FMRI data preprocessing

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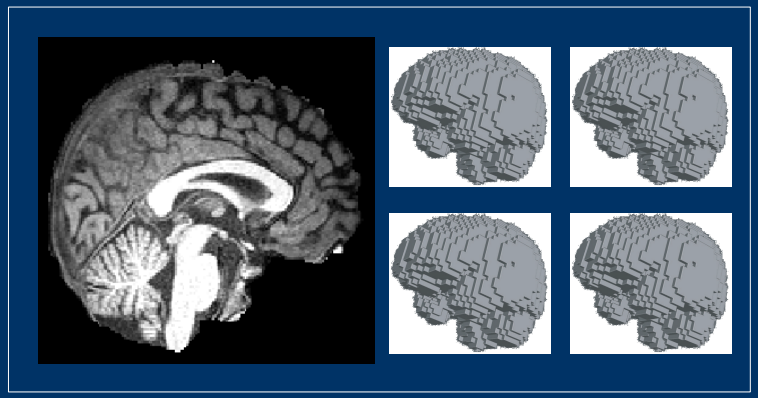
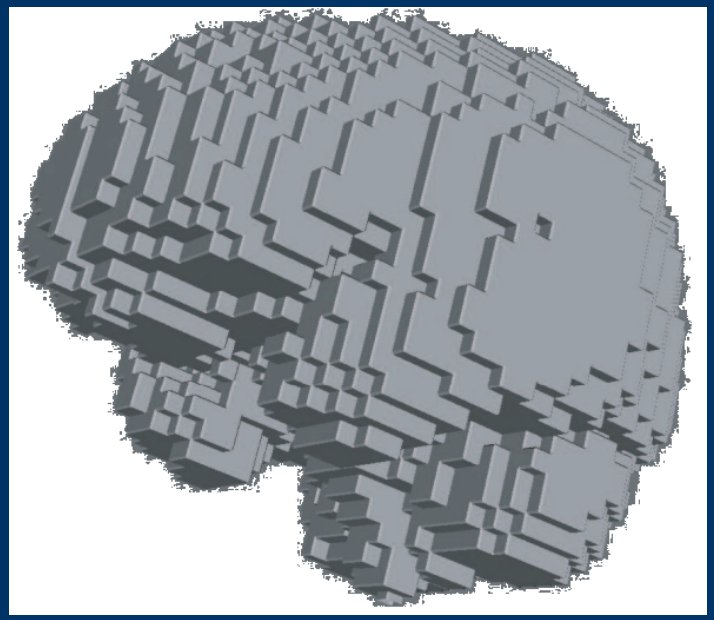
UCLA Department of Psychology

Typical dataset



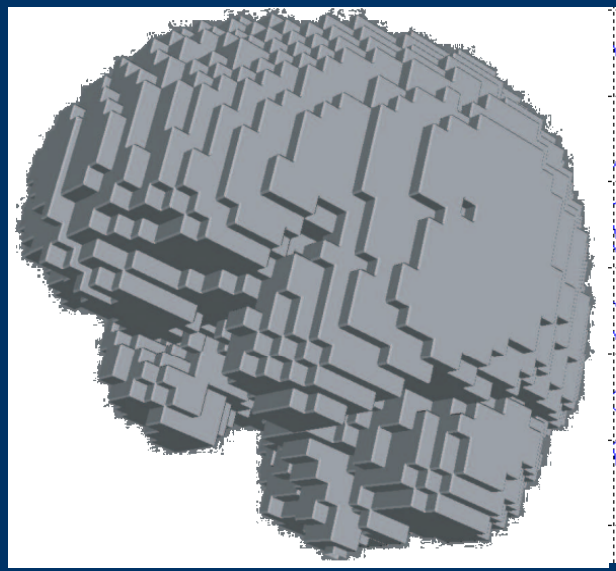


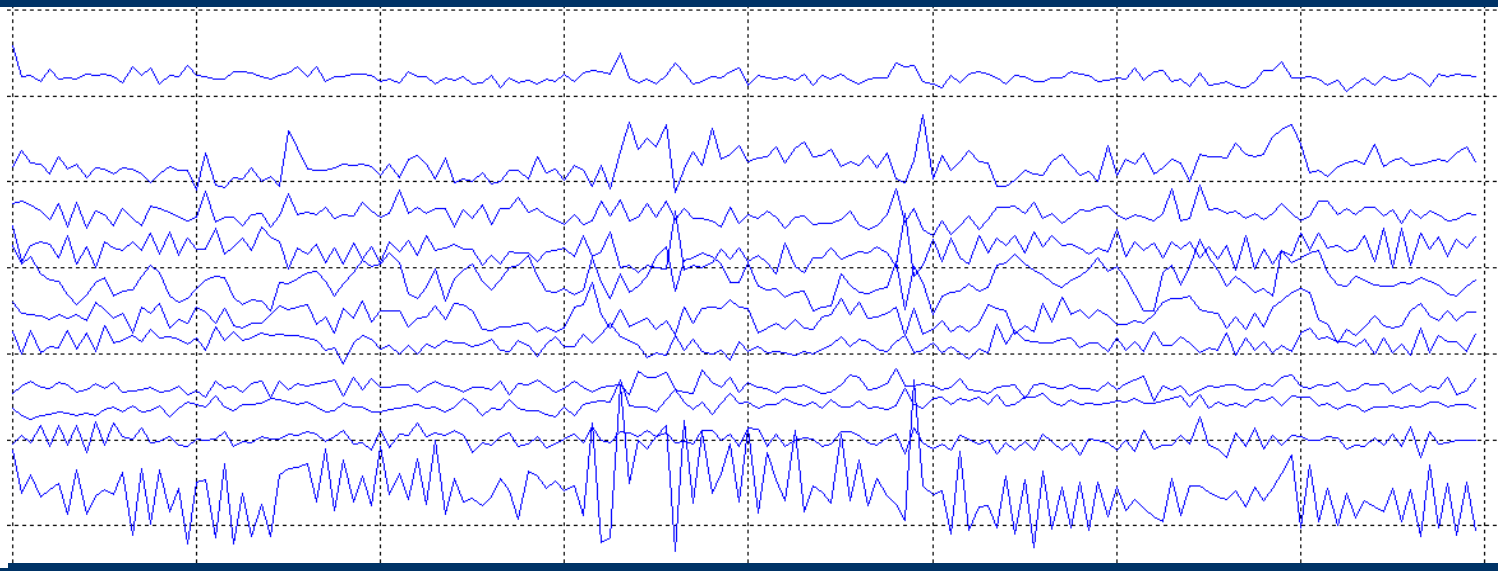
Typical dataset

Run

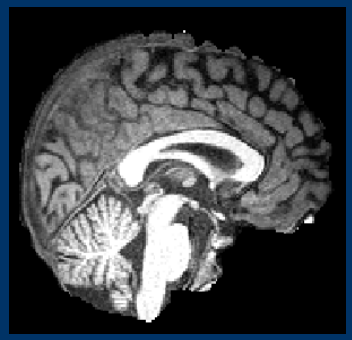
Volume

Time





Typical fMRI analysis sequence



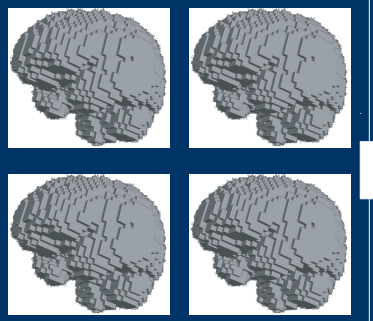
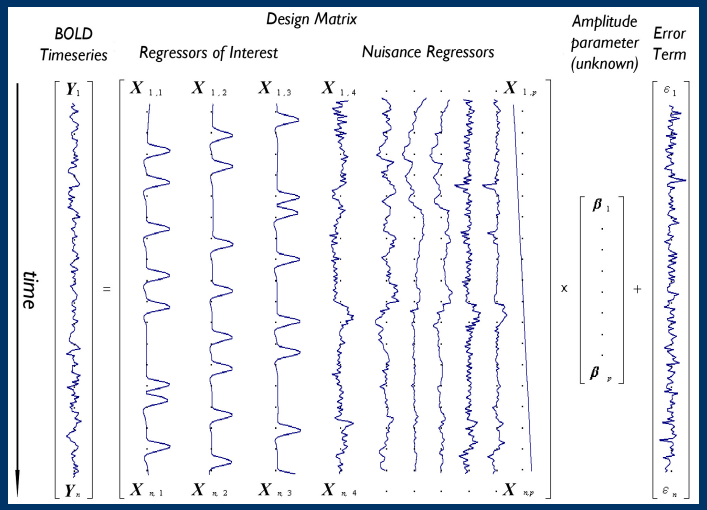


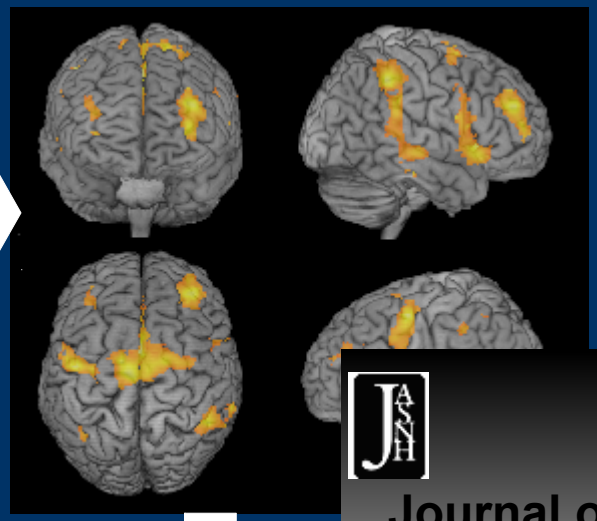
Image Pre-processing

Single Subject Analysis



Normalization

Group Analysis



Journal of Articles in Support of The Null Hypothesis

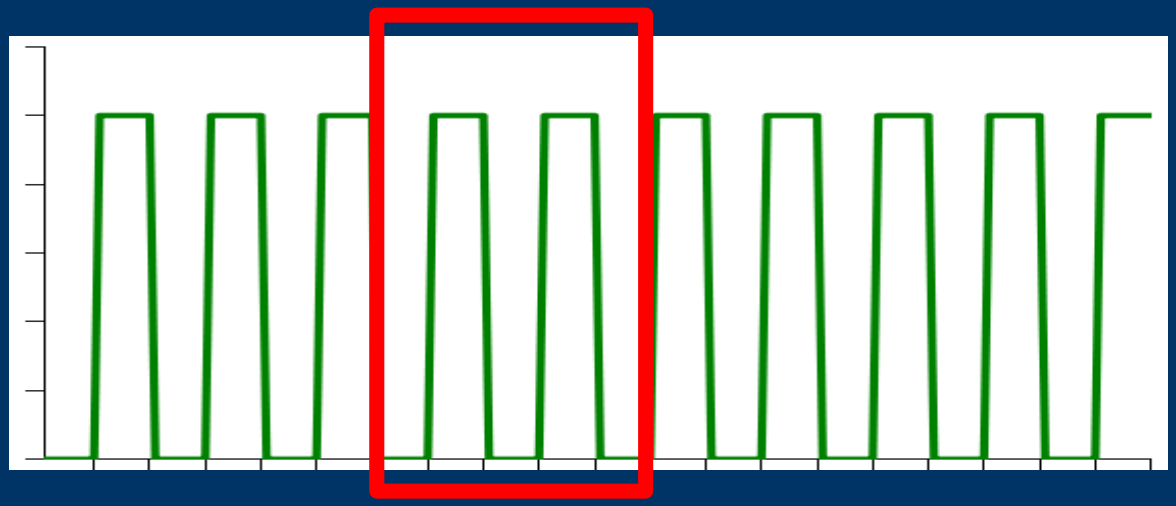
Preprocessing: what/why?

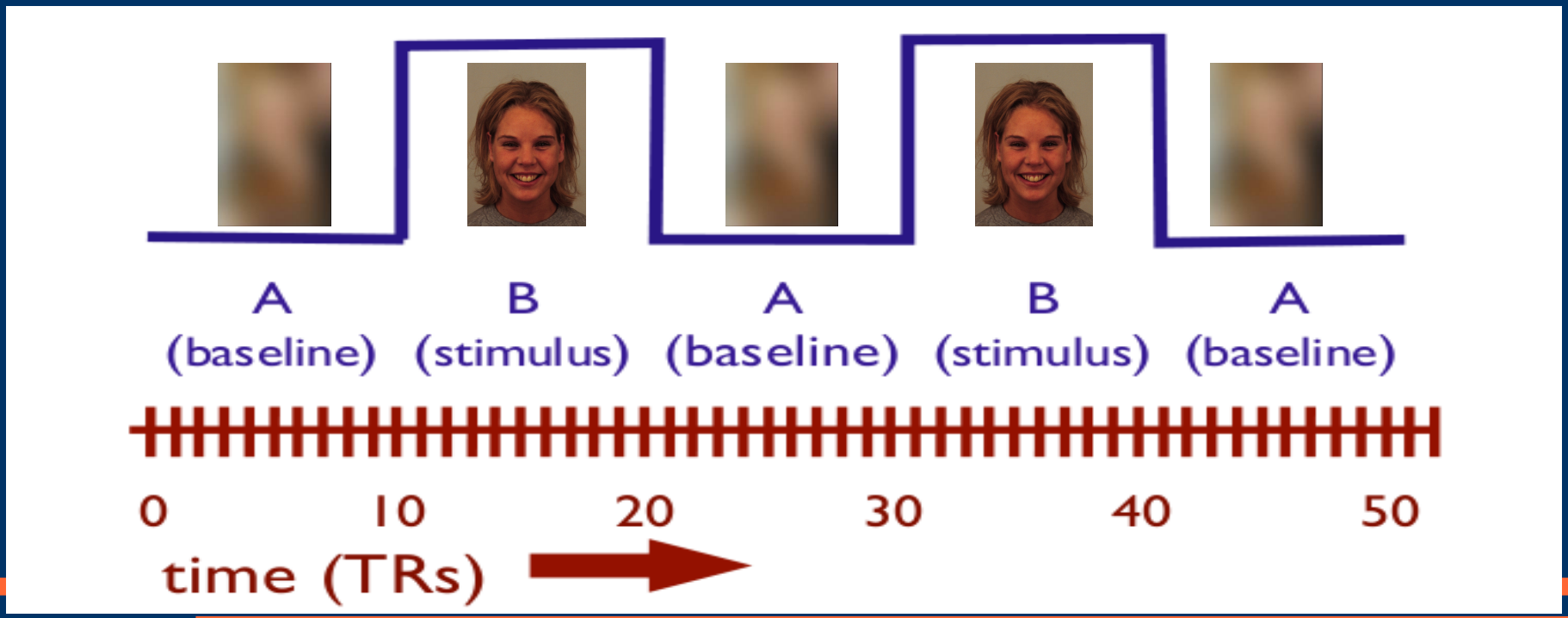
Preprocessing is a series of data transformations ("data conditioning") aimed at reducing sources of noise in order to:

1) Increasing sensitivity of analysis (SNR)
2) Ensuring validity of the statistical model

Sample Experiment: SNR

TR = 2s
Vols = 160
10 AB Cycles
Cycle = 8A + 8B





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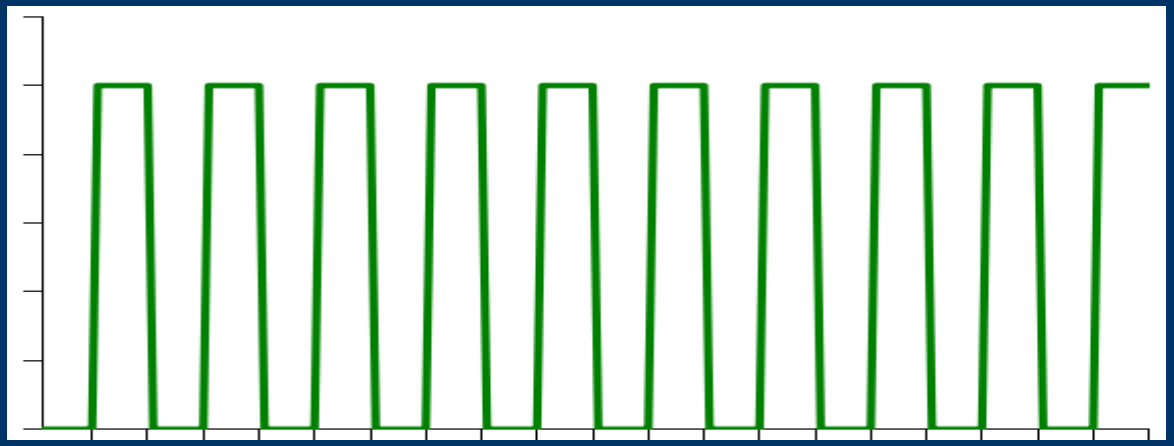

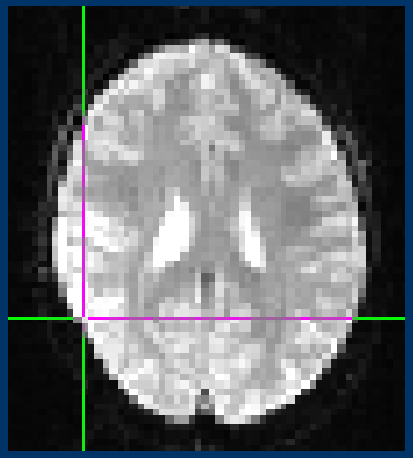

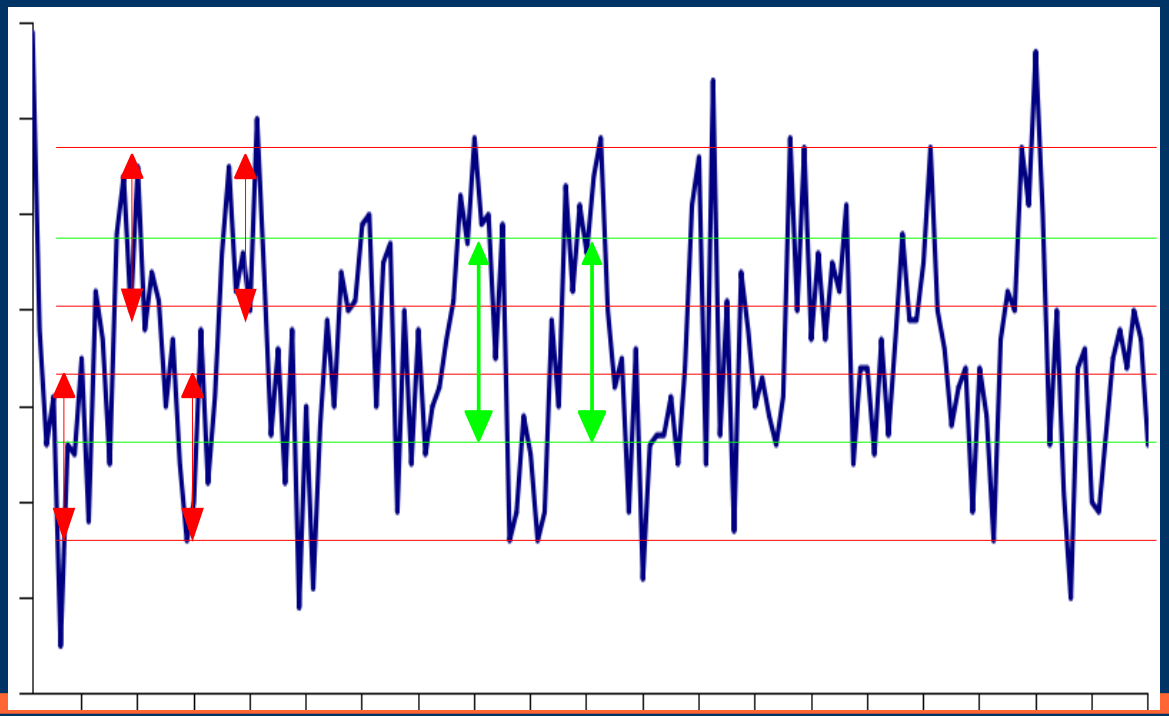

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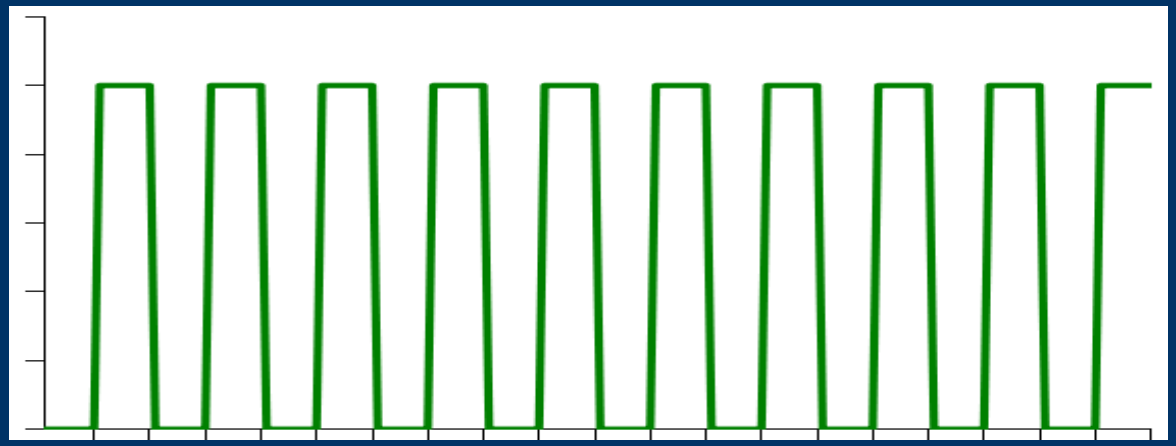

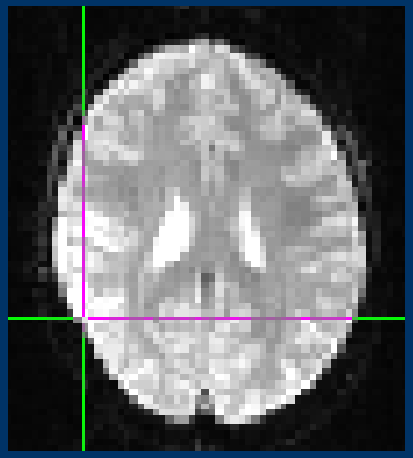

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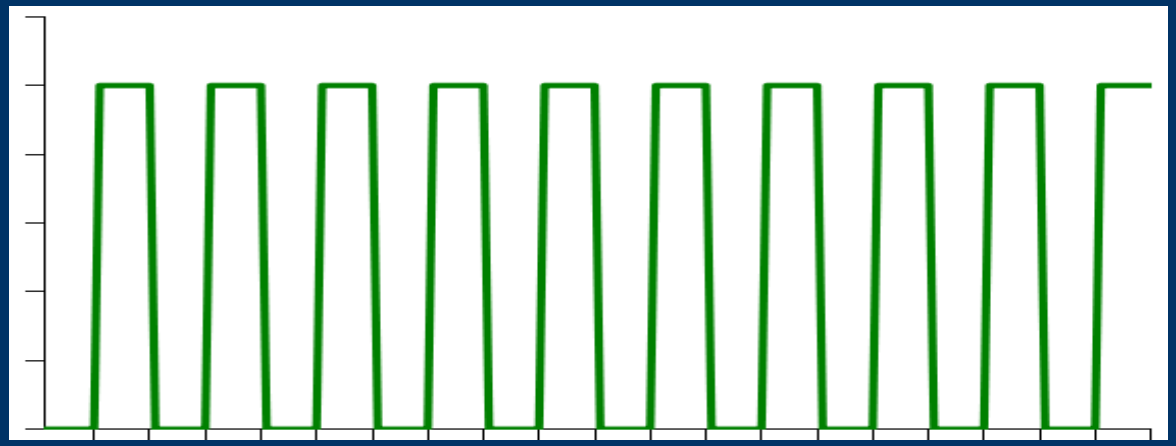
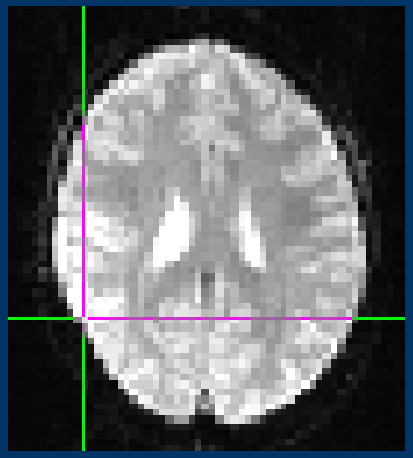
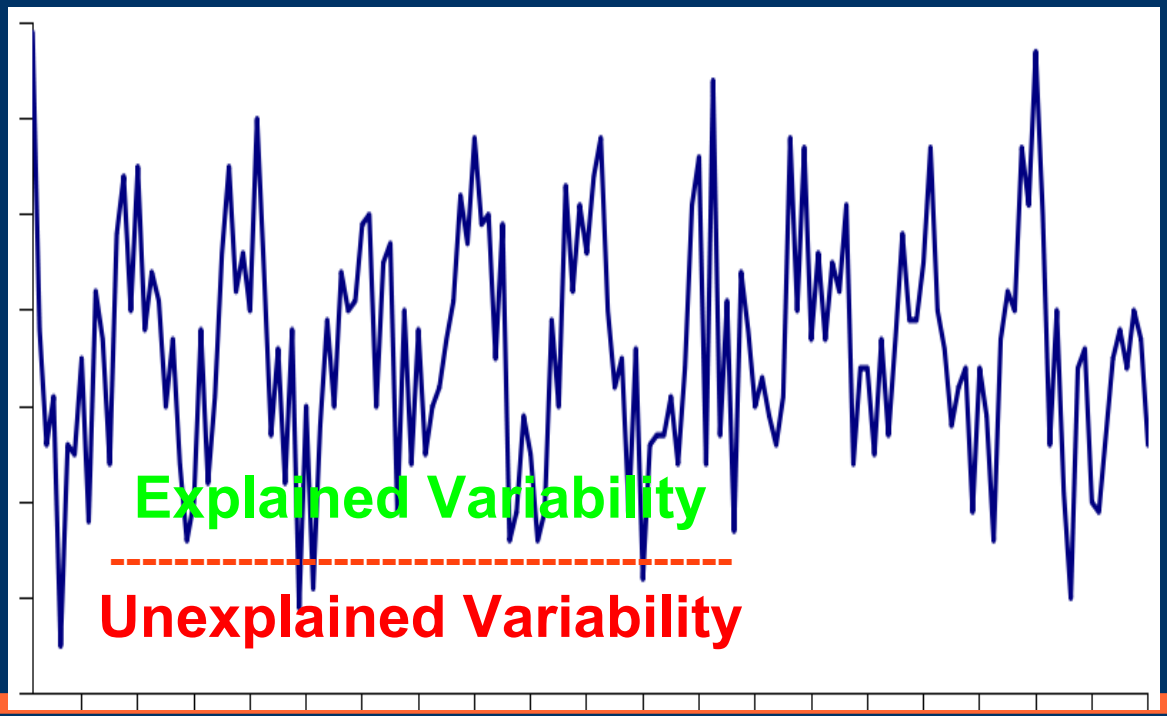


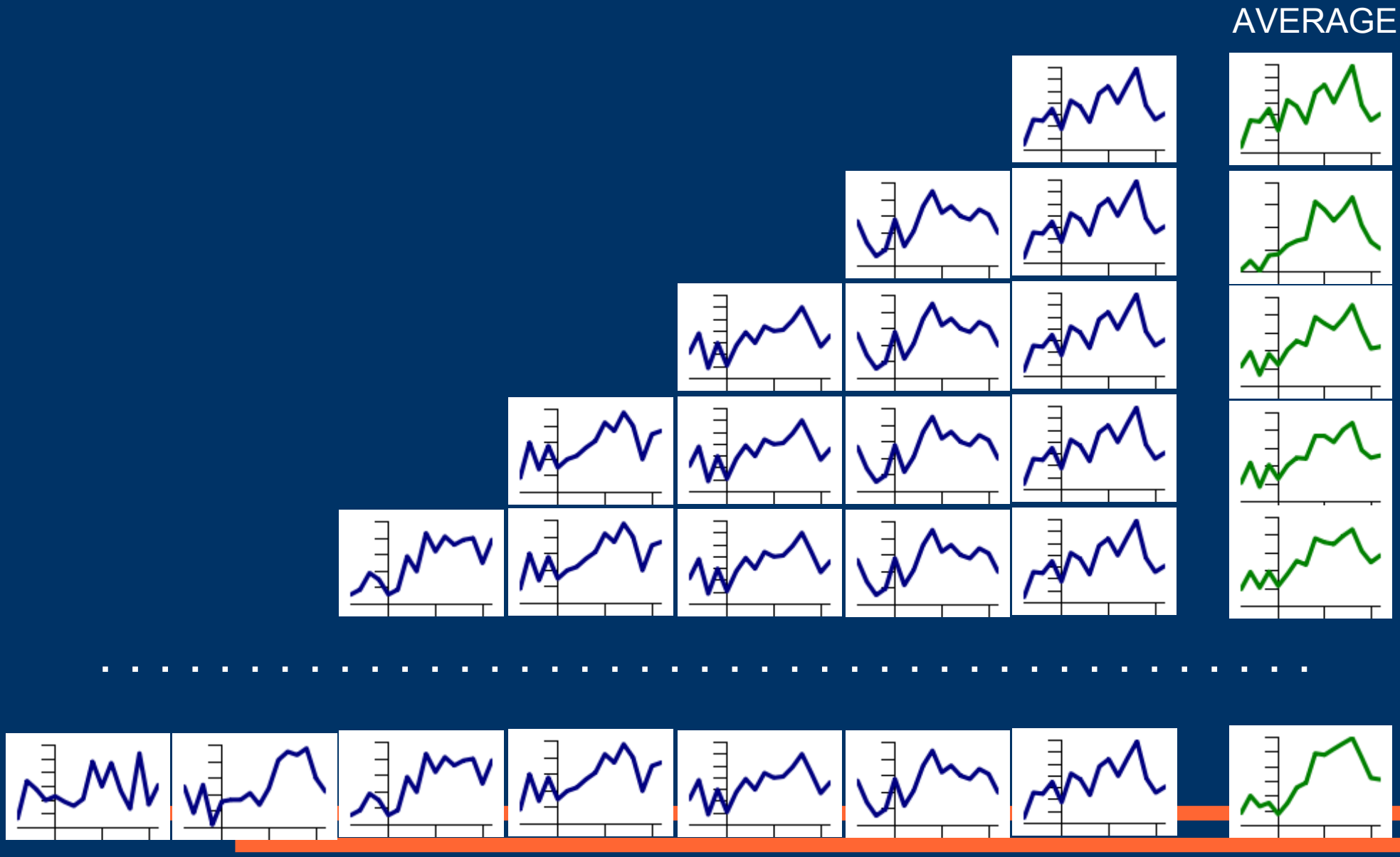




Noise in fMRI

- Hardware & acquisition related
  - Thermal noise (intrinsic noise)
  - System noise (scanner drift)
  - Field inhomogeneities
  - Slice acquisition timing
  - ...
- Subject related
  - Oscillatory physiological noise (heartbeat, respiration)
  - Head motion
  - Psychological (alertness, learning)
- White noise

Coping with Gaussian noise



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The General Linear Model (GLM)

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

fMRI Signal = Design Matrix x Parameter + Residuals

"our data" = *"what we CAN explain"* x *"how much of it we CAN explain"* + *"what we CANNOT explain"*

Preprocessing: what/why?

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1) Increasing sensitivity of analysis (SNR)
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Preprocessing

i. Motion correction
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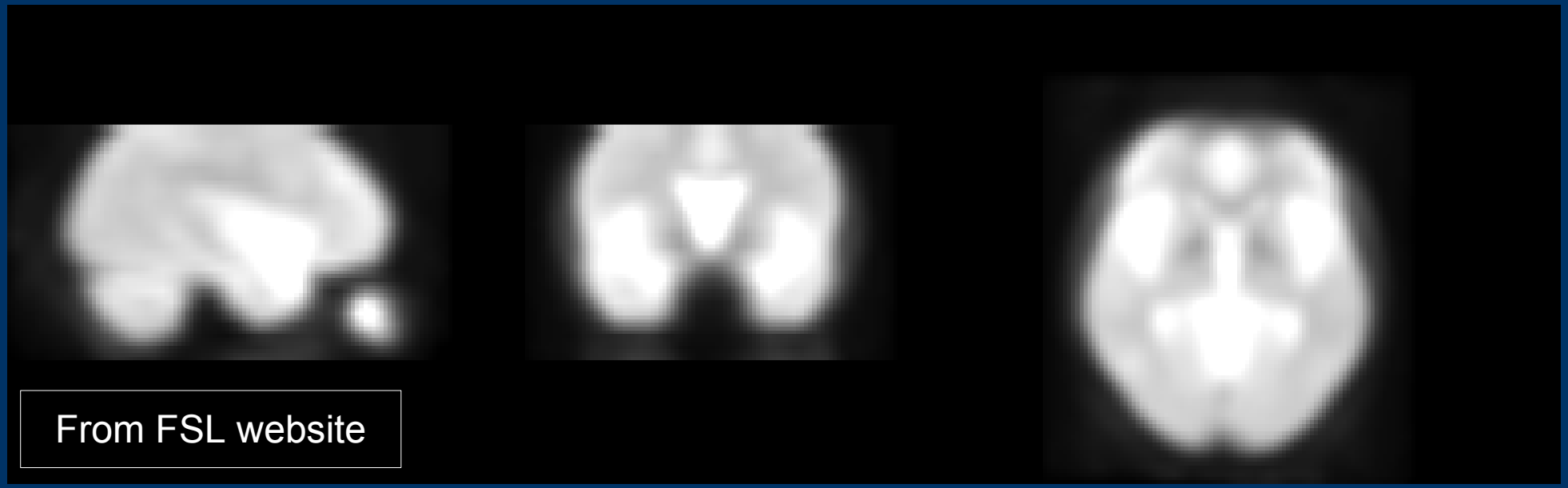
Subject Motion

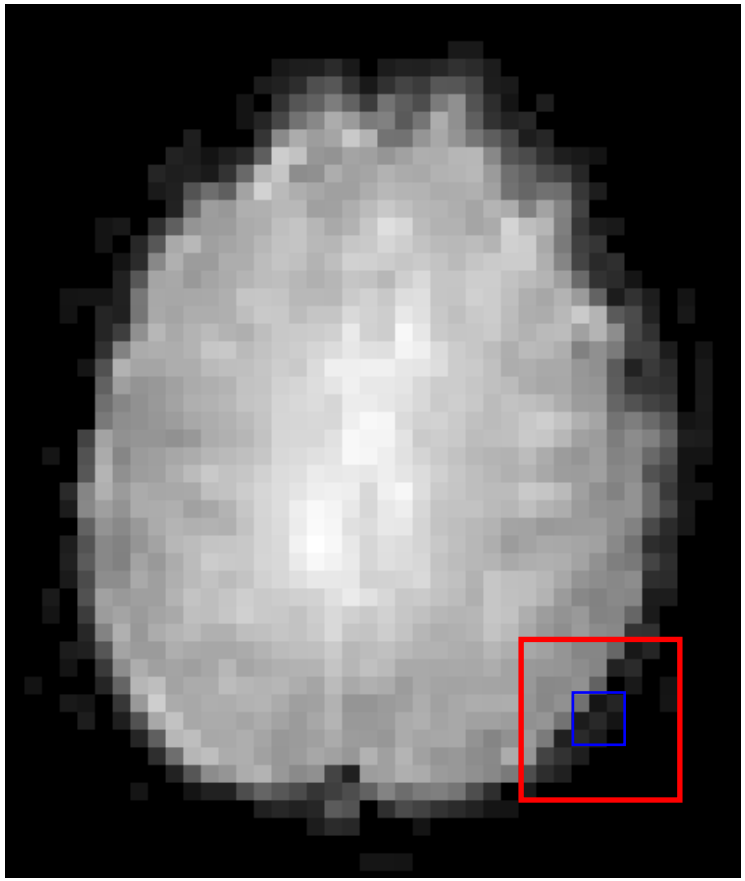


Motion within a time-series can have several unwanted consequences:

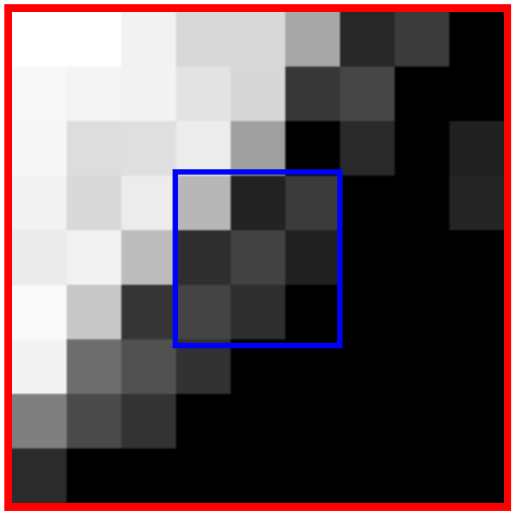
- Motion can produce signal changes of a greater magnitude than the BOLD signal
- Lose the correspondence between a voxel and anatomical location

Subject Motion

A

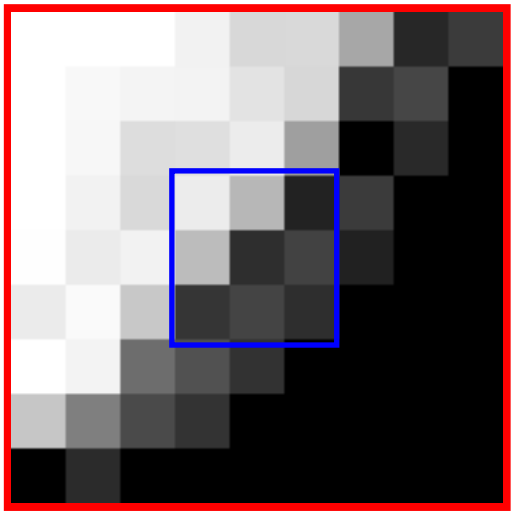


B



507	89	154
119	171	83
179	117	53

C



663	507	89
520	119	171
137	179	117

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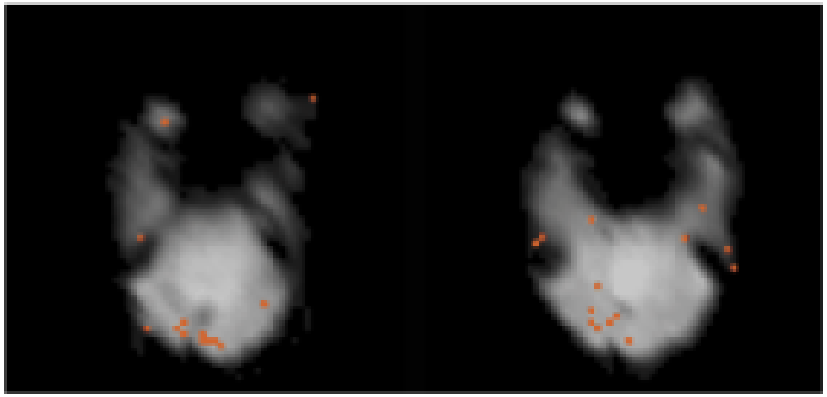
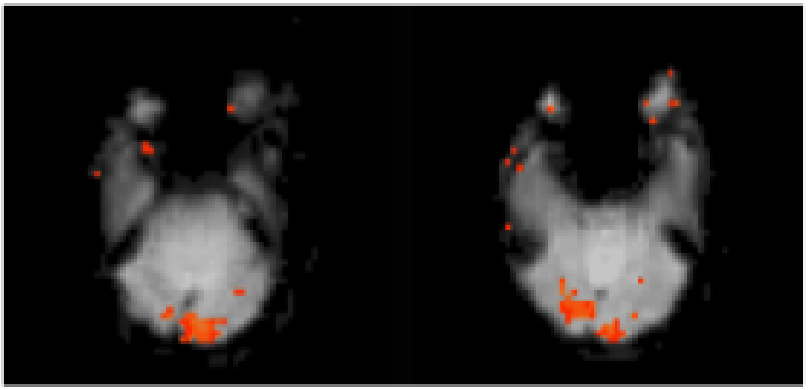
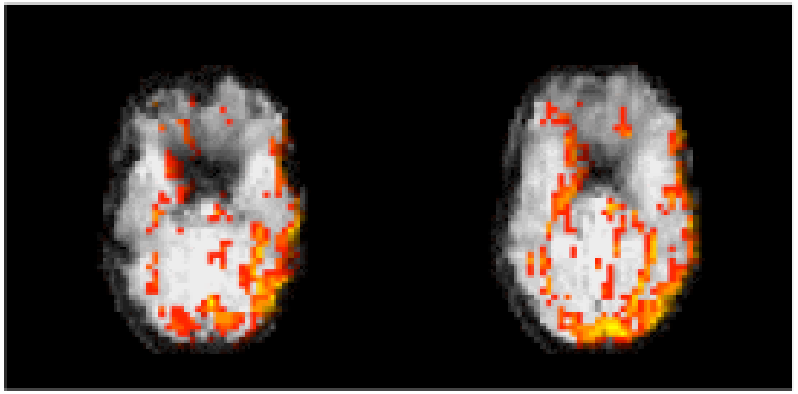
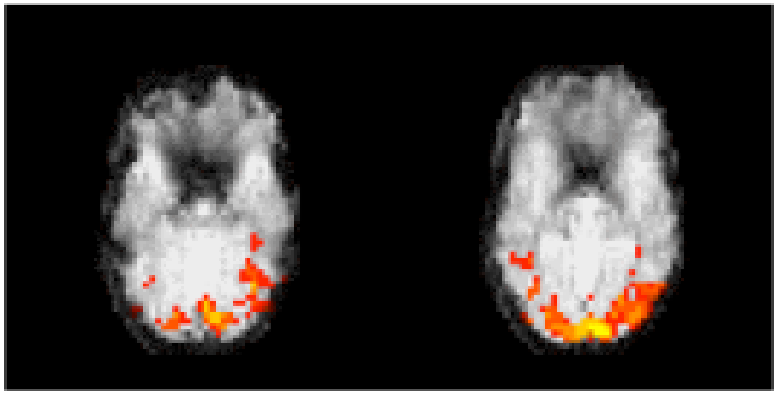
Effect of Motion Correction





Stimulus Correlated Motion

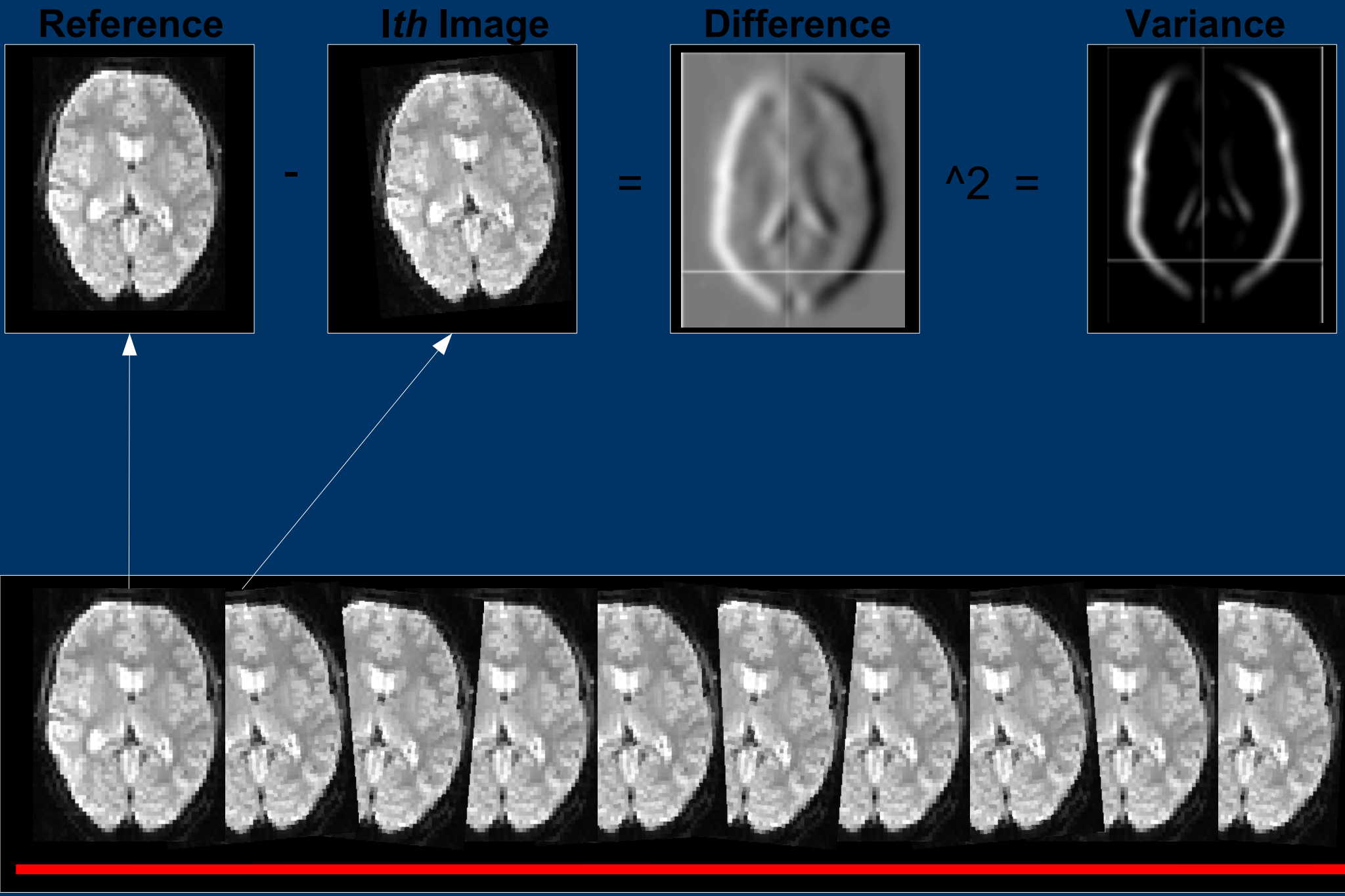




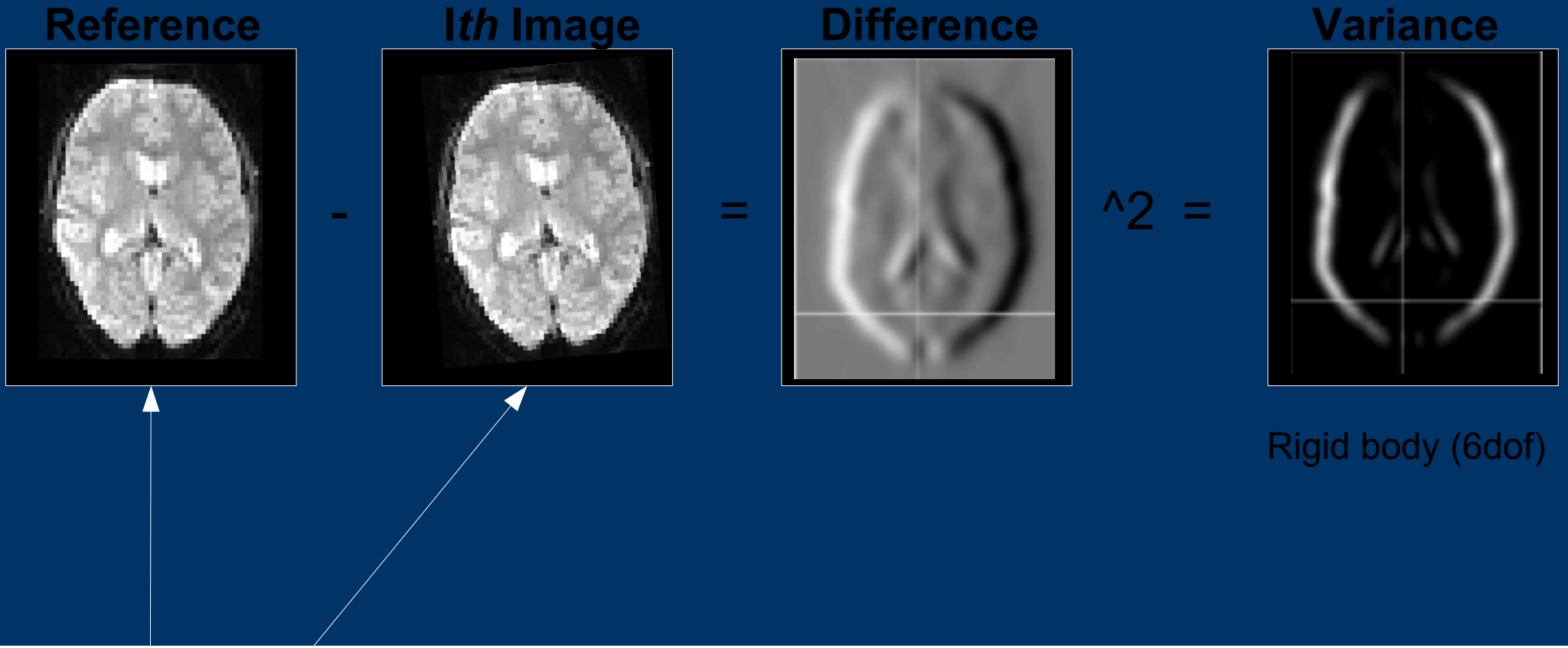
Without MC

With MC

Motion Correction



Motion Correction



Rigid body transformations parameterised by:

Translations

$$\begin{pmatrix} 1 & 0 & 0 & X_{trans} \\ 0 & 1 & 0 & Y_{trans} \\ 0 & 0 & 1 & Z_{trans} \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Pitch

$$\times \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\Phi) & \sin(\Phi) & 0 \\ 0 & -\sin(\Phi) & \cos(\Phi) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

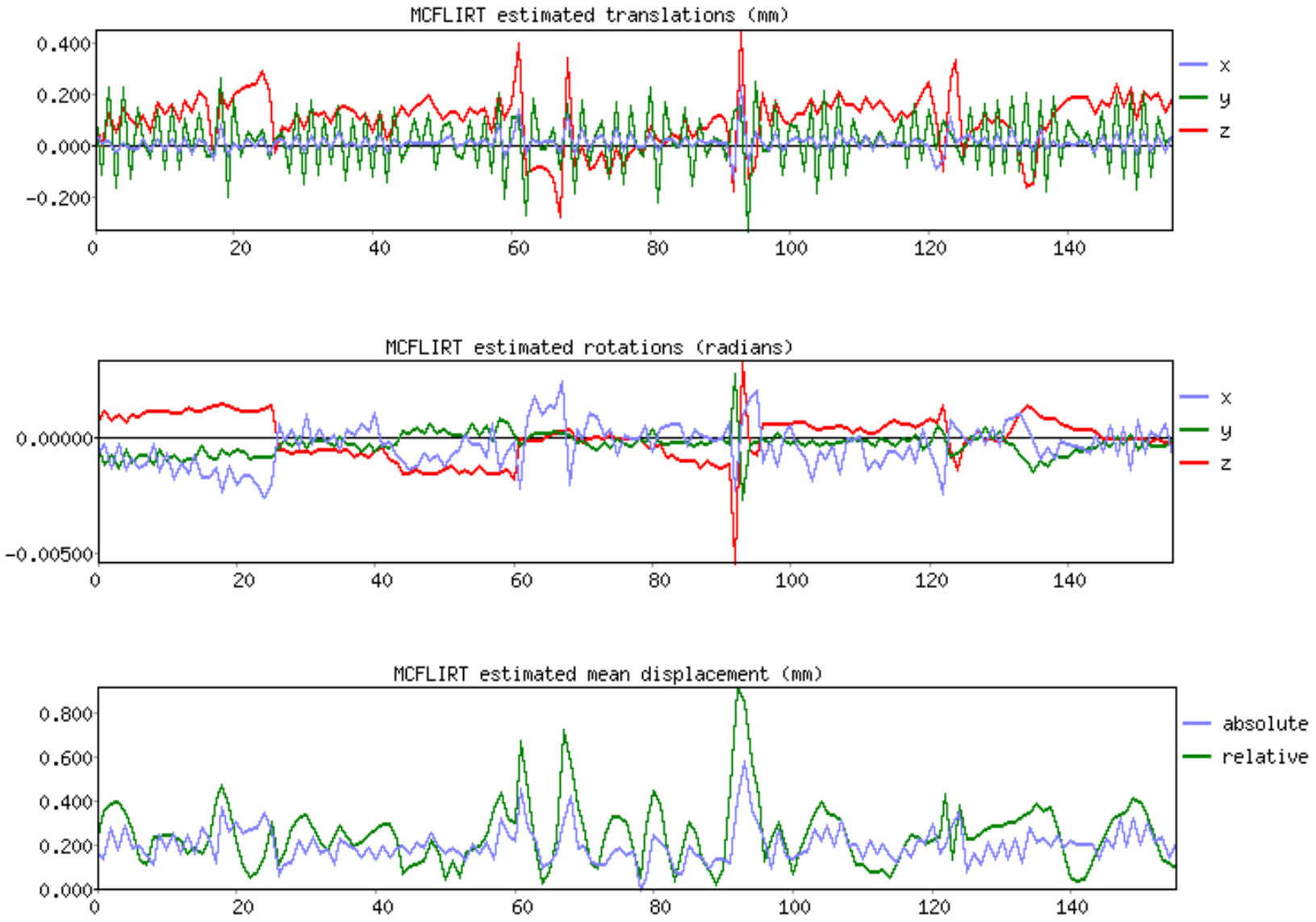
Roll

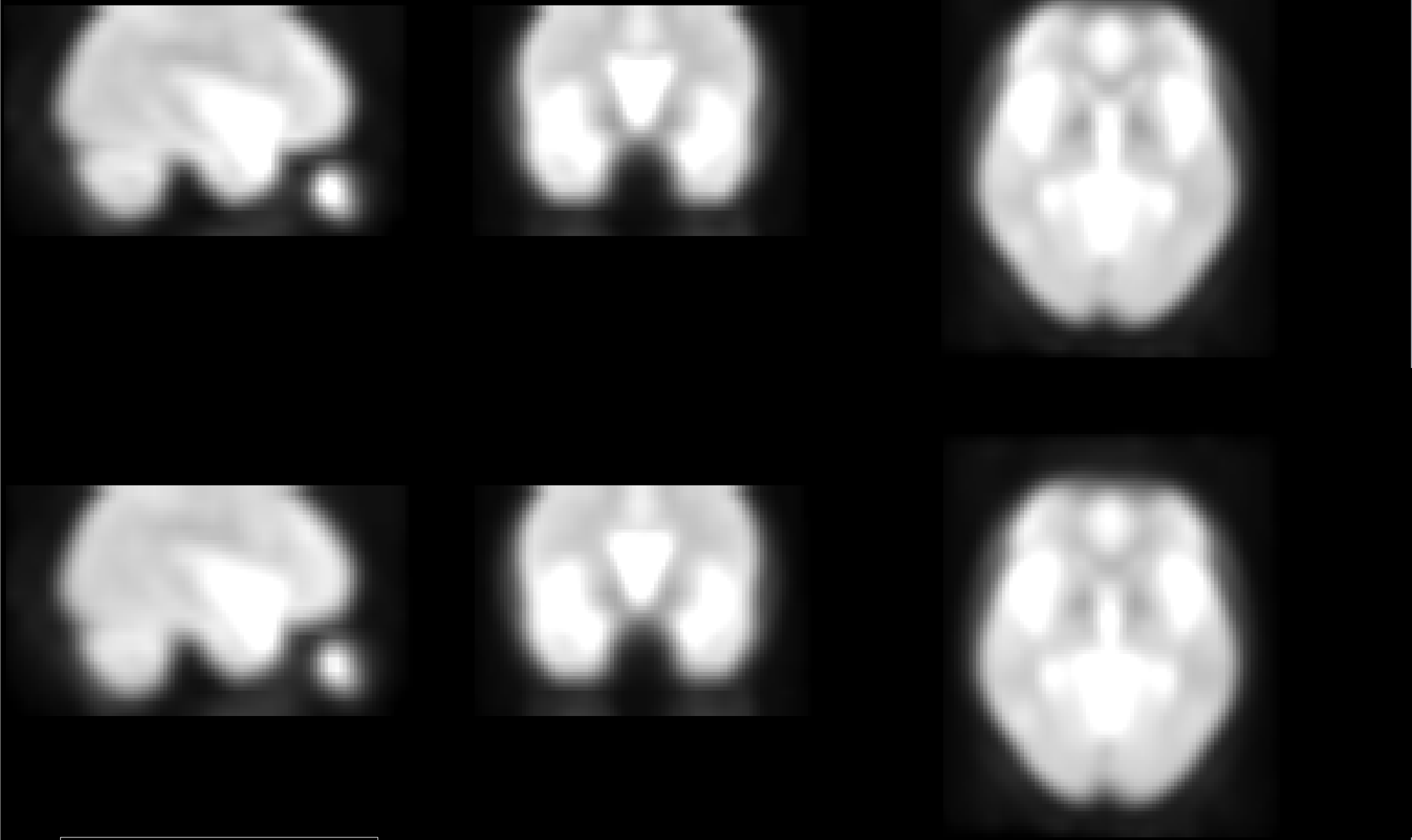
$$\times \begin{pmatrix} \cos(\Theta) & 0 & \sin(\Theta) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\Theta) & 0 & \cos(\Theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Yaw

$$\times \begin{pmatrix} \cos(\Omega) & \sin(\Omega) & 0 & 0 \\ -\sin(\Omega) & \cos(\Omega) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

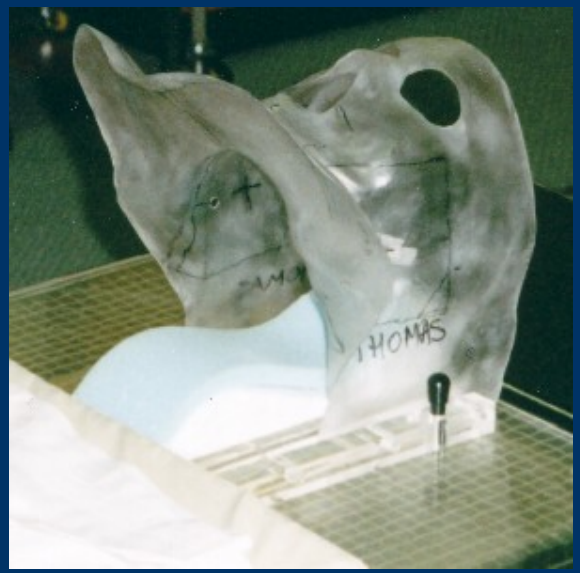
Viewing motion correction



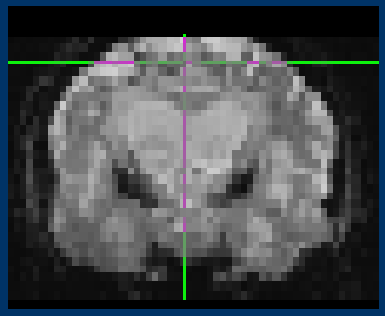


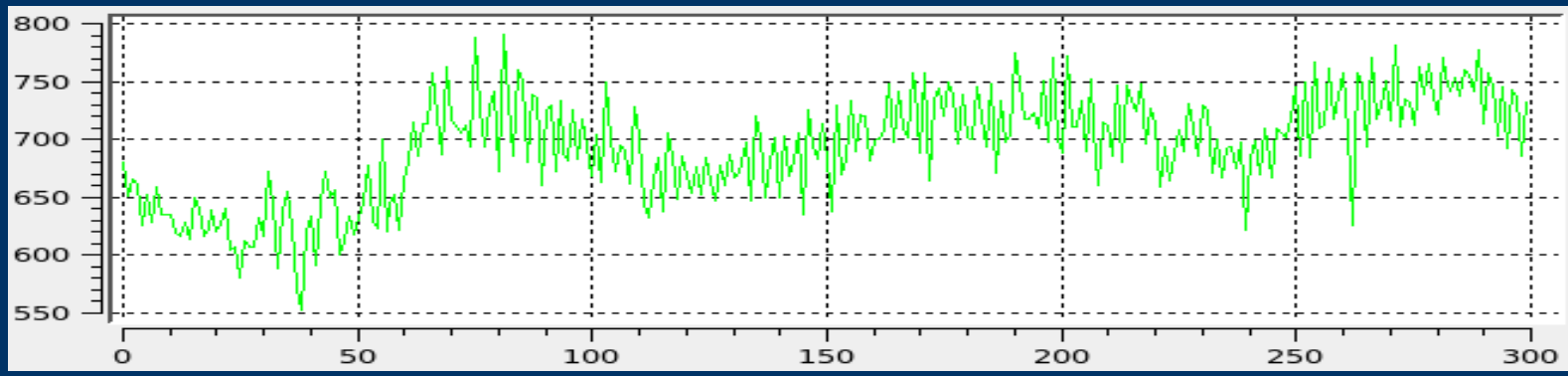
From FSL website

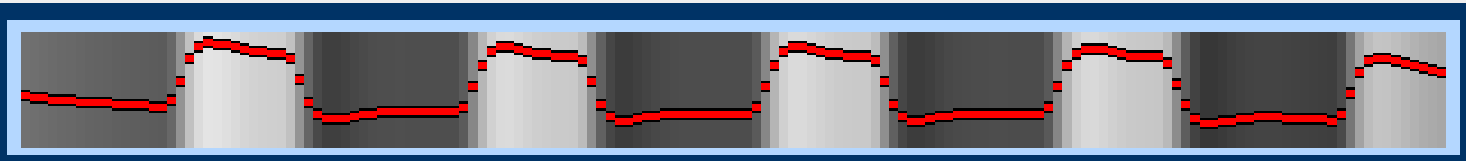
Coping with motion I: prevent it

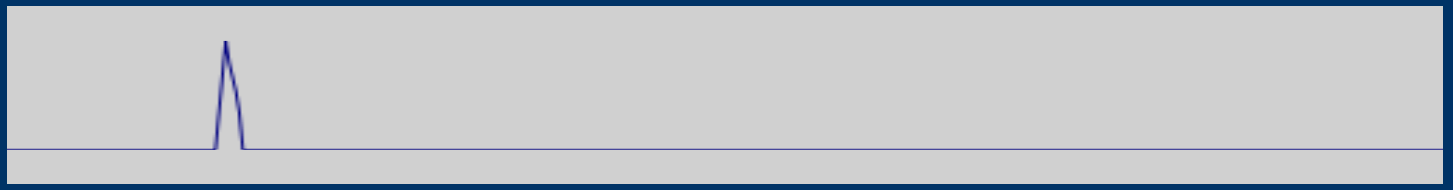


Coping with motion II(a): model it

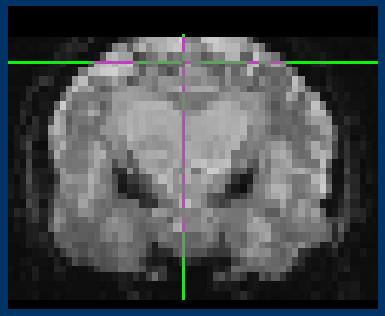


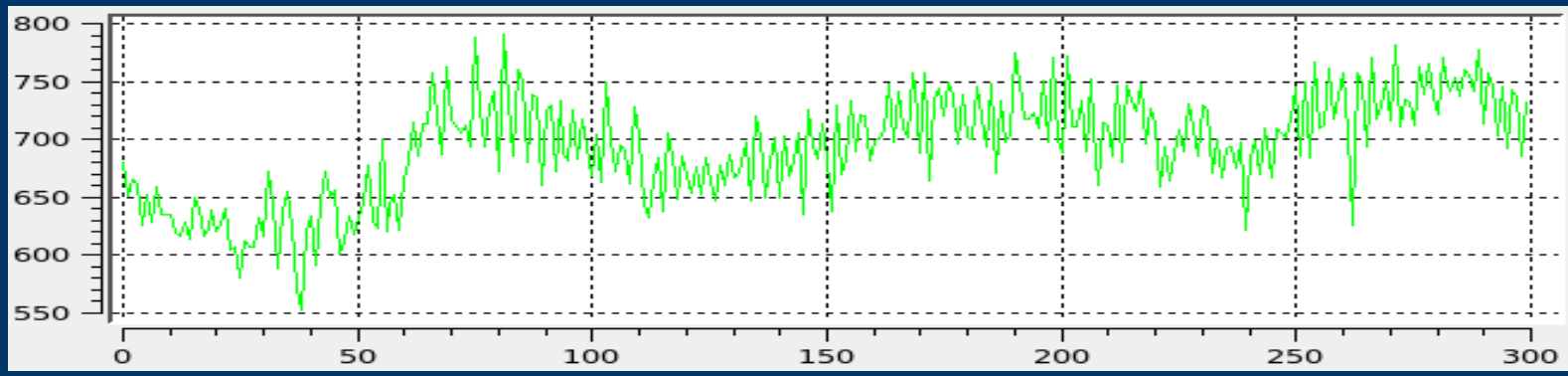


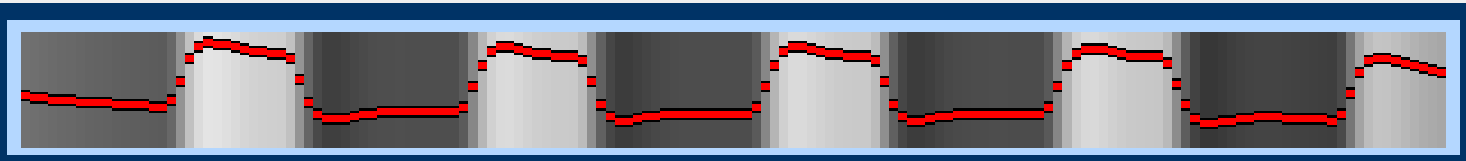


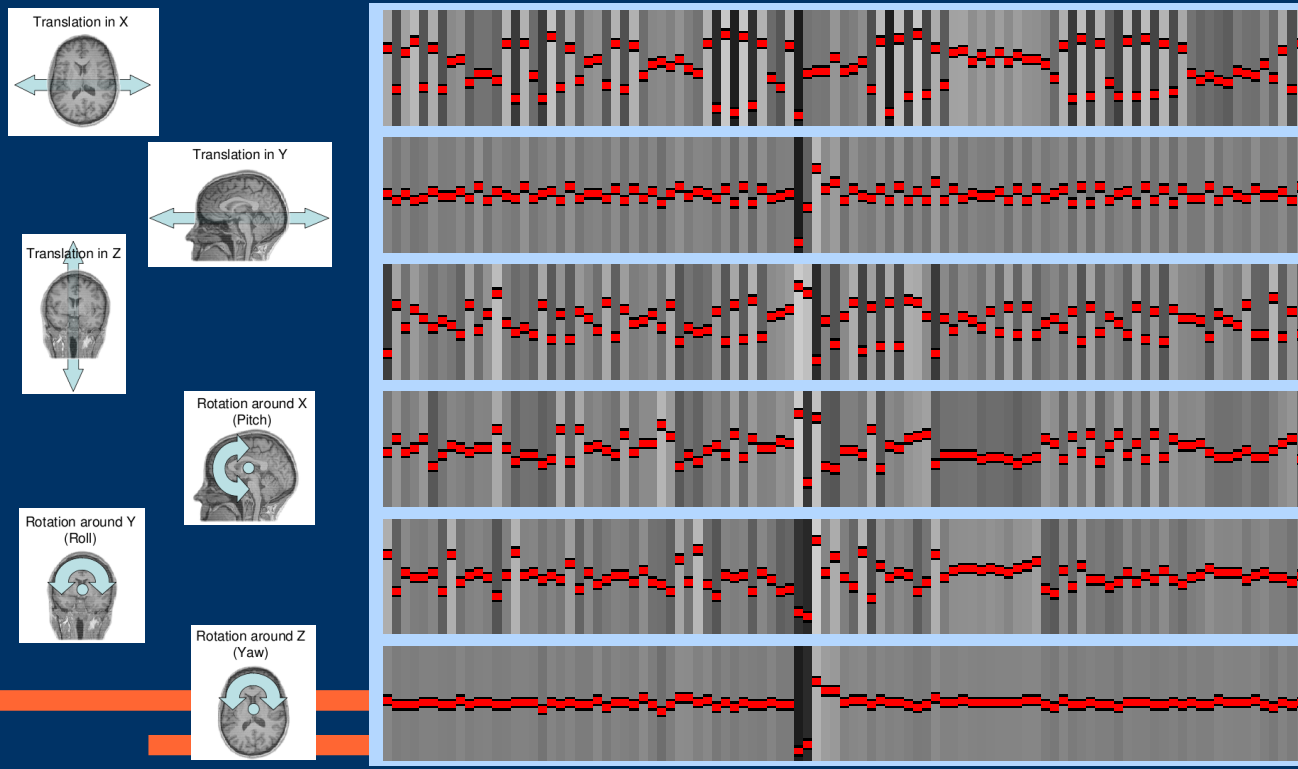


Coping with motion II(b): model it

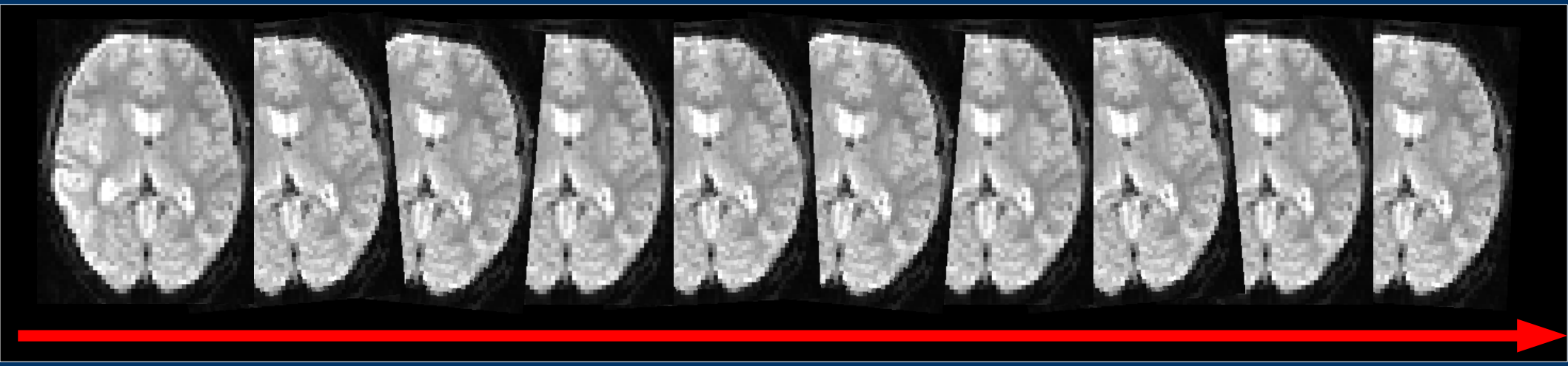


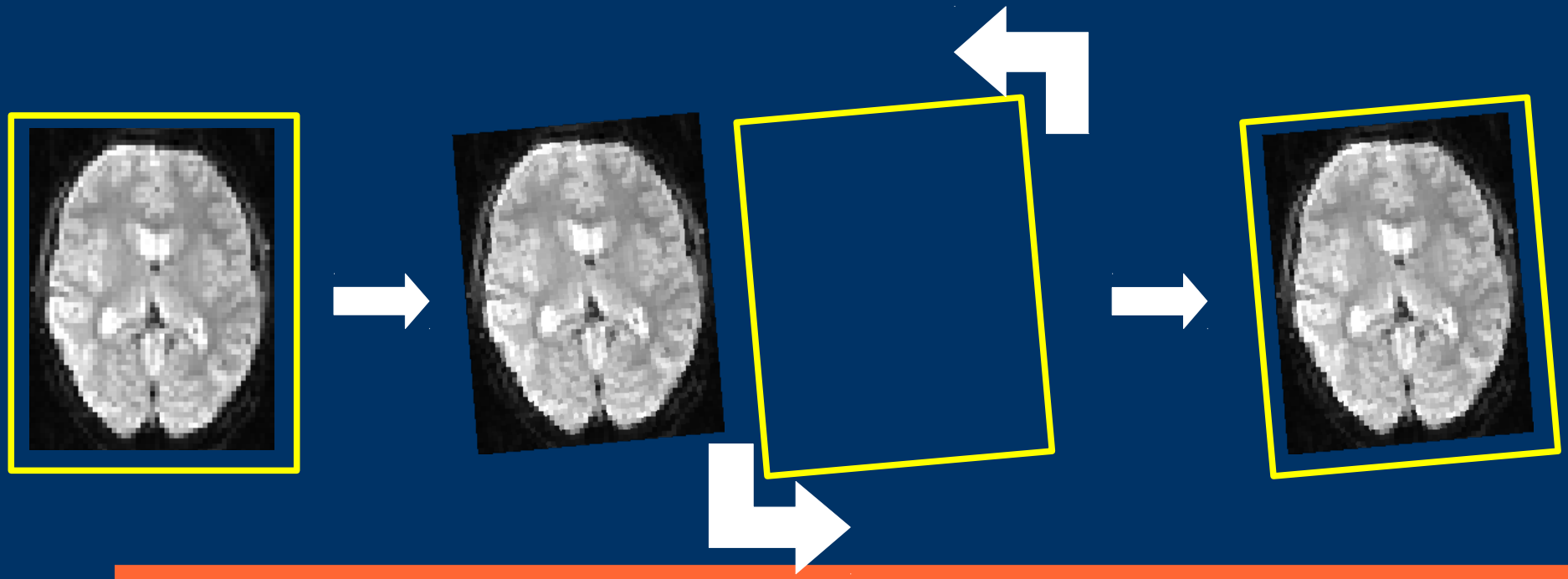




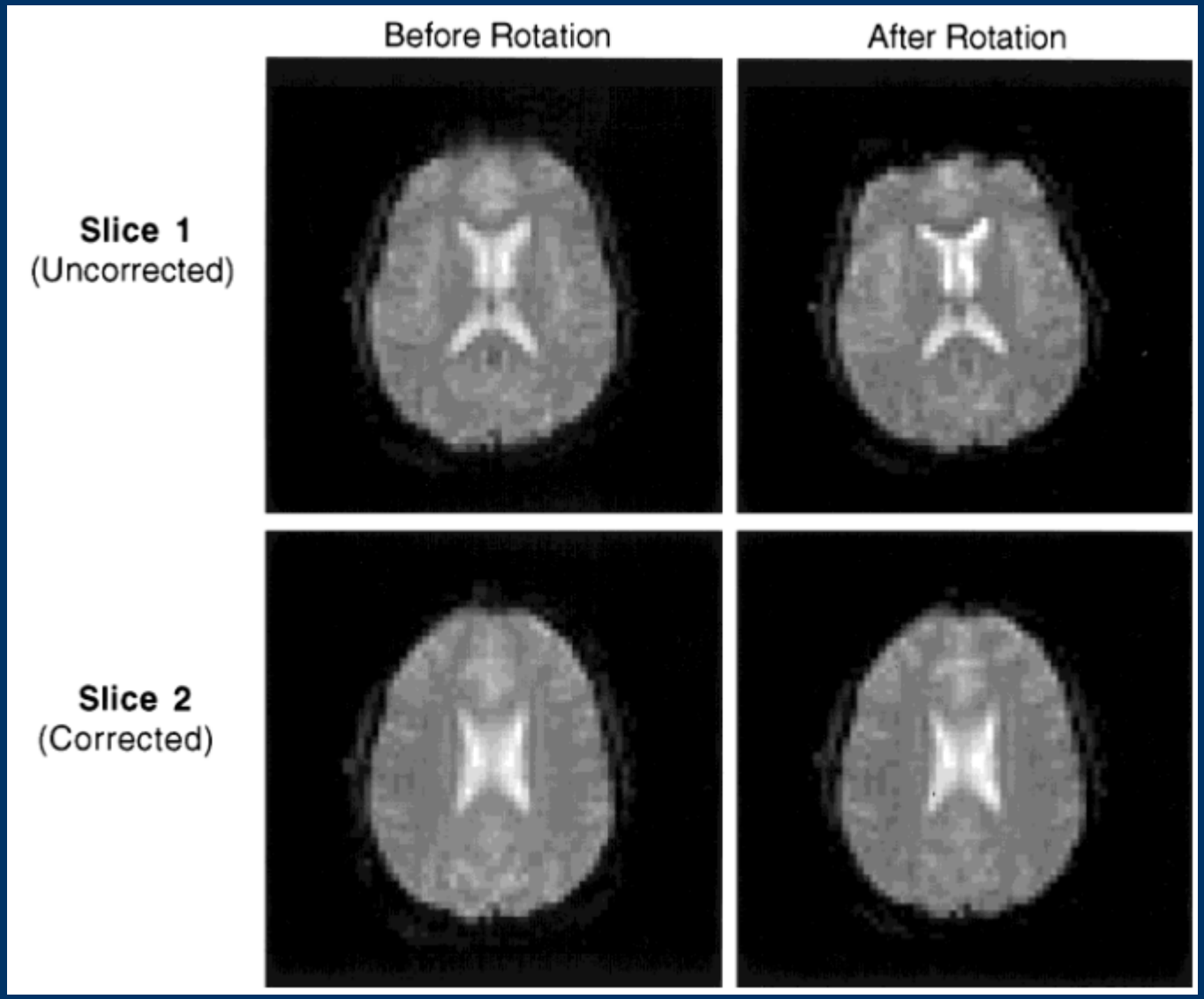


Coping with motion III: Prospective MC



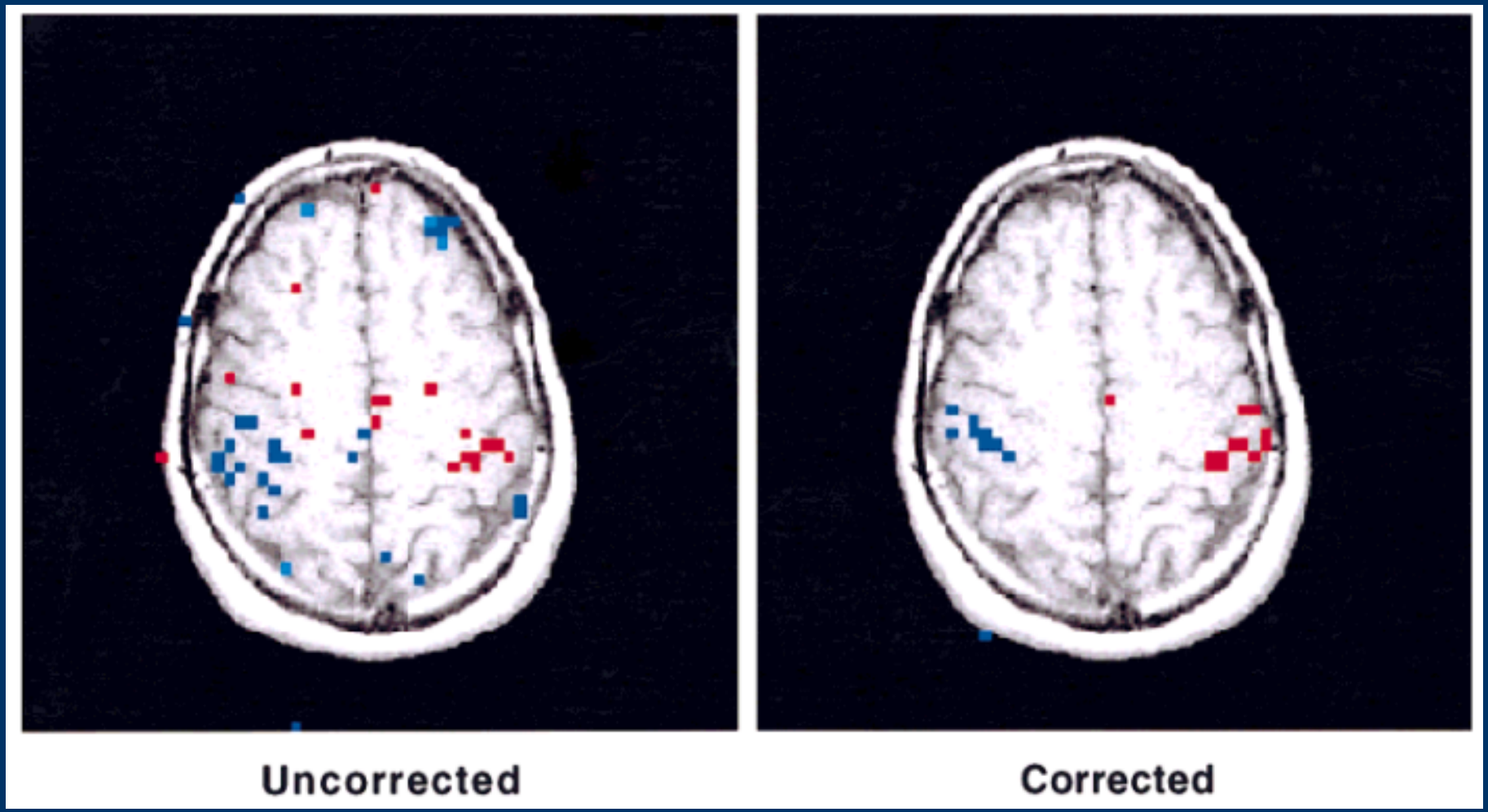


Prospective motion correction



Ward et al 2000 MRM

Prospective motion correction



Ward et al 2000 MRM

Motion correction is good, however:

- Even after all this, movement artefacts still remain
  - Residual (uncorrected) motion
  - There's no way of detecting rapid movements within a scan
  - Spin history effects*
  - Voxels will be in different magnetic fields as a result*
  - Task correlated motion

The moral of the story...

- ***Stop people from moving***
  - Make sure they're comfortable to begin with
  - Tell them that motion is a big problem
  - Train subjects?
  - Reward them?
- Decouple motion-prone tasks from cognitive event of interest
- Model motion out
- Reject run/subject

Preprocessing

i. Motion correction
ii. Slice timing correction
iii. Spatial filtering
iv. Temporal filtering
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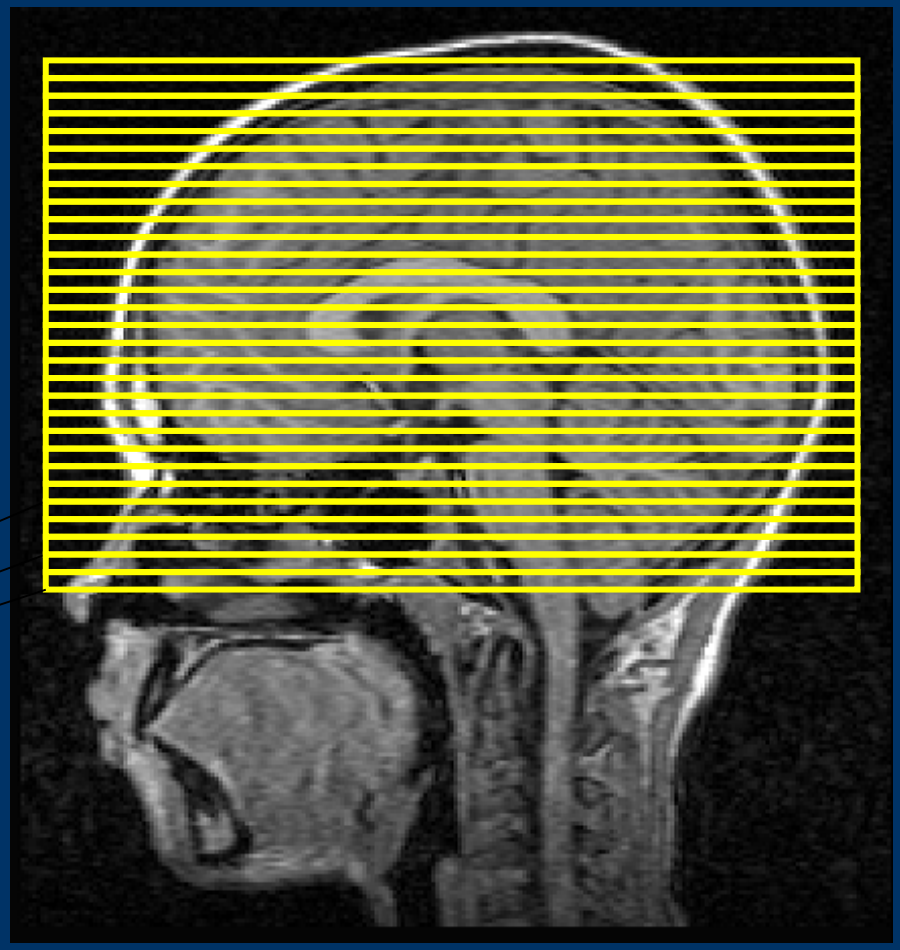
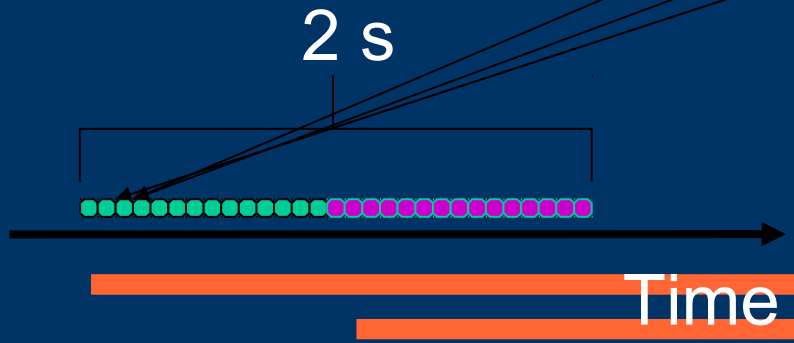
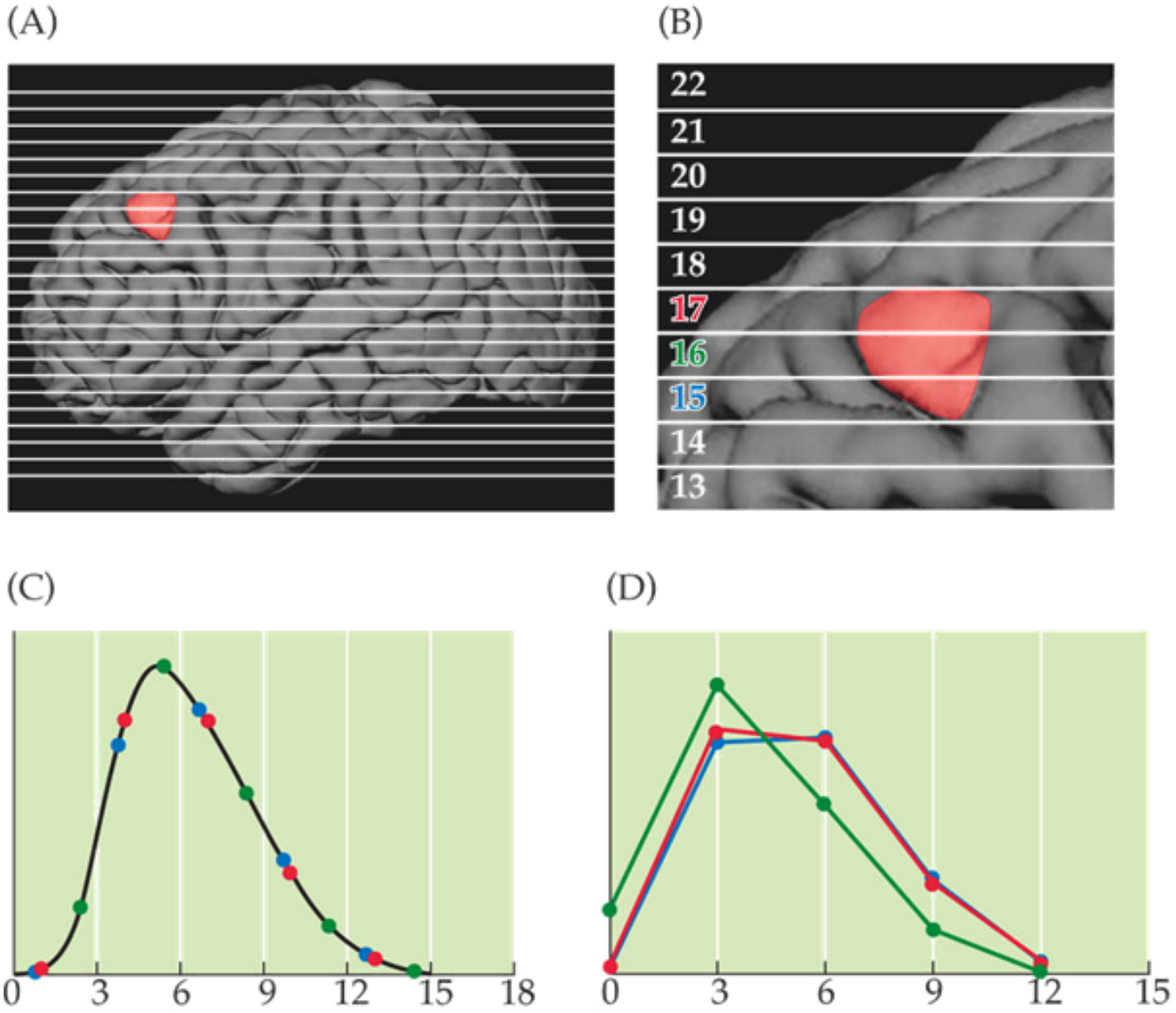
Slice timing correction

- In our exp we took a full functional image (volume) of the brain every 2 s.
- Each volume was acquired in 30 axial slices (interleaved).





Slice timing correction



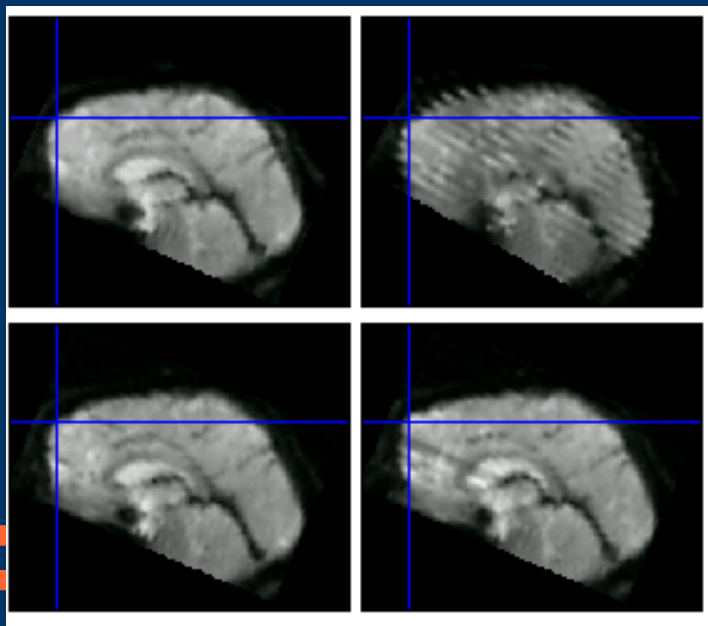
Huettel et al. Functional Magnetic Resonancel Imaging

Slice timing correction

- Most people now suggest not to do it

i. Not all that helpful & requires interpolation
ii. It may worsen artefacts (e.g., smearing spikes)
iii. Interacts in unpredictable ways with motion correction
iv. We spatially smooth across proximal slices
v. Mismatching TR and task
vi. Include temporal derivative of HRF

- What order? Ascending, descending, contiguous, interleaved.



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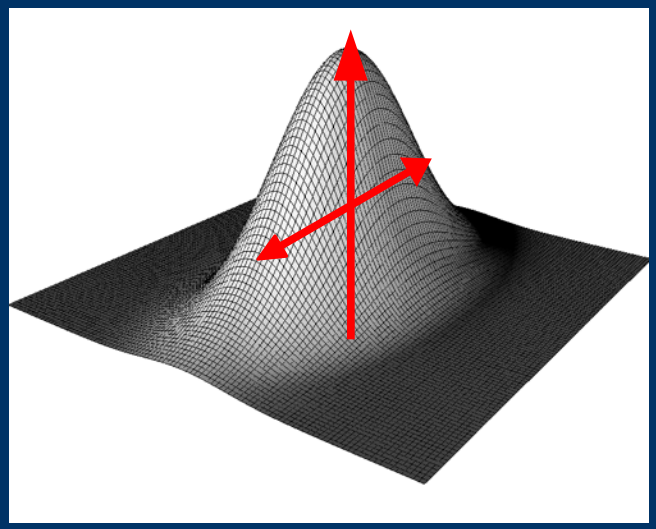
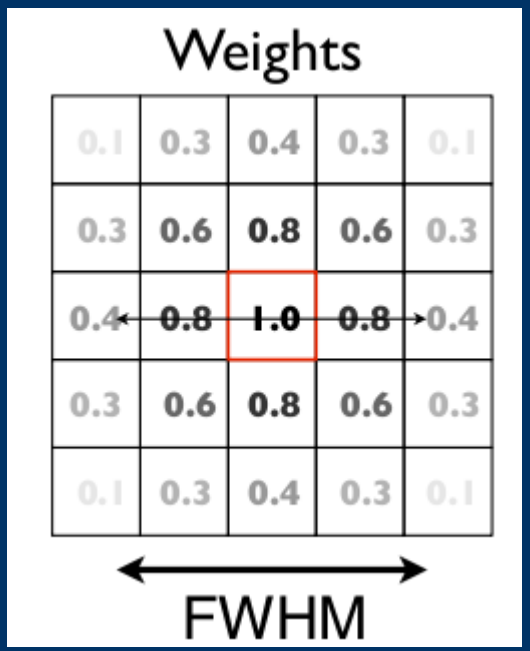
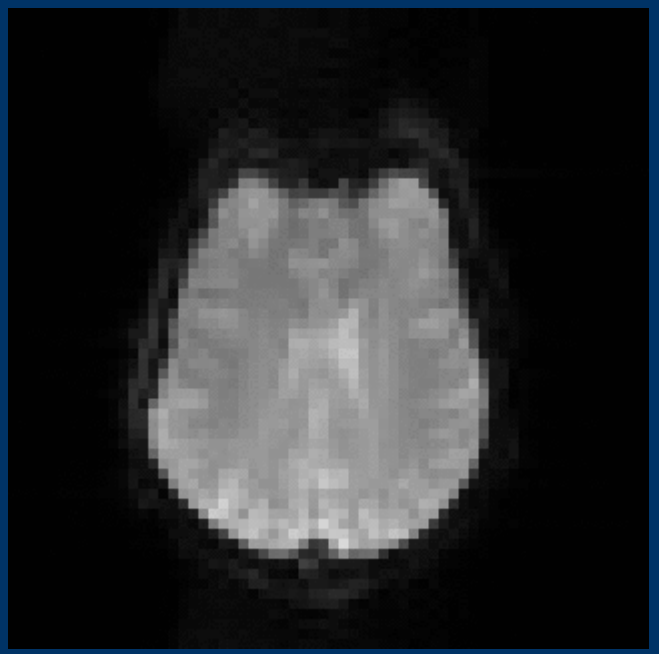
Spatial Filtering

- Replace each voxel's value with a weighted average of its value and the value of it's neighbouring voxels.
- Gaussian kernel (mm FWHM)



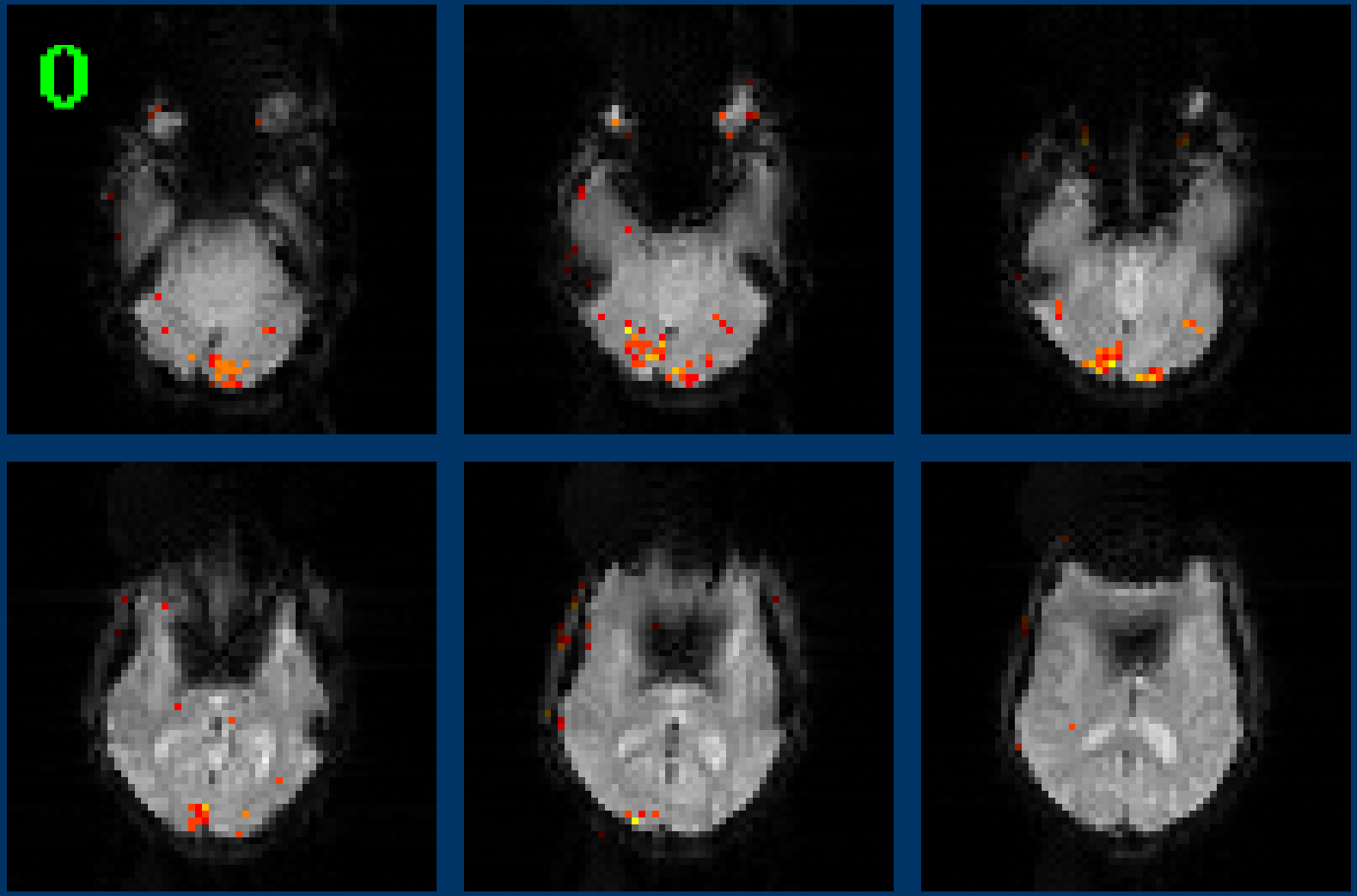




Spatial Filtering

- Advantages
  - Increases Signal to Noise Ratio (SNR)
    - *Matched Filter Theorem*: Maximum increase in SNR by filter with same shape/size as signal
  - Allows application of Gaussian Field Theory
  - May improve comparisons across subjects
- Disadvantages
  - Reduces spatial resolution
  - May reduce your signal if smaller than your filter size!

Spatial Filtering



Source FSL website

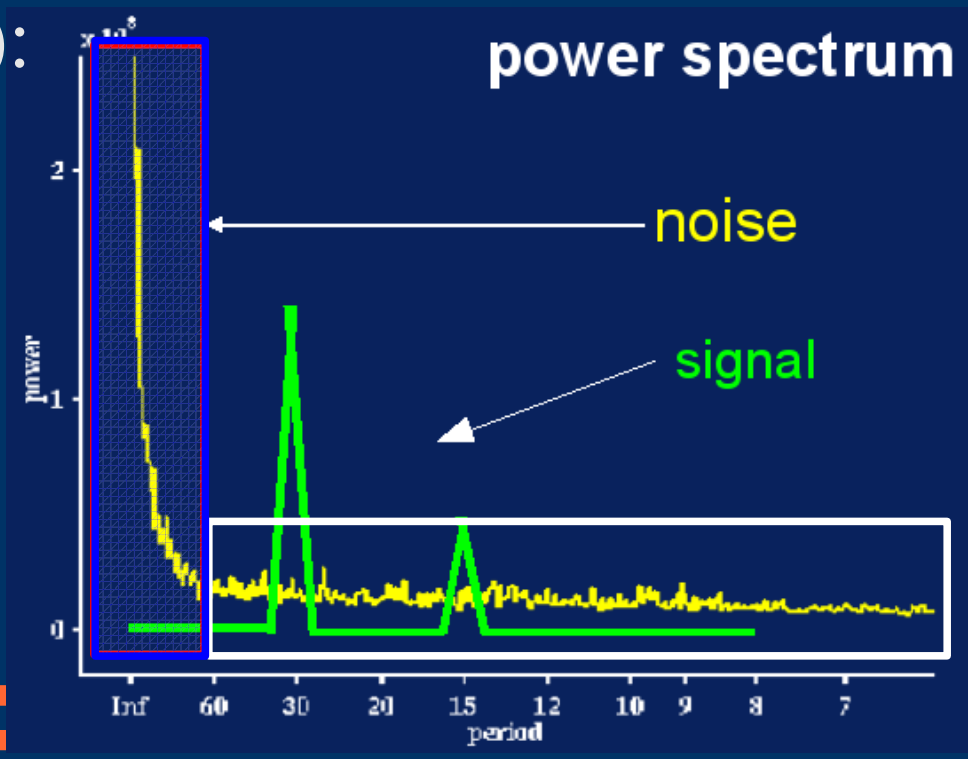
Preprocessing

i. Motion correction
ii. Slice timing correction
iii. Spatial filtering
iv. Temporal filtering
v. Intensity normalization
vi. Field distortion correction (unwarping)

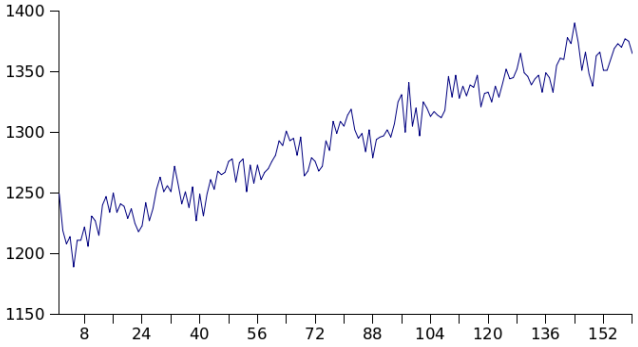
Temporal Filtering

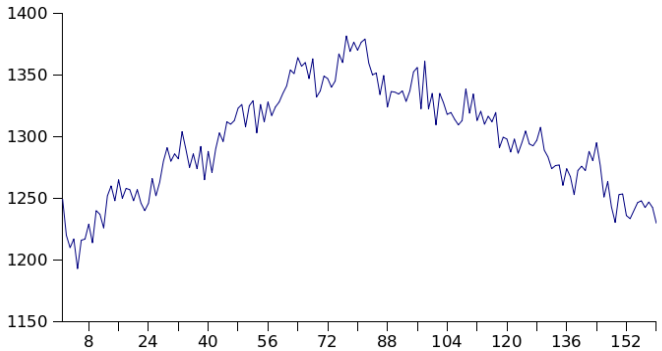
- You are interested in the signal fluctuations that have to do with your task, and thus are at a specific frequency

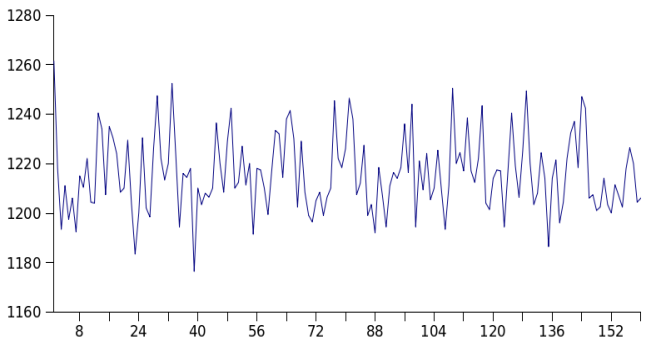
- But there is a lot of activity at many other frequencies (particularly at low ones: 1/f):
  - Scanner drift
  - Thermal noise
  - Heart beat
  - Respiration
  - Alertness
  - Learning

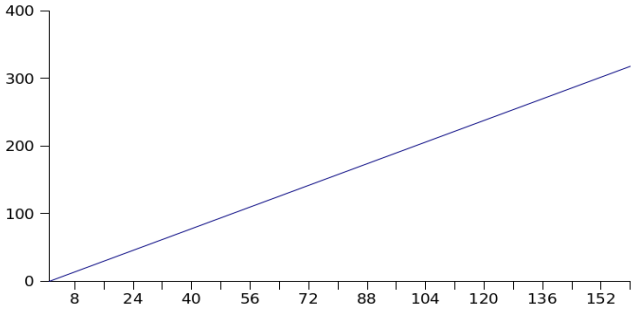


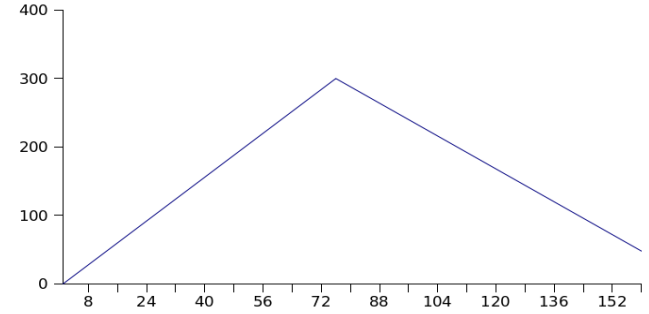
Signal & Noise

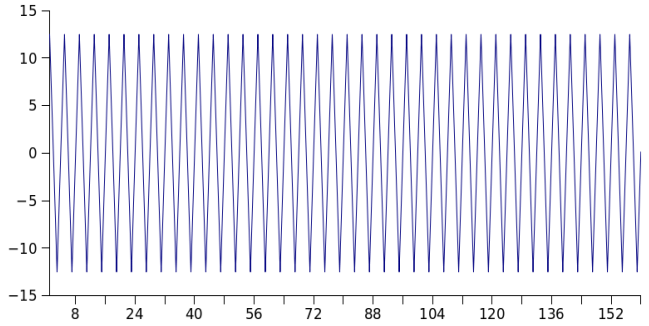


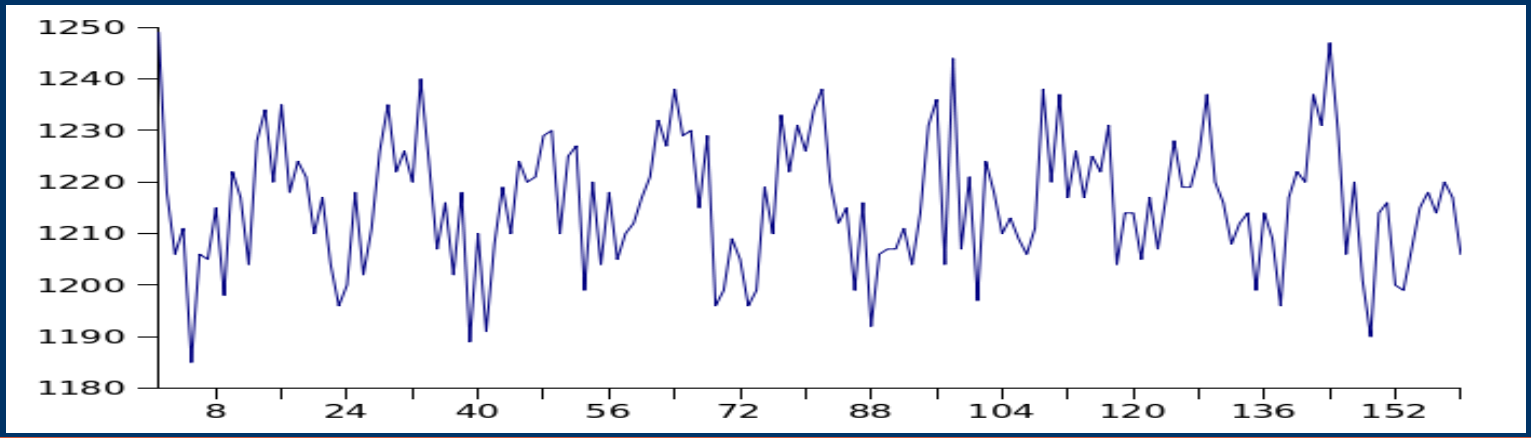






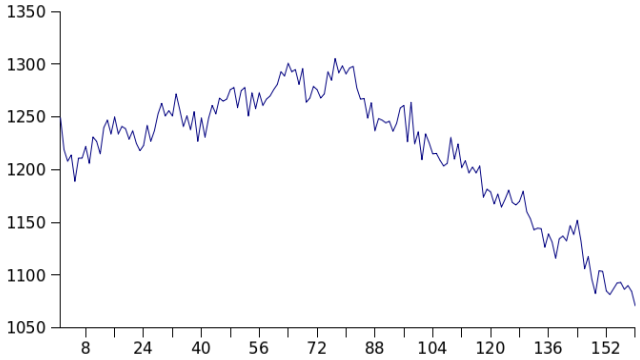




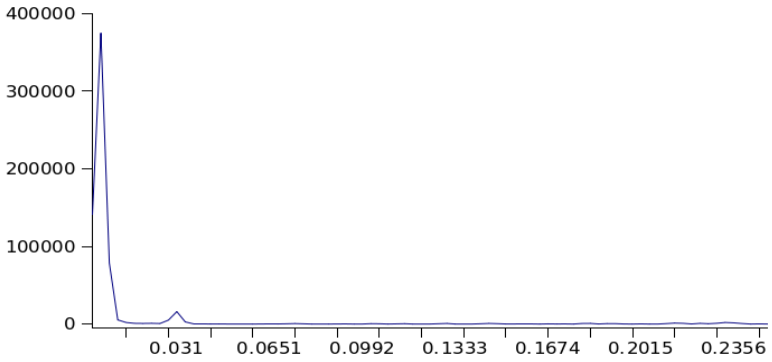


High-Pass Filtering

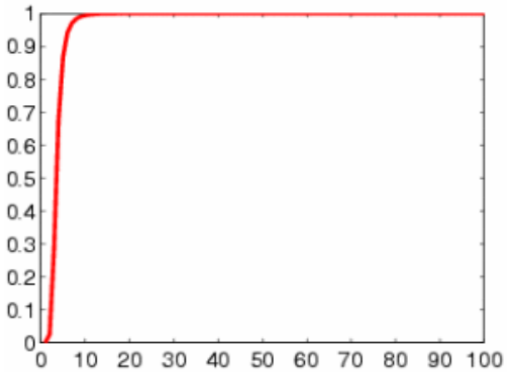
Timecourse

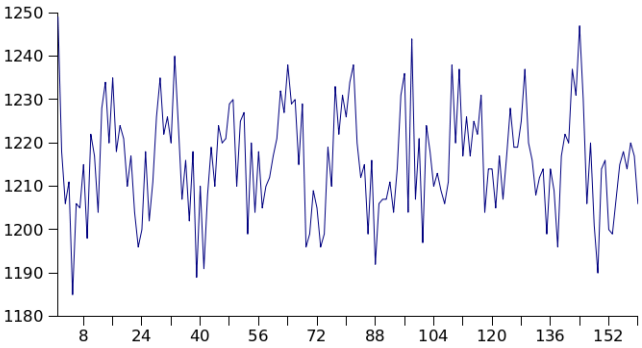


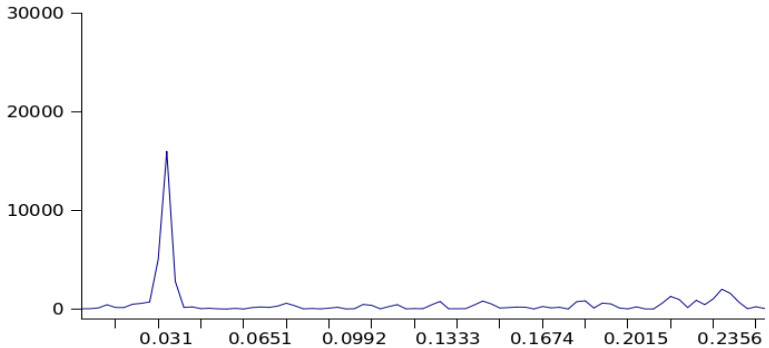
Power Spectrum



HP Filter

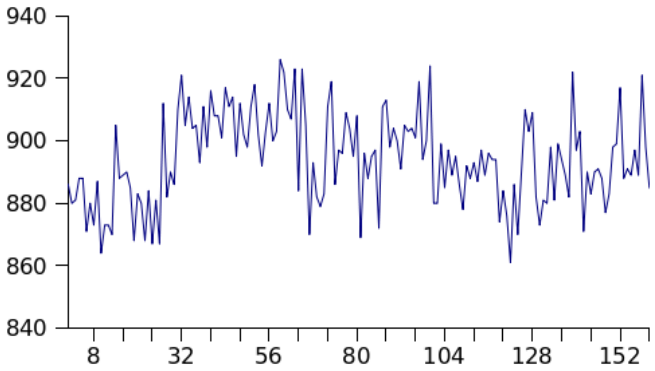


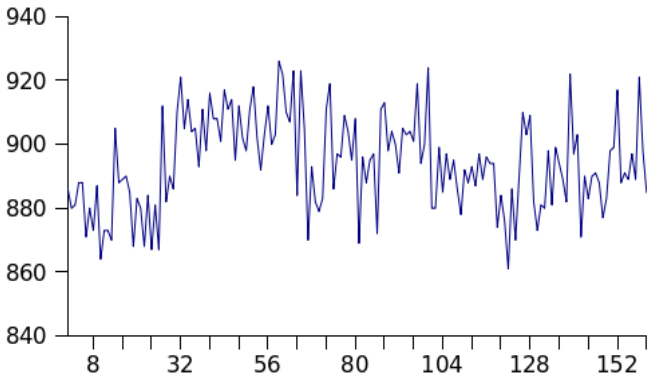




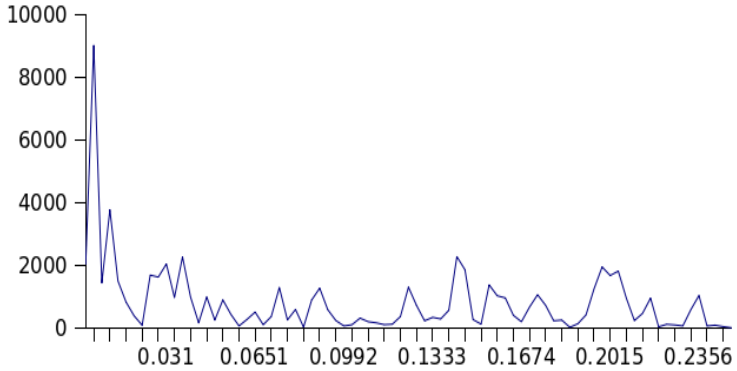
High-Pass Filtering

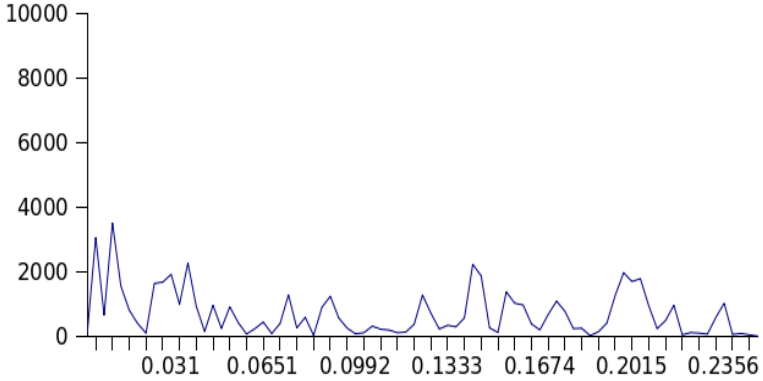
Timecourse



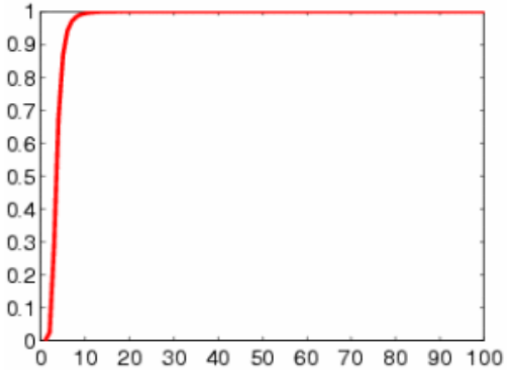


Power Spectrum



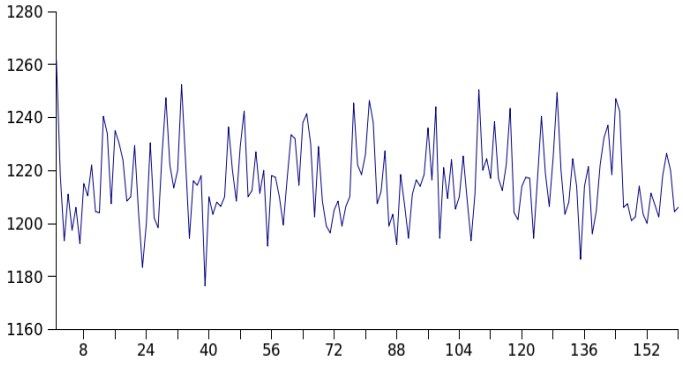


HP Filter

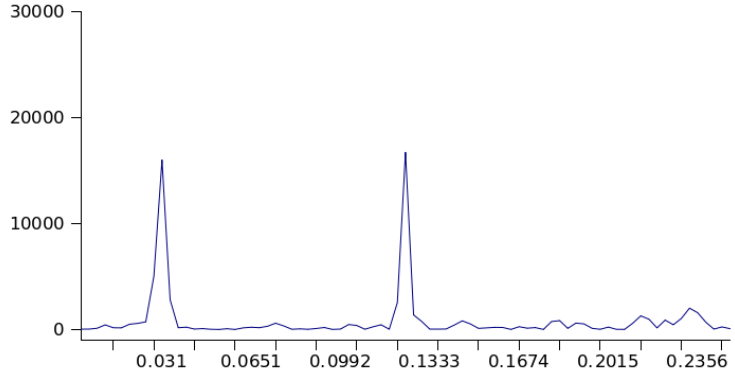


Low-Pass Filtering

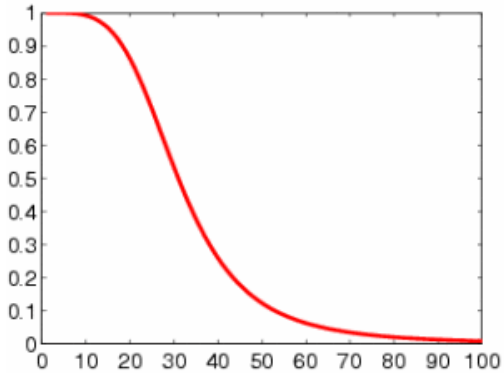
Timecourse

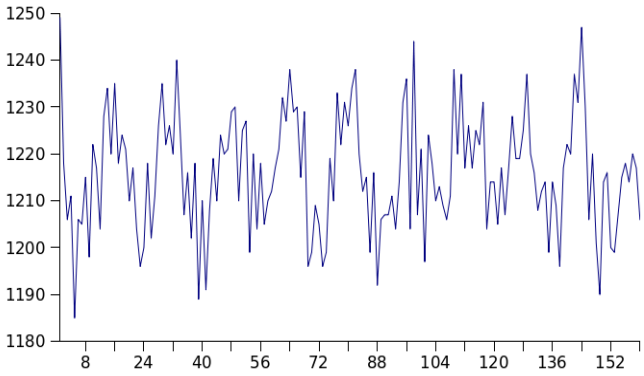


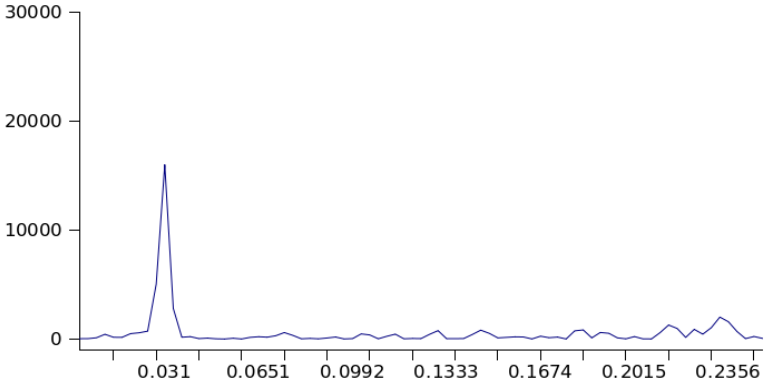
Power Spectrum



LP Filter

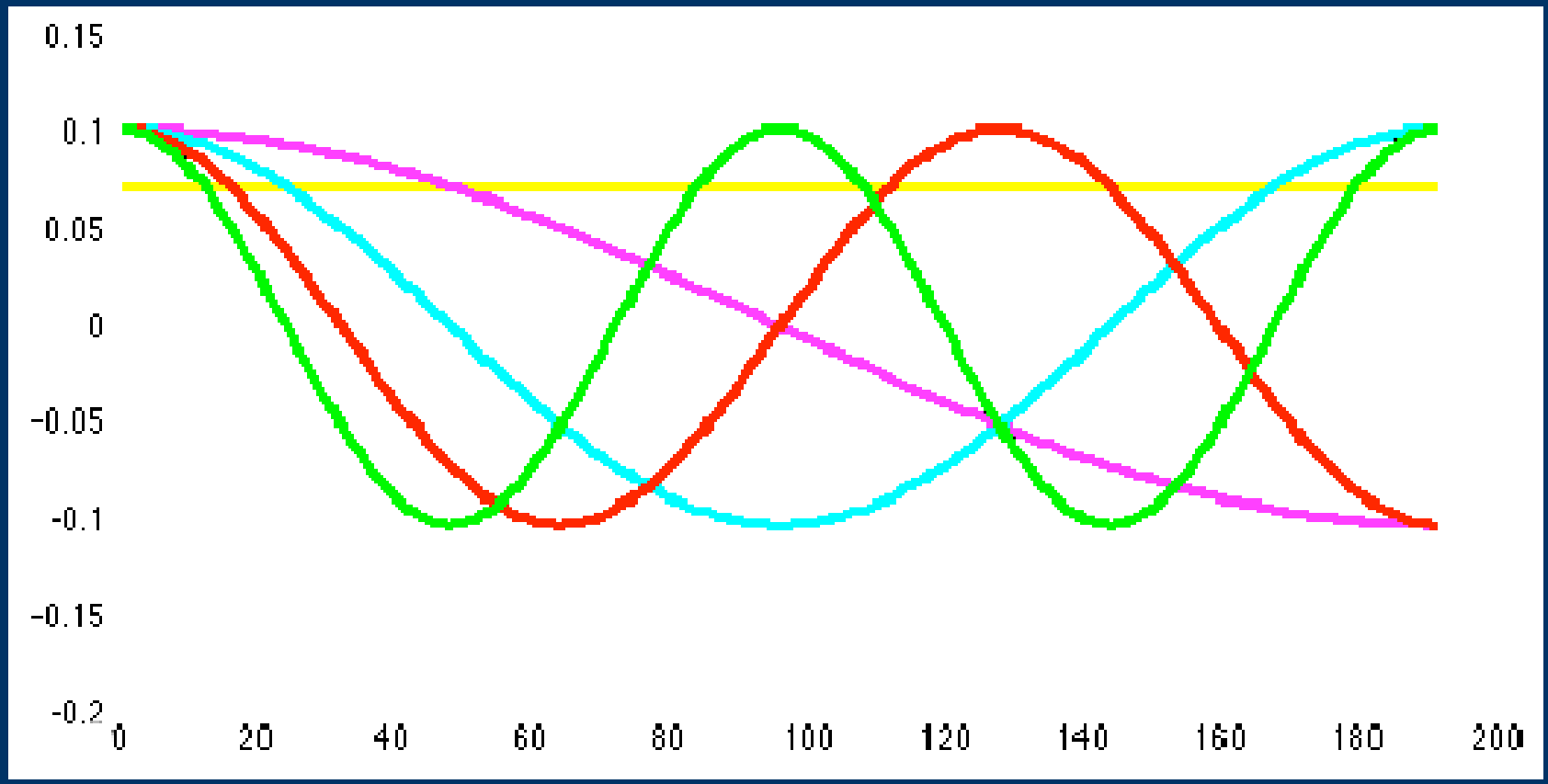






HP Filtering Strategy I: SPM

- Model low drifts to “soak up” their variance (using a discrete cosine transform basis set).



HP Filtering Strategy I: SPM

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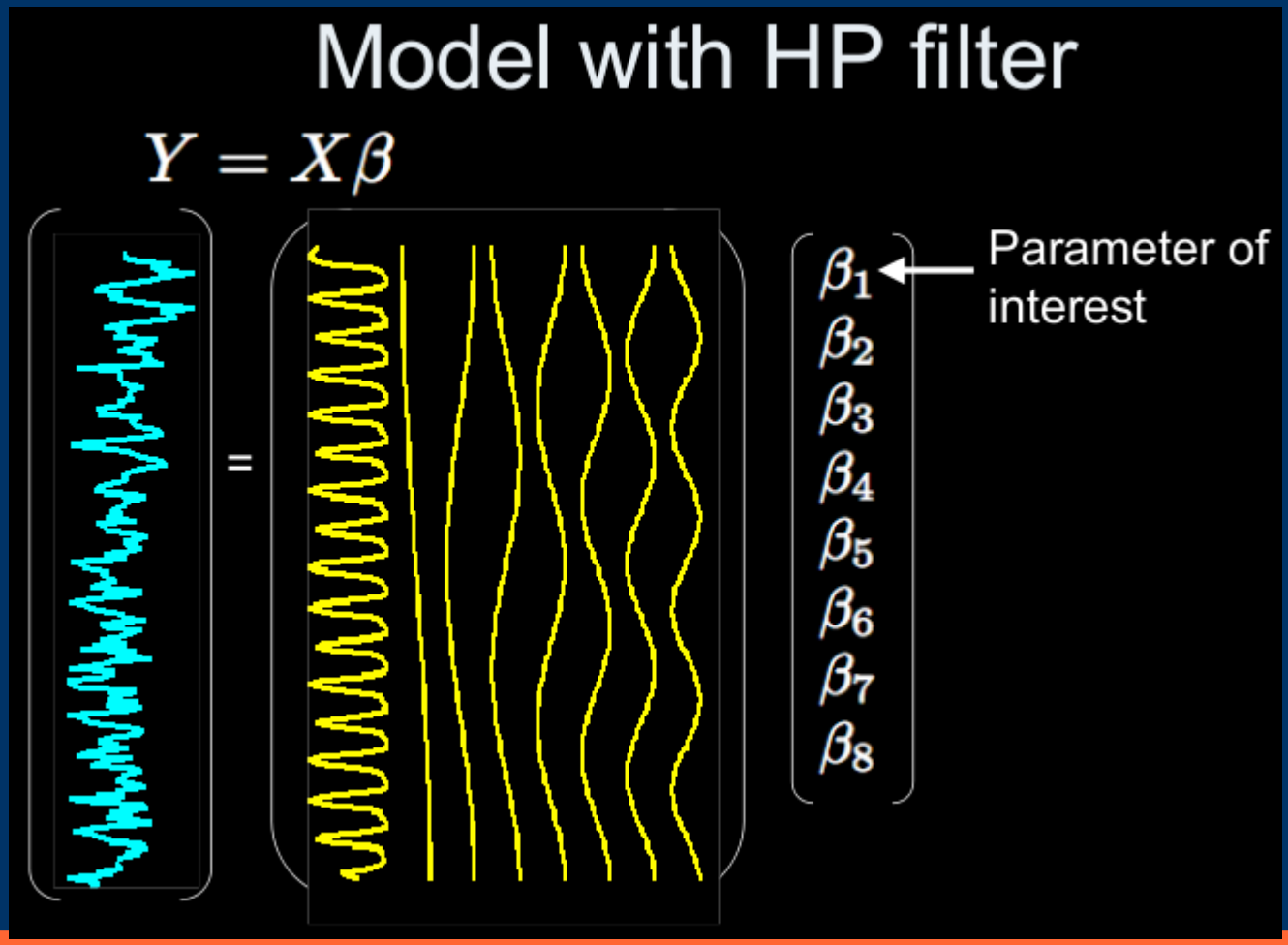
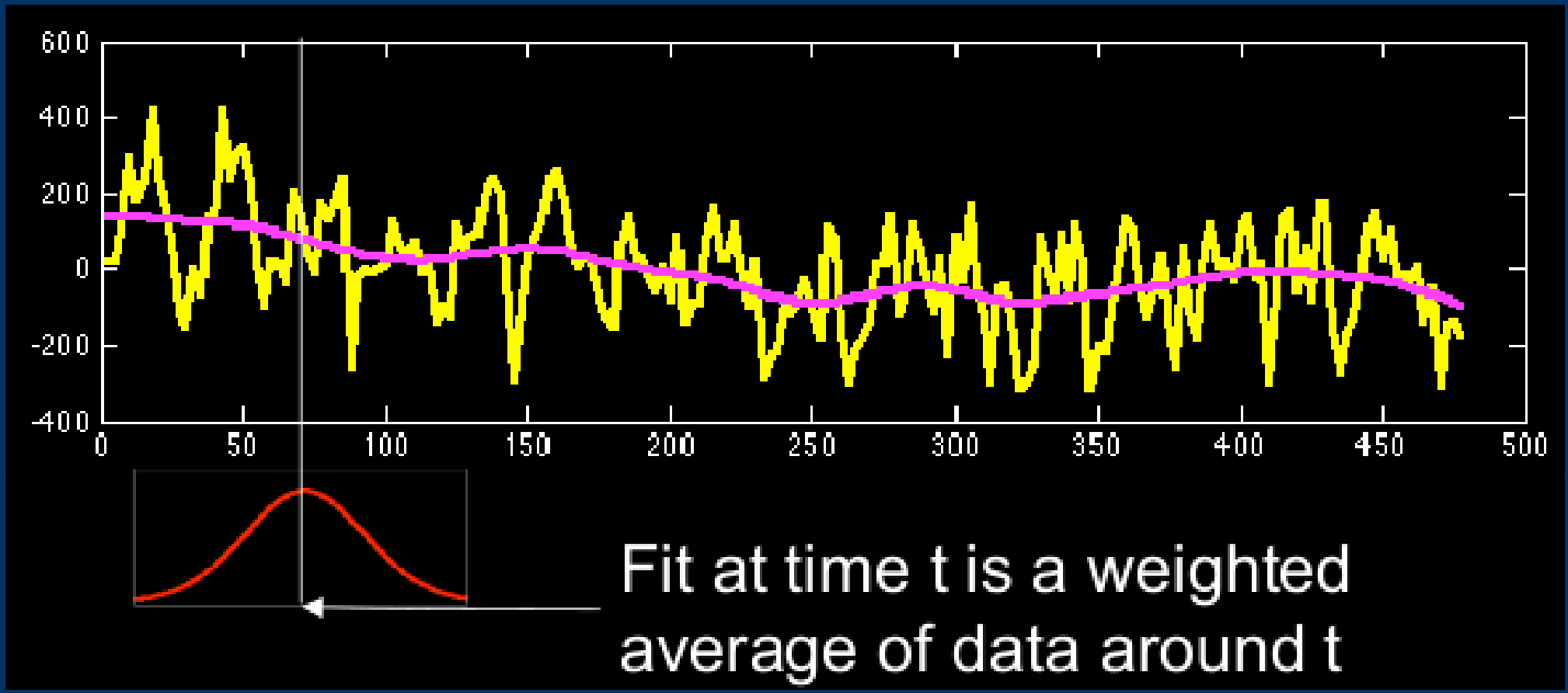


HP Filtering Strategy II: FSL

- Remove low drifts from the signal:
  i. Fit a Gaussian-weighted running line

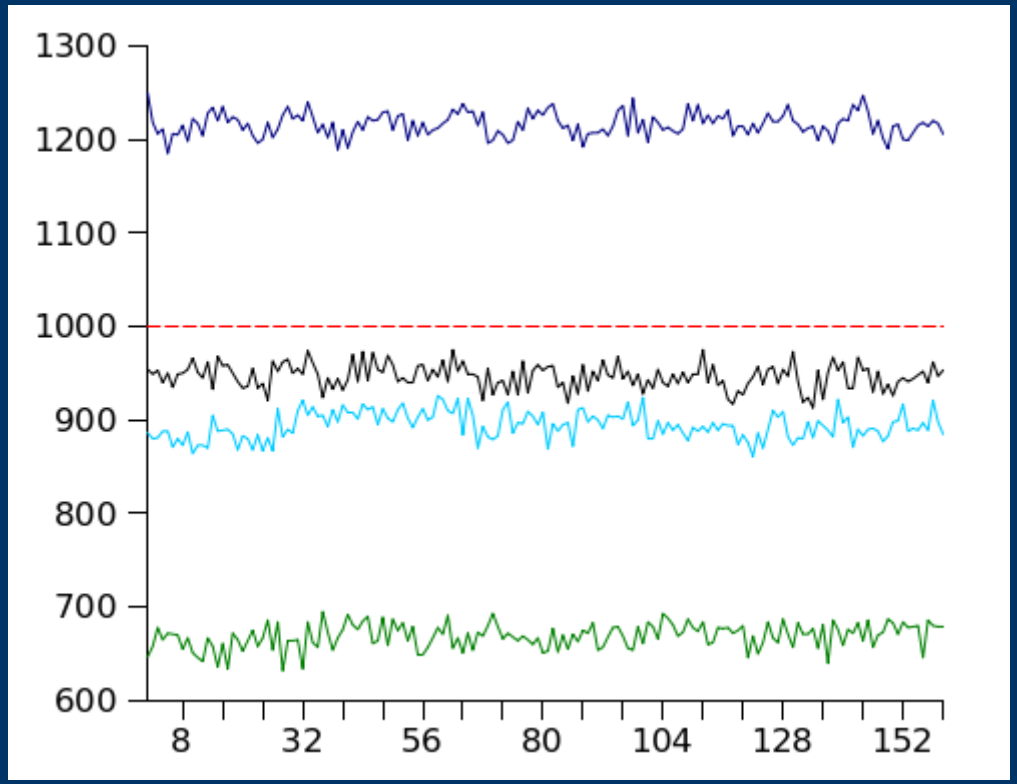


Preprocessing

i. Motion correction
ii. Slice timing correction
iii. Spatial filtering
iv. Temporal filtering
v. Intensity normalization
vi. Field distortion correction (unwarping)

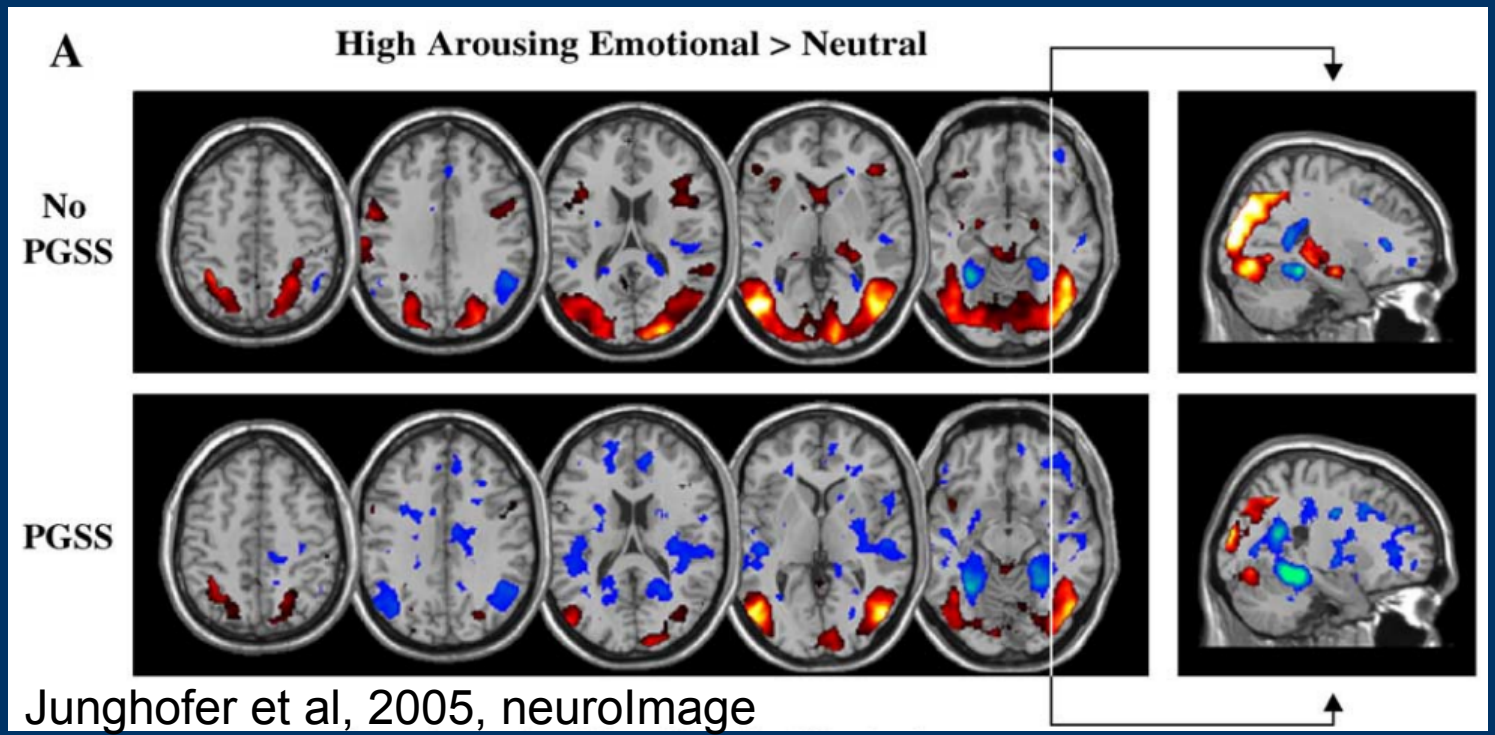
Intensity Normalization

- ***Between-session (grand mean scaling)***
- The mean intensity of each 4D dataset varies for non-experimentally interesting reasons.
- Scale each 4D time-series by a single factor.
- Time-series from different runs are now centred around the same mean.



Intensity Normalization

- ***Within-session***
- Forces each volumes (***within a run***) to have the same mean intensity.

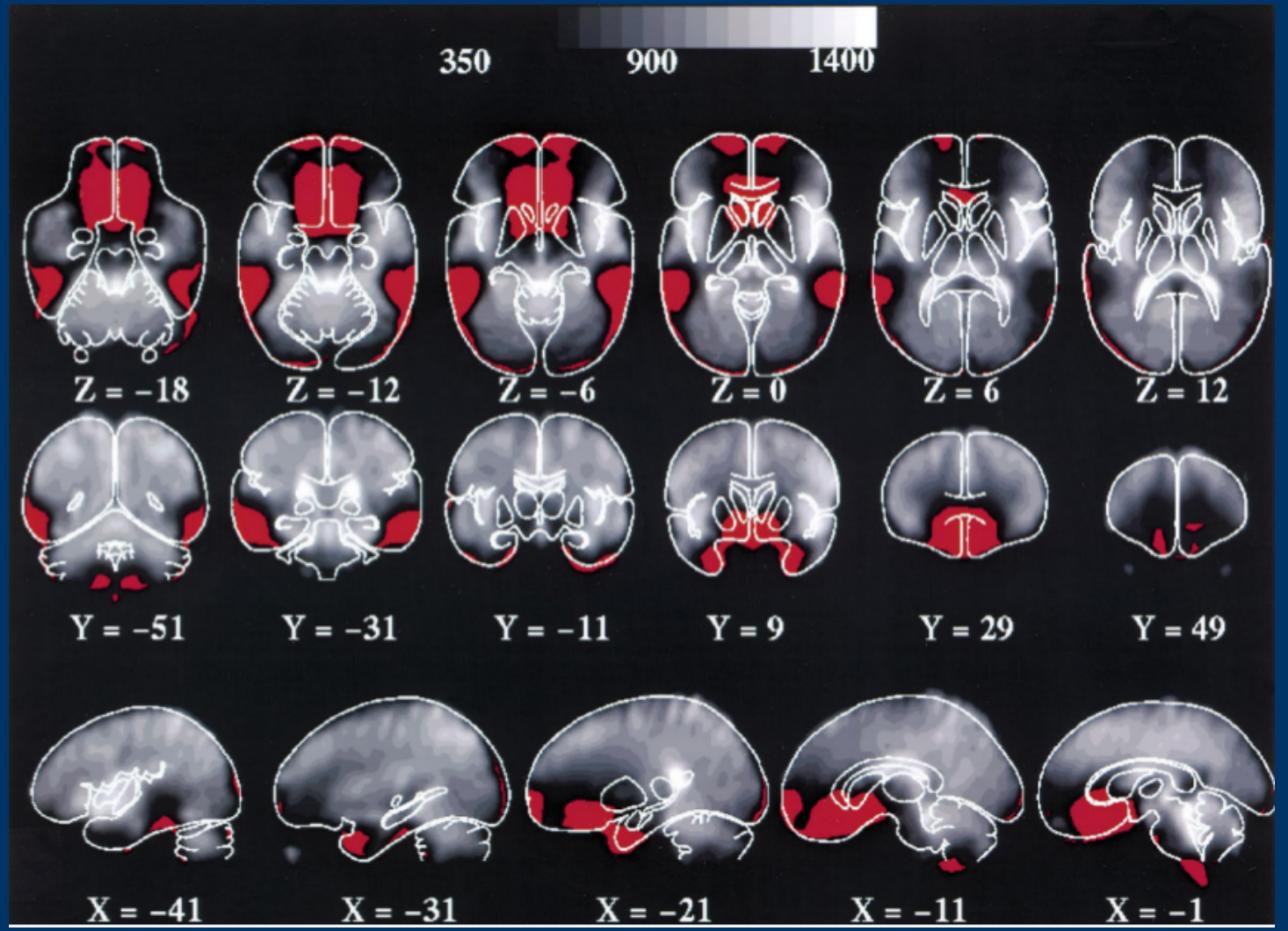


Junghofer et al, 2005, neuroImage

Preprocessing

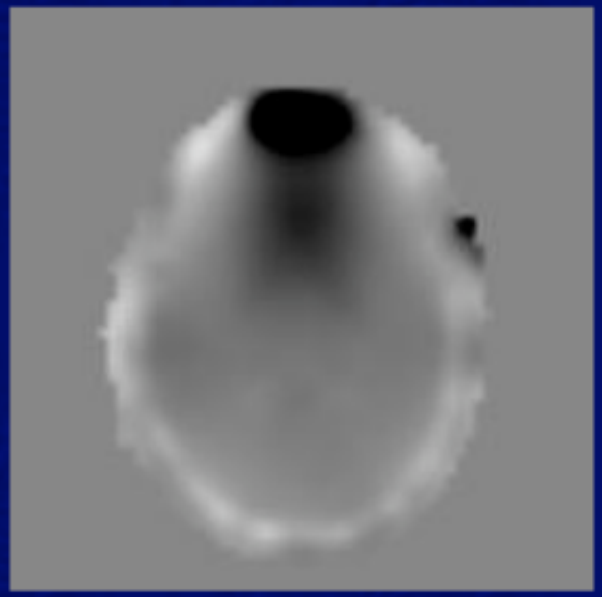
i. Motion correction
ii. Slice timing correction
iii. Spatial filtering
iv. Temporal filtering
v. Intensity normalization
vi. Field distortion correction (unwarping)

Geometric distortions

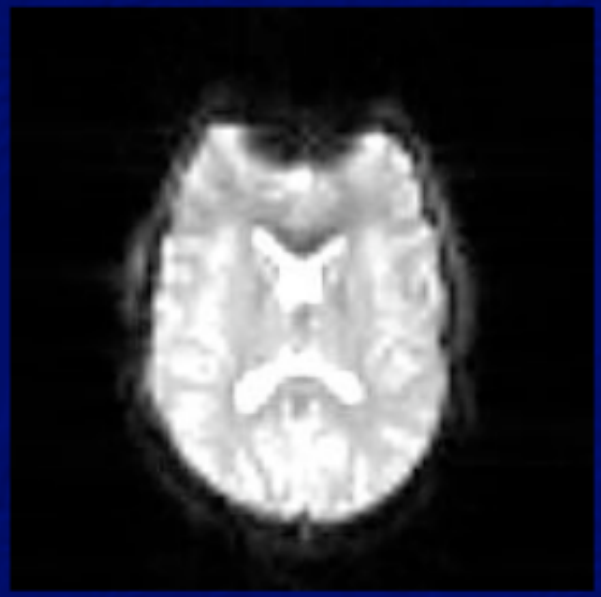


Un-warping for field distortion

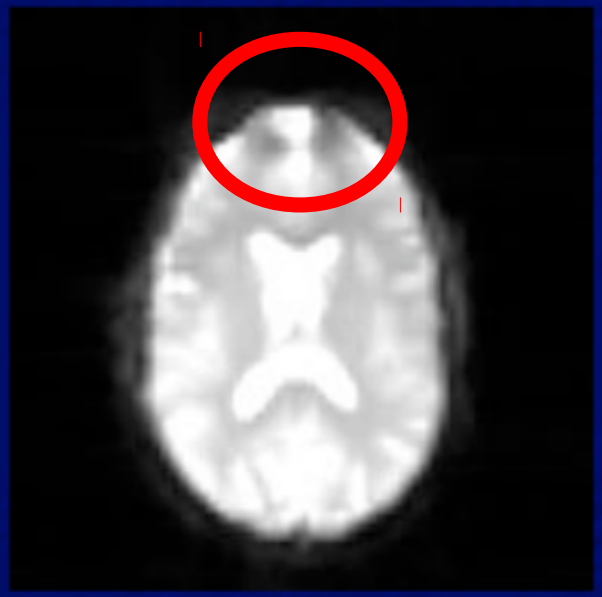
Field Map

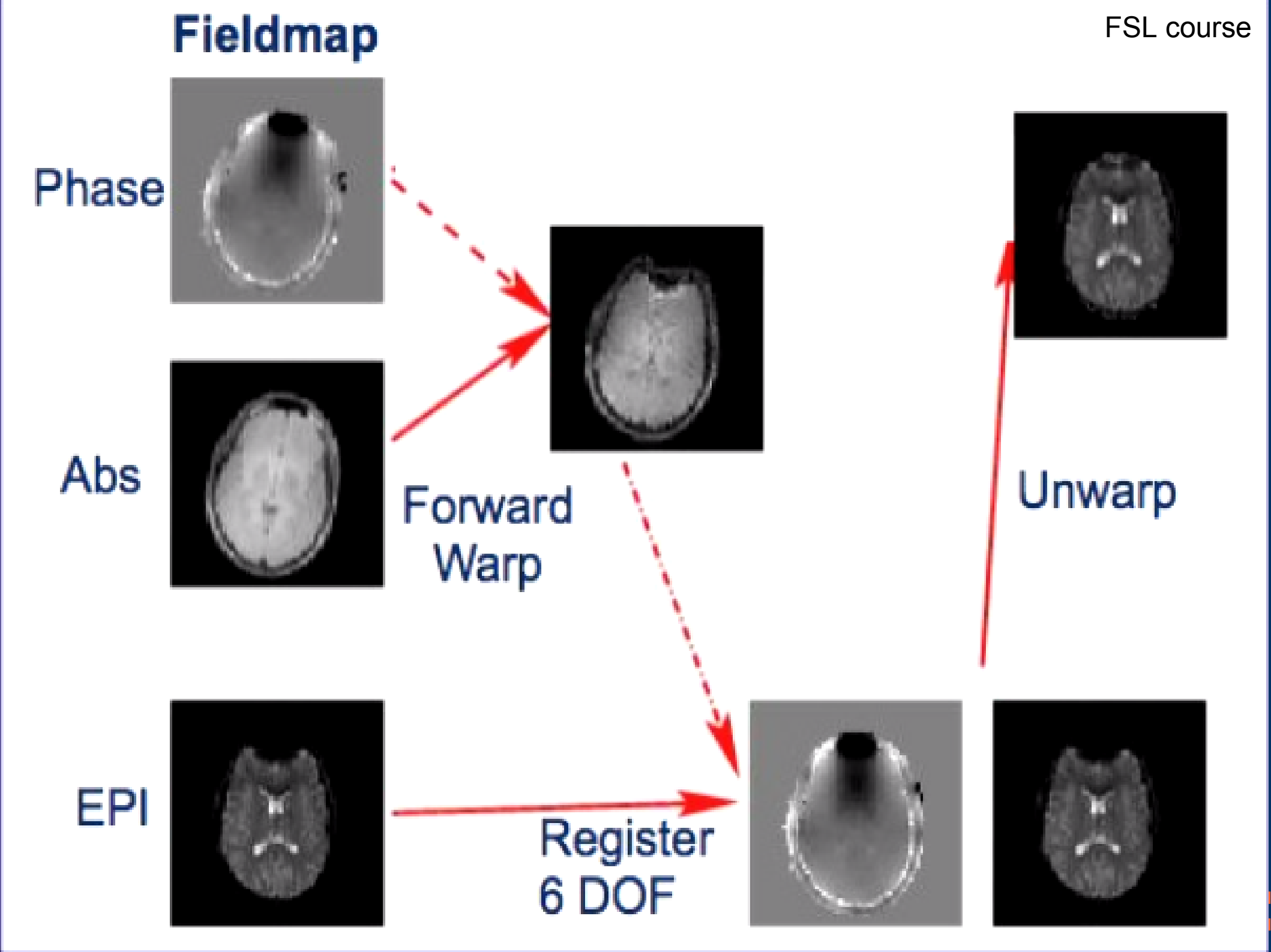


EPI



Unwarped EPI

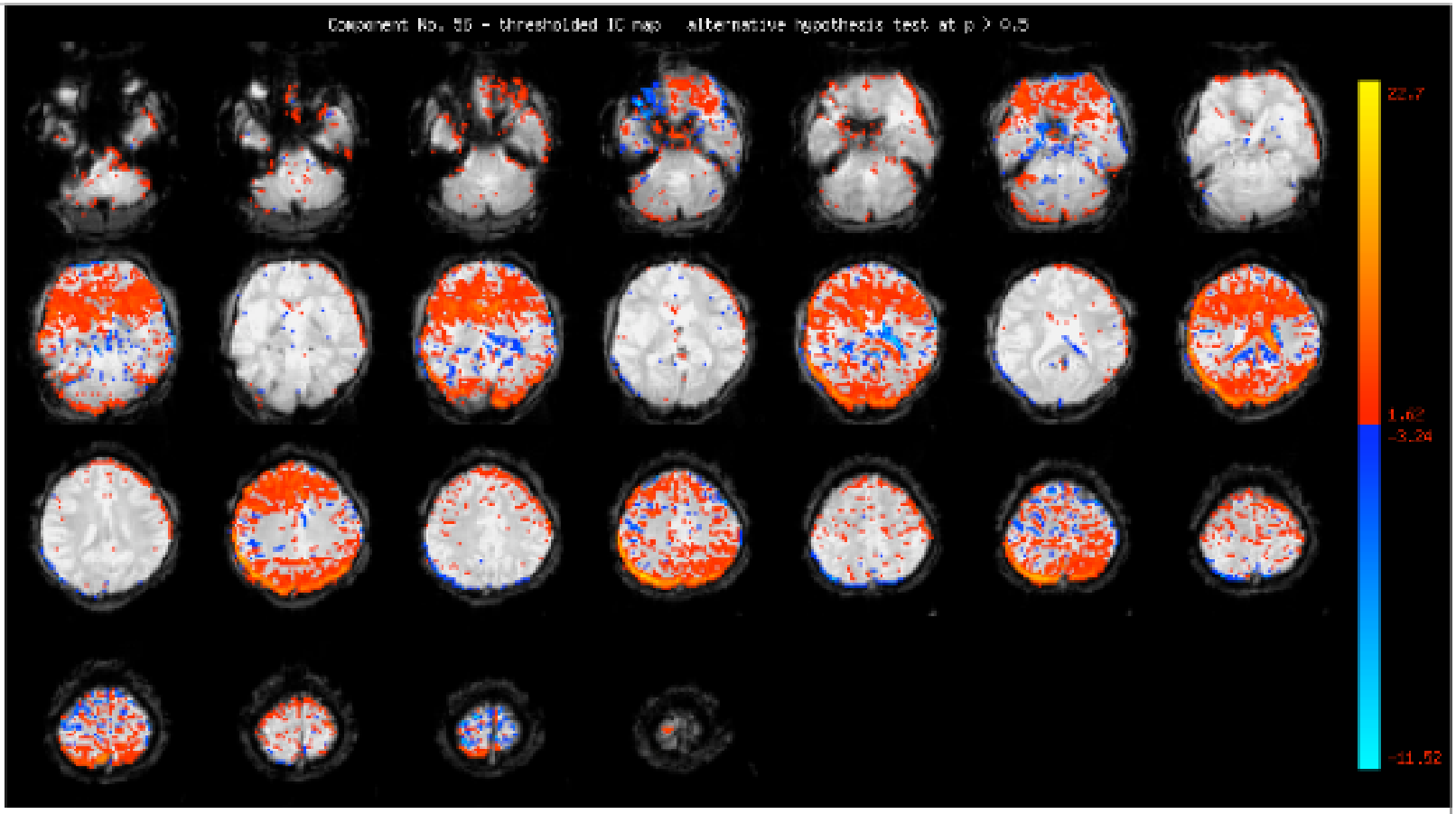


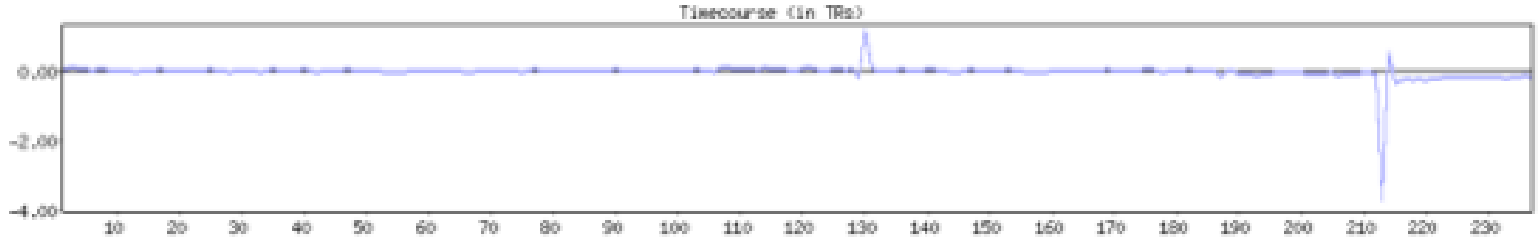

Fieldmap
Phase
Abs
Forward
Warp
Unwarp
EPI
Register
6 DOF

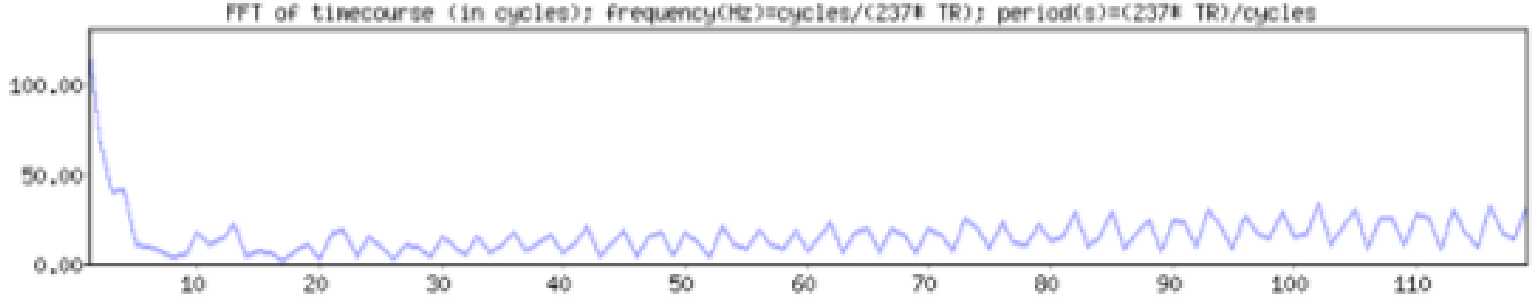
Preprocessing 2.0: ICA

1. Run an Independent Component Analysis
2. Find noise components
3. “Clean” the data
4. Run analysis on de-noised data

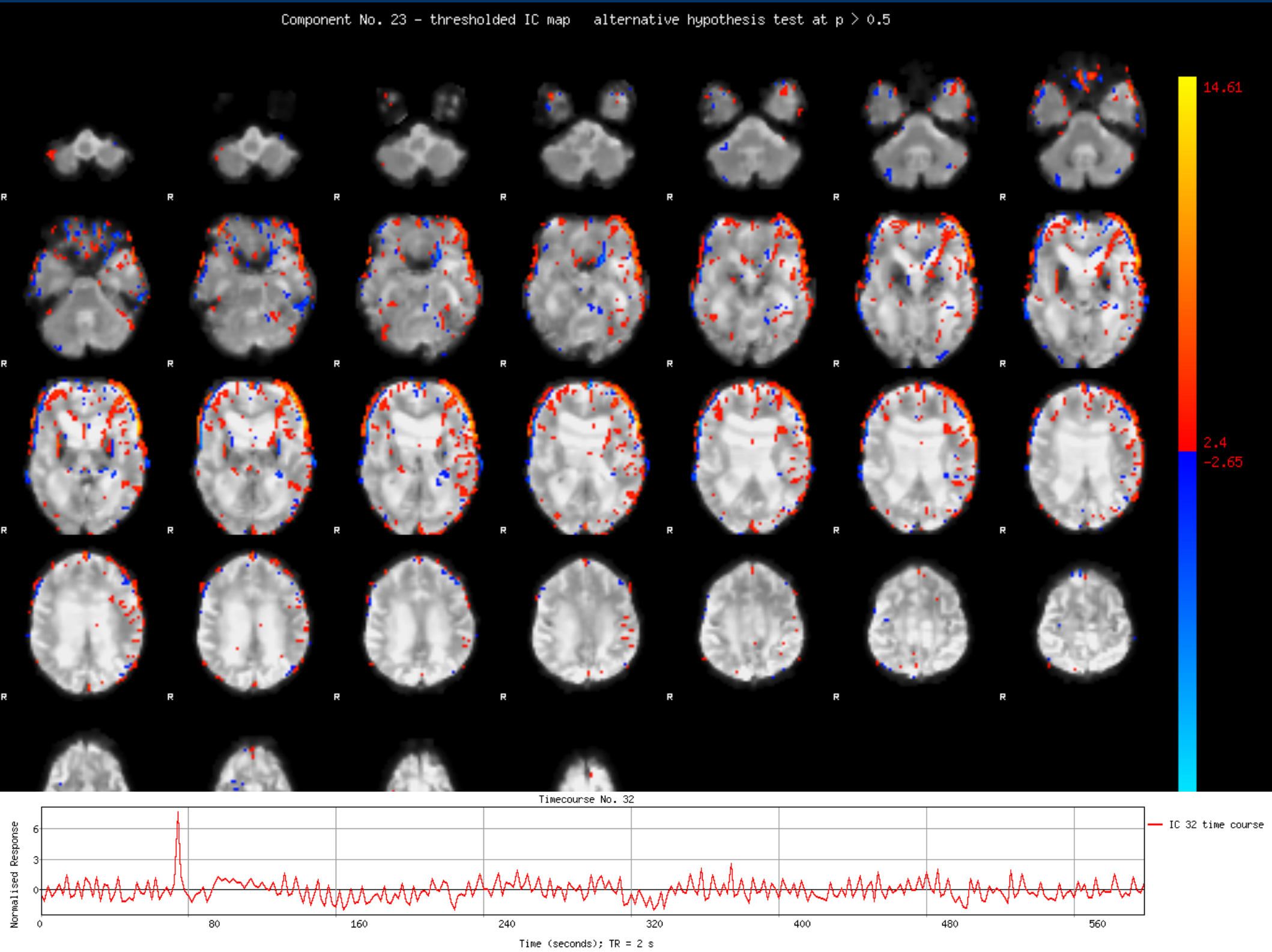
Abrupt motion



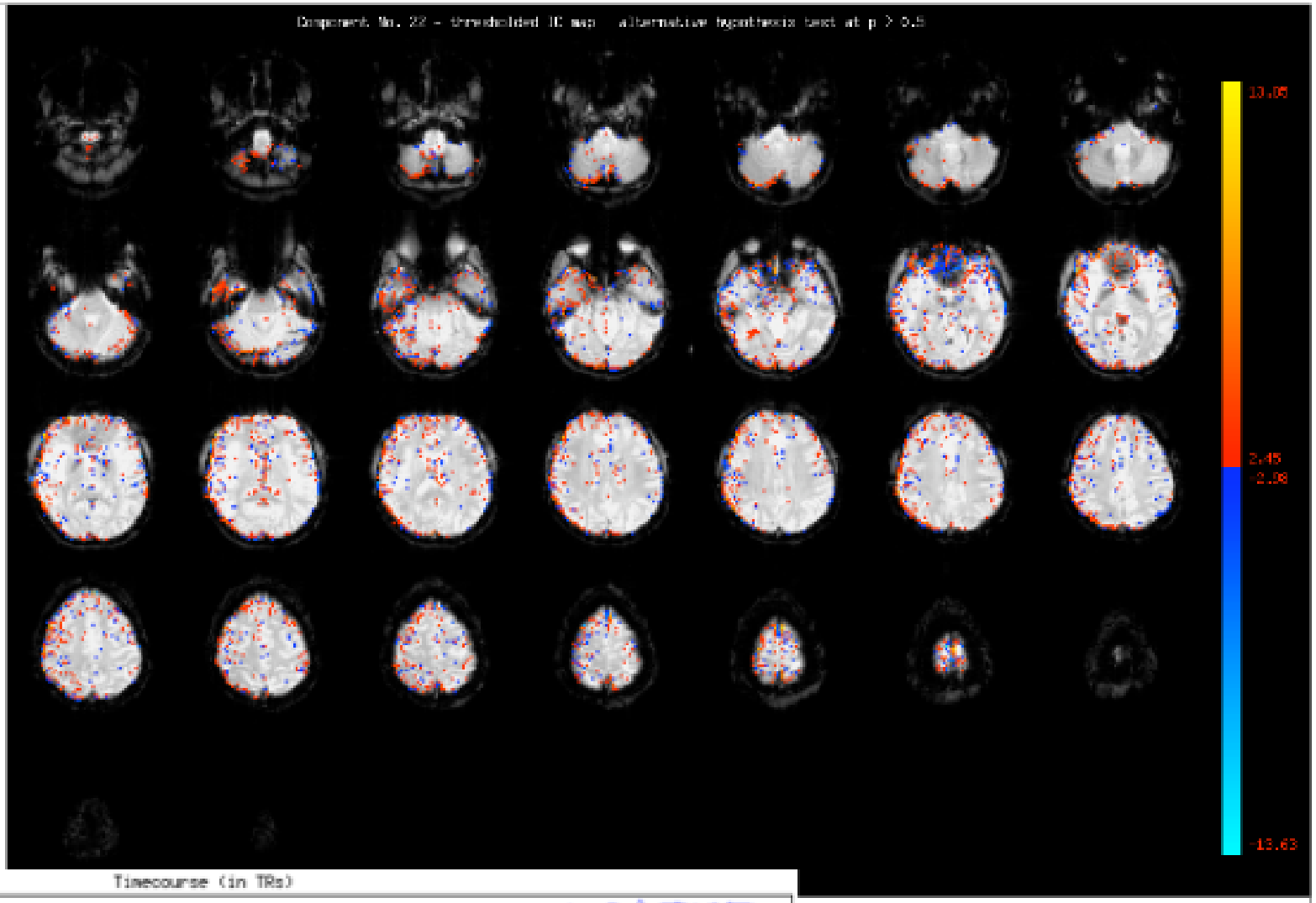


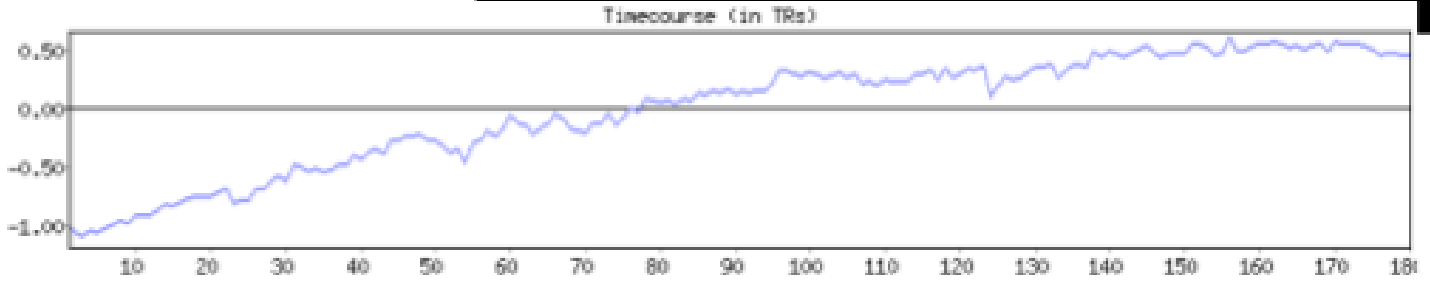


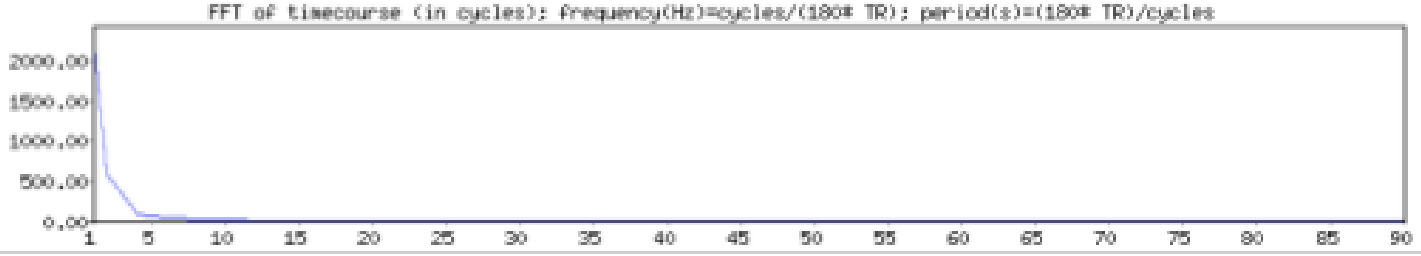
Source: R. Poldrack


Component No. 23 - thresholded IC map alternative hypothesis test at p > 0.5
14.61
2.4
-2.65
R
Timecourse No. 32
Normalised Response
6
3
0
0
80
160
240
320
400
480
560
Time (seconds); TR = 2 s
IC 32 time course

Slow drift

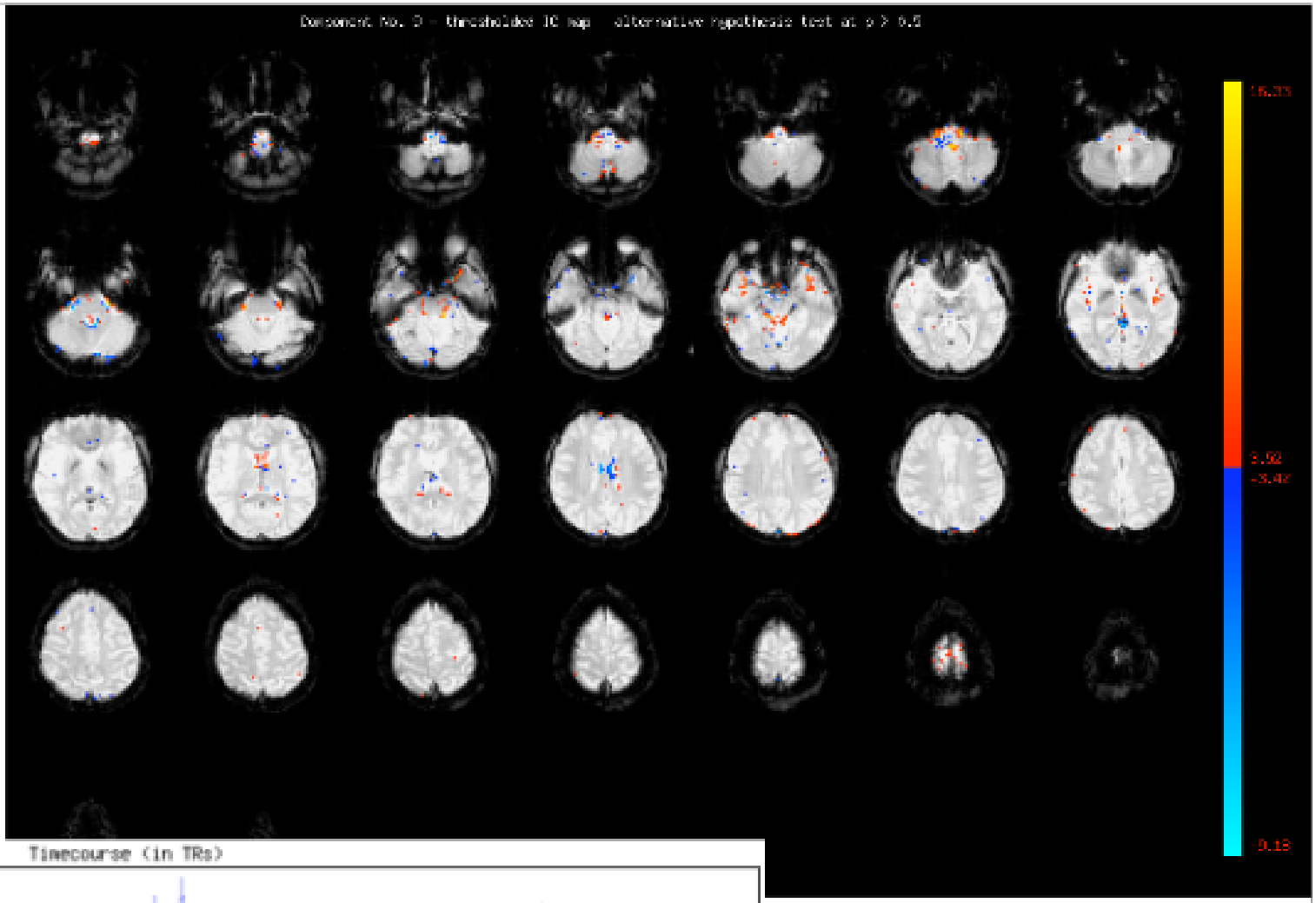


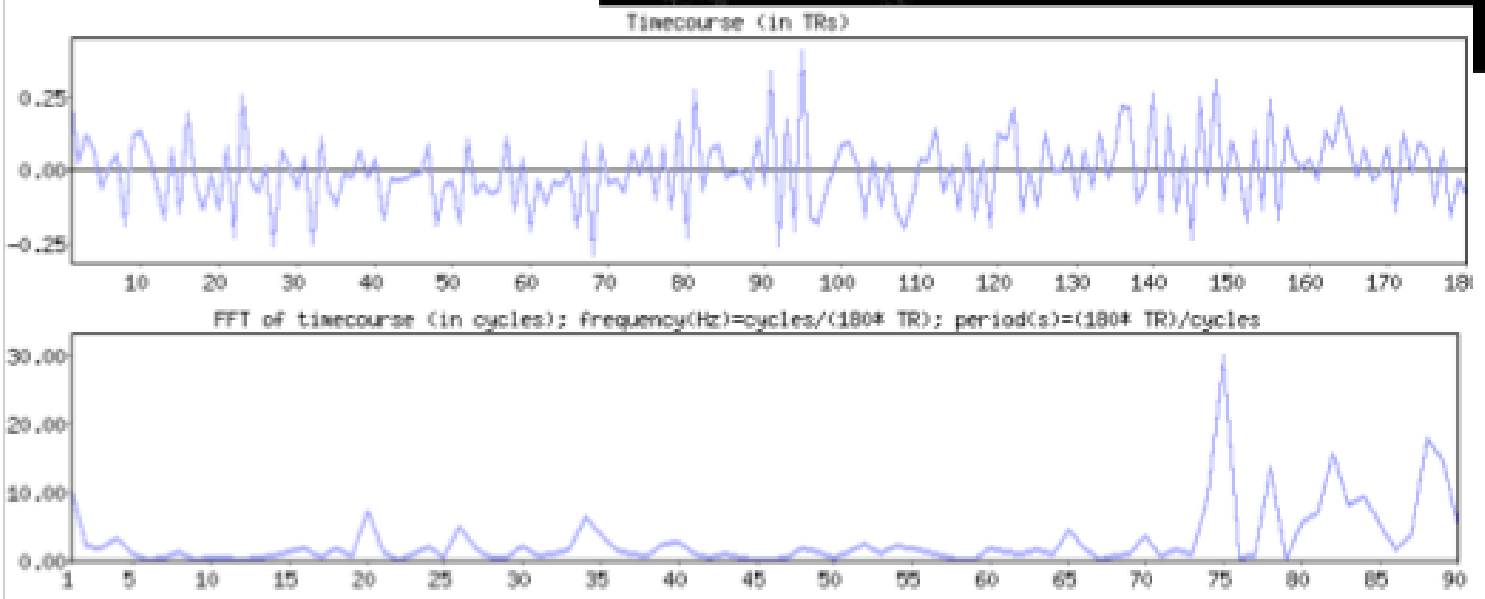




Source: R. Poldrack

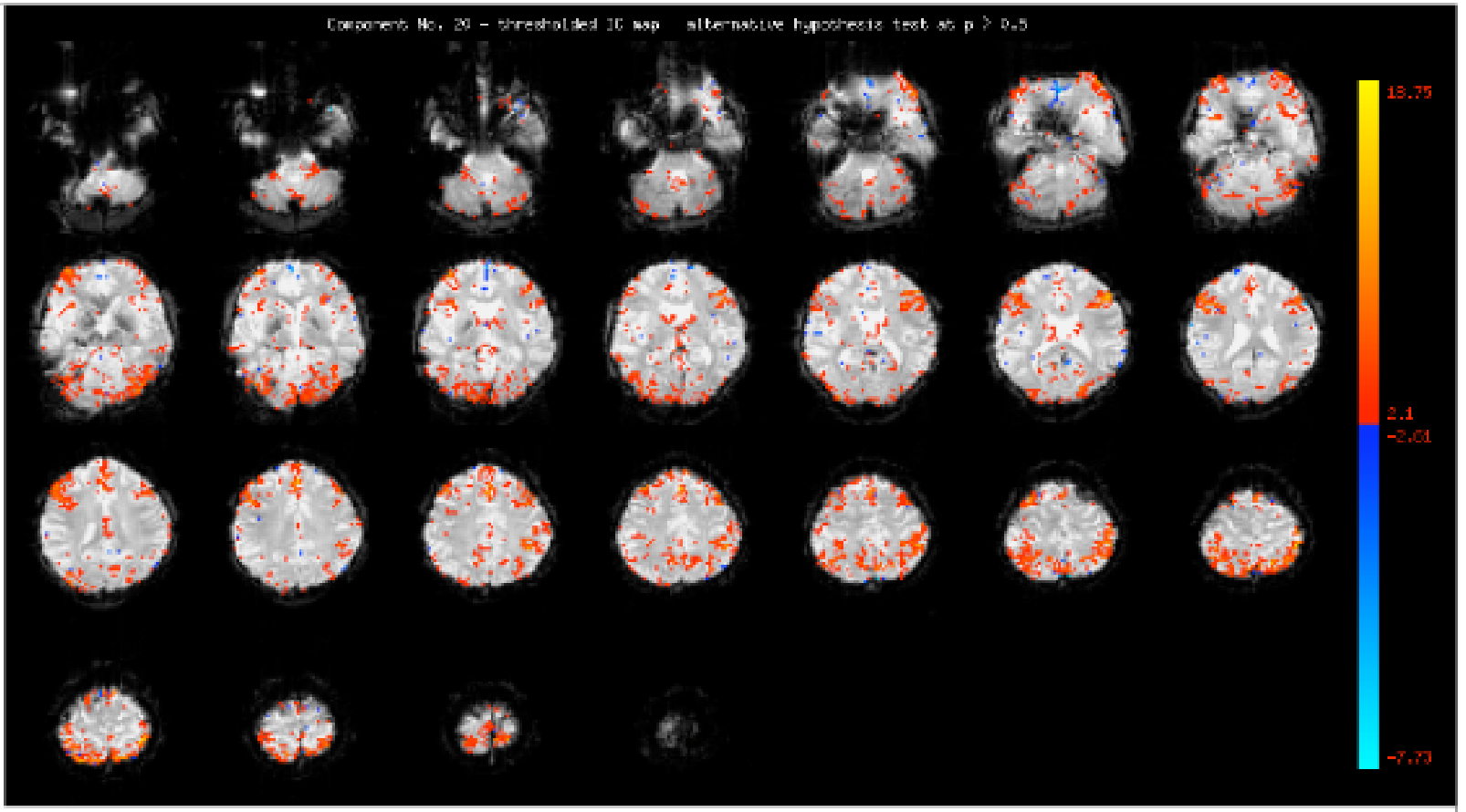
High frequency noise

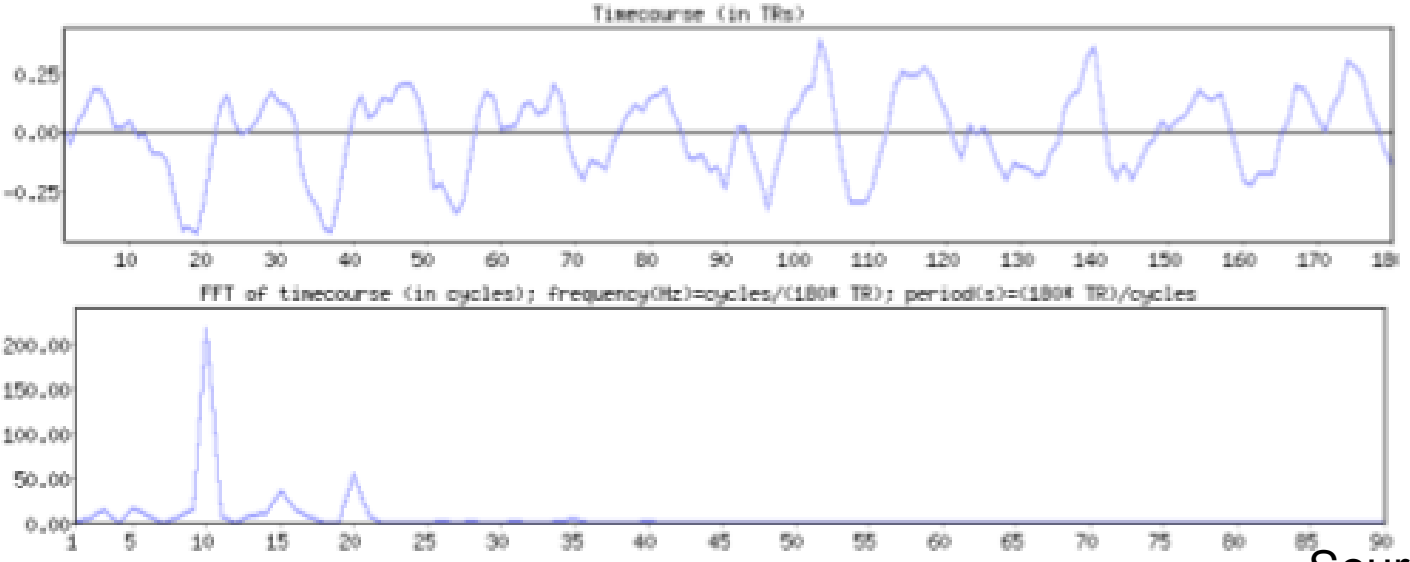




Source: R. Poldrack

Task





Source: R. Poldrack

Registration

Functional

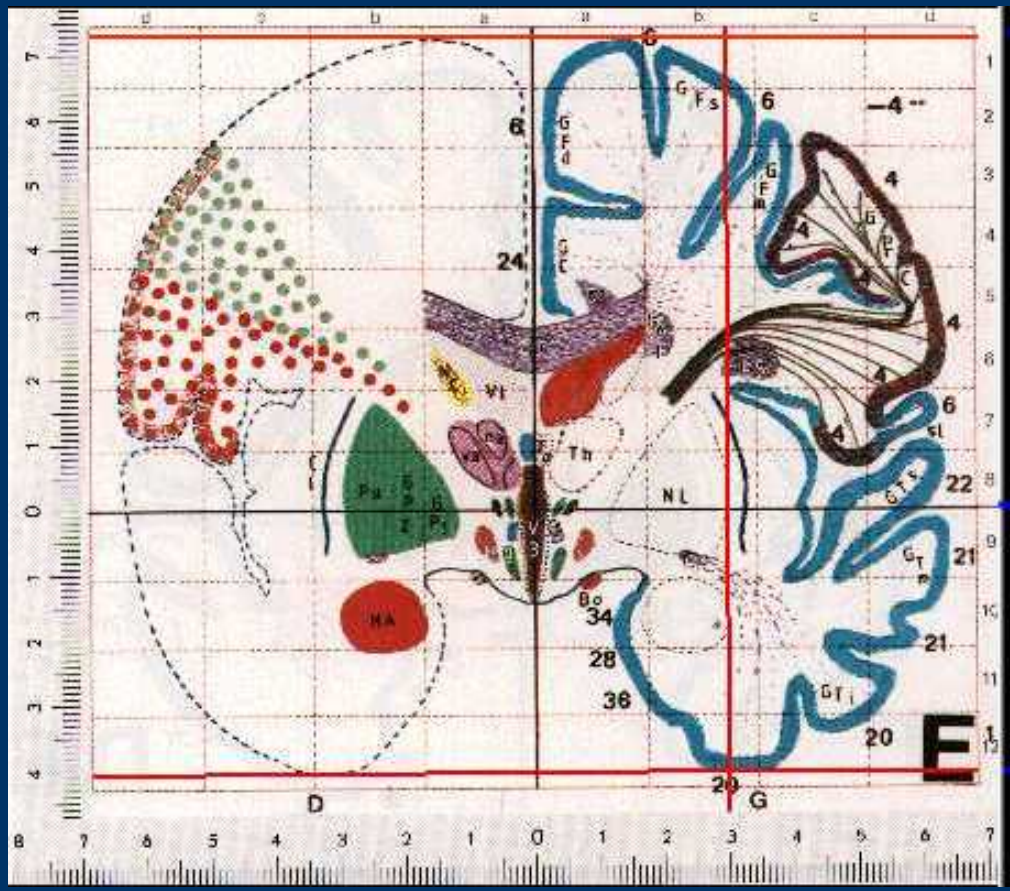
Anatomical

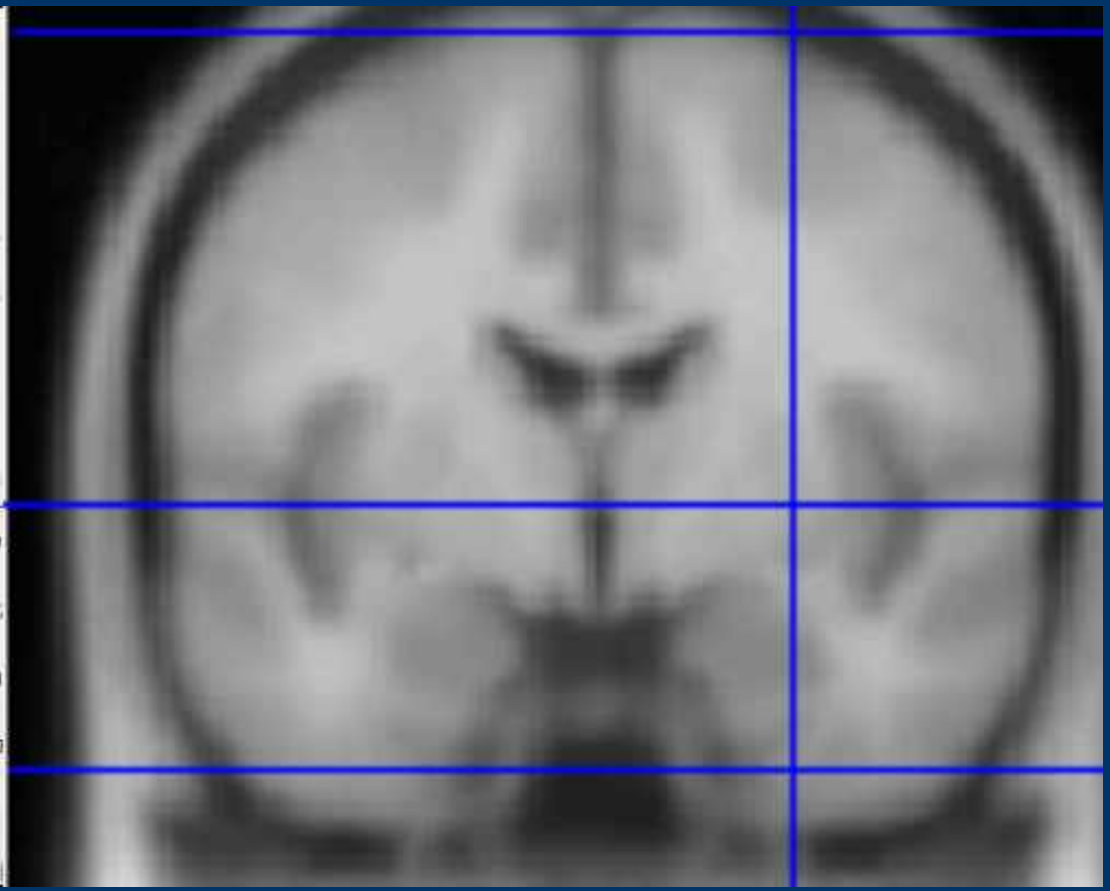
Template

Standard Space

- Common reference frame
- Talairach & Tournoux 1988, based on post mortem dissection of 1 brain
- MNI (152) non linear average of multiple individuals

Standard Space





Registration

1. **Transformation:** How to manipulate an image to fit it from its native space into a different space?
2. **Cost function:** How to assess the quality of the manipulation?
3. **Interpolation:** How create the intensity values to be assigned to the new “grid”?

Transformations

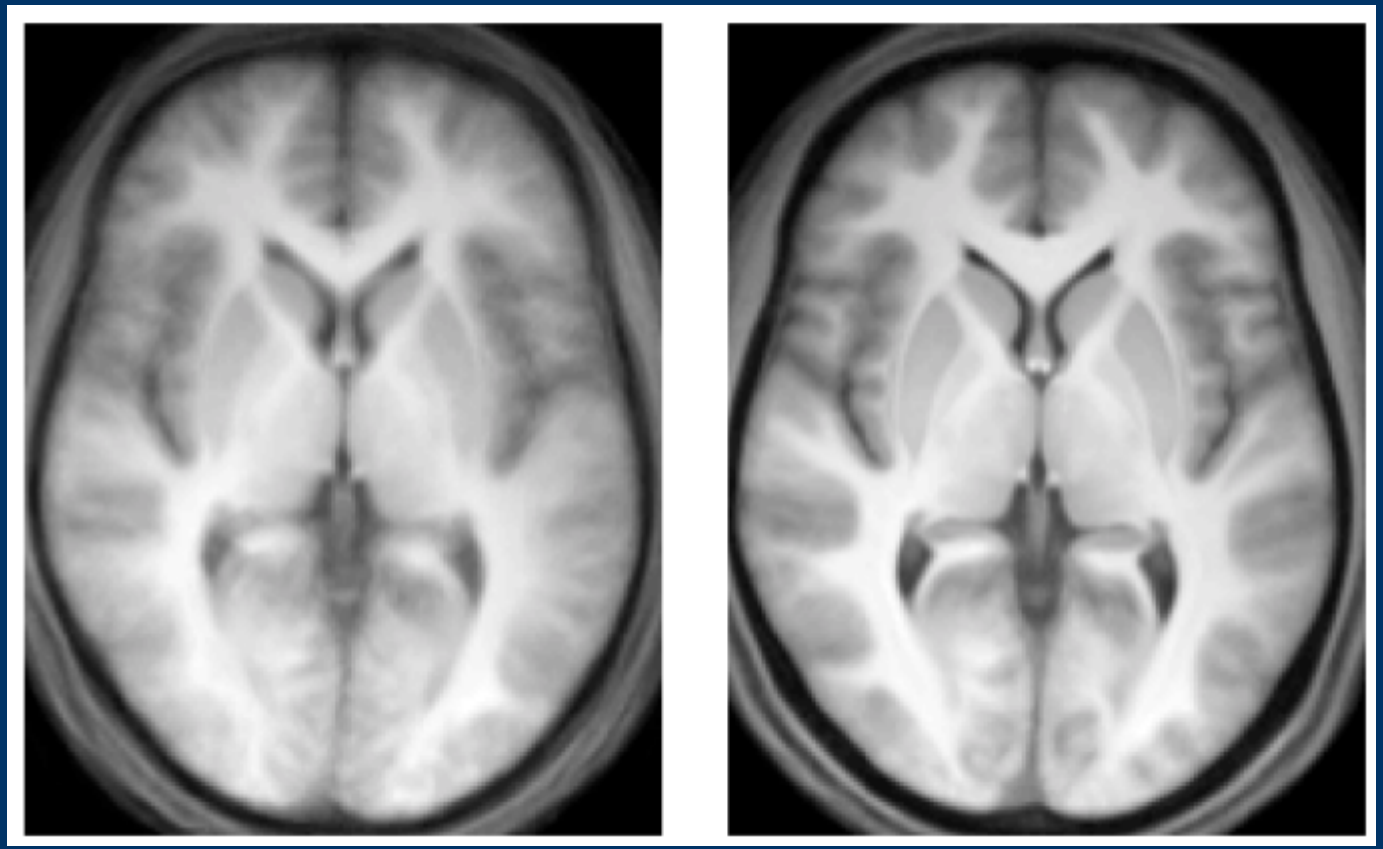
- Rigid body (6dof):
  - 3 rotations, 3 translations
  - Typically used for intra-subject registration.

- Rigid body + global scaling (7dof)
  - 3 rotations, 3 translations, global scaling
  - Typically used for within subject/between modalities (i.e., functional to structural)

- Affine (12dof)
  - 3 rotations, 3 translations
  - 3 scalings, 3 sheers/skews
  - Typically used for registering a subject to the template

Transformations

- Non-linear (> 12dof)
  - Can be local
  - Can be constrained (e.g.,, regularization, topology preservation)

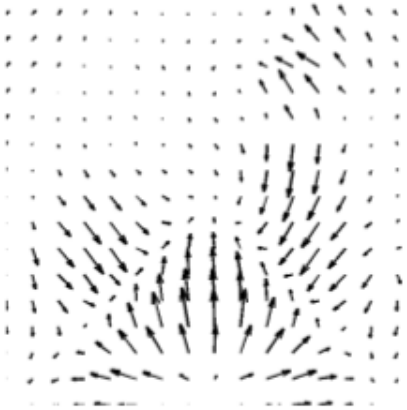


Transformations

- Non-linear (> 12dof)
  - Can be local
  - Can be constrained (e.g.,, regularization, topology preservation)

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

An affine transformation is represented by these 12 numbers.
This matrix multiplies coordinate vectors to define the transformed coordinates.



A non-linear transformation is represented by a ***deformation field***.

Cost functions

FLIRT: Cost Functions

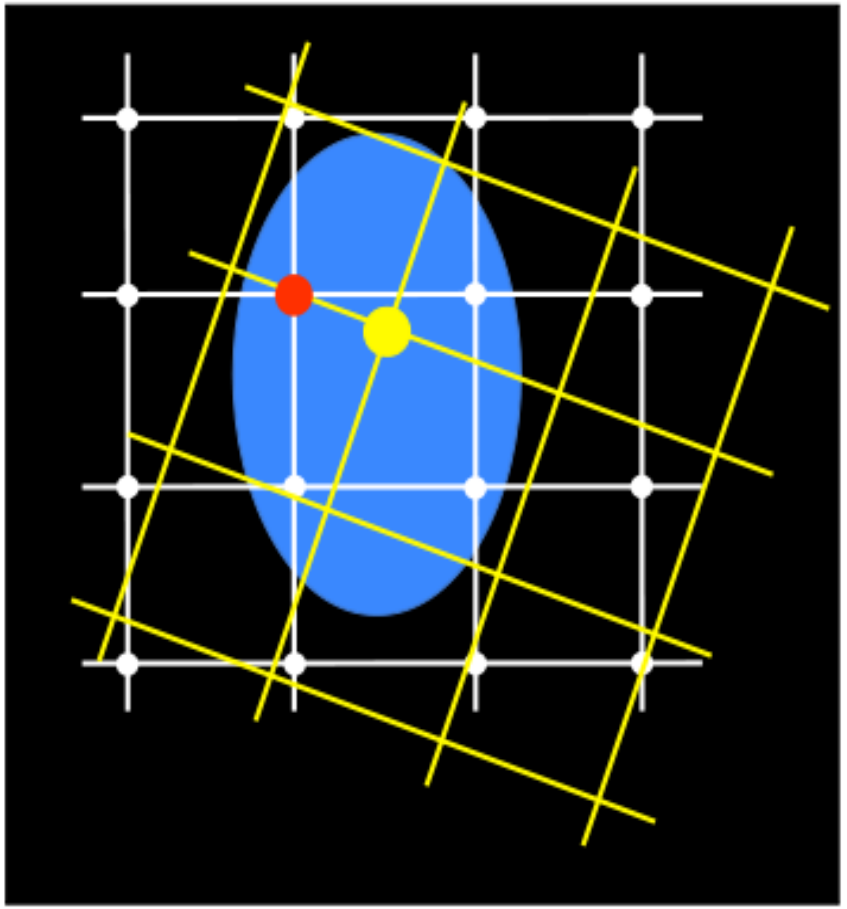
Important: Allowable image modalities

Less important: Details

Least Squares	***Same modality*** (exact sequence parameters)
Normalised Correlation	***Same modality*** (can change brightness & contrast)
Correlation Ratio	***Any MR modalities***
Mutual Information	***Any modalities*** (including CT, PET, etc.)
Normalised Mutual Info.	***Any modalities*** (including CT, PET, etc.)

Interpolation

Finds intensity values between grid points

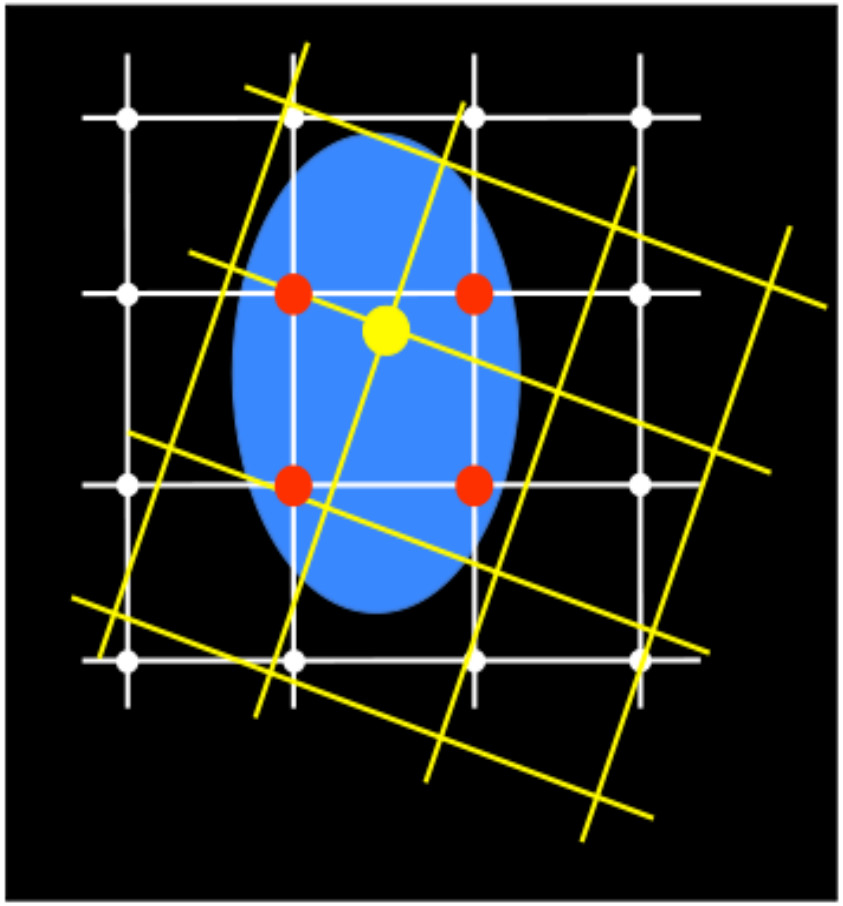


Various types include

- Nearest Neighbour
- Trilinear
- Sinc
- Spline
- k-Space methods

Interpolation

Finds intensity values between grid points

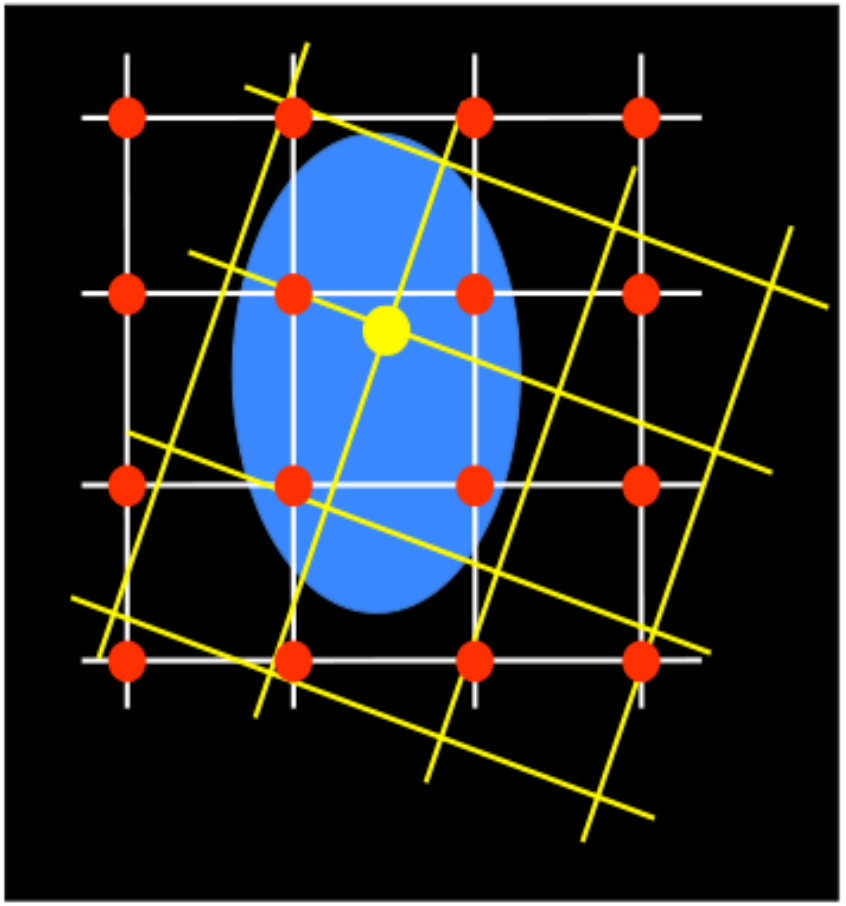


Various types include

- Nearest Neighbour
- Trilinear
- Sinc
- Spline
- k-Space methods

Interpolation

Finds intensity values between grid points



Various types include

- Nearest Neighbour
- Trilinear
- Sinc
- Spline
- k-Space methods

Considerations: speed, accuracy, stability