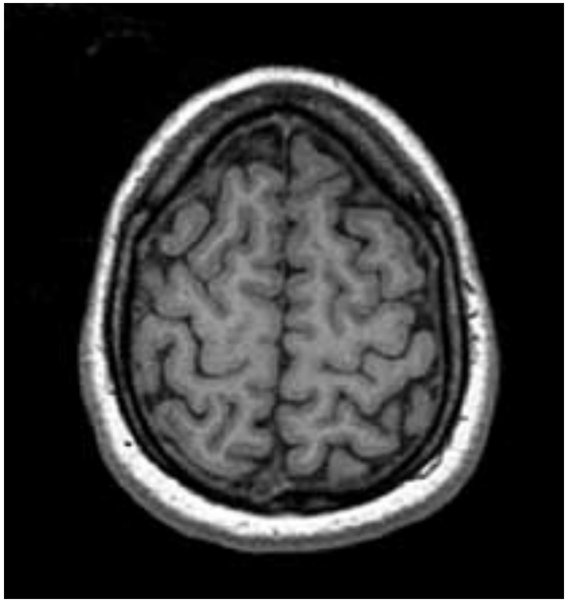
Module 5:
fMRI Signal & Noise

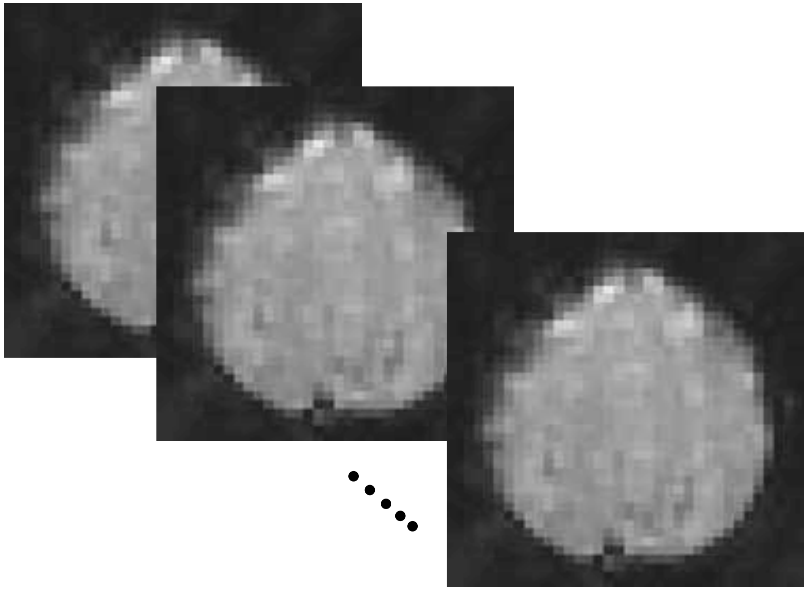
MRI

- MRI studies brain anatomy.
  - Structural (T1) images
  - High spatial resolution
  - Can distinguish different types of tissue



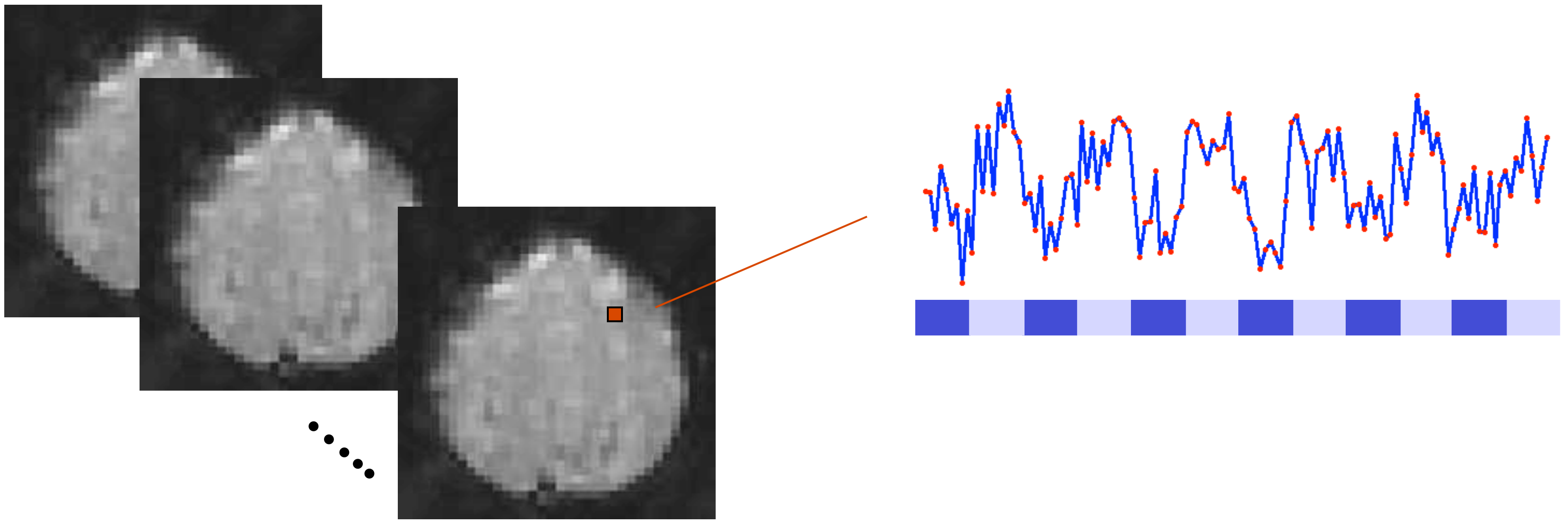
fMRI

- fMRI studies brain function.
  - Functional (T2*) images
  - Lower spatial resolution/ Higher temporal resolution
  - Relate changes in signal to experimental manipulation



Functional MRI

- An fMRI experiment consists of a sequence of individual MR images, where one can study oxygenation changes in the brain across time.



BOLD fMRI

- The most common approach towards fMRI uses the Blood Oxygenation Level Dependent (BOLD) contrast.

- It allows us to measure the ratio of oxygenated to deoxygenated hemoglobin in the blood.

- It doesn’t measure neuronal activity directly, instead it measures the metabolic demands (oxygen consumption) of active neurons.

BOLD Contrast

- Hemoglobin exists in two different states each with different magnetic properties producing different local magnetic fields. (Pauling 1936)
  - Oxyhemoglobin is diamagnetic.
  - Deoxyhemoglobin is paramagnetic.

- BOLD fMRI takes advantage of the difference in T2* between oxygenated and deoxygenated hemoglobin.
  - Deoxyhemoglobin suppresses the MR signal.
  - As the concentration of deoxyhemoglobin decreases the fMRI signal increases.

BOLD Signal

- The change in the MR signal triggered by instantaneous neuronal activity is known as the hemodynamic response function.

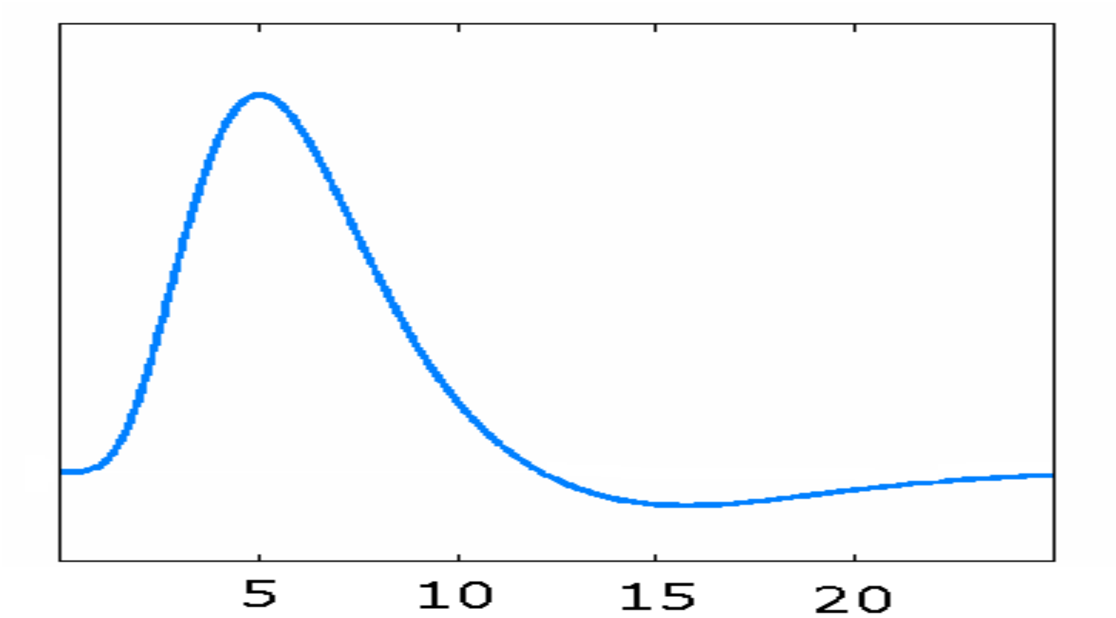
- As neural activity increases, so does metabolic demand for oxygen and nutrients.

- As oxygen is extracted from the blood, the hemoglobin becomes paramagnetic which creates distortions in the magnet field that cause a T2* decrease (i.e. a faster decay of the signal).

BOLD Signal

- An over-compensation in blood flow dilutes the concentration of deoxyhemoglobin and tips the balance towards oxyhemoglobin.
  - This leads to a peak in BOLD signal about 4-6 s following activation.
- After reaching its peak, the BOLD signal decreases to an amplitude below baseline level.
  - This poststimulus undershoot is due to a combination of reduced blood flow and increased blood volume.

HRF



The strongest signal appears 5-6 seconds after activation.

HRF Properties

- Magnitude of signal changes is quite small
  - 0.1 to 5%
  - Hard to see in individual images
- Response is delayed and quite slow
  - Extracting temporal information is tricky, but possible
  - Even short events have a rather long response
- Exact shape of the response has been shown to vary across subjects and regions.

Interpretation

- How well does BOLD signal reflect increases in neural firing?
- The BOLD signal corresponds relatively closely to the local electrical field potential surrounding a group of cells, which is likely to reflect changes in post-synaptic activity, under many conditions.
- Demonstrations have shown that high-field BOLD activity closely tracks the position of neural firing and local field potentials.

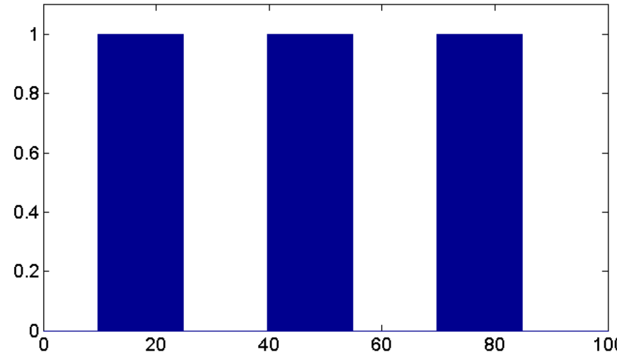
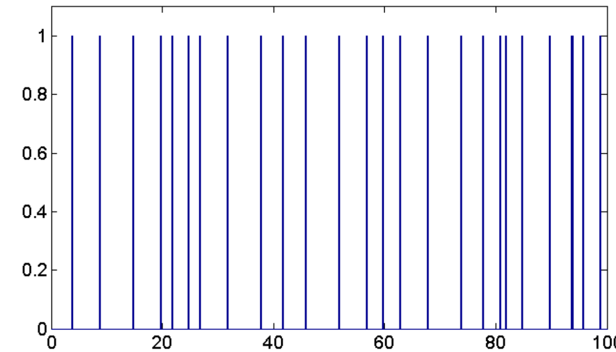
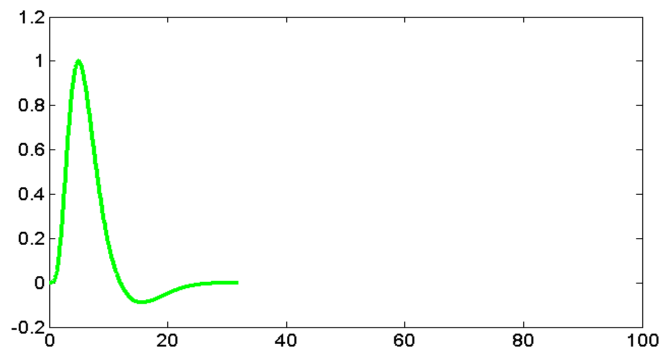
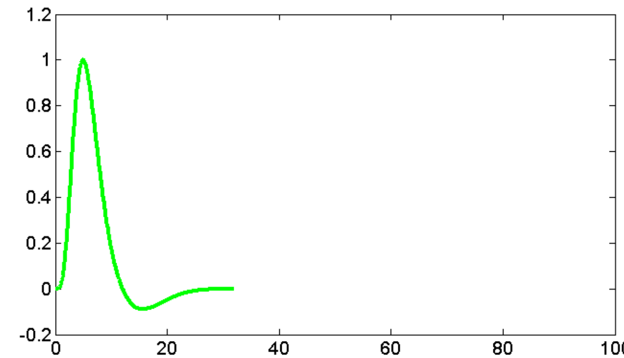
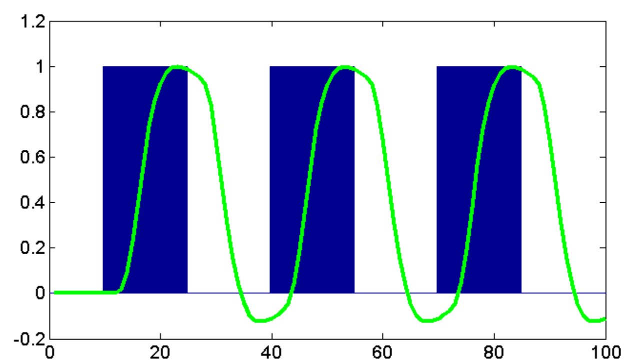
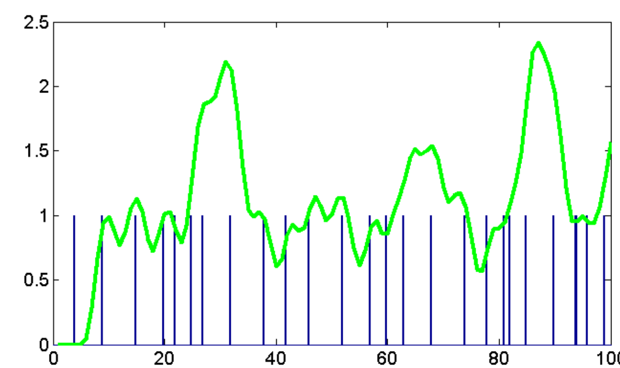
LTI System

- The relationship between stimuli and the BOLD response is often modeled using a linear time invariant (LTI) system.
  - Here the neuronal activity acts as the input or impulse and the HRF acts as the impulse response function.

- In this framework the signal at time *t*, $x(t)$, is modeled as the convolution of a stimulus function $v(t)$ and the hemodynamic response $h(t)$, that is,

$$x(t) = (v * h)(t)$$

Convolution Examples

	Block Design	Event-Related
Experimental Stimulus Function		
Hemodynamic Response Function		
Predicted Response		

Non-linearity

- Studies have shown that the BOLD response is roughly linear, with some departures from linearity.
- There is some evidence of refractory effects, which are reductions in amplitude of a response as a function of inter-stimulus intervals.
- There is evidence of non-linearity if the stimulus are spaced closer than 5-6 s apart.

fMRI Noise

- The measured fMRI signal is corrupted by random noise and various nuisance components that arise due to hardware reasons and the subjects themselves.

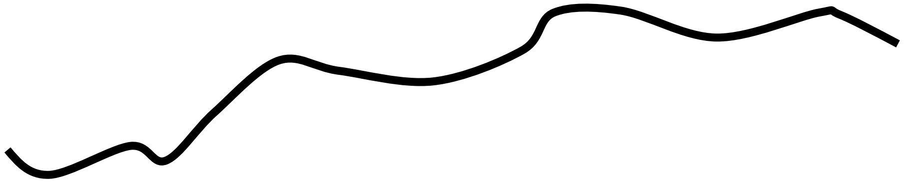
- Sources of noise:
  - Thermal motion of free electrons in the system.
  - Patient movement during the experiment.
  - Physiological effects, such as the subject's heartbeat and respiration.
  - Low frequency signal drift.

Drift

- Slow changes in voxel intensity over time (low-frequency noise) is present in the fMRI signal.

- Scanner instabilities and not motion or physiological noise may be the main cause of the drift, as drift has been seen in cadavers.

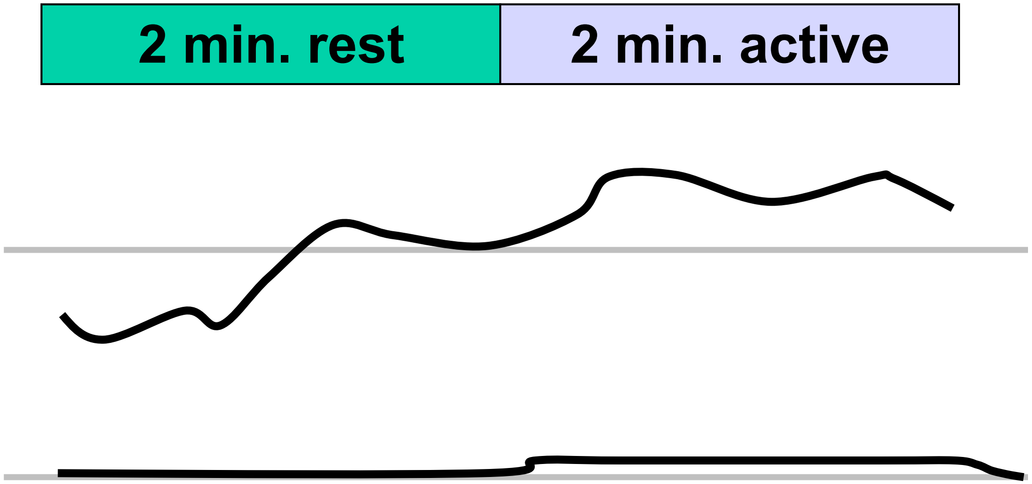
- We need to include drift parameters in our future models.



Issues

- Drift can have serious consequences:
  - Experimental conditions that vary slowly may be confused with drift.
  - Experimental designs should use high frequencies (more rapid alternations of stimulus on/off states).

- Bad Design:



Typical Drift Pattern & Magnitude

Typical Signal Magnitude

... you'll never detect this signal, due to the drift

Motion

- Subject motion during the experiment can also give rise to serious problems.
- Typically motion correction is performed in the pre-processing stages of the analysis.
- However, ‘spin-history’ artifacts may remain that cannot be removed.
  - This is caused by through-plane motion.
  - Attempts to account for it are often made in the modeling stage.

Physiological Noise

- Respiration and heart beat give rise to high-frequency noise.

- It can potentially be modeled, but if the TR is too low there will be problems with aliasing.

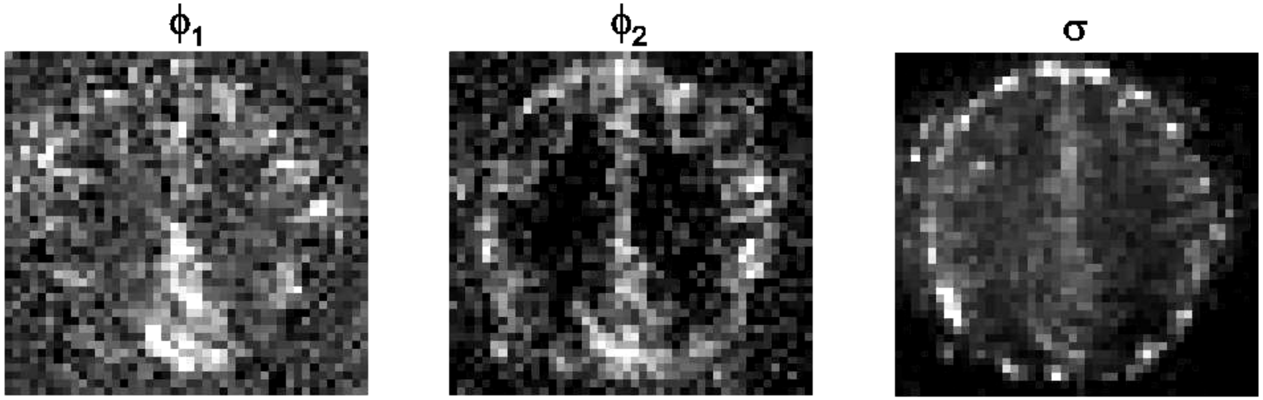
- For standard TR values (~ 2s) this type of noise is difficult to remove and is often left in the data giving rise to temporal autocorrelations.

fMRI Noise

- Some noise components can be removed prior to analysis, while others need to be included as components in subsequent models.
- However, it is difficult to remove or model all sources of noise and therefore significant autocorrelation will be present in the signal.
- In fMRI we typically use autoregressive (AR) or autoregressive moving-average (ARMA) processes to model the correlation.

Spatio-temporal Behavior

- The spatiotemporal behavior of these noise processes is complex.



Spatial maps of the model parameters from an AR(2) model estimated for each voxel's noise data.

End of Module