Image Processing for fMRI

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Contents

Rigid-Body Transformations

* Assume that brain of the same subject doesn't change shape or size in the scanner.
  * Head can move, but remains the same shape and size.
  * Some exceptions:
    * Image distortions.
    * Brain slops about slightly because of gravity.
    * Brain growth or atrophy over time.
* If the subject's head moves, we need to correct the images.
  * Do this by image registration.

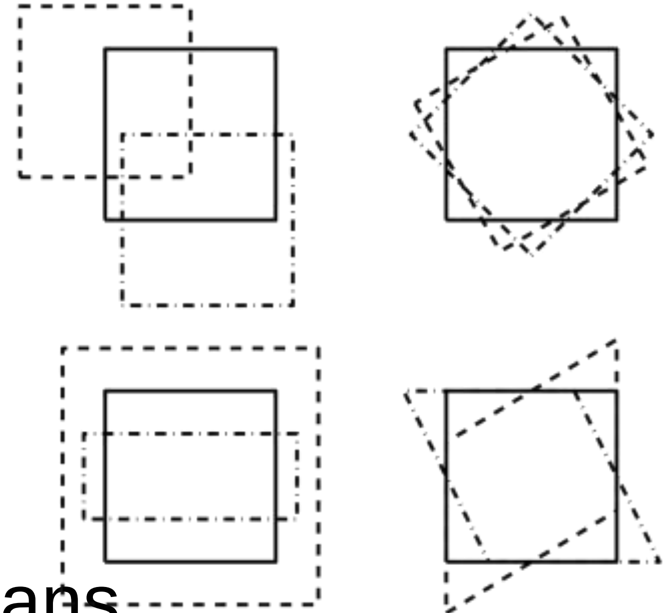
Image Registration

Two components:

- **Registration** - i.e. Optimise the parameters that describe a spatial transformation between the source and reference images

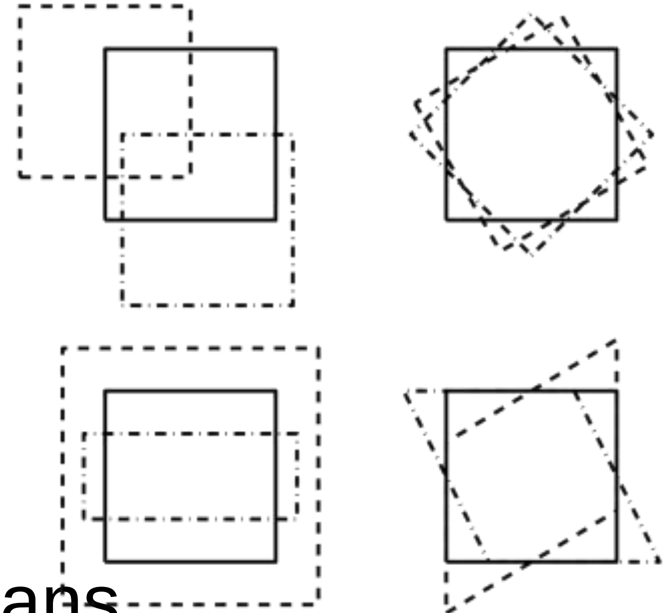
- **Transformation** - i.e. Re-sample according to the determined transformation parameters

2D Affine Transforms



- Translations by t_x and t_y
  - $x_1 = x_0 + t_x$
  - $y_1 = y_0 + t_y$
- Rotation around the origin by Θ radians
  - $x_1 = \cos(\Theta)\, x_0 + \sin(\Theta)\, y_0$
  - $y_1 = -\sin(\Theta)\, x_0 + \cos(\Theta)\, y_0$
- Zooms by s_x and s_y
  - $x_1 = s_x\, x_0$
  - $y_1 = s_y\, y_0$
- Shear
  - $x_1 = x_0 + h\, y_0$
  - $y_1 = y_0$

2D Affine Transforms



* Translations by t_x and t_y
  * $x_1 = 1\ x_0 + 0\ y_0 + t_x$
  * $y_1 = 0\ x_0 + 1\ y_0 + t_y$
* Rotation around the origin by Θ radians
  * $x_1 = \cos(\Theta)\ x_0 + \sin(\Theta)\ y_0 + 0$
  * $y_1 = -\sin(\Theta)\ x_0 + \cos(\Theta)\ y_0 + 0$
* Zooms by s_x and s_y:
  * $x_1 = s_x\ x_0 + 0\ y_0 + 0$
  * $y_1 = 0\ x_0 + s_y\ y_0 + 0$
* Shear
  * $x_1 = 1\ x_0 + h\ y_0 + 0$
  * $y_1 = 0\ x_0 + 1\ y_0 + 0$

3D Rigid-body Transformations

- A 3D rigid body transform is defined by:
  - 3 translations - in X, Y & Z directions
  - 3 rotations - about X, Y & Z axes
- The order of the operations matters

$$\begin{pmatrix} 1 & 0 & 0 & X_{trans} \\ 0 & 1 & 0 & Y_{trans} \\ 0 & 0 & 1 & Z_{trans} \\ 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\Phi & \sin\Phi & 0 \\ 0 & -\sin\Phi & \cos\Phi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\Theta & 0 & \sin\Theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\Theta & 0 & \cos\Theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\Omega & \sin\Omega & 0 & 0 \\ -\sin\Omega & \cos\Omega & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

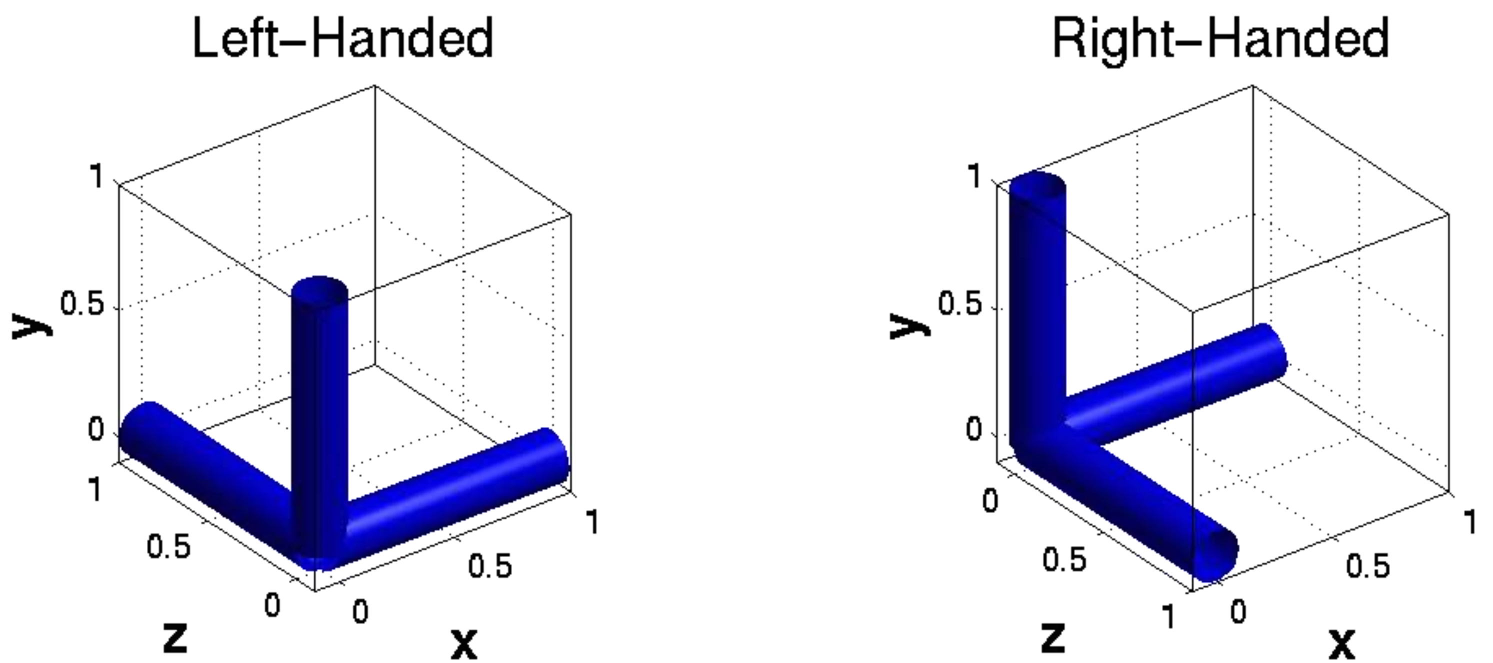
Translations	Pitch about x axis	Roll about y axis	Yaw about z axis

Voxel-to-world Transforms

* Affine transform associated with each image
  * Maps from voxels ($x=1..n_x$, $y=1..n_y$, $z=1..n_z$) to some world co-ordinate system. e.g.,
    * Scanner co-ordinates - images from DICOM toolbox
    * T&T/MNI coordinates - spatially normalised
* Registering image B (source) to image A (target) will update B's voxel-to-world mapping
  * Mapping from voxels in A to voxels in B is by
    * A-to-world using M_A, then world-to-B using M_B^{-1}
    * $M_B^{-1} M_A$

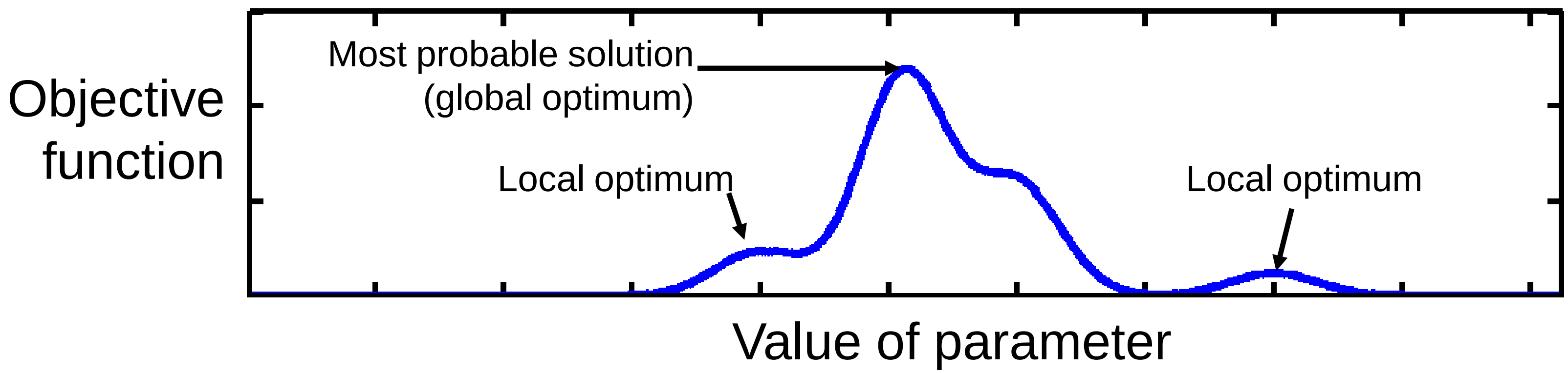
Left- and Right-handed Coordinate Systems

* NIfTI format files are stored in either a left- or right-handed system
  * Indicated in the header
* Talairach & Tournoux uses a right-handed system
* Mapping between them sometimes requires a flip
  * Affine transform has a negative determinant

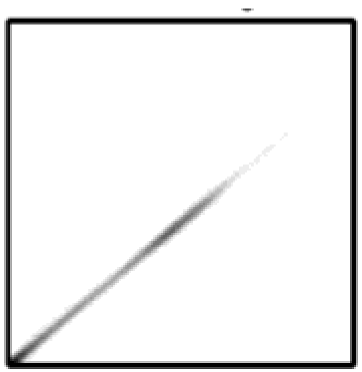


Optimisation

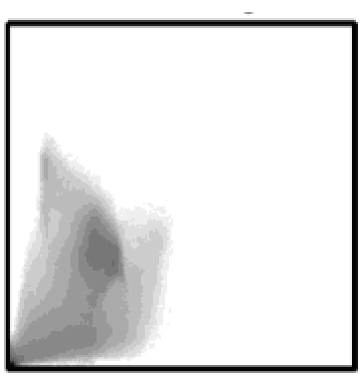
* Image registration is done by optimisation.
* Optimisation involves finding some "best" parameters according to an "objective function", which is either minimised or maximised
* The "objective function" is often related to a probability based on some model



Objective Functions



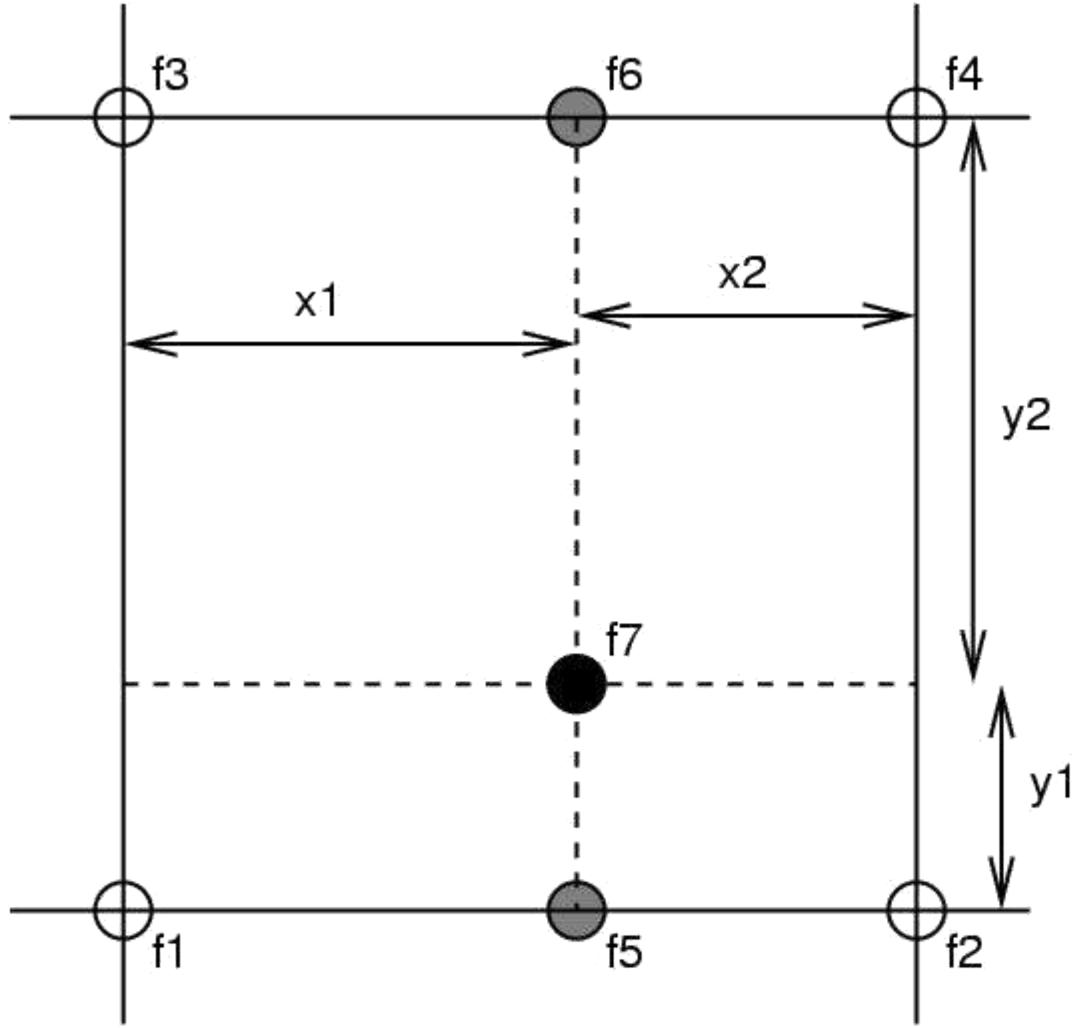
* Intra-modal
  * Mean squared difference (minimise)
  * Normalised cross correlation (maximise)



* Inter-modal (or intra-modal)
  * Mutual information (maximise)
  * Normalised mutual information (maximise)
  * Entropy correlation coefficient (maximise)

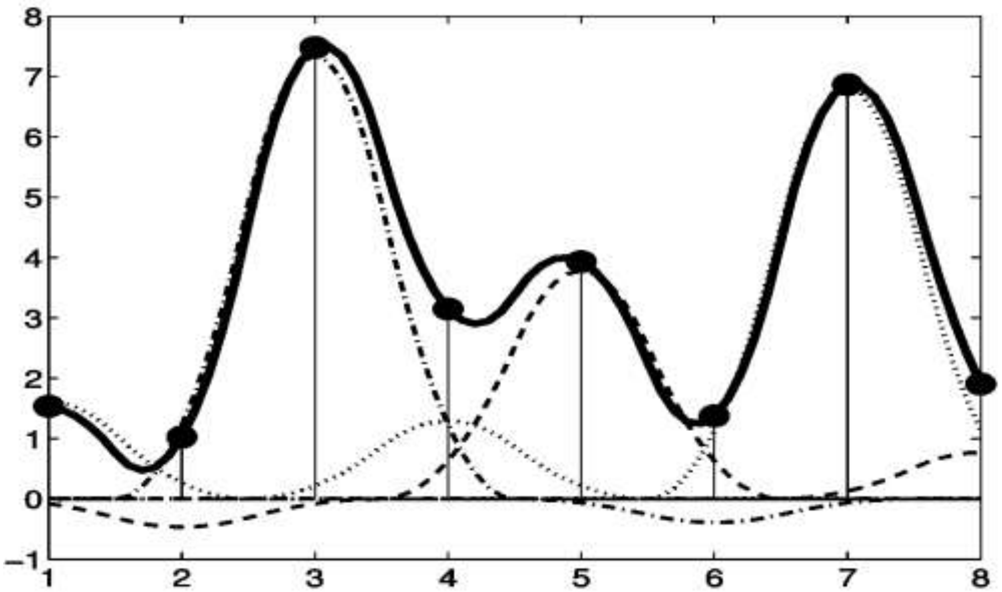
Simple Interpolation

* Nearest neighbour
  * Take the value of the closest voxel
* Tri-linear
  * Just a weighted average of the neighbouring voxels
  * $f_5 = f_1\, x_2 + f_2\, x_1$
  * $f_6 = f_3\, x_2 + f_4\, x_1$
  * $f_7 = f_5\, y_2 + f_6\, y_1$

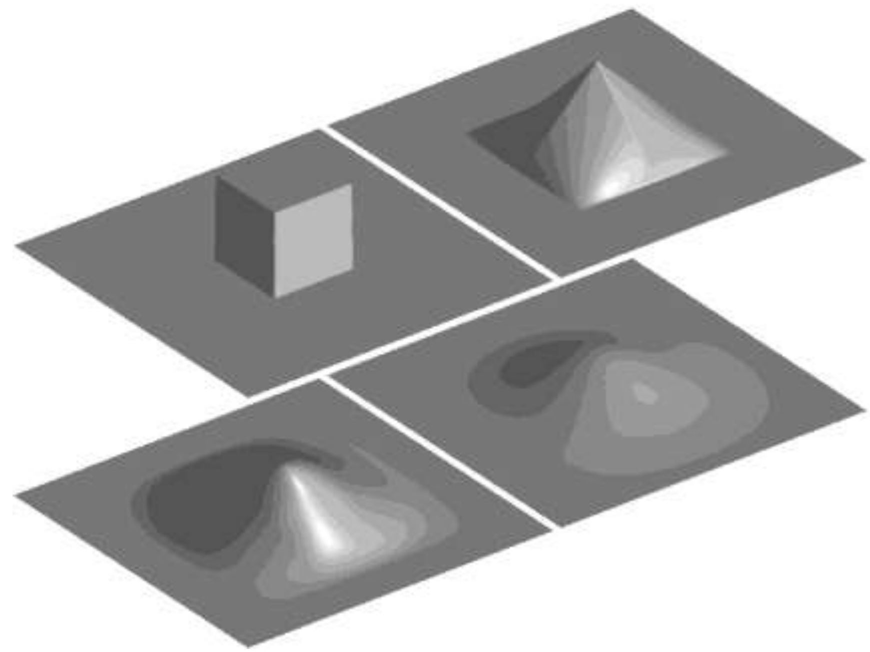


B-spline Interpolation

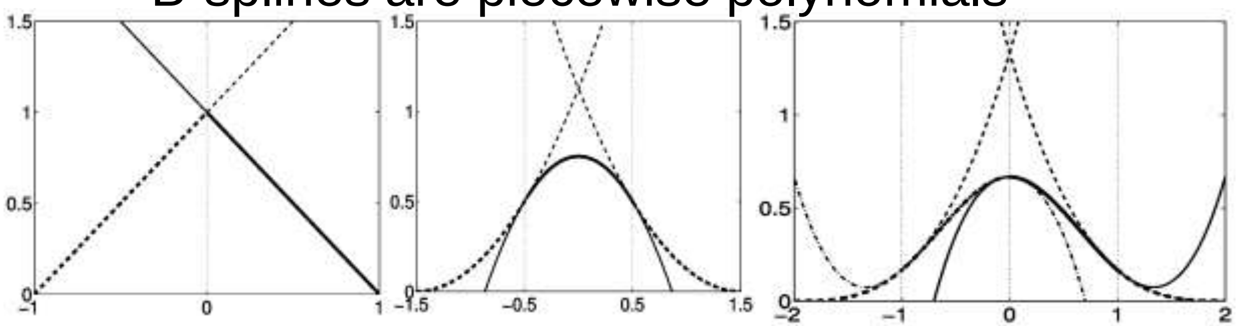
A continuous function is represented by a linear combination of basis functions



2D B-spline basis functions of degrees 0, 1, 2 and 3



B-splines are piecewise polynomials



Nearest neighbour and trilinear interpolation are the same as B-spline interpolation with degrees 0 and 1.

Contents

* Preliminaries
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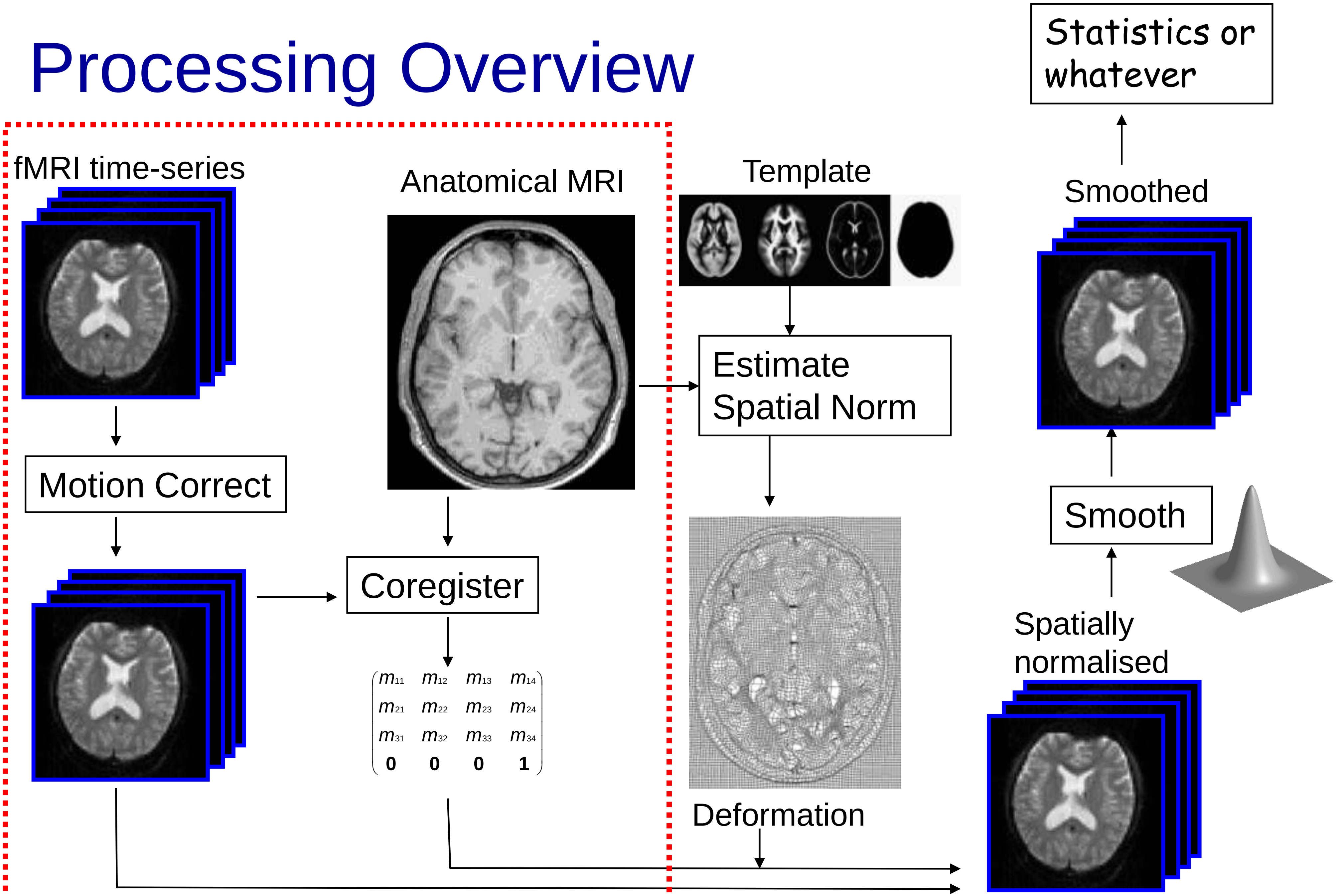
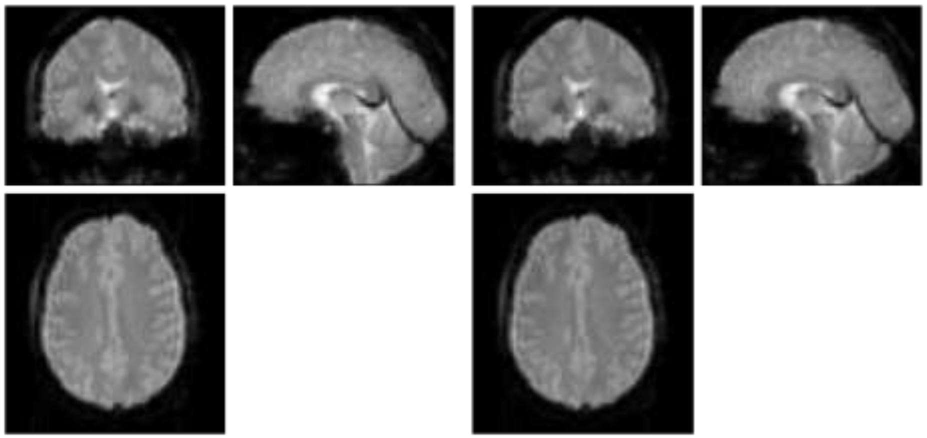
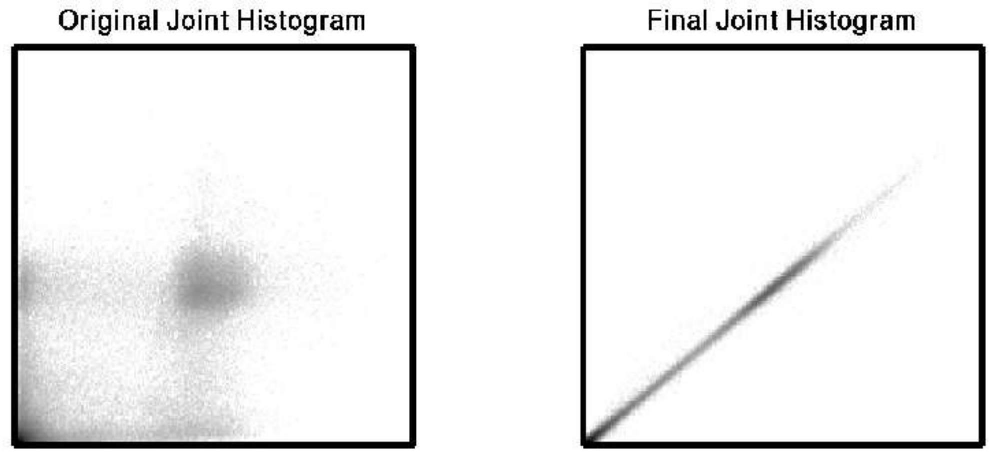
  * **Realignment by minimising mean-squared difference**
  * **Residual artifacts and distortion correction**
  * **Coregistration by maximising mutual information**
* Between Subject: Spatial Normalisation & Smoothing

Processing Overview



Mean-squared Difference





* Minimising mean-squared difference works for intra-modal registration (realignment)
* Simple relationship between intensities in one image, versus those in the other
  * Assumes normally distributed differences

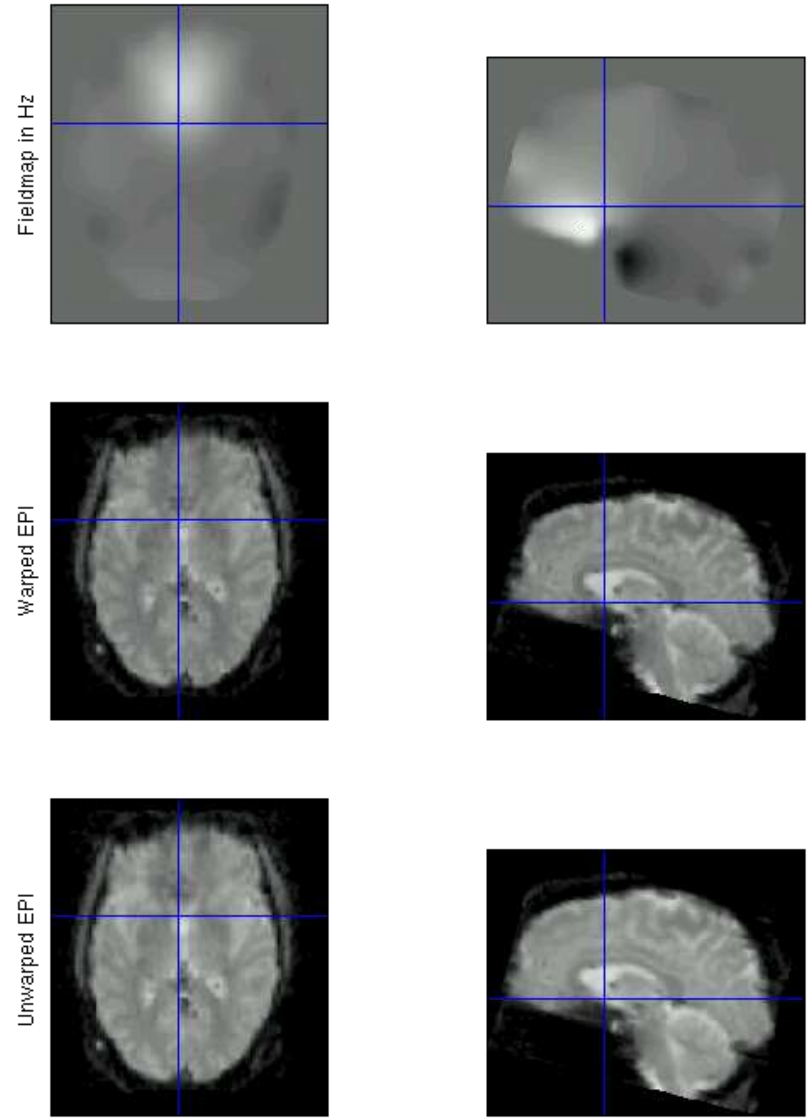
Residual Errors from aligned fMRI

* Re-sampling can introduce interpolation errors
  * especially tri-linear interpolation
* Gaps between slices can cause aliasing artefacts
* Slices are not acquired simultaneously
  * rapid movements not accounted for by rigid body model
* Image artefacts may not move according to a rigid body model
  * image distortion
  * image dropout
  * Nyquist ghost

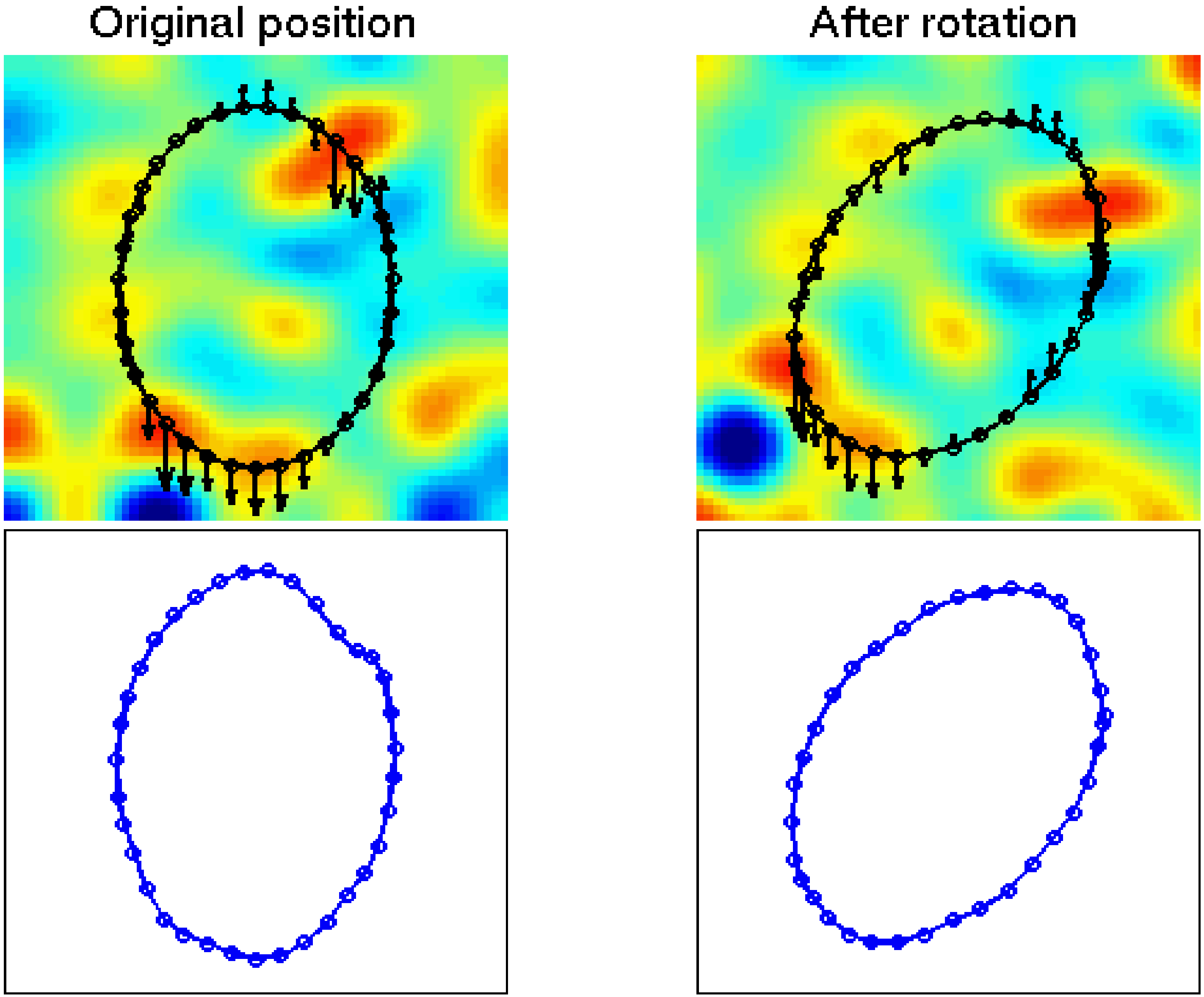
* Functions of the estimated motion parameters can be modelled as confounds in subsequent analyses

Movement by Distortion Interaction of fMRI

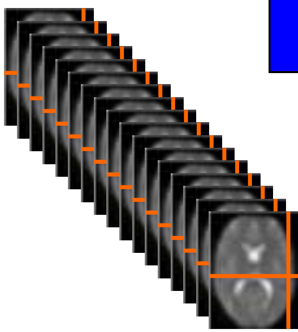
* Subject disrupts B_0 field, rendering it inhomogeneous
    * distortions in phase-encode direction
* Subject moves during EPI time series
* Distortions vary with subject orientation
    * shape varies



Movement by distortion interaction



Correcting for distortion changes using Unwarp

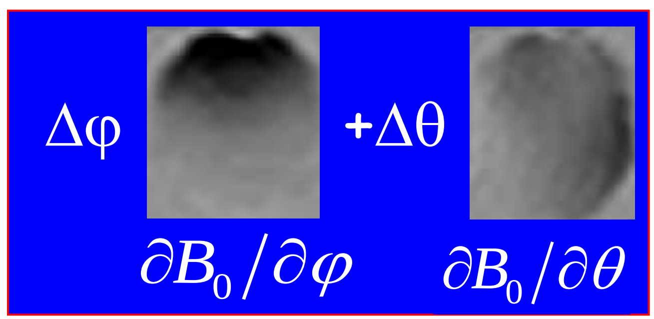


Estimate movement parameters.

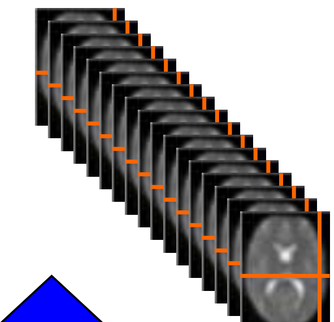
Estimate reference from mean of all scans.

Estimate new distortion fields for each image:

- estimate rate of change of field with respect to the current estimate of movement parameters in **pitch** and **roll**.



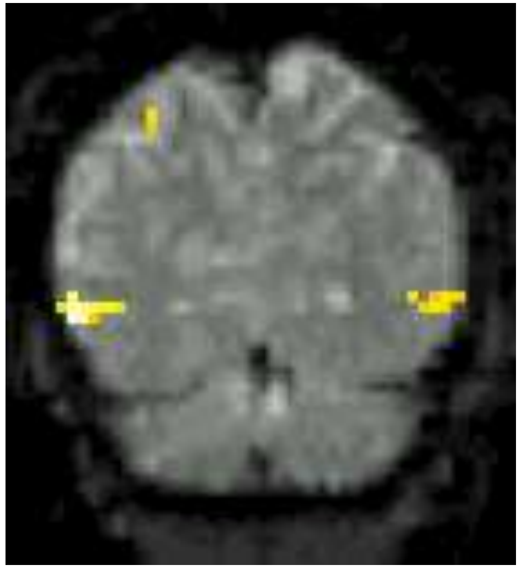
Unwarp time series.

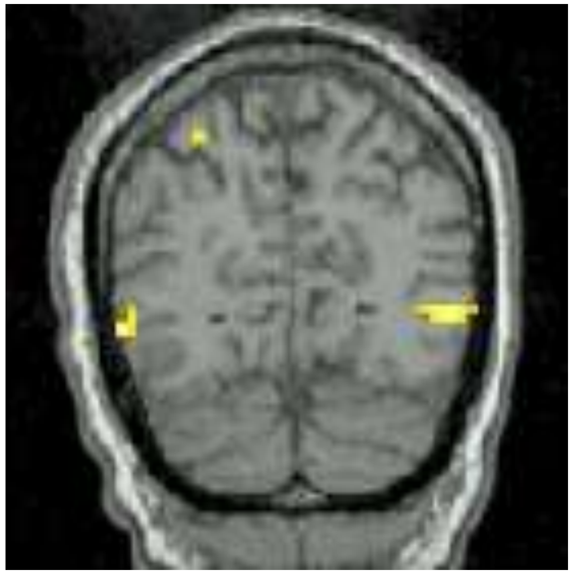


Andersson et al, 2001

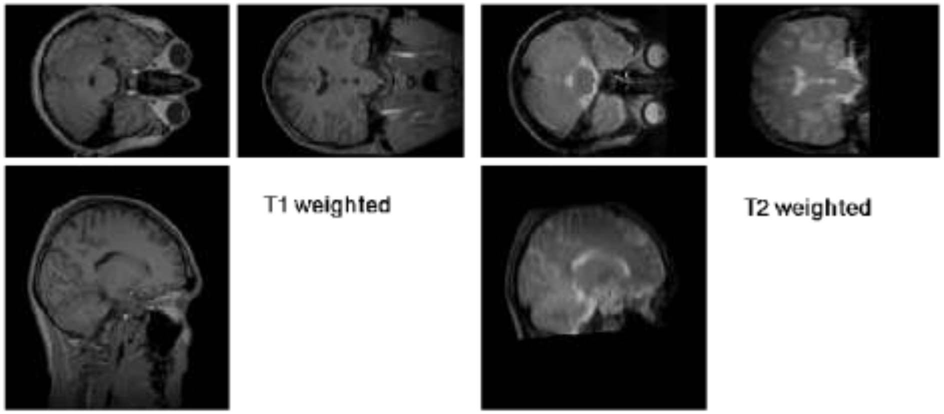
Coregistration

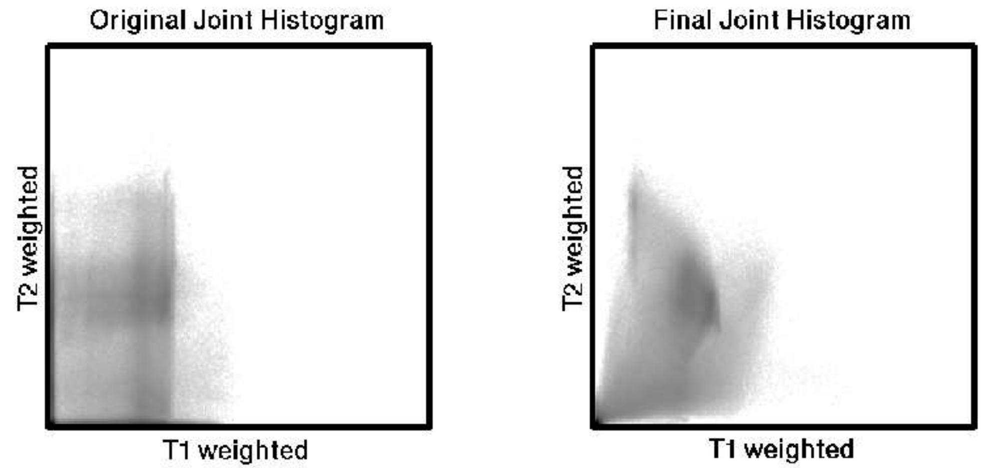
- Inter-modal registration.
- Match images from same subject but different modalities:
  - anatomical localisation of single subject activations
  - achieve more precise spatial normalisation of functional image using anatomical image.





Coregistration maximises Mutual Information





* Used for between-modality registration
* Derived from joint histograms
* $MI = \int_{ab} P(a,b) \log_2 [P(a,b)/(P(a) P(b))]$
  * Related to entropy: $MI = -H(a,b) + H(a) + H(b)$
    * Where $H(a) = -\int_a P(a) \log_2 P(a)$ and $H(a,b) = -\int_a P(a,b) \log_2 P(a,b)$

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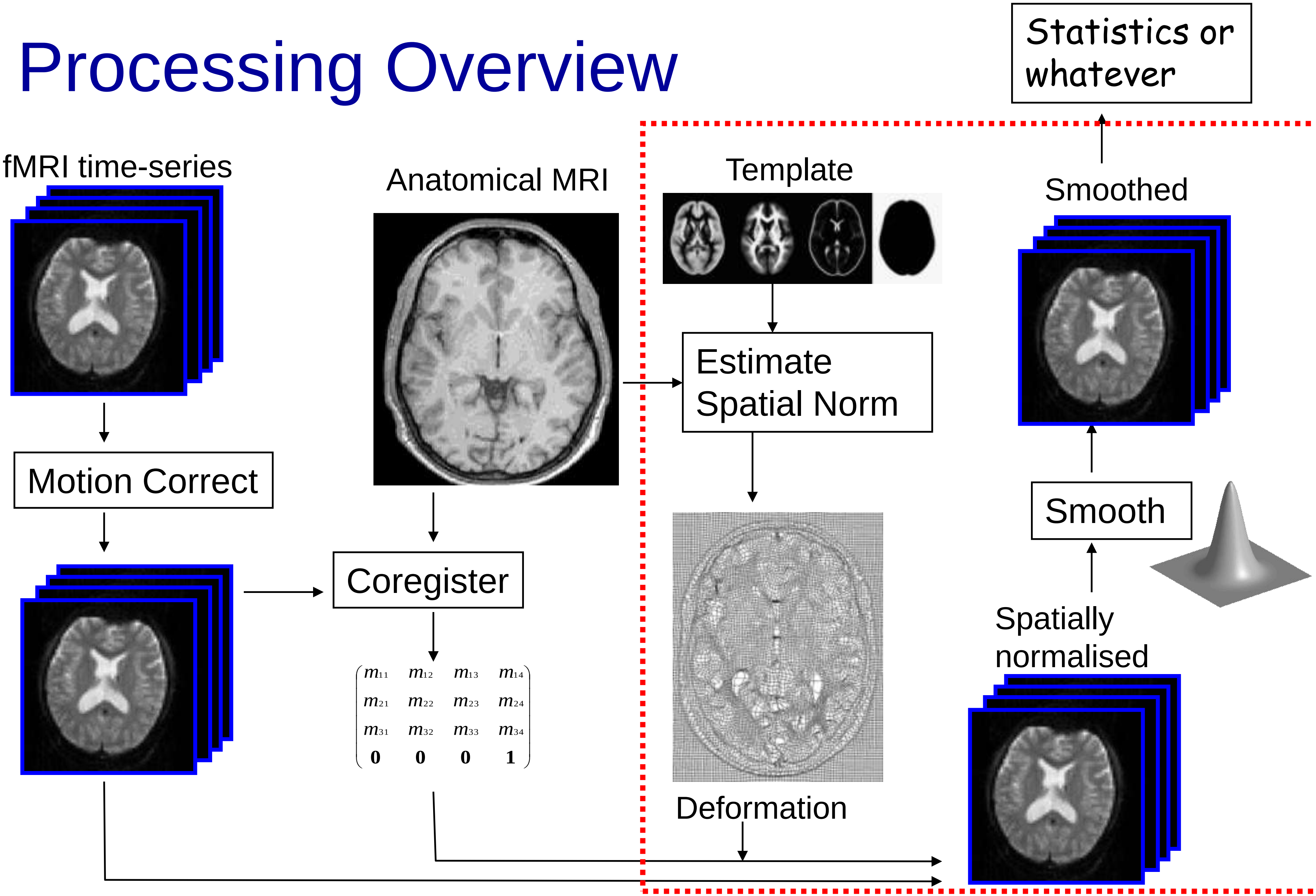
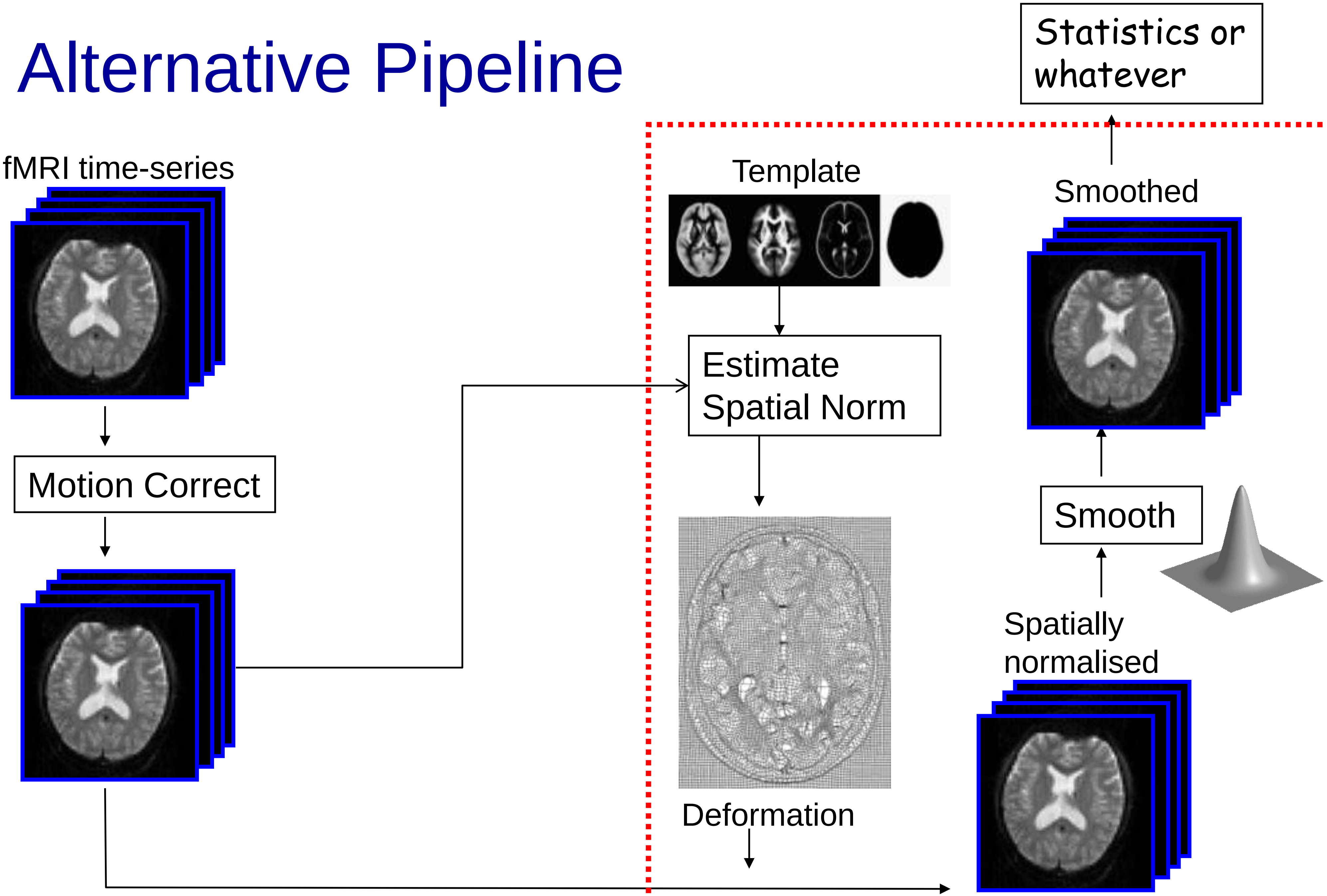
* **Between Subject: Spatial Normalisation & Smoothing**
  * **Segmentation for spatial normalisation**
  * **Smoothing**

Processing Overview



Alternative Pipeline

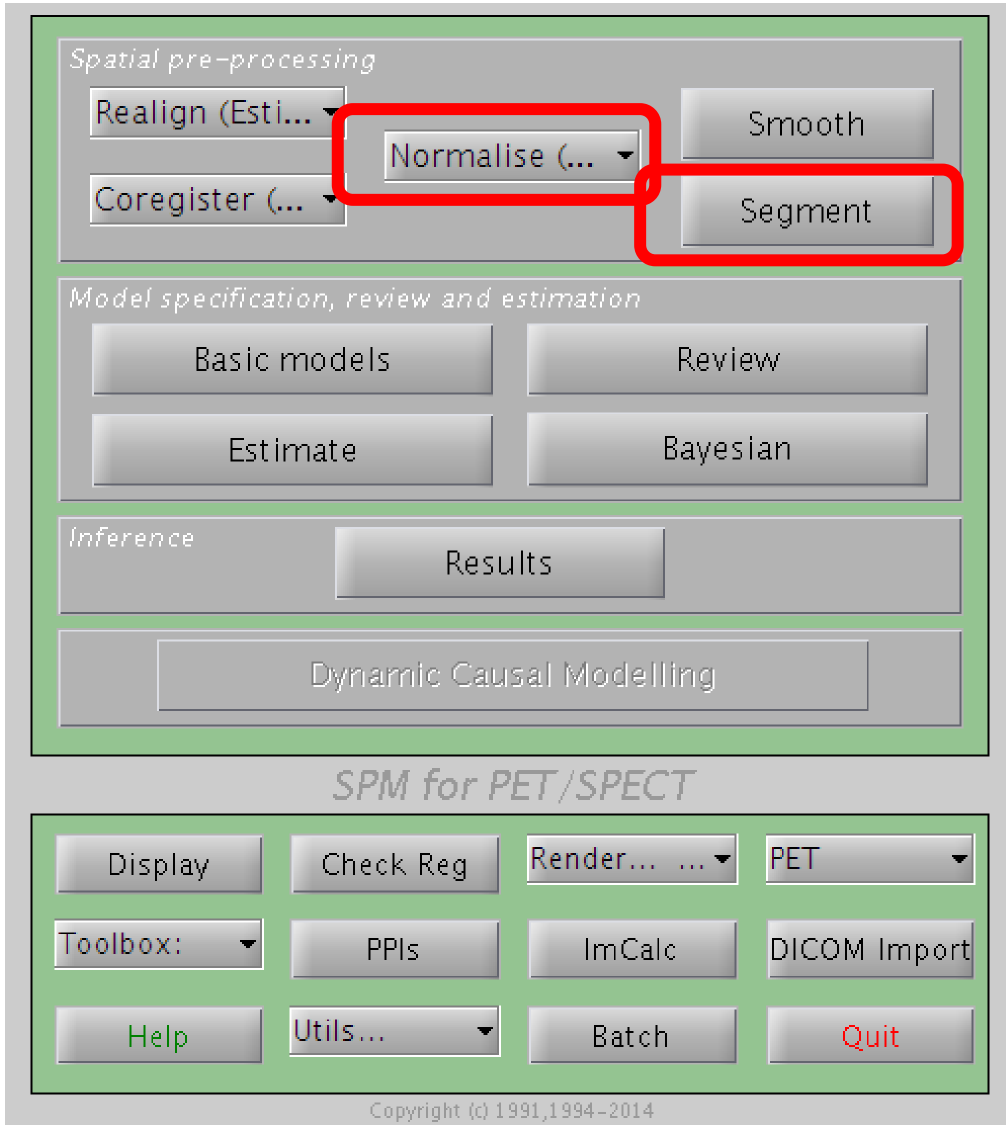


Spatial Normalisation

* Brains of different subjects vary in shape and size.
* Need to bring them all into a common anatomical space.
  * Examine homologous regions across subjects
    * Improve anatomical specificity
    * Improve sensitivity
  * Report findings in a common anatomical space (eg MNI space)

Spatial Normalisation

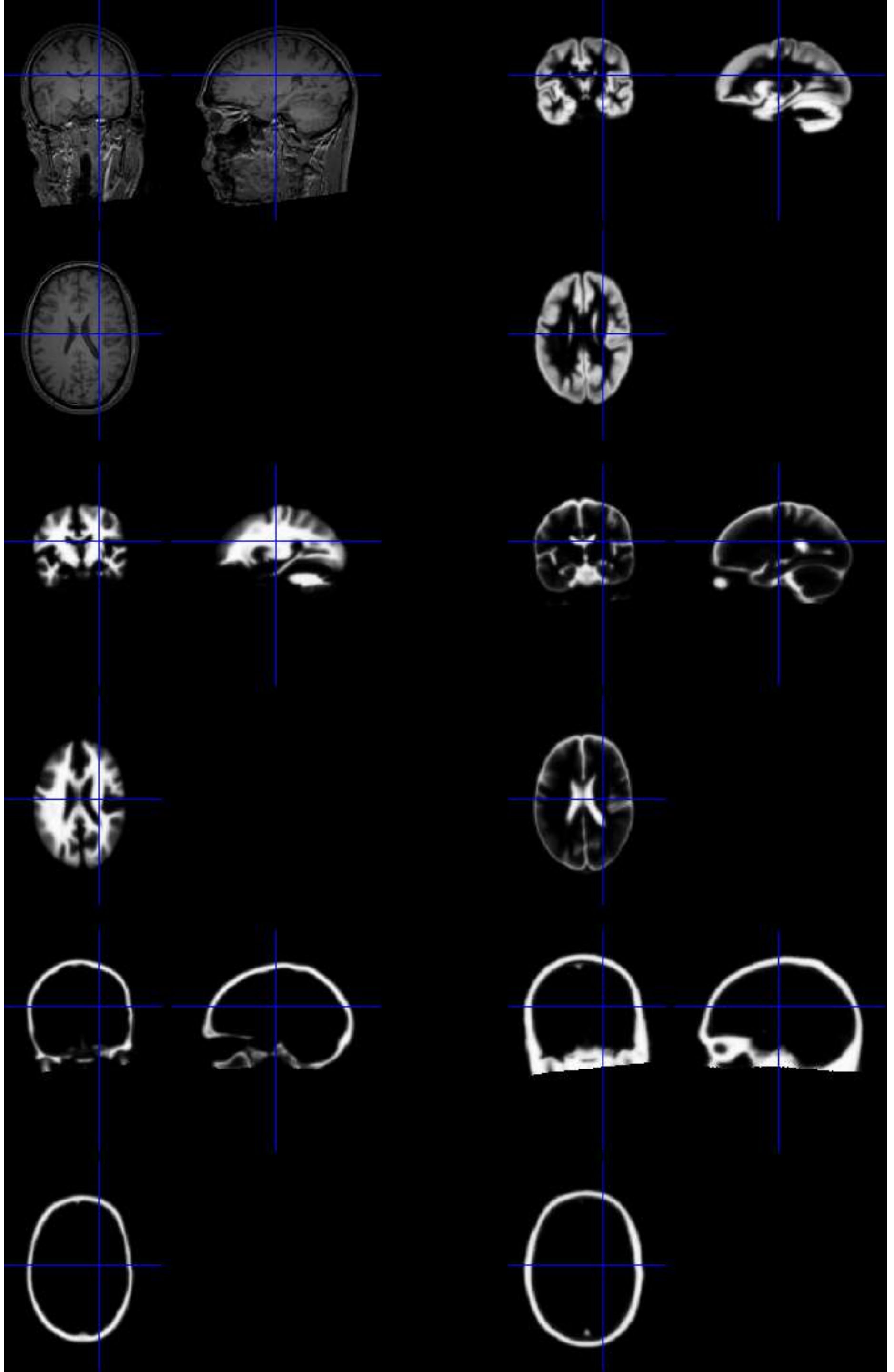
* This is the same algorithm as for tissue segmentation.
* Combines:
  * Mixture of Gaussians (MOG)
  * Bias Correction Component
  * Warping (Non-linear Registration) Component



Spatial Normalisation

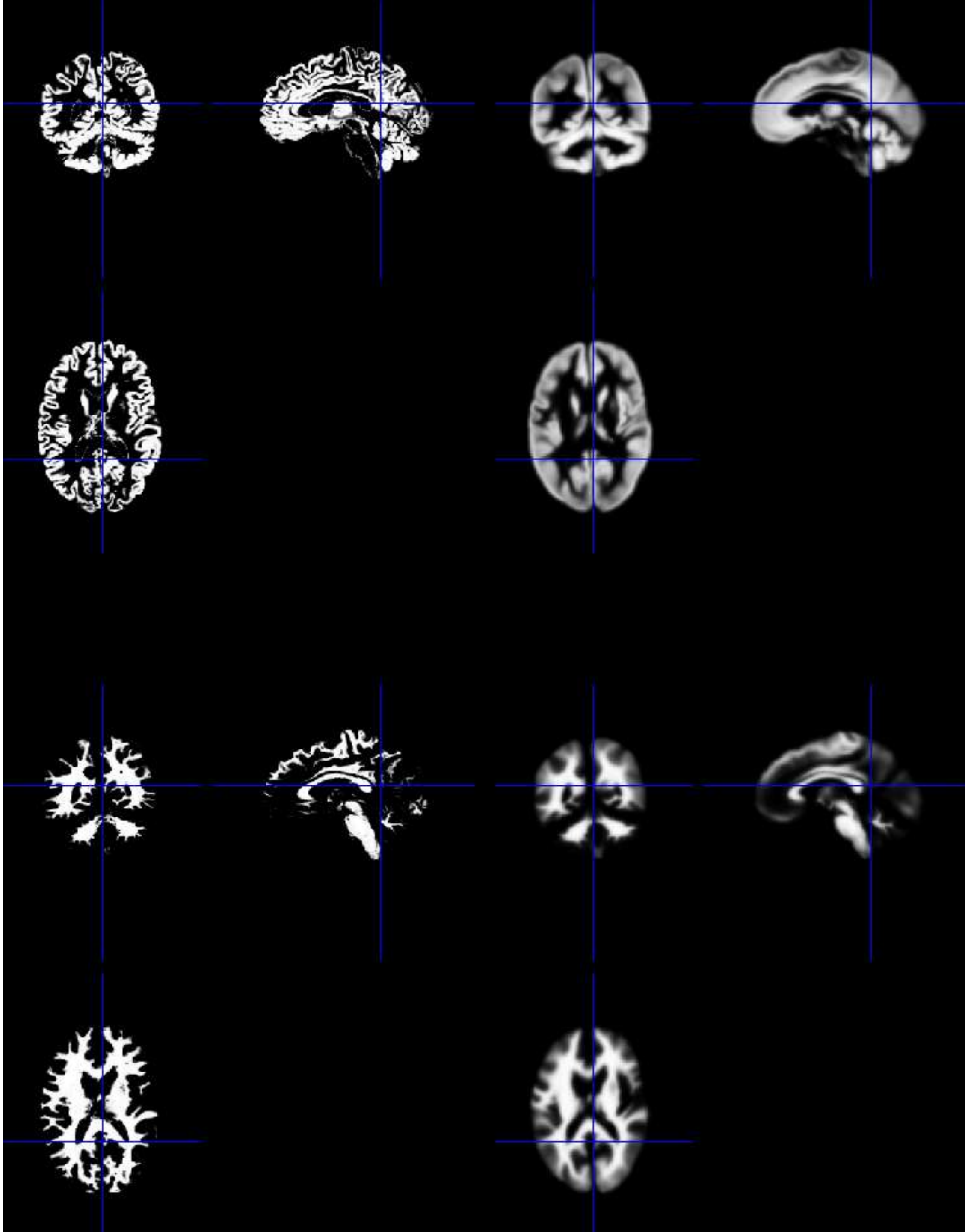
* Default spatial normalisation in SPM12 estimates nonlinear warps that match tissue probability maps to the individual image.

* Spatial normalisation achieved using the inverse of this transform.

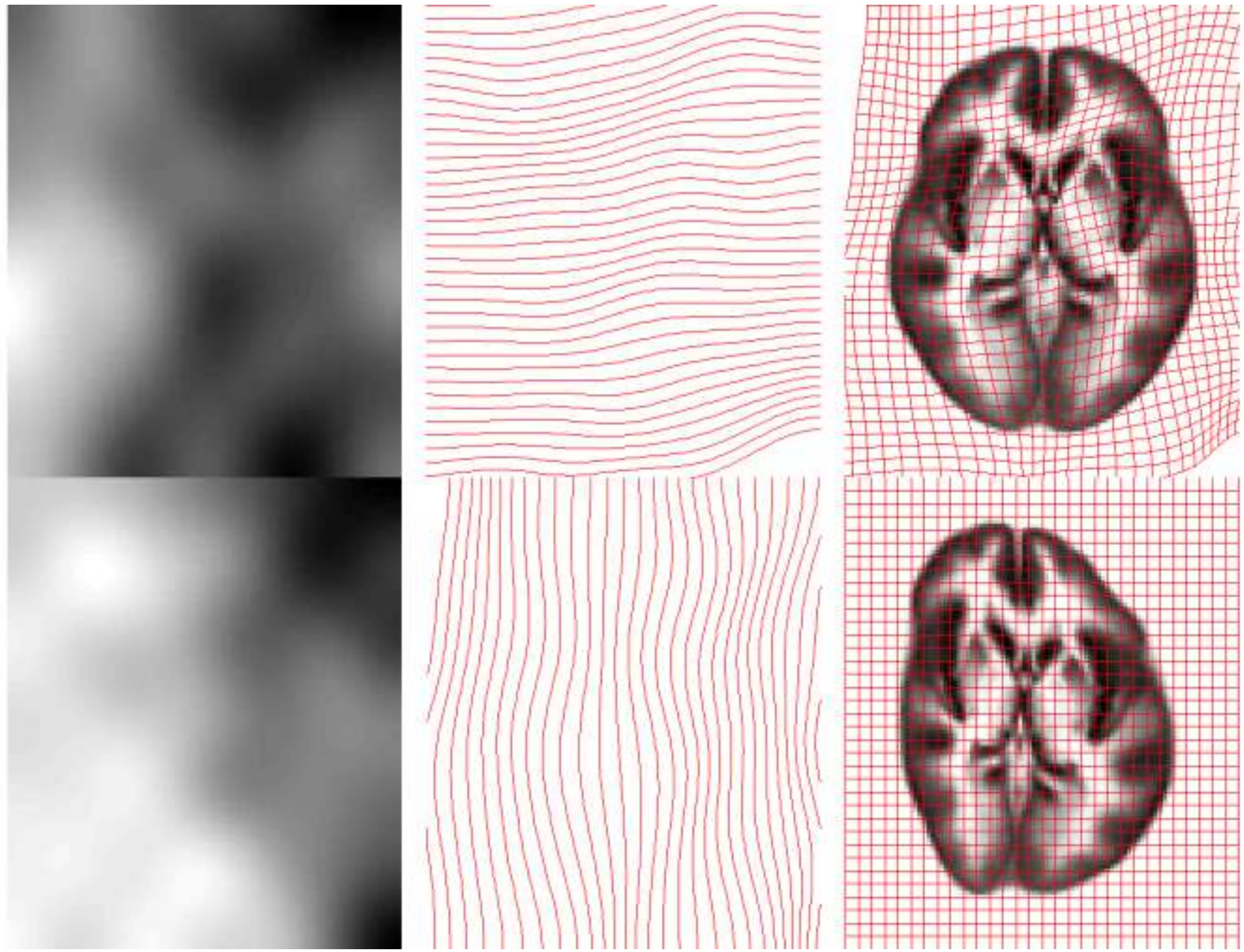


Modelling deformations

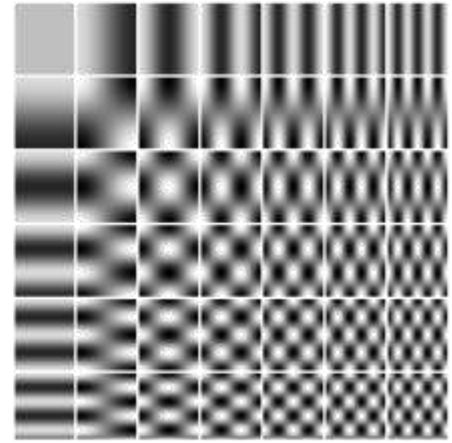
* Tissue probability maps are warped to align with tissues identified in image.

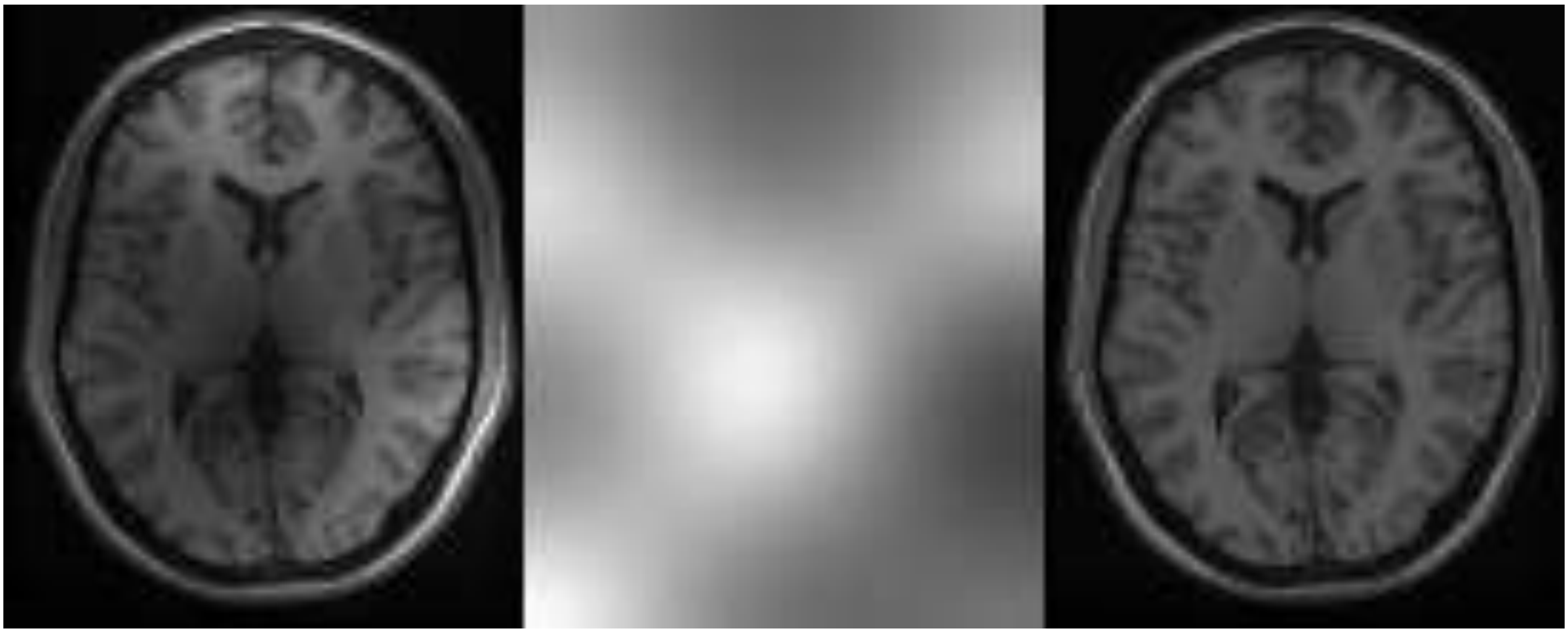


Modelling deformations



Modelling a bias field



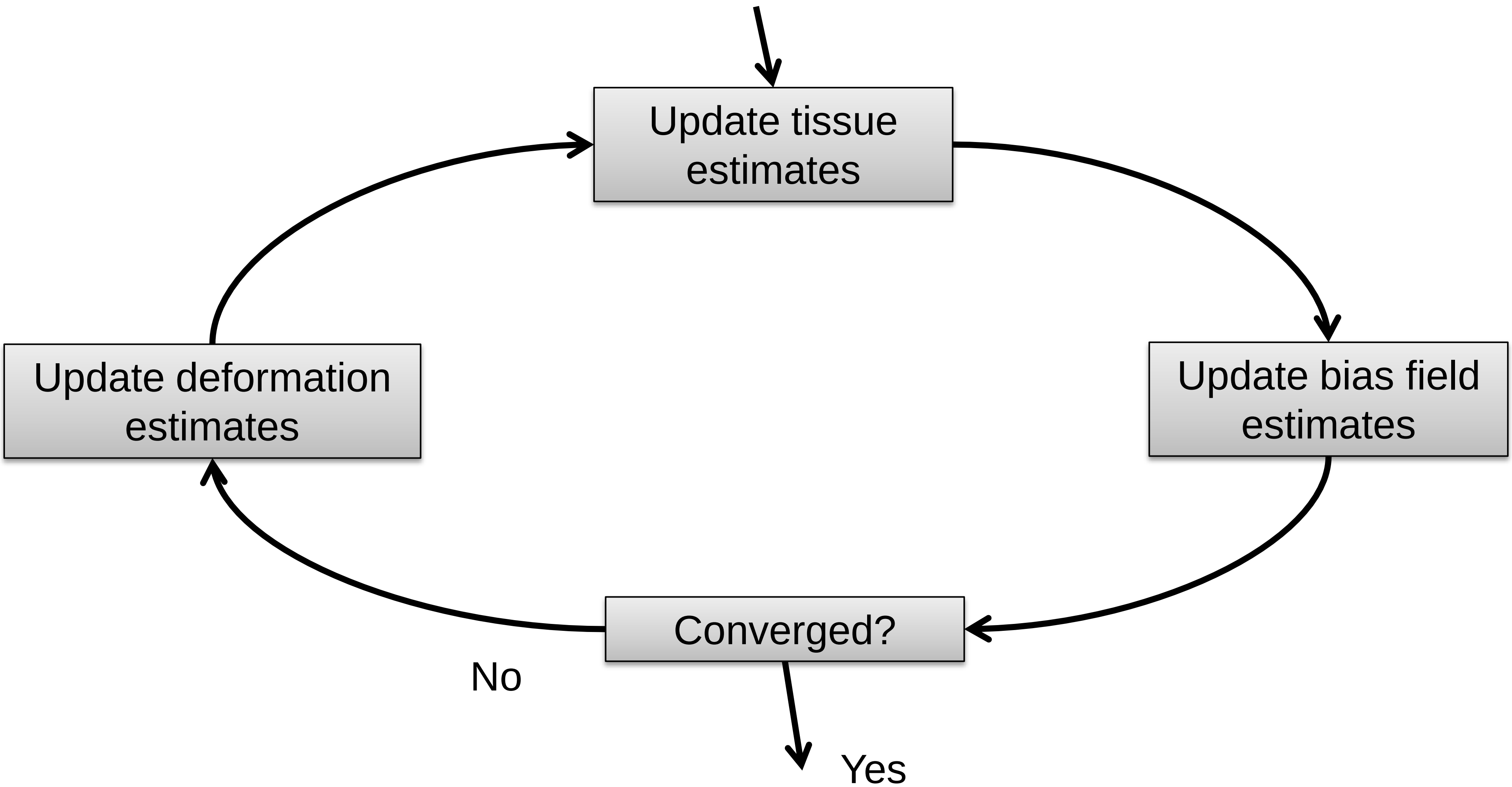


Corrupted image

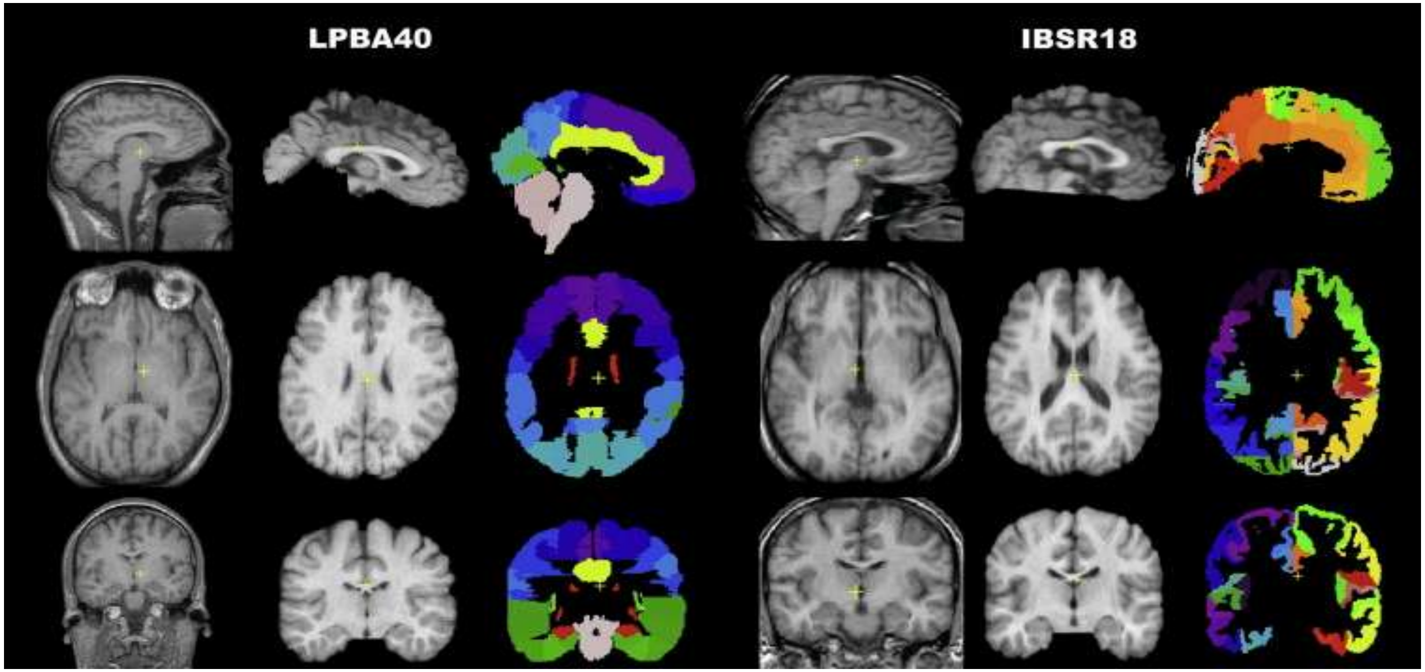
Bias Field

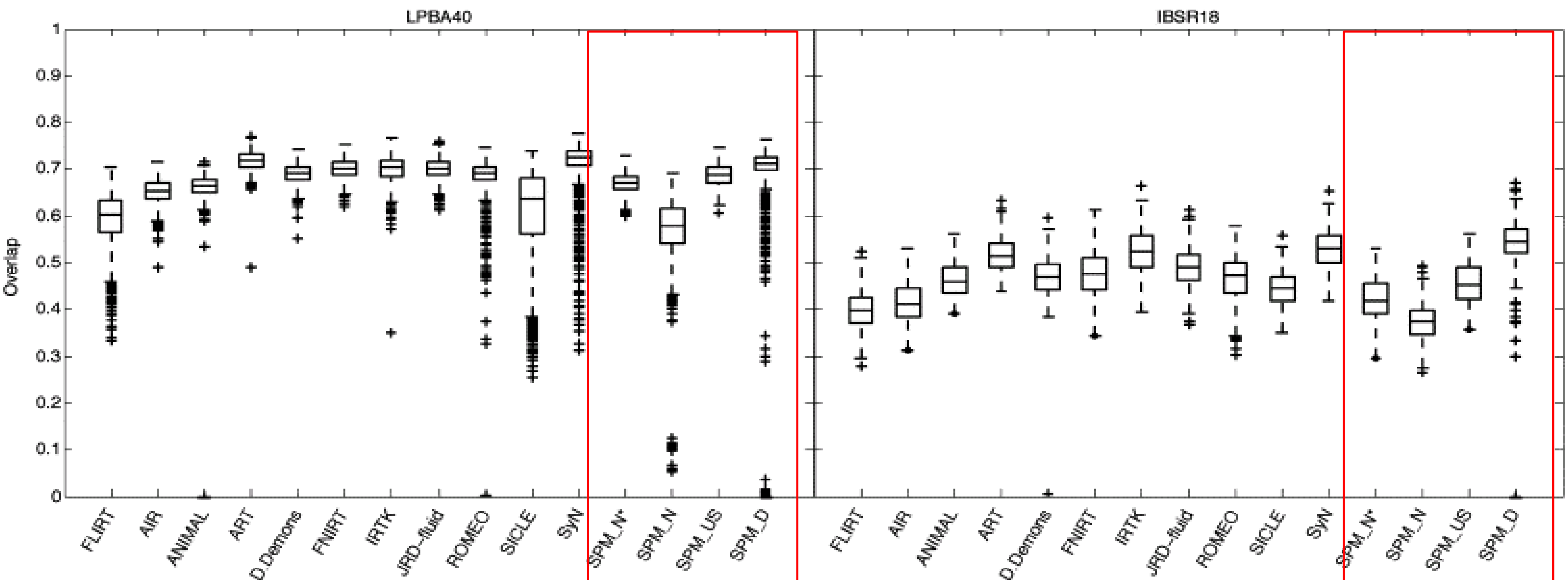
Corrected image

Iterative optimisation scheme



Evaluations of nonlinear registration algorithms

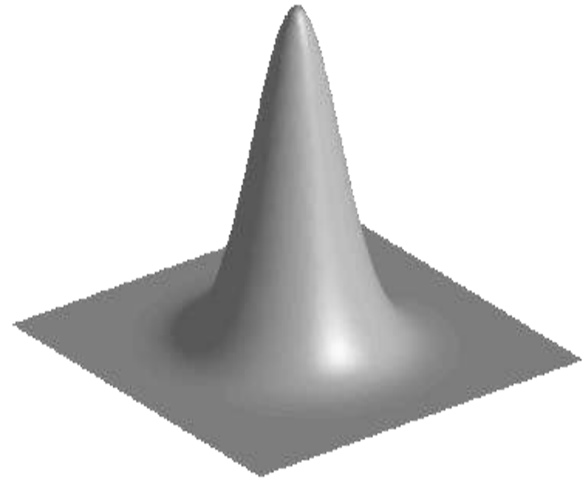




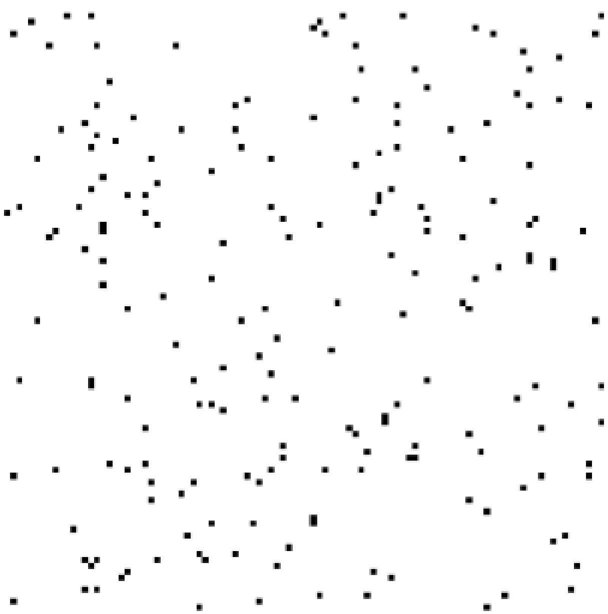
Smooth

Blurring is done by convolution.

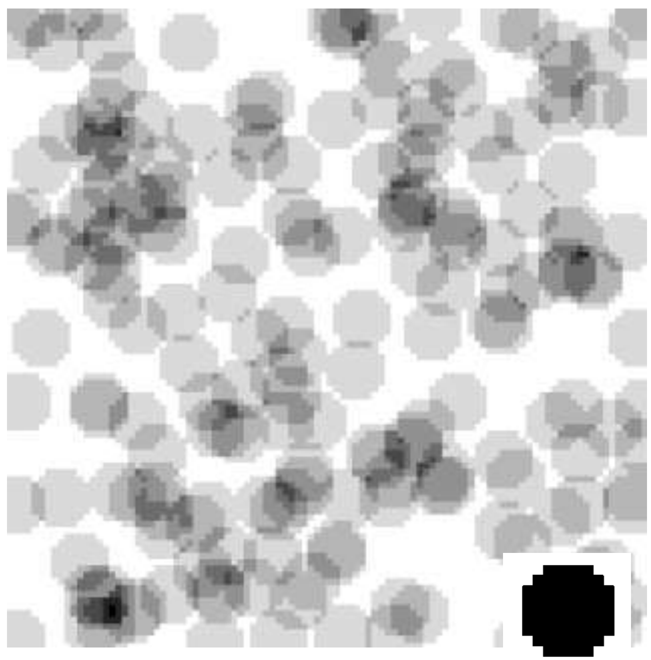
Each voxel after smoothing effectively becomes the result of applying a weighted region of interest (ROI).



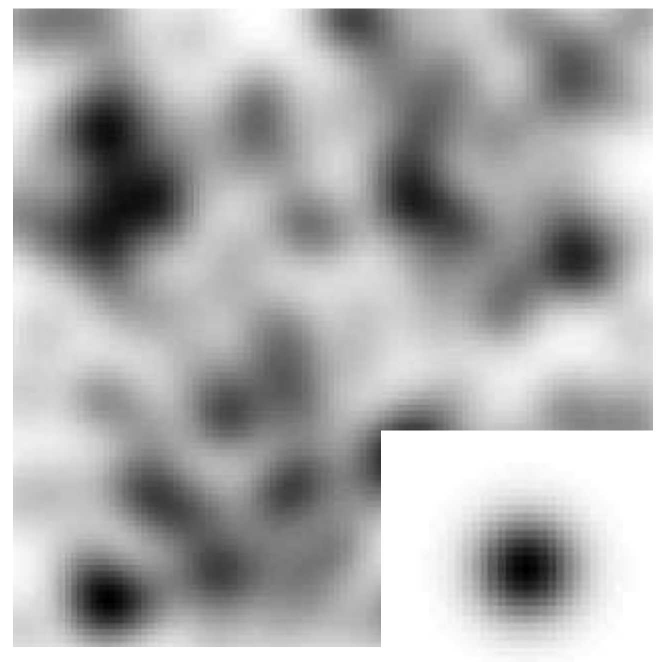
Before convolution



Convolved with a circle



Convolved with a Gaussian



References

* Friston et al. *Spatial registration and normalisation of images*. Human Brain Mapping 3:165-189 (1995).
* Collignon et al. *Automated multi-modality image registration based on information theory*. IPMI’95 pp 263-274 (1995).
* Thévenaz et al. *Interpolation revisited*. IEEE Trans. Med. Imaging 19:739-758 (2000).
* Andersson et al. *Modeling geometric deformations in EPI time series*. Neuroimage 13:903-919 (2001).
* Ashburner & Friston. *Unified Segmentation*. NeuroImage 26:839-851 (2005).
* Klein et al. *Evaluation of 14 nonlinear deformation algorithms applied to human brain MRI registration*. NeuroImage 46(3):786-802 (2009).