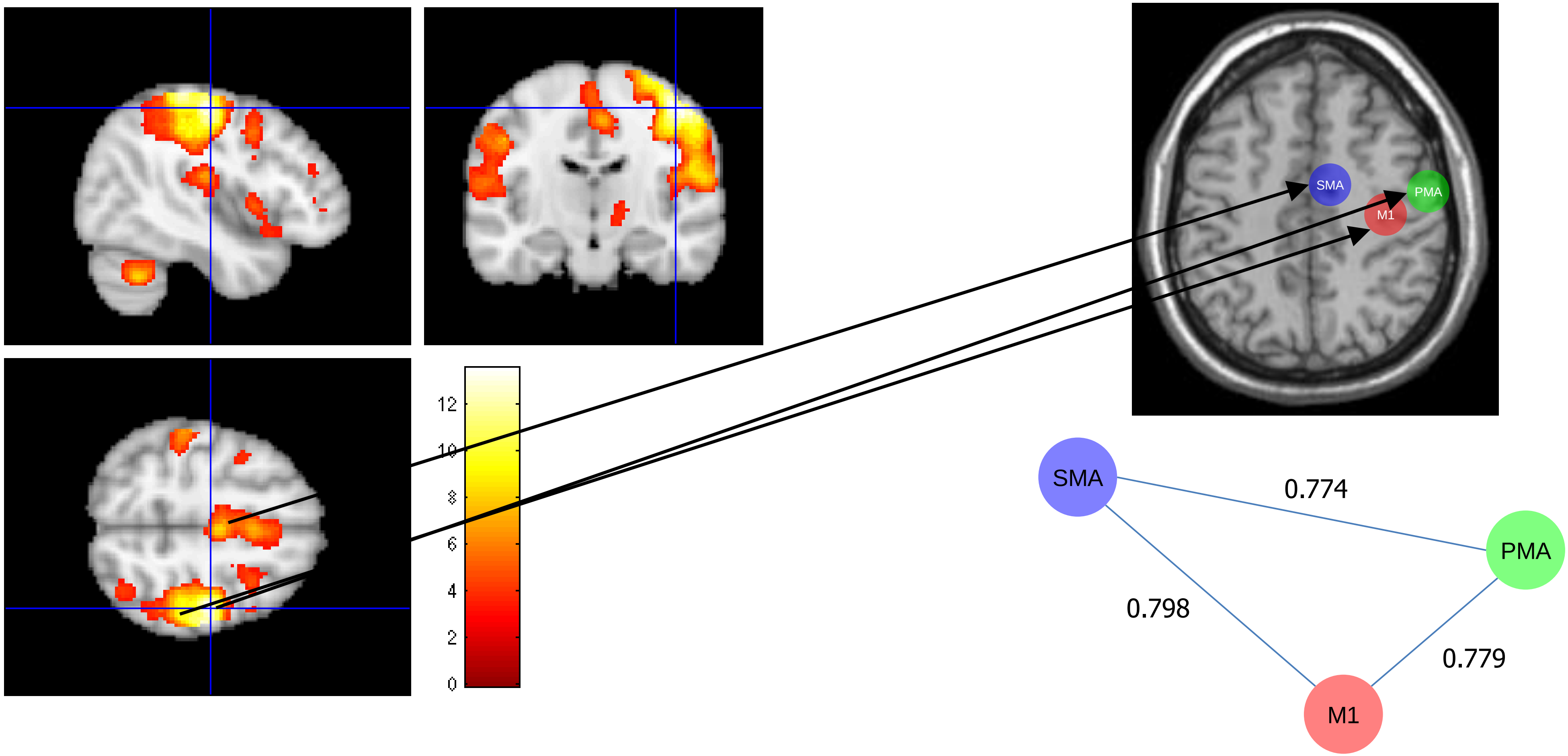




[Eguíluz et al., 2005; Watts and Strogatz, 1998]

Network Architecture of the Brain

- Complementary roles of functional segregation and integration
  - Exhibited as a dynamic interplay between functional segregation and integration in the brain
    - Certain tasks may require highly specialized processing within specific areas (segregation), while the coordination and combination of information from these areas are necessary for holistic processing and decision-making (integration)
  - Explored by fMRI to gain insights into how functional segregation and integration contribute to various functions and how they may be disrupted in neurological and psychiatric disorders



Functional Segregation and Integration Contributing to Motor Function