fMRI Basics

1

Goals for today

- Provide a **broad overview** of fMRI
  - Enough to get you primed for analyzing some data
- Get you comfortable with some relevant **terminology**
- People at this workshop come from different backgrounds and levels of expertise
  - For some, this will be mostly review, for others it will not.
  - NOT being discussed in detail: MR physics, image formation, optimal pulse sequence parameters...

2

Magnetic Resonance Imaging (MRI)

"…an amazing combination of advanced science and engineering, including the use of superconductivity, cryogenics, quantum physics, digital and computer technology…"

"Because of the diversity of sciences and technologies that gave birth to and continue to nurture MR, it is an extremely hard subject to learn. **A lifetime is not enough to become an expert in every aspect.**" *–MRI From Picture To Proton*

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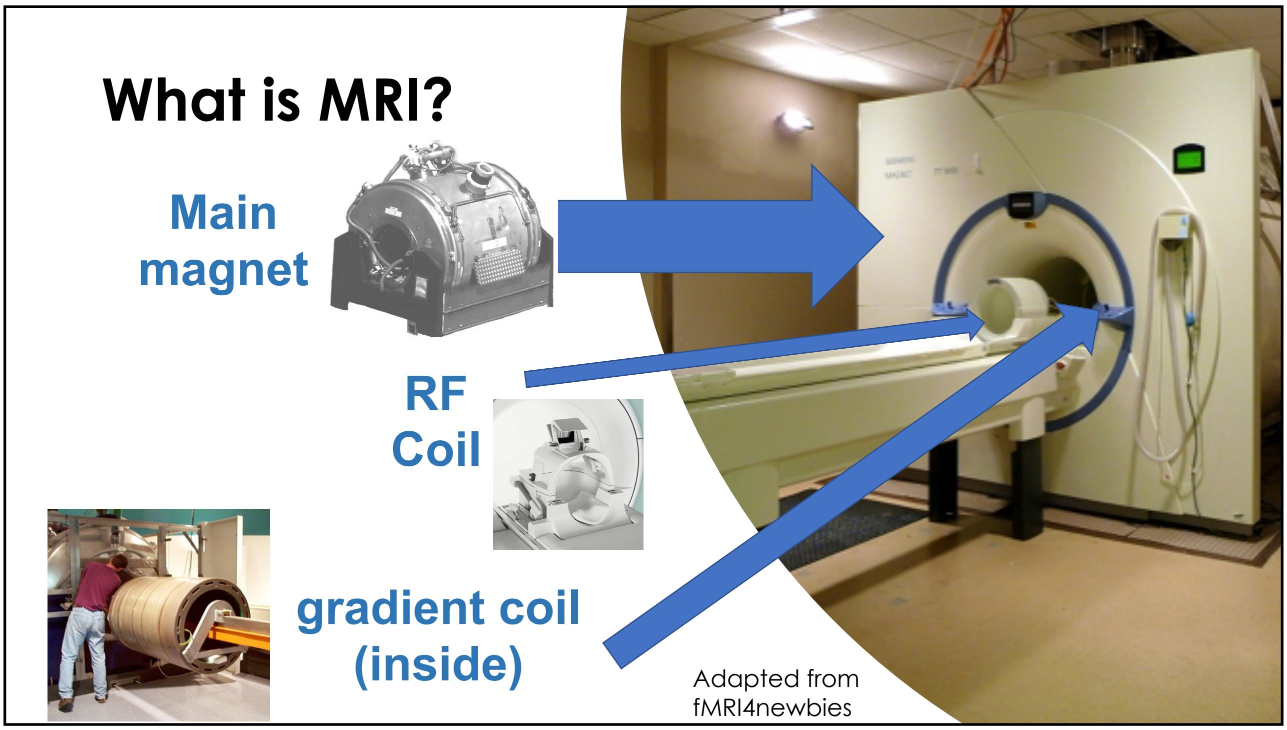
What is MRI?



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32 channel head coil

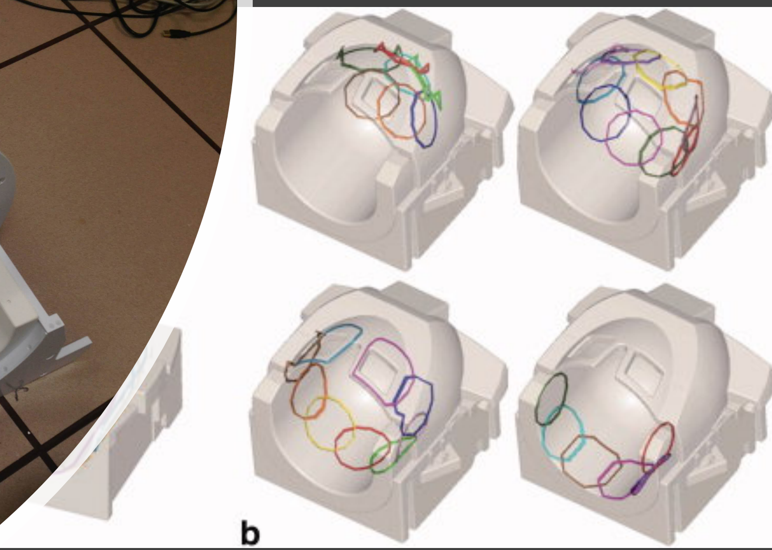

Image from fMRI4newbies

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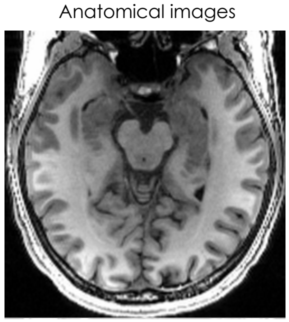
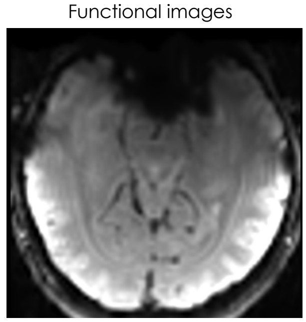
MRI provides many different types of imaging data

Anatomical images



Functional images



Diffusion-weighted images

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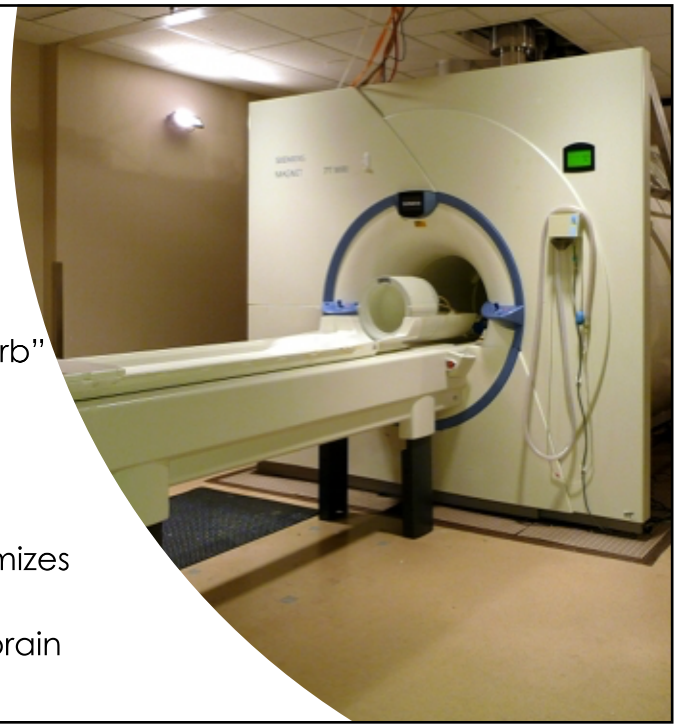
What is MRI?

- Use strong magnetic field to magnetize protons in water
- Heads have lots of water and therefore lots of protons
- Use radio frequency (RF) to "perturb" magnetic spins (flip the protons)
- Once RF is turned off, protons start returning to their normal state
- Measure the RF energy as they're returning (e.g., at a time that optimizes tissue contrast)
- Convert RF energy into image of brain



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What is functional MRI (fMRI)?

- Variations in blood oxygenation have effect on signal strength
- Blood oxygenation level dependent (BOLD) signal is indirectly coupled to neural activity
- Put subjects in the scanner and have them do (1) different sensory, cognitive, motor tasks and relate tasks to brain response, or (2) "nothing" (resting state) and analyze connectivity

- **Noninvasive**
- **Excellent coverage**
- **Good spatial and temporal resolution**

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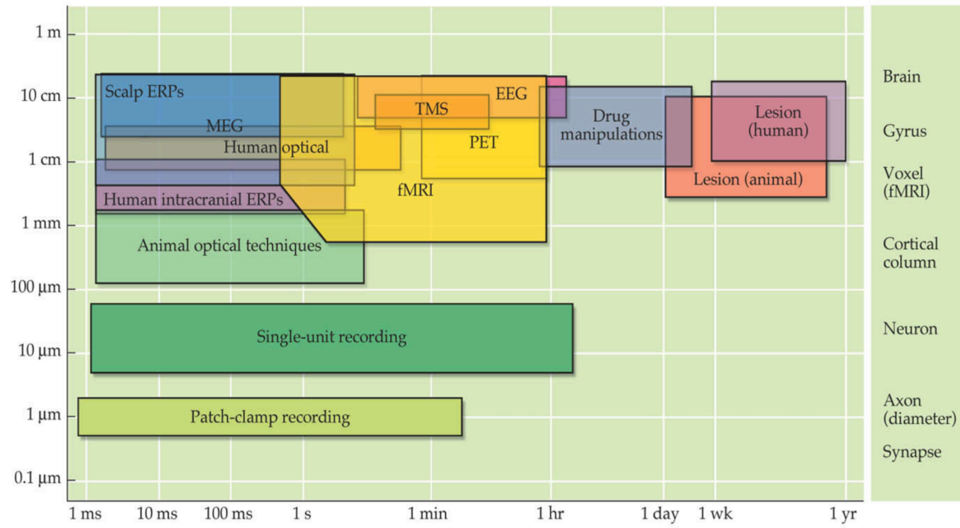
What is fMRI good for?

Coverage of the entire brain at reasonably good resolution!



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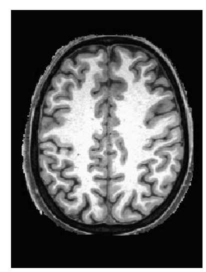
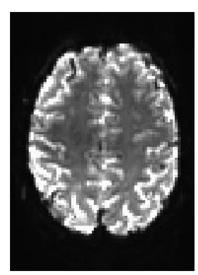
Structural and functional data

- **Structural (i.e., anatomical) data: MRI**
  - Brightness and darkness in images related to differences in tissue types (e.g., gray matter vs white matter)
- **Functional data: fMRI**
  - An indirect measure of neural activity in the brain
  - Brightness and darkness in images related to how active or inactive different parts of the brain are over time.
- Both are important!





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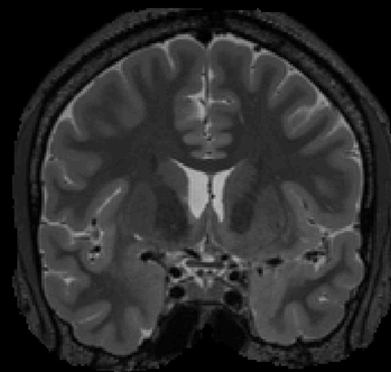
Structural data: T1 vs T2

T1



T2

- shorter TR and TE
- gray matter looks **gray**
- white matter looks **lighter gray**
- CSF looks **dark**

- longer TR and TE
- gray matter looks **gray**
- white matter looks **darker gray**
- CSF looks **bright**

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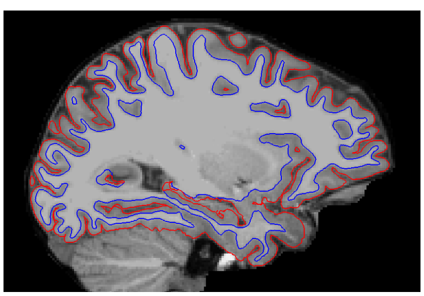
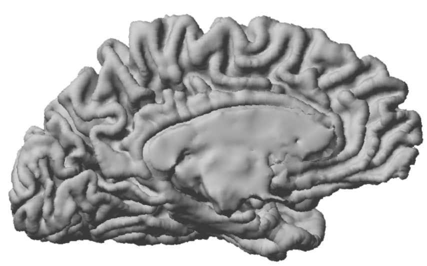
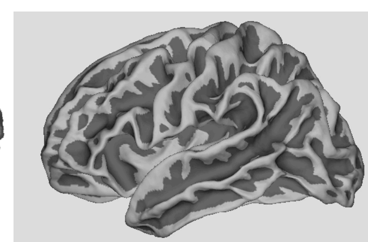
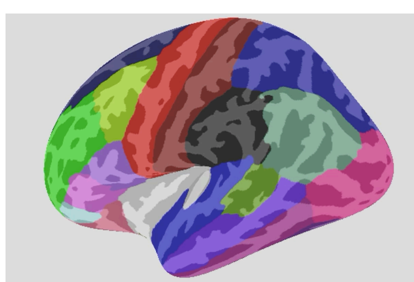
Structural (anatomical) data are useful for surface reconstruction (e.g., in Freesurfer)









Knowledge of anatomy and accurate localization are essential

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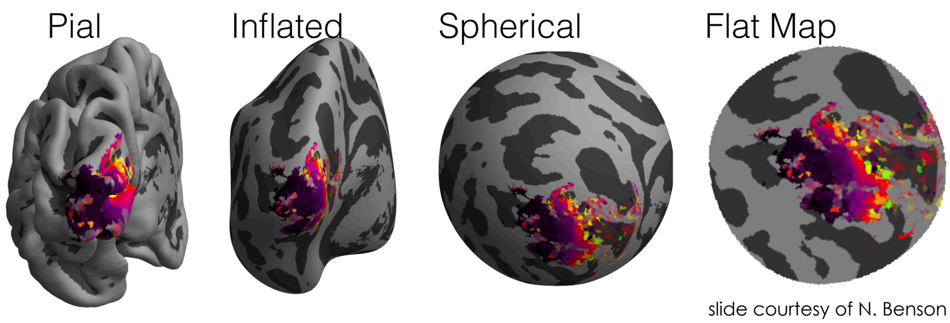
Structural (anatomical) data are useful for surface reconstruction (e.g., in Freesurfer)



slide courtesy of N. Benson

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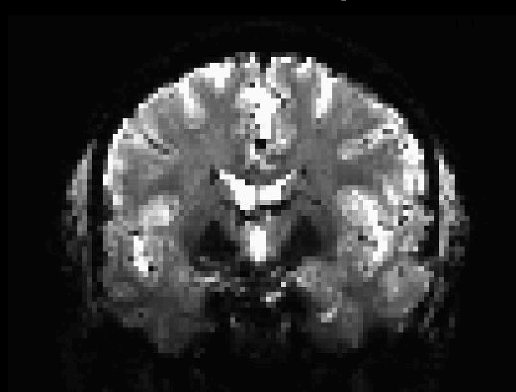
Functional data: T2* (mostly)



- Most commonly acquired using echo planar imaging (EPI) which is a fast imaging technique
- Measures rapid increases in blood flow to different brain areas
- The more oxygenated the hemoglobin, the brighter it is.
- In other words, more "active" areas are brighter and less "active" areas are darker
- Susceptible to distortion (so fieldmaps are acquired for distortion correction)

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fMRI is an indirect measure of neural activity

Change in Neuronal Activity

↓

Increases in Local Cerebral Blood Flow

↓

Decreases in deoxyhemoglobin

↓

Change in Magnetic Susceptibility (BOLD)

↓

Change in fMRI Signal

↓

Neural Inferences

slide adapted from T. Braver

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What is fMRI data collection like?

www.youtube.com/watch?v=DpL5OqoAMUo

www.youtube.com/watch?v=ywTlA9k5UbU

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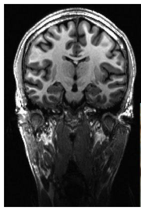
Terminology

Coronal view

R



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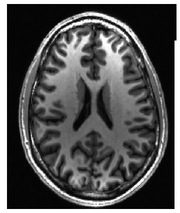
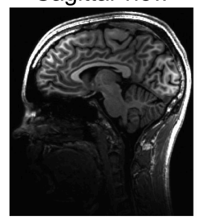
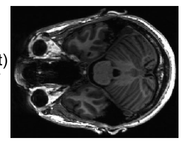
Axial view



Sagittal view

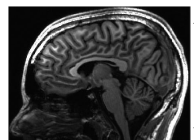


Anterior/Rostral (front)



Posterior/Caudal (back)

Lateral (towards the side) ↓ ↑ Medial (towards the middle)



Dorsal/Superior (up)

Ventral/Inferior (down)

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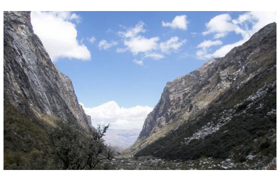
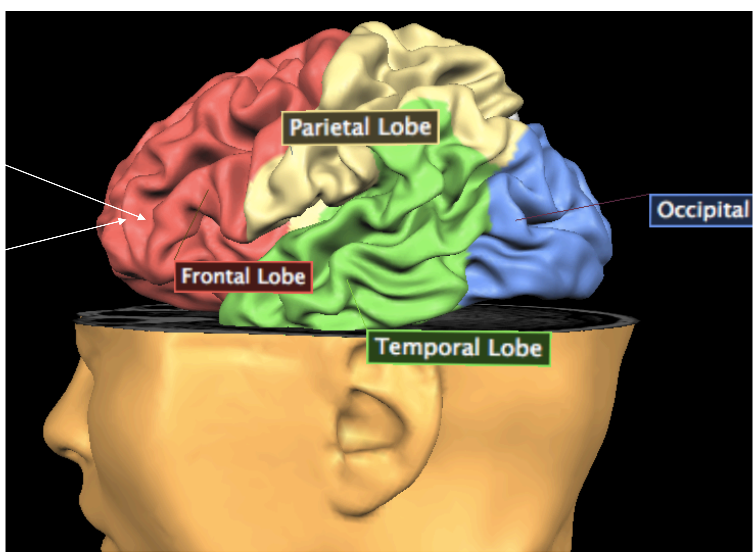
Lobes of the Brain



Sulcus (valley)

Gyrus (ridge)



From: BrainVoyager Brain Tutor

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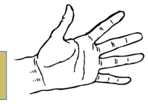
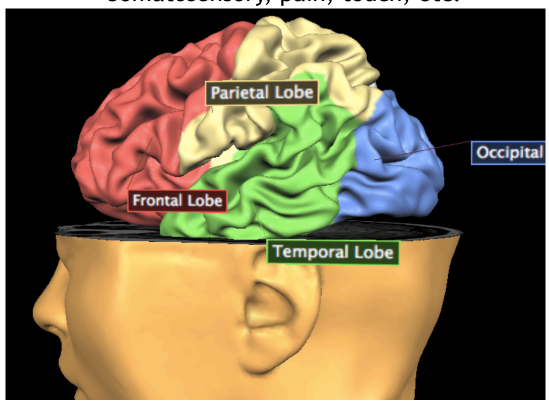
Rough Guide to the Lobes

Parietal


Somatosensory, pain, touch, etc.

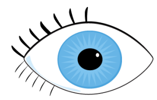
Frontal

Executive function,
Attention,
Motor control



Occipital

Vision



Temporal

Auditory, Speech processing

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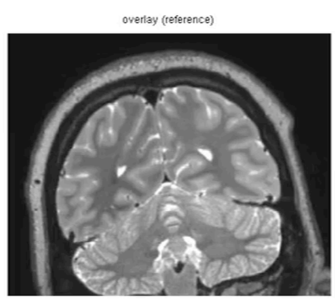
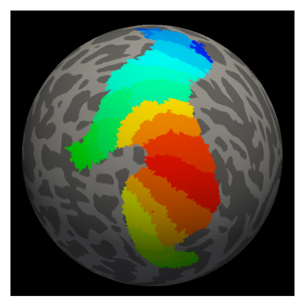
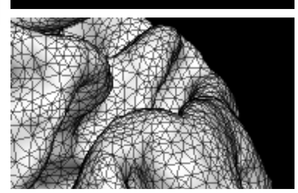
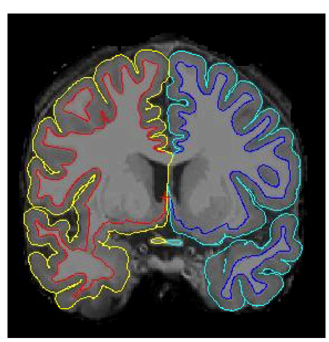
Terminology

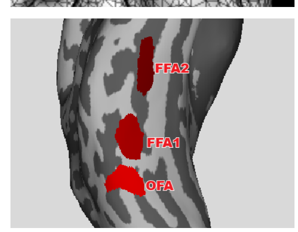
- **Volumes:** single images of the brain; consists of multiple slices; individual elements are called 'voxels'
- **Surfaces:** 3D reconstructions of the cortical sheet. Typically a 2D manifold, but note that the actual cortex has a variable thickness.
- **Coregistration/alignment:** The process of determining the spatial alignment of two images or volumes. Can be linear or nonlinear.
- **Atlas:** A labeling of different parts of the brain. Atlases are often used as approximate estimates of the organization of an individual subject.
- **Parcellation:** defining distinct partitions in the brain
- **Region of interest (ROI):** an anatomically or functionally-defined region of the brain, often used to summarize or describe a dataset
- **Resting-state:** fMRI data acquired during which no explicit task is being performed by the subject (i.e. fixate a cross and "rest").
- **Diffusion:** MRI sequences can be sensitive to the diffusion of water molecules; this is useful for revealing white-matter pathways in the brain











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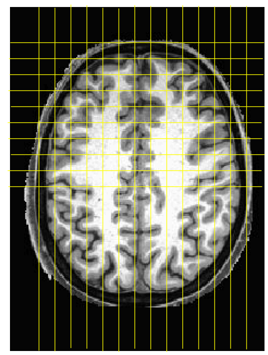
Voxels

- A 3D pixel or "volumetric" pixel (often a cube).
- The brain image (i.e., brain "volume") is divided into voxels
- The **resolution** of the image is based on the size of the voxel
  - 1.8 mm^3 = 1.8 mm "isotropic"



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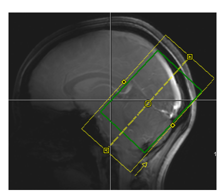
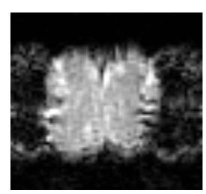
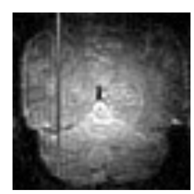
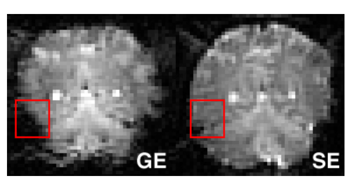
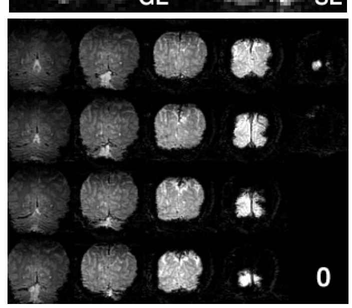
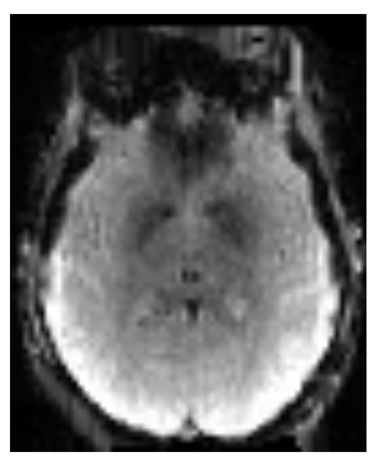
More terminology

- **MNI:** a commonly used volume-based space derived from averaging structural scans from hundreds of subjects.
- **Interpolation:** The process of "filling-in" or estimating intermediate values based on surrounding data points.
- **Head motion:** movement of the subject's head during a scan; adds undesirable noise to the data (primarily at the short time-scale) and imposes the need for motion correction.
- **Image quality:** the fidelity of the image to the underlying object being sampled
- **Image stability:** how consistent the image quality is over time
- **Dropout:** a lack of signal in the image (i.e. pixels becoming dark) due to spin dephasing caused by magnetic field inhomogeneity
- **Distortion:** an effect, typically associated with EPI imaging, in which there is unwanted spatial displacement of signals along the phase-encode direction due to magnetic field inhomogeneity
- **Coverage:** the location/amount of brain for which we are acquiring data (e.g., "partial" vs. "whole-brain")
- **Resolution (spatial and temporal):** how large voxels are (mm^3) and how fast you are acquiring the images (repetition time = TR)





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Block and event-related experimental design

- **Block design**
  - Several successive trials of the same type = one block. Measuring long periods of activity.
    - Advantage: easier to implement and analyze and more robust for finding differences in response amplitudes
- **Event-related design**
  - A single presentation or brief period of activity (usually up to a few seconds long) = one event.
    - Advantage: enables studying of certain phenomena that cannot be disentangled in block-design data
    - Disadvantage: generates weaker signals
  - NSD uses a rapid event-related design. It is rapid because there is only 1 second between trials. Each trial ("event") is 3 seconds long.

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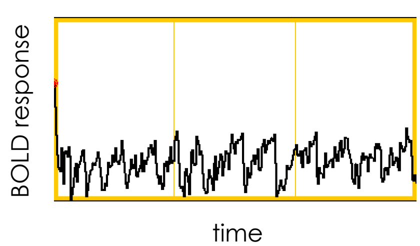
Activity over time

- **Timeseries**: The relative brightness or darkness of a voxel over time
- The brightness is due to how **oxygenated** the blood is. The brighter a voxel is, the less deoxygenated blood there is in that area.
- This is the **BOLD** signal: blood oxygenation level dependence



Timeseries for a voxel

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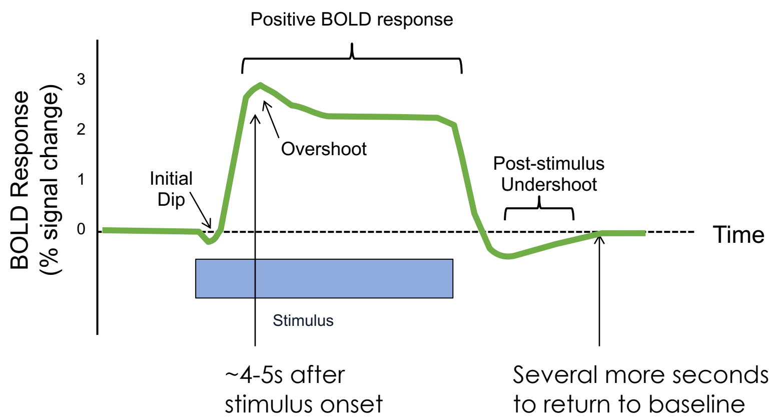
BOLD response



- Timing varies with brain region, subject, caffeine consumption, etc.

Adapted from: fMRI4Newbies

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Data quality issues

- **Acquisition errors:**

Black volumes, RF pulse failures, gradients refuse to run in the middle of a scan, Larmor frequency failed to converge, recon failure, local dark spots in image due to a few coil elements breaking (or transmit inhomogeneity problem)

- **Image quality problems:**

Images don't look "right". This could be due to subject motion or a very poor shim. Could affect just a few volumes, entire runs, or entire sessions.

- **Subject errors:**

Subject drastically moves or coughs or sneezes or constantly wiggles

- **Known problems with fMRI:**

Head motion, dropout, EPI distortion, gradient nonlinearities, image inhomogeneity due to coil sensitivity profiles, measurement noise

- **What's under your control:**

Online data assessment, offline quality control assessment, pulse sequence design (all the parameters), training and being nice to your subjects, posthoc fixes for motion, distortion, and gradient nonlinearities, using analysis strategies to denoise the data

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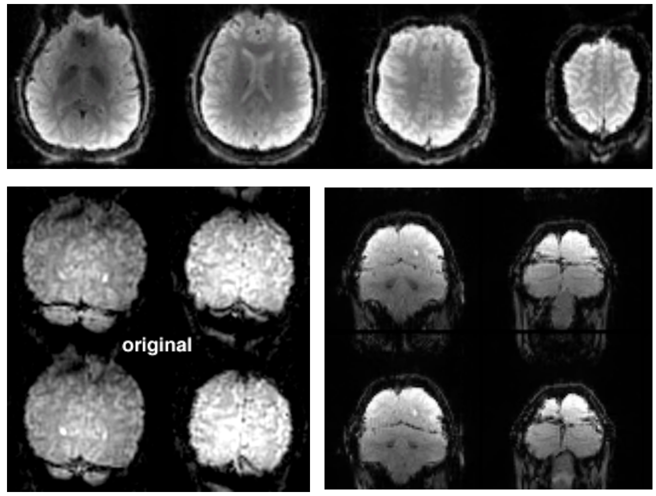
Typical pre-processing steps

- Motion correction
- Distortion correction
- Slice time correction
- Spatial and temporal filtering
- Anatomical / subject registration
- Time-series denoising approaches



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What is noise?

- Assuming that the experimental manipulations are known and correct (and the subject is compliant), anything in the time-series data that does not conform to the model
- Also known as residuals.

In fMRI, noise is NOT independent:

- It's not independent in time (i.e. noise tends to be correlated over time)
- It's not independent in space (e.g. the subject might sneeze during a trial, global respiratory noise).

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Source of noise in fMRI

Many reasons that the signal will be variable across trials:
1. Subject motion (i.e., head motion)
2. Thermal noise (even a phantom image fluctuates)
3. Low-frequency drifts (e.g. due to heating)
4. Subject mental compliance (sleeping / eyes-closed)
5. Cognitive/behavioral variability across trials
6. Cardiac/respiratory-related fluctuations
7. Neural adaptation, neural noise
8. Imaging artifacts (e.g. distortion can change over time)
9. Noise due to incorrect model specification

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What can noise be computed over?

1. Variability across trials (or runs)
2. Variability across experimental conditions
3. Variability across subjects

These are all different and tell you different types of information. Which ones you use depends on what you want to know.

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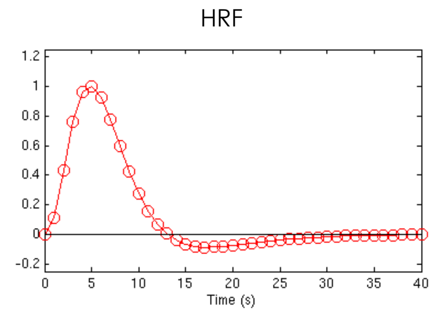
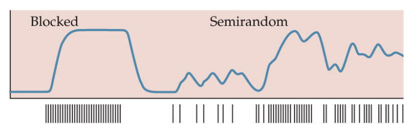
BOLD as a linear system

- Cognitive tasks can evoke a rich variety of different neural dynamics
- Working assumption: neural activity is linearly coupled to BOLD activity through convolution with an HRF (hemodynamic response function)
- Sluggishness of the HRF makes analyzing fMRI data with GLM approaches complex





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General linear model (GLM)

- GLM is just a way of applying linear regression to task-based fMRI data

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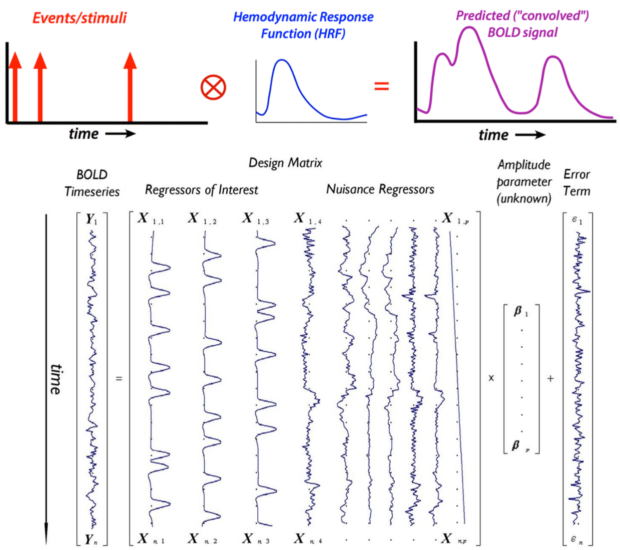
General linear model (GLM)



http://mriquestions.com/general-linear-model.html

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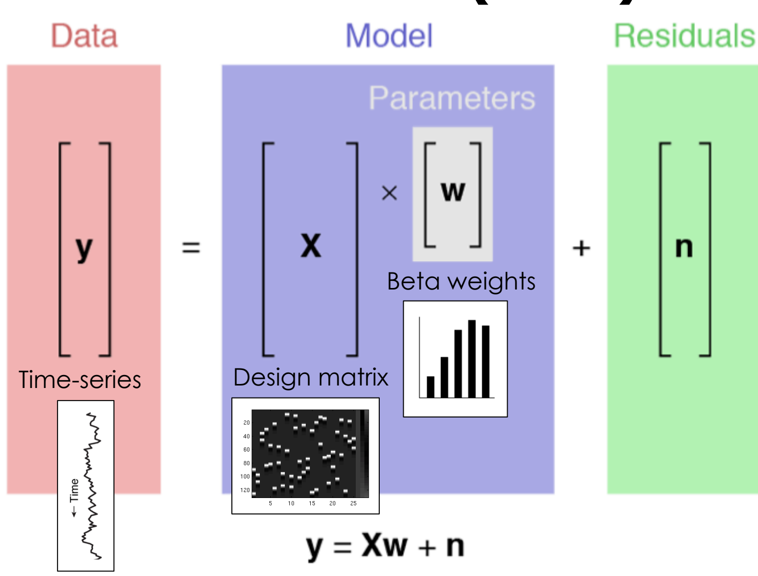
General linear model (GLM)



$\mathbf{y} = \mathbf{X}\mathbf{w} + \mathbf{n}$

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Estimating the timecourse of response

- **Detection** – assume a response timecourse (HRF), detect significant activations

vs.

- **Estimation** – try to estimate the response timecourse
  - How to perform estimation:
    - FIR (Finite Impulse Response) model
    - Other basis function approaches
    - (Note that these are just specific variations of the GLM)

This is more advanced and less typical, but is still quite useful for certain applications

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Summary

- This was a quick and dirty overview of MRI and fMRI.
- Lots of terminology– feel free to revisit these slides any time!
- Preprocessing/processing/analysis consist of many different steps and can be done many different ways.
- Given the complexity of fMRI analyses, there's no one single "right" way to analyze fMRI data, but if you are targeting a specific analysis step, there may be a correct/better way of doing things.
- Substantive differences do exist between different software packages/toolboxes, which is good to keep in mind.
- It's good to be mindful of data quality issues and noise sources as you design your acquisition and analysis.

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