Fundamentals of Functional Magnetic Resonance Imaging Data

Andrew DiLernia

Department of Statistics
Grand Valley State University

February 16, 2023

Overview

Motivation

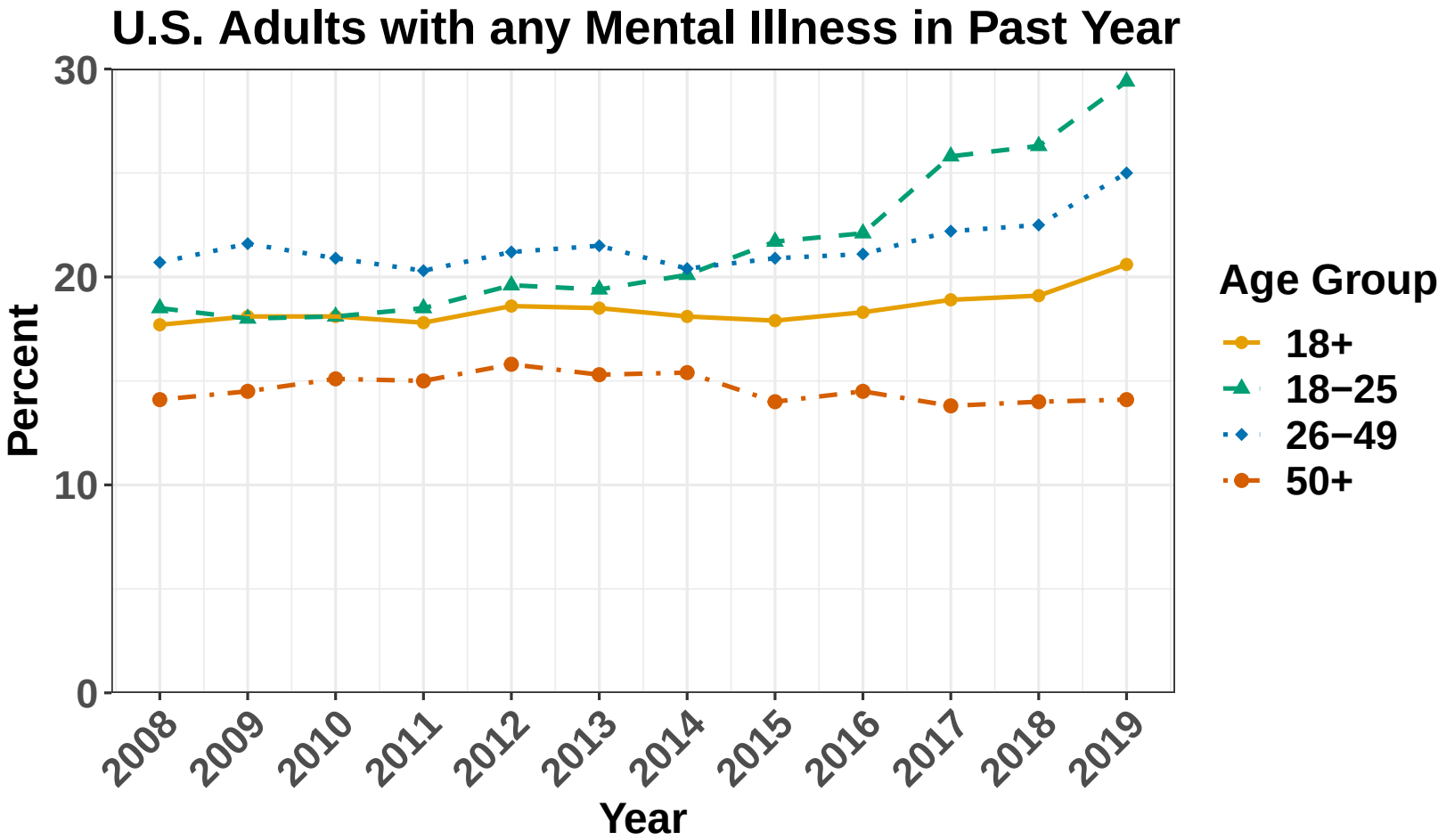


Figure 1: Data from Substance Abuse and Mental Health Services Administration (2020).

Importance of Neuroimaging

- Neuroimaging broadly refers to data collection and analysis methods using measurements of the brain
- Techniques for analyzing neuroimaging data important for improving clinical practice for mental illnesses and neurodegenerative diseases
- Two main types of brain images: structural & functional

Structural Images

- Positron Emission Tomography (PET)
- Computed Tomography (CT)
- Magnetic Resonance Imaging (MRI)

PET involves injection into the bloodstream of radioactive compounds, CT scans use X-rays, and MRI scans use magnetism

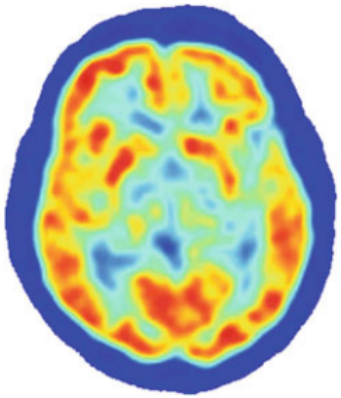


Figure 2: A PET structural image of the brain.

Magnetic Resonance Imaging

- First used in the 1970s (Lauterbur, 1973 and Mansfield 1977), MRI is a non-invasive medical imaging technique.
- Involves generating strong magnetic fields and radio waves to produce images of internal organs and tissues.

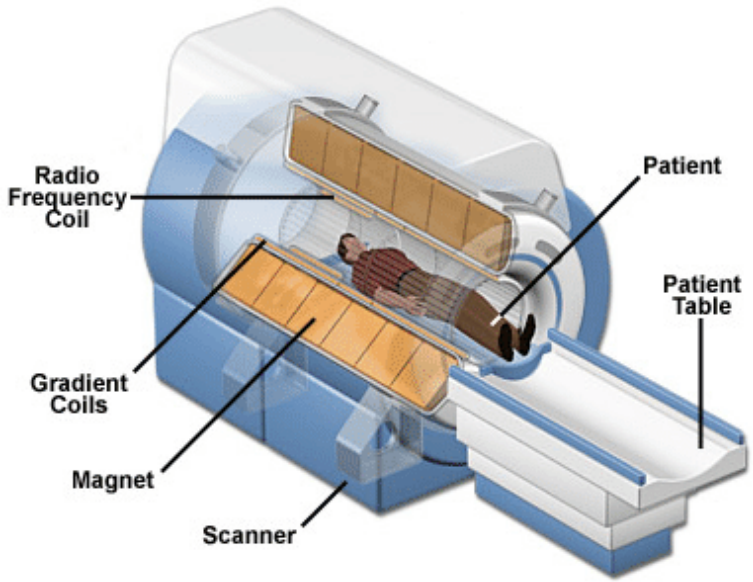


Figure 3: Image obtained from The National MagLab.

Structural MRI Data

- The structural images obtained are static 3-dimensional volumes consisting of a large number of volumetric pixels called voxels.
- For structural MRI, voxels are commonly around 1 mm^3 (1 mm x 1 mm x 1 mm) in size, although this can vary.

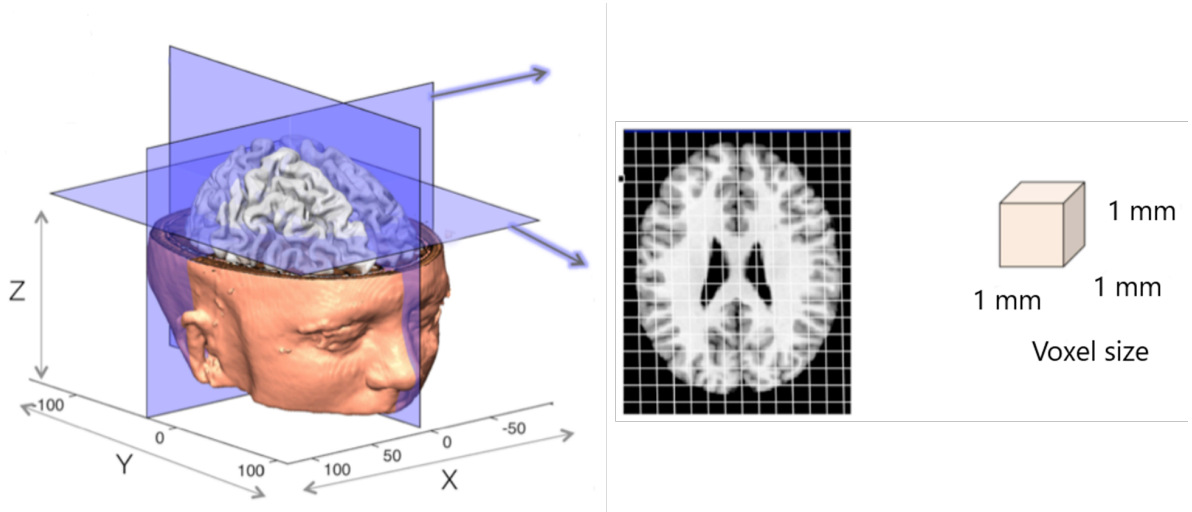


Figure 4: Image from Wager and Lindquist (2015).

Functional Images

- Electroencephalography (EEG)
- Magnetoencephalography (MEG)

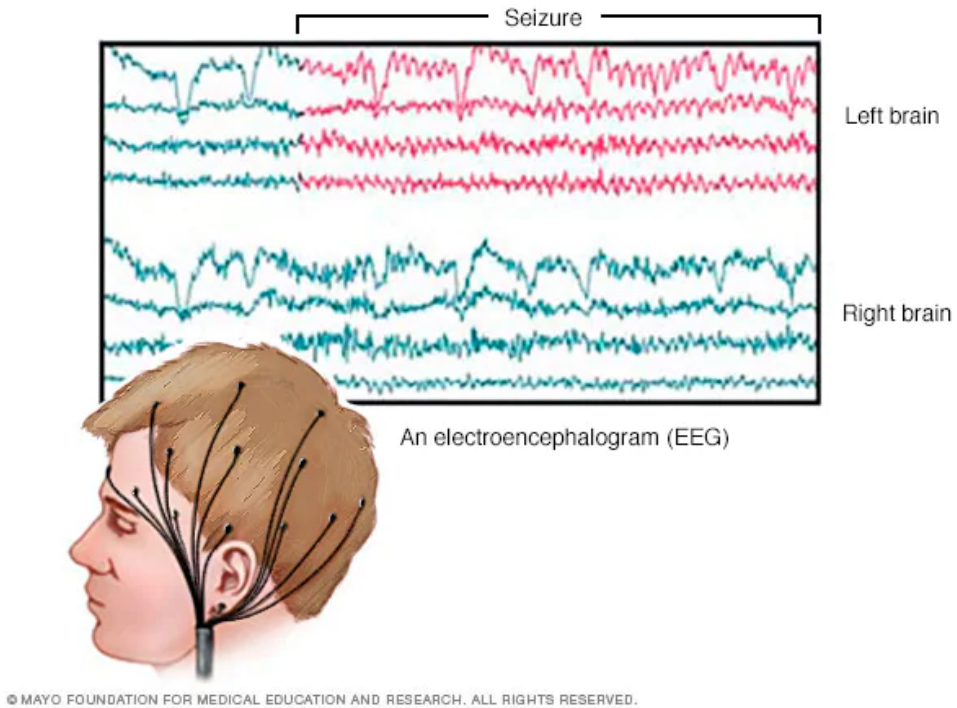


Figure 5: Depiction of electroencephalography (EEG).

Functional MRI (fMRI)

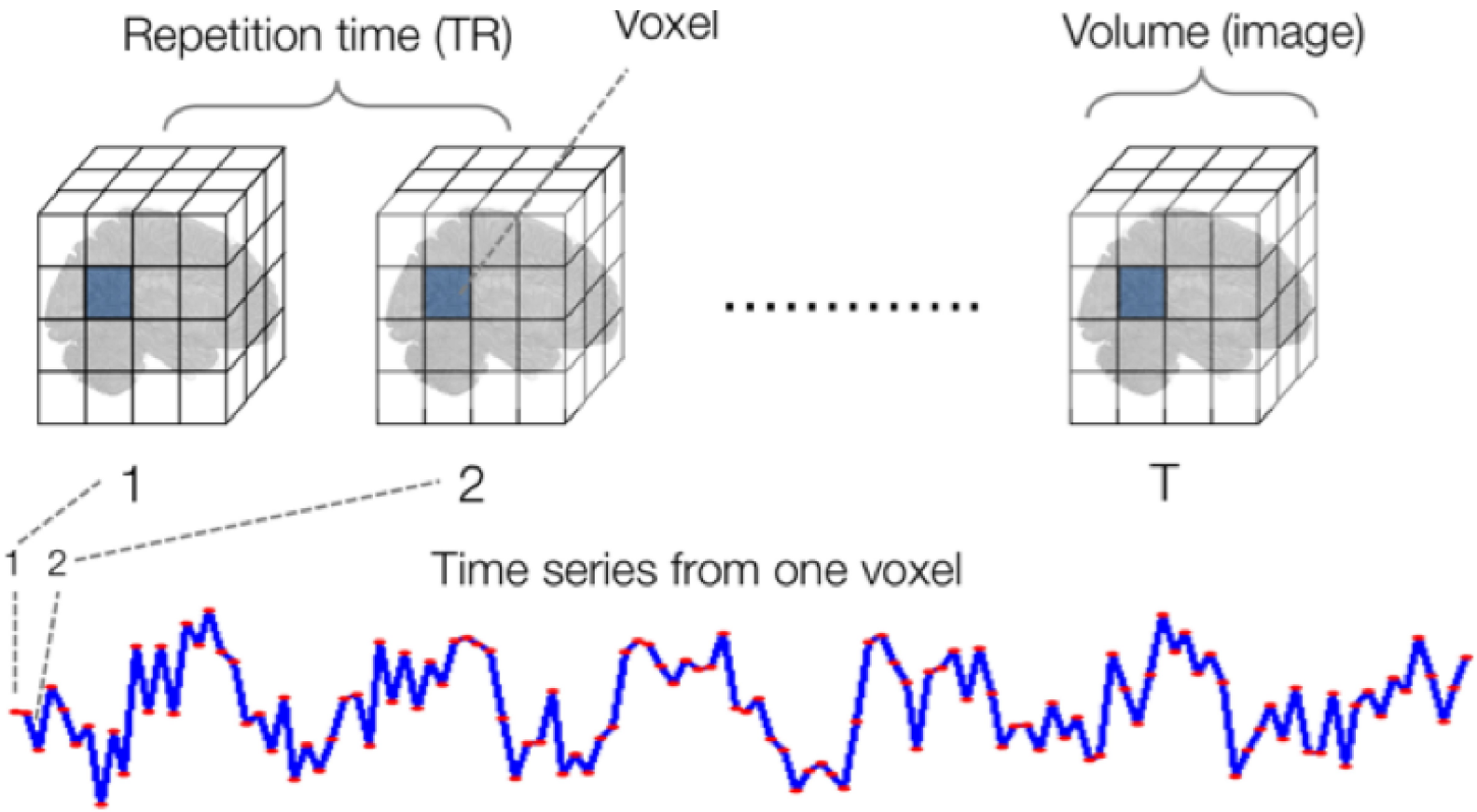


Figure 6: Image from Wager and Lindquist (2015).

fMRI Data

- Most commonly used measure of activation in fMRI is the blood oxygenation level-dependent (BOLD) signal, serves as a surrogate measure for neuronal activity.
- The BOLD signal is based on blood flow and the varying magnetic properties of oxygenated and deoxygenated blood, which is related to neuronal activity.

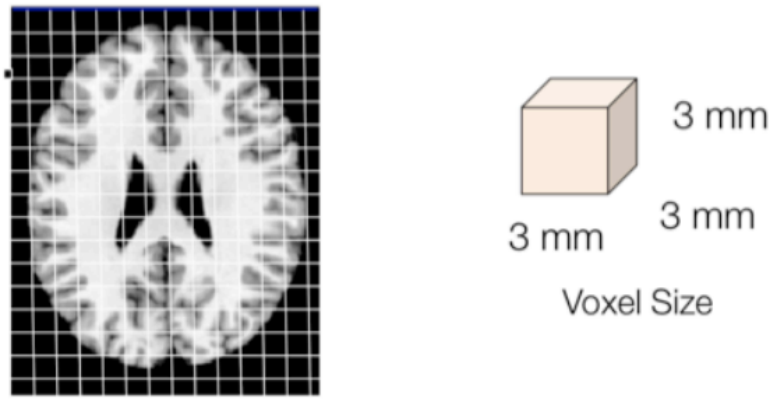


Figure 7: Image from Wager and Lindquist (2015).

Reconstruction

Initially data is in k-space (left) as a numeric array, with points containing spatial frequency and phase information about each pixel in the MR image (right).

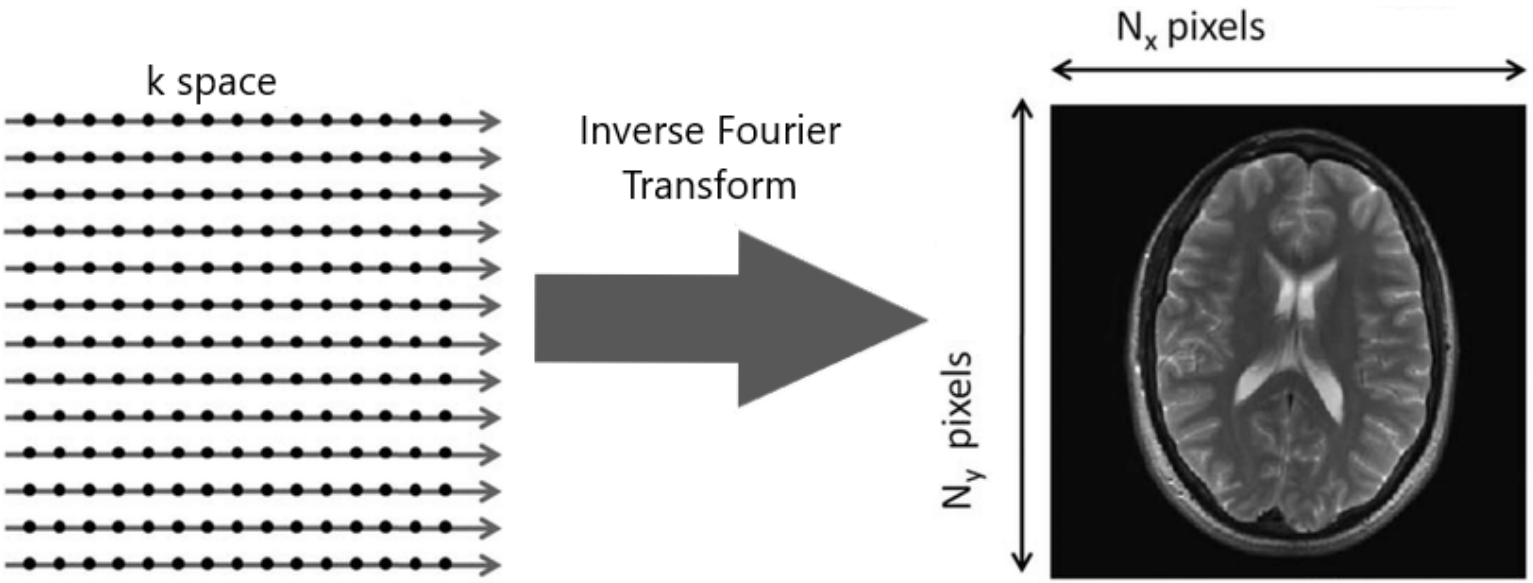


Figure 8: Image obtained from Deshmane et al. (2012).

Motion Correction

- Participant movement or physiological processes e.g., respiration or swallowing can cause motion artifacts.
- Images are realigned based on a single reference image

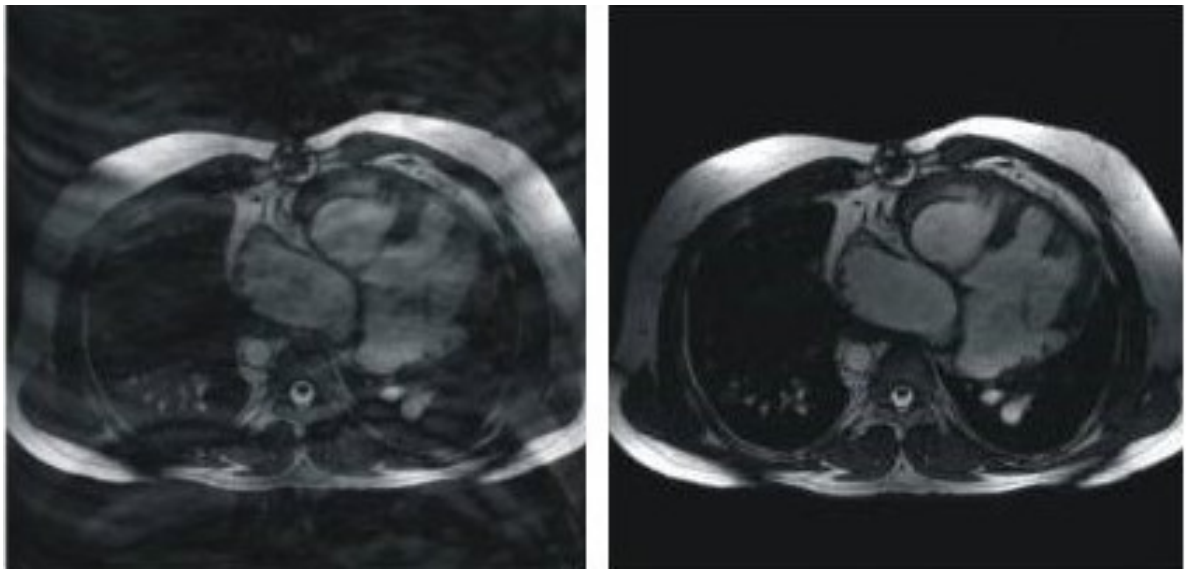
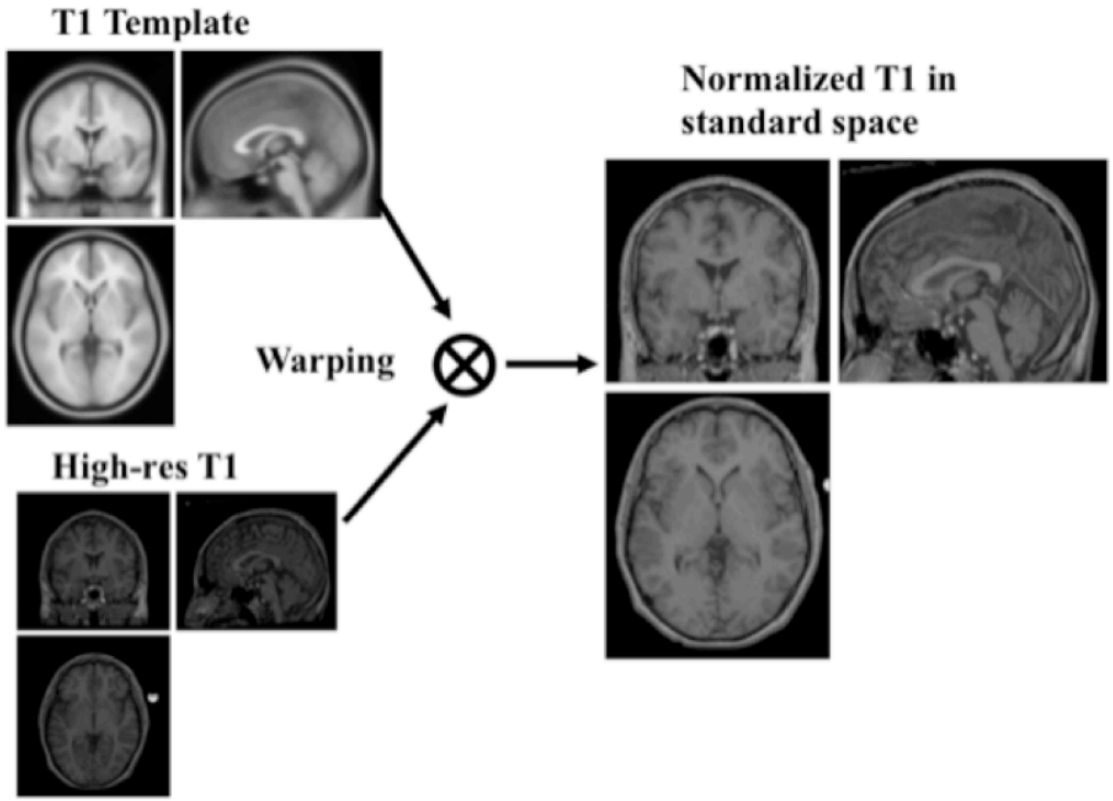


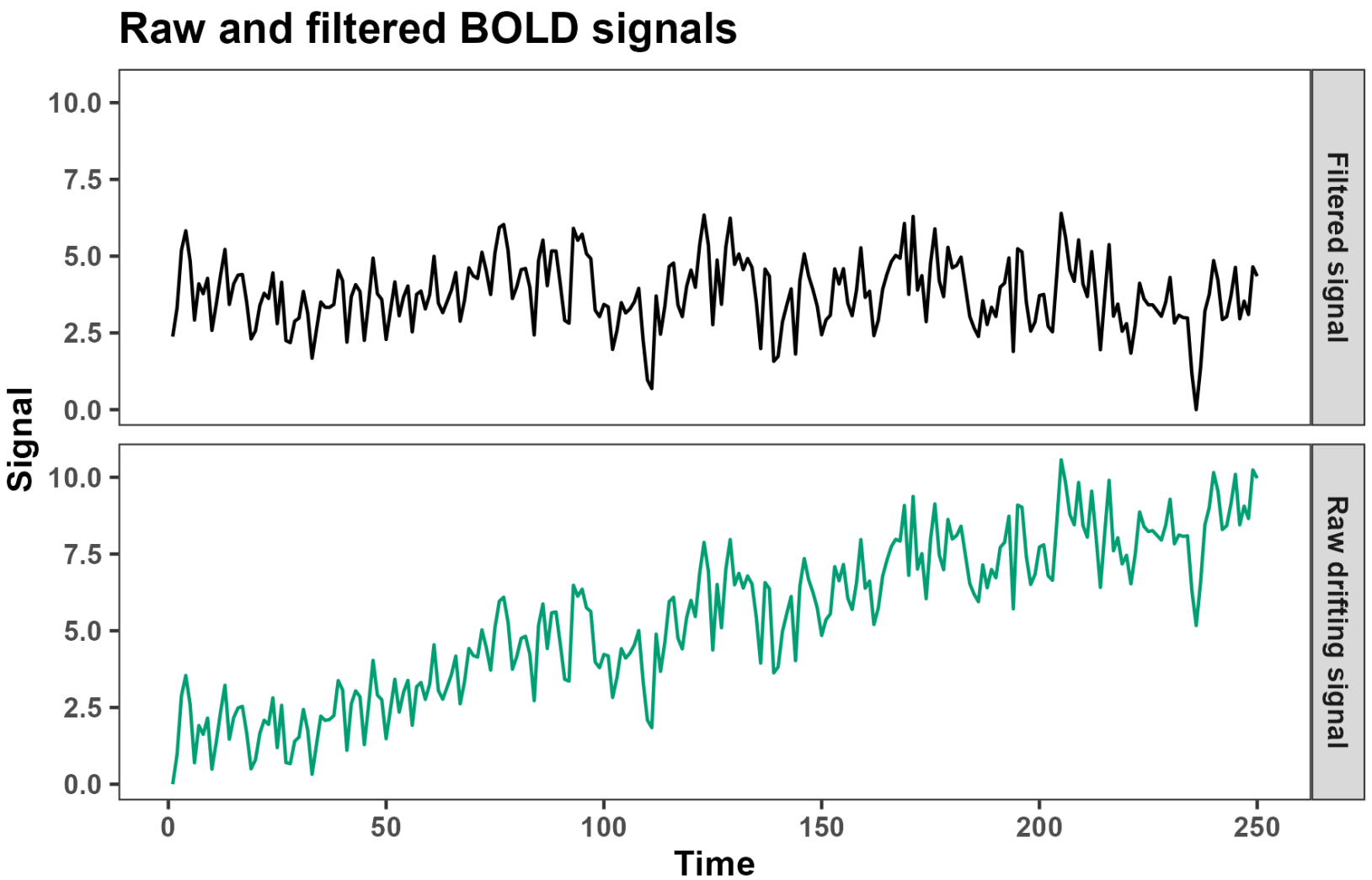
Figure 9: Image with motion artifacts (left) and motion-corrected image (right).

Normalization / Registration

- Data are commonly standardized to a reference image
- Facilitates group-level analyses for multi-subject data



Signal Drift



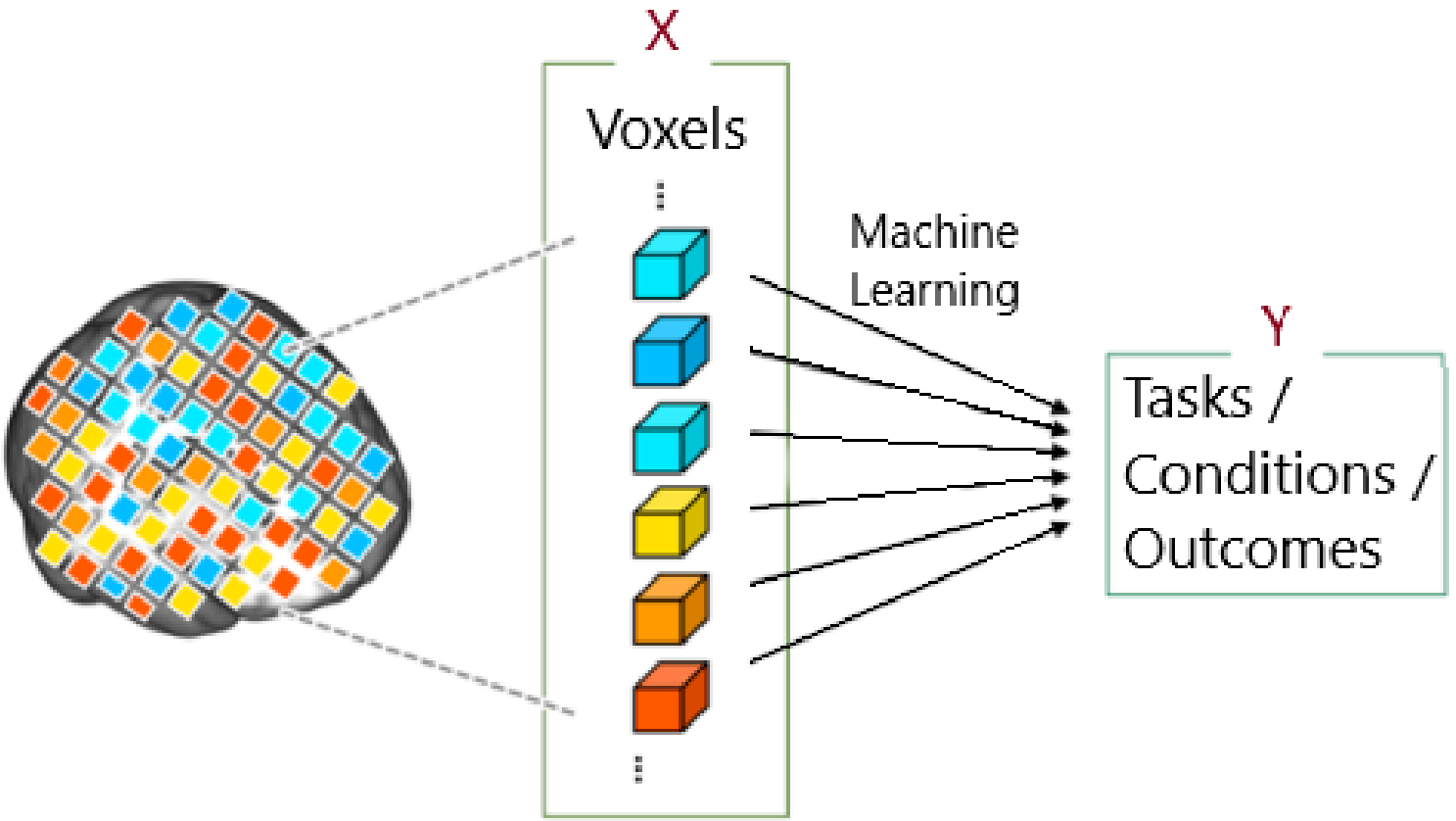
The General Linear Model

For data from a single participant, the time series from a single voxel is the response variable, $y \in \mathbb{R}^N$.

$$y = X\beta + \varepsilon$$

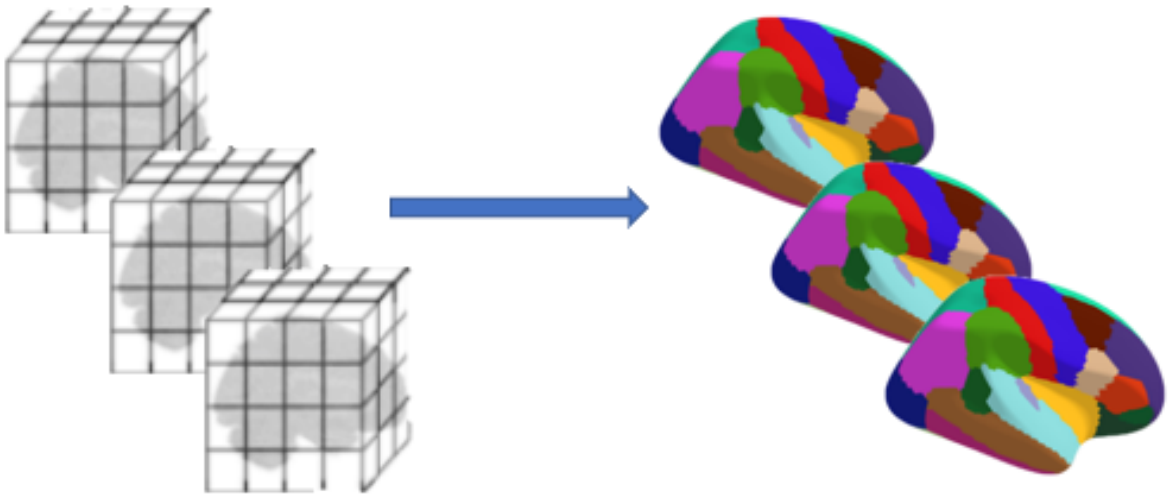
- Demographic and experimental treatment information can be encoded in the design matrix, $X \in \mathbb{R}^{N \times p}$.
- $\beta \in \mathbb{R}^p$ is a vector of regression coefficients
- $\varepsilon \in \mathbb{R}^N$ describes unexplained noise
- Many methods fall under the umbrella of GLMs: ANOVA, multiple linear regression, and t-tests

Predictive Mapping

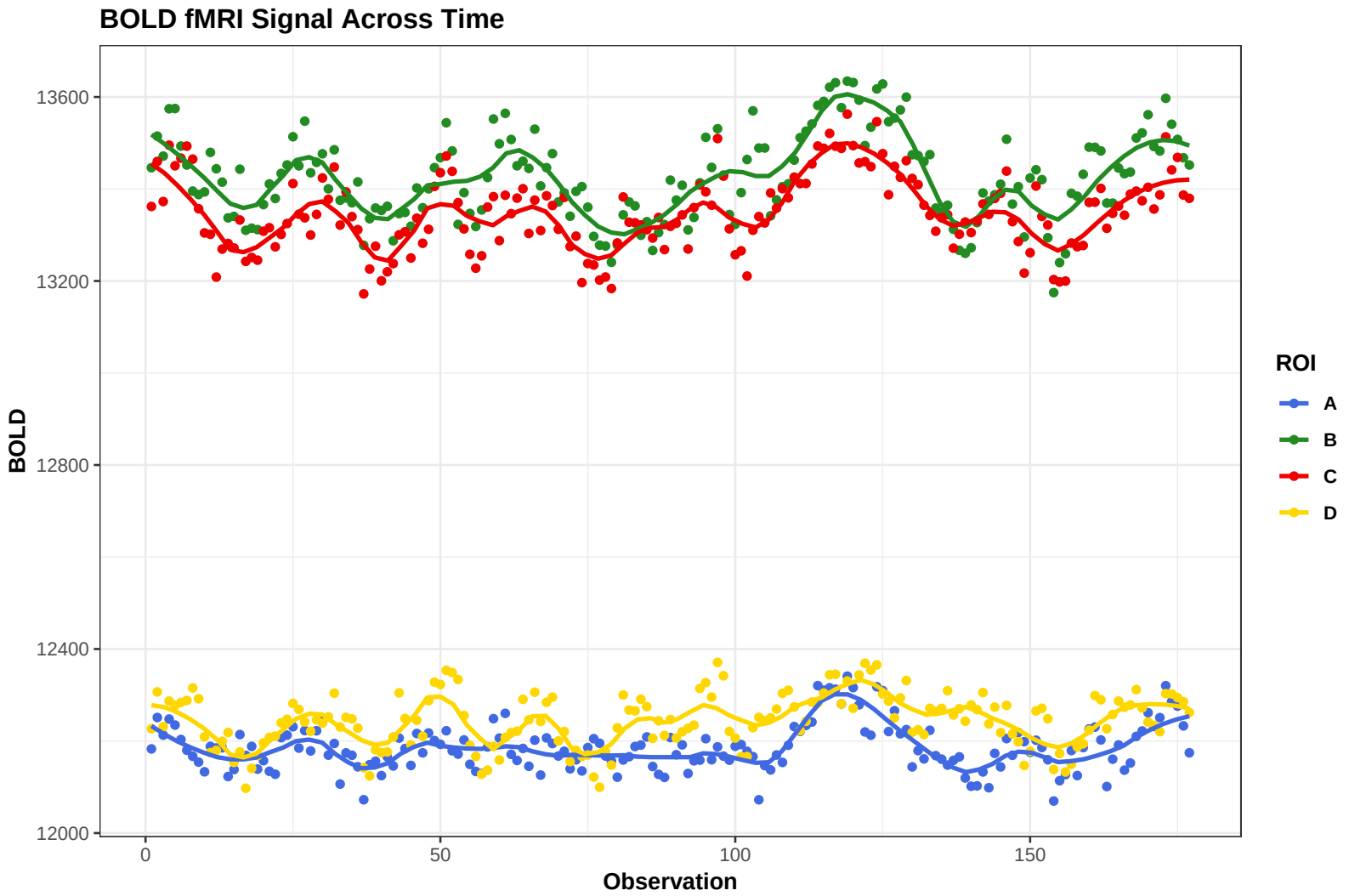


Dimension Reduction

- Data often consists of $>$ 100,000 voxels for each volume, yielding high-dimensional data
- Can average activation levels within sets of voxels called regions of interest (ROIs) at each time point



Regions of Interest (ROIs)



Functional Connectivity (FC)

- **Functional Connectivity (FC)**: temporal dependence of neuronal activity in regions of the brain (Friston et al., 1993)
- Alterations in FC associated with psychiatric disorders and neurodegenerative diseases
- Metrics to describe FC connections: marginal correlation, partial correlation, coherence, and mutual information among others.

Common FC Analysis Methods

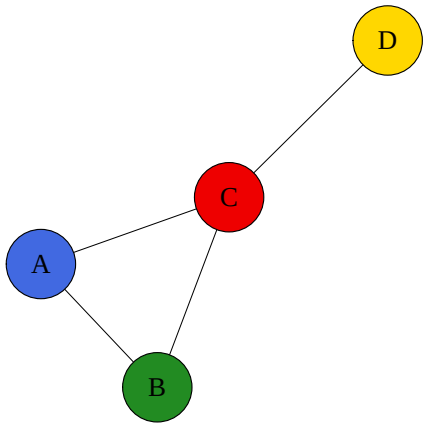
- **Seed-based methods**: Set certain ROIs as reference regions or seeds, then estimate the relatedness of other ROIs to the seeds to produce a connectivity map of the brain

- **Graphical modeling**: Commonly an undirected graph is constructed with nodes commonly representing ROIs and edges connecting pairs of dependent nodes.

Gaussian Graphical Models (GGMs)

- GGMs useful for exploring relationships between ROIs to describe FC
- ROIs constitute vertices, nonzero entries in the inverse covariance matrix, called the precision matrix, imply edges between vertices

$$\boldsymbol{\Omega} = \begin{array}{c} \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cccc} A & B & C & D \end{array} \\ \begin{pmatrix} 0.61 & 0.14 & 0.05 & 0 \\ 0.14 & 0.61 & 0.15 & 0 \\ 0.05 & 0.15 & 0.61 & 0.15 \\ 0 & 0 & 0.15 & 0.61 \end{pmatrix} \end{array} \longrightarrow$$



Challenges of fMRI

No consensus on steps of the preprocessing pipeline, so they often vary across studies, creating several issues:

- Reproducibility / integrity of results
- Integrating data across multiple studies for meta analyses

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Other challenges:

- High-dimensional data
- Temporal and spatial dependencies
- Small signal-to-noise ratio

Final Remarks

- fMRI is a powerful tool for improving understanding of brain activity and mechanisms underlying mental illnesses and neurodegenerative diseases.
- The applications and utility of fMRI for researchers and clinicians continues to grow as its availability and cost-effectiveness improves

Thank you

Questions?

References

Friston, K. J., Frith, C. D., Liddle, P. F., and Frackowiak, R. S. J. (1993). Functional connectivity: The principal-component analysis of large (PET) data sets. *Journal of Cerebral Blood Flow & Metabolism*, 13(1):5–14.

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Wager, T. D. and Lindquist, M. A. (2015). *Principles of fMRI*, chapter 6. Leanpub.