Temporal preprocessing of fMRI data

Blaise Frederick, Ph.D.

McLean Hospital Brain Imaging Center

Scope

- fMRI data contains temporal noise and acquisition artifacts that complicate the interpretation of resting state and task data.
- This talk will summarize the sources and characteristics of unwanted temporal features of fMRI signals, how they are recorded in MR data, and how they can be removed or attenuated prior to further processing, without compromising the signal of interest.
- I will discuss spectral filtering, removal of single point discontinuities and slice time correction; later talks will discuss more sophisticated methods for removing specific motion- and physiology- related signals, such as GLM filters and modelling.

Temporal preprocessing - goals

- Characterize and remove noise from various sources.
- Preserve signal.
- Make sure that data are ready for analysis by ensuring that the assumptions underlying the analyses are correct.

Noise in fMRI - sources

- Subject generated
  - Physiology
    - Heartbeat, respiration, low frequency oscillations
  - Motion
- Equipment generated
  - Machine instability
- Externally generated
  - Interference from inside or outside of the scan suite

Noise in fMRI - characteristics

- Physiological
  - Cardiac signal: Pseudoperiodic, 40-120 beats/min (0.66-4.0 Hz, accounting for harmonics)
  - Respiration: Pseudoperiodic, 12-20 breaths/min (0.2-0.33Hz)
  - Low frequency oscillations: Aperiodic, (0.01-0.15*Hz)
  - Motion: Aperiodic, usually impulsive discontinuities any frequency, but also pseudoperiodic at the respiratory rate.
- Equipment generated
  - Machine instability: could be anything, but in a modern scanner, this is usually constrained to very low frequencies from thermal drift in shims, gradients, and RF components, (below ~0.1Hz), or extremely high frequency (single point spikes).
- External signals
  - Best dealt with at the source (eliminate the interference before running the experiment).
- With the exception of cardiac and respiratory signals and spikes, fMRI noise follows a 1/f distribution.

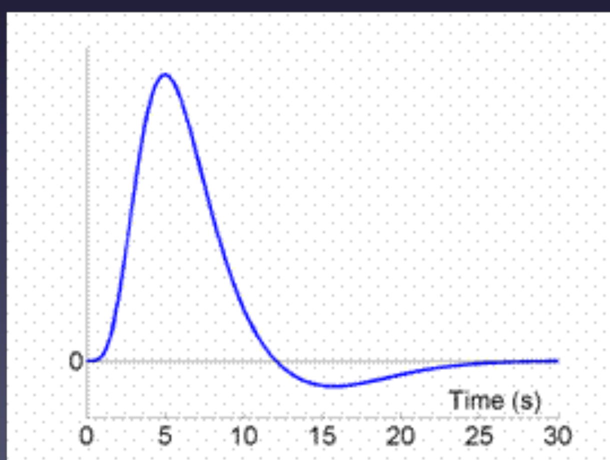
*the exact boundaries of this range are the subject of some debate.

fMRI signal - sources

- Task response
  - Changes in neuronal activity in response to stimuli or directed cognitive activity
- Resting state signals
  - Changes in neuronal activity due to correlated activity in connected brain regions
- In both cases, the fMRI signal comes from the hemodynamic response to the neuronal activity, not the activity itself
  - This has important implications for the temporal characteristics of the signal

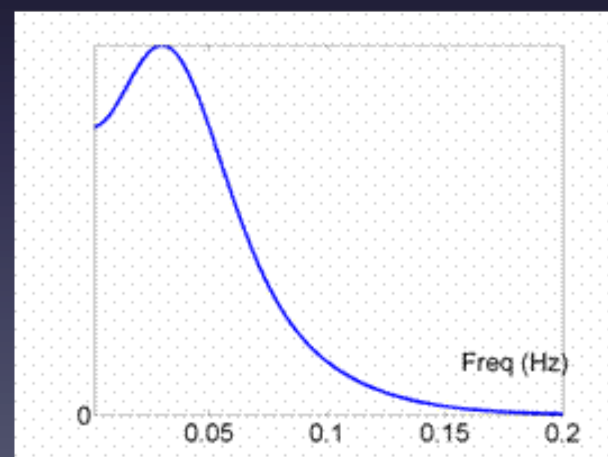
Hemodynamic response

- fMRI doesn't see neuronal activation – it sees the hemodynamic response to neuronal activation.
- As a result, any neuronal signal we want to look at is filtered by the hemodynamic response function (HRF) – this is the response to a neuronal event of the shortest possible duration (shown below on the left). No neuronal fMRI signal can be faster than this.
- This puts a hard limit on the frequency spectrum of "true" activations (see below right).



Hemodynamic response function

Fourier Transform



Power spectrum of HRF

Figures from: http://imaging.mrc-cbu.cam.ac.uk/imaging/DesignEfficiency

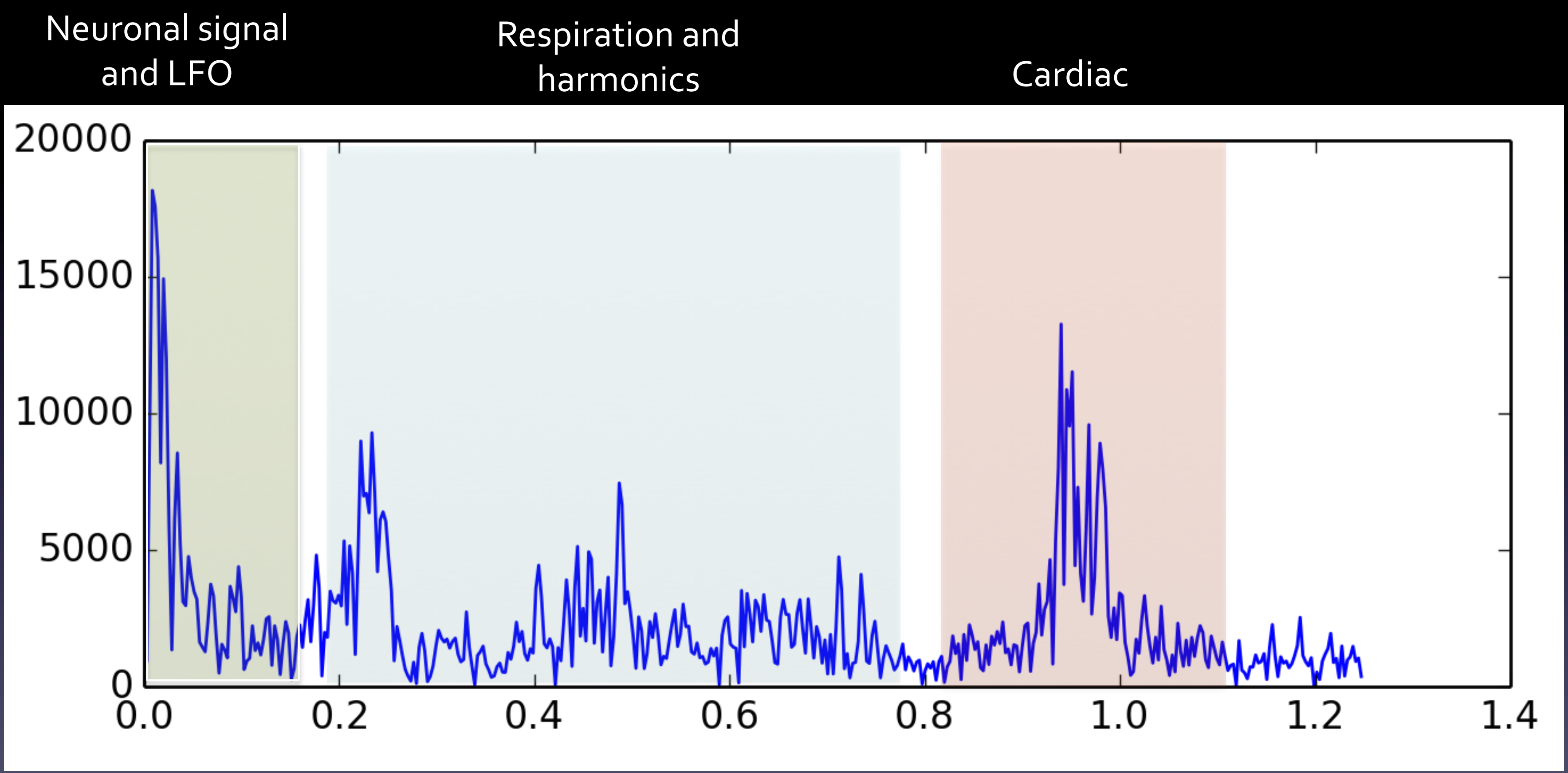
fMRI signal - characteristics

- The spectral properties of fMRI signals are determined by the underlying neuronal activation and the HRF filter function.
  - For resting state data, the spectrum is just that of the filter function.
  - For for task data, it varies (but is limited to the range of the filter function) – the HRF imposes a design constraint on tasks. For maximum design efficiency, you try to concentrate the task spectrum in the area of peak HRF response – i.e. around 0.03Hz .

Filtering

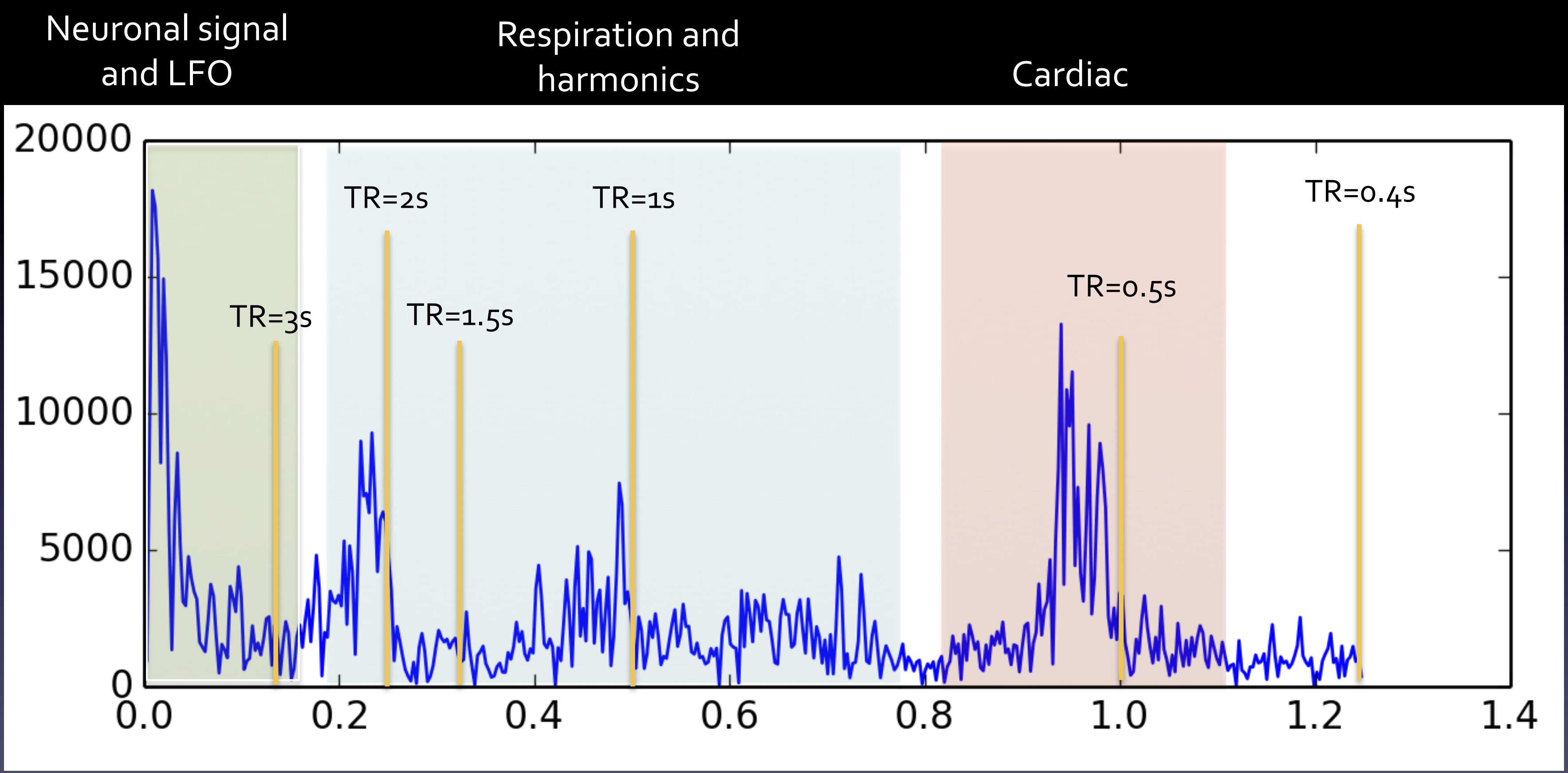
- The easiest way to improve SNR is to preprocess your data with a filter matching the spectral characteristics of your signal of interest.
  - This will preserve your signal, while eliminating out of band noise.
  - In band noise you either have to live with, or model (see following talks).

fMRI spectrum (resting state)



This is a voxel from the frontal lobe near a blood vessel from a 400ms TR EPI dataset. The voxel is near a blood vessel, and was chosen to show all the physiological noise components – most voxels aren't nearly this bad!

fMRI spectrum (resting state)



Increasing the TR will reduce the acquisition bandwidth. As a result, certain physiological processes will not be fully sampled at higher TR values, resulting in aliasing. When that happens, you can't remove that process using only a spectral filter.

What are your best choices?

- Lowpass filtering:
  - Neuronal signals will be below 0.15Hz (6.6s cycle time), so that's a good place to set the maximum frequency of a lowpass filter.
  - If your TR is 2s or shorter, you can attenuate respiratory noise (if your TR is 1s or less, you can eliminate it).
  - If your TR is 0.5s or shorter, you will remove the majority of the cardiac signal as well.
- Even if your TR is not sufficient to fully sample these signals, some of the aliased energy will end up above 0.15Hz, so you still gain by filtering to this band.

What are your best choices?

- Highpass filtering:
  - The answer to this depends on your experiment.
  - For resting state data, 0.01Hz (100s cycle time) is usually chosen to eliminate 1/f noise, scanner drift, and linear trends. This is a good compromise that preserves the low frequency connectivity signals.
  - For task data, you should set your highpass filter frequency as high as possible without attenuating the task waveform. (for example, with a 20s off, 20s on block paradigm, you would eliminate everything below a 40s cycle time, or 0.025Hz.)

How do you do this?

- In FSL, you can set the highpass filter cutoff in the “Data” tab of the feat gui, and turn the highpass filter on in the “Pre-Stats” tab (to apply a lowpass filter, you need to use the “-bptf” option of fslmaths.
- In SPM, this is set ???
- In BrainVoyager, this is set in the Preprocessing dialog box.
- In AFNI it is set ???

Spikes

- Spikes are impulsive positive or negative going discontinuities in the timecourse, followed by a return to normal.
- Multiple sources:
  – Electrical sparks (from gradient problems, metal in bore)
  – Rapid motion (coughing)
  – External interference
- They cannot be effectively removed by frequency domain filtering.

Preprocessing strategy

- Detect “abnormal” timepoints (excessive motion, large change in signal)
- Remove the affected timepoints (volumes) and interpolate
- Generate single point regressors to model out the variance

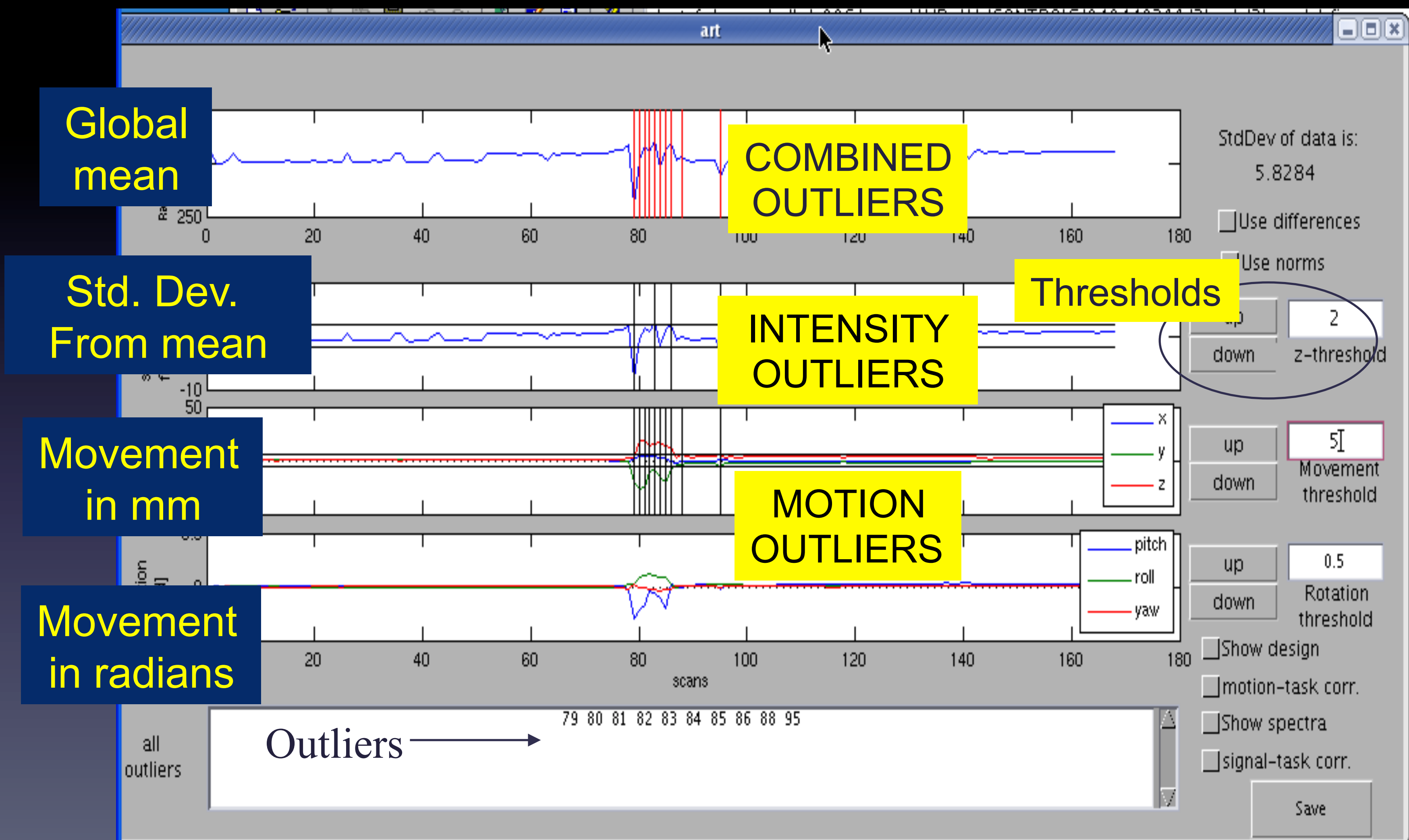
Tools for spike removal

- ART (from Susan Gabrieli at MIT)
- despike (from me, on NITRC)

Artifact Detection Toolbox (ART)

- ART is a GUI tool for remedying a number of problems in datasets. Among its tools is one for detecting and removing spikes from fMRI data.
- Examines the global mean signal and motion parameters to detect "anomalous" timepoints that need to be dealt with.

Data Review



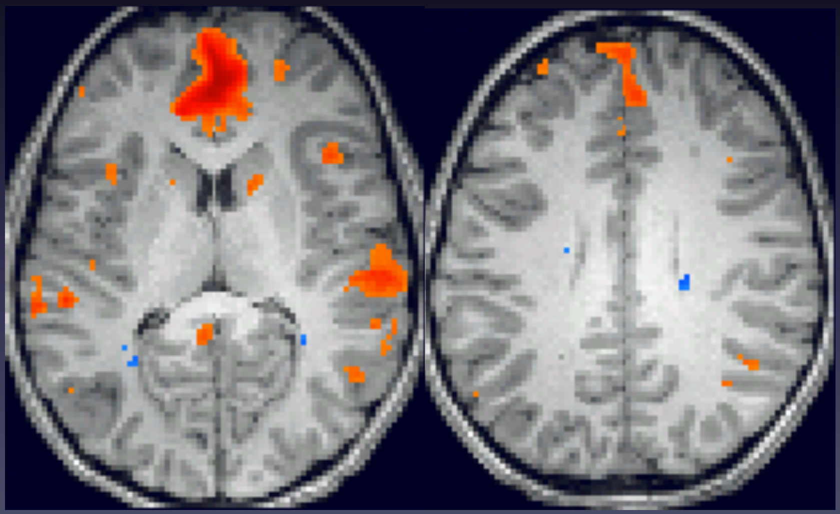
Whitfield-Gabrieli

Artifact detection rs-fcMRI (Child 10yrs)

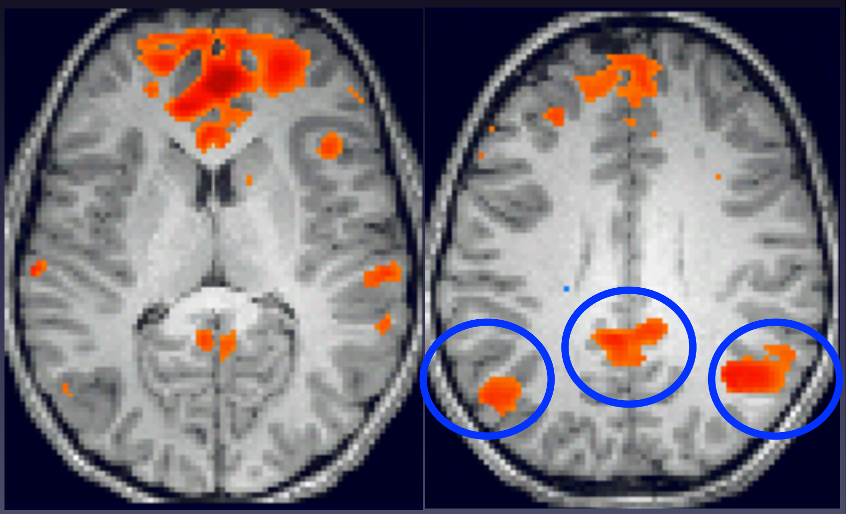
Whitfield-Gabrieli

Effect of artifact rejection on first-level connectivity map – MPFC seed

Regressing out motion parameters only



Regressing out motion parameters + outliers



Whitfield-Gabrieli

Slice time correction

- Slices in an fMRI volume are acquired all through the TR.
- The time between acquisitions of different slices within a volume can be significant.

Slice acquisition order - problem

- GLM analyses assume that all the slices in a volume were recorded at time zero.
- This assumption will generally be incorrect in all but one of the slices, sometimes very badly so.
- The GLM is very sensitive to timeshifts
  - In task based studies, it will cause poor estimation of the regressor betas in certain slices.
  - In resting state analyses, slice timing differences may obscure connectivity between slices.
- You should account for this, especially with longer TR's (>=2s or so).

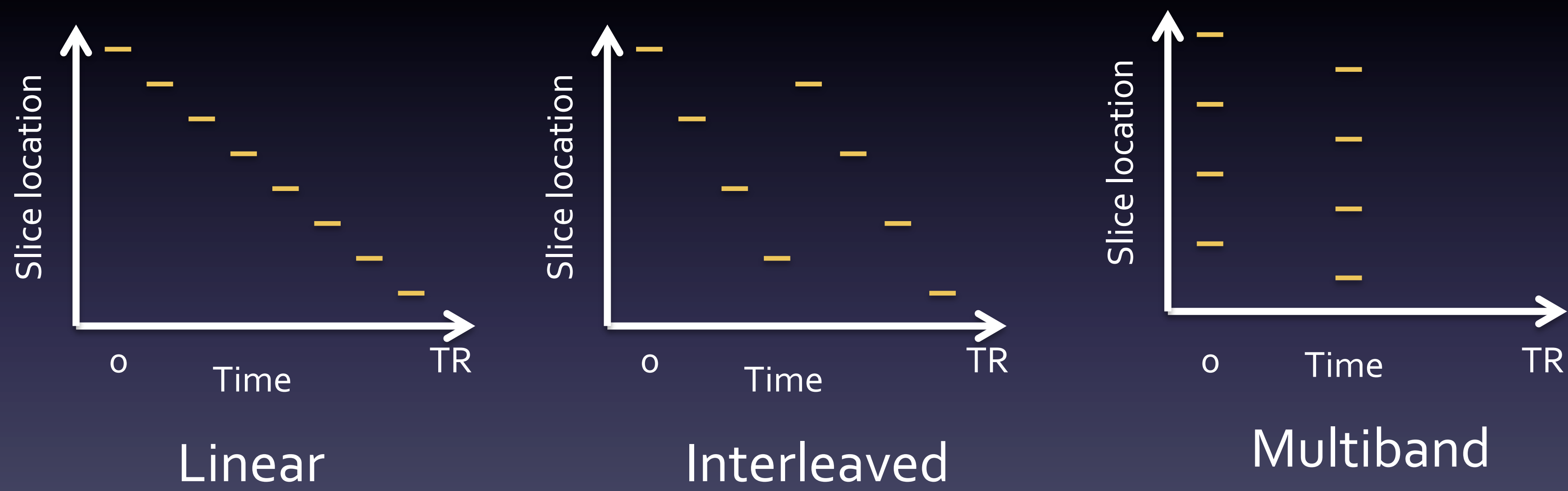
Analysis with no slice time correction

Slice acquisition order - solution

- You can interpolate the data from each slice to the start of the TR (as long as you have fully sampled the signal you are interested in, this is legal).
  - Most major analysis packages have this as a built-in function.
  - The other option is to make slice-selective regressors, but that doesn't help you if you are doing resting state analysis – slice time correction always works.
  - The MOST IMPORTANT THING to do with slice correction is to correctly specify the slice acquisition times – if you get it wrong, you can make the problem worse rather than better.
- When do I do it?
  - Some investigators believe that slice time correction should be done after motion correction, while others think it should be done before. If it matters a lot, your data is probably in pretty bad shape. FSL does it before. SPM, AFNI, BrainVoyager ?

Slice acquisition order

- There are many slice acquisition orders.



- There are also multiple variants (ascending, descending, odd or even start for interleaving, etc.).

Interpolation process

Analysis after slice time correction

Summary

- Temporal preprocessing is a necessary step in preparing your data for analysis.
- Filtering, spike removal, and slice time correction can each make a significant contribution to the power of your analysis (or more precisely, not doing them can significantly degrade your analysis).