Quantitative Neuro-Anatomic and Functional Image Assessment

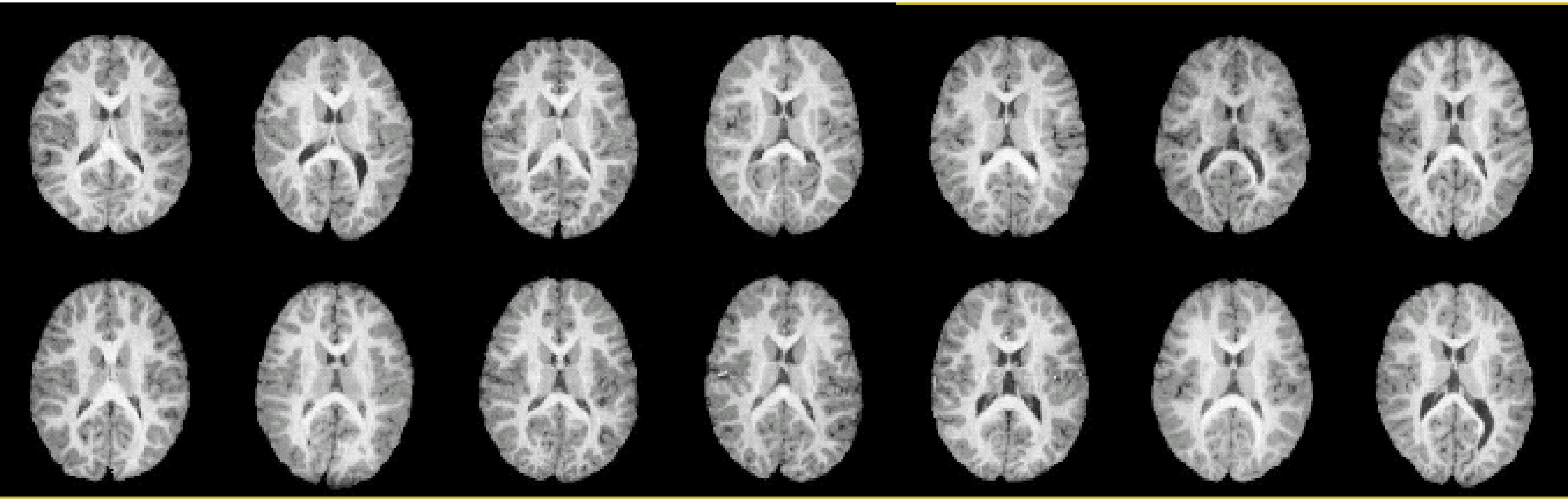
Recent progress on image registration and its applications

Guido Gerig
Sarang Joshi
Tom Fletcher

Applications of image registration in neuroimaging

- Atlas construction
  - Probabilistic atlases
  - Statistical atlases
  - Unbiased atlases
- Atlas-based segmentation
  - Atlases are used as prior knowledge
  - Tissue and/or anatomical segmentation
- Quantification of anatomical and functional differences
  - across time $\Rightarrow$ longitudinal studies
  - across groups $\Rightarrow$ cross-sectional studies

Motivation: A Natural Question



- Given a collection of Anatomical Images what is the Image of the “Average Anatomy”.

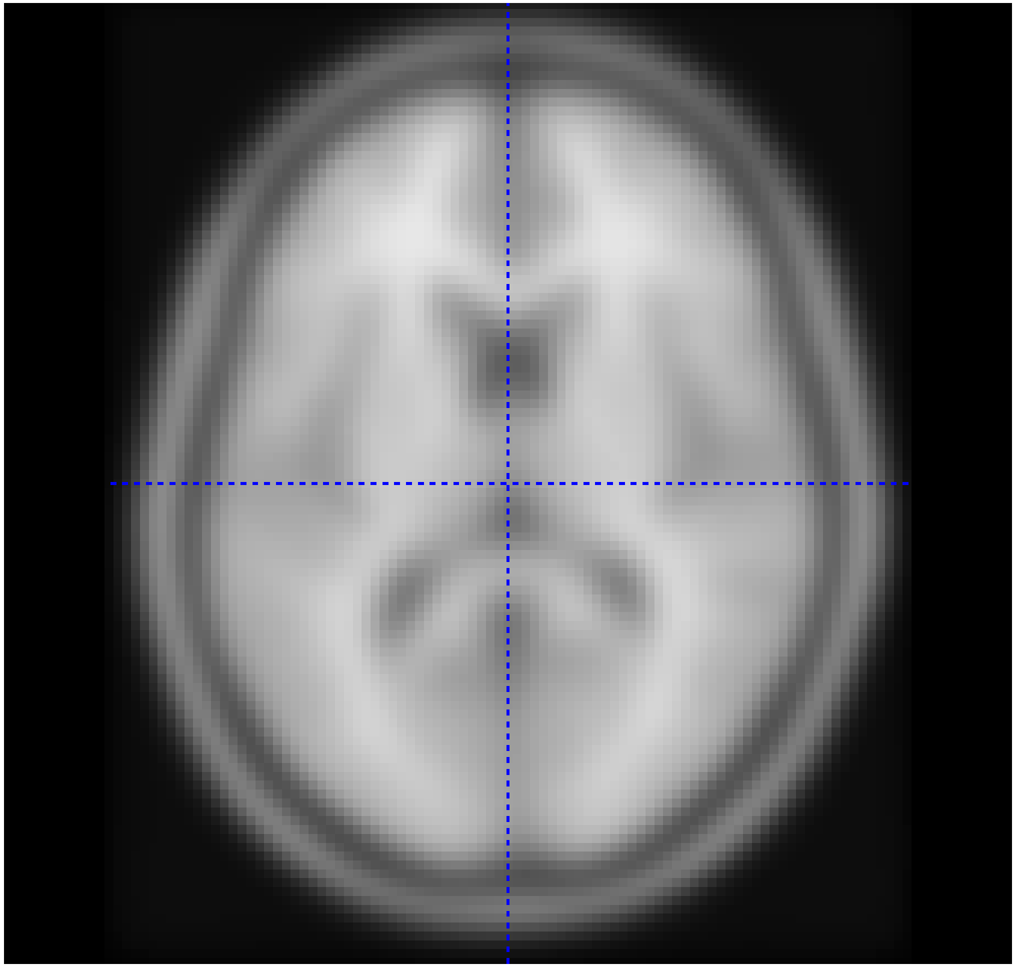
Courtesy S. Joshi

Population Variability

- How to compare and measure structures across different subjects?

Courtesy S. Joshi

Average after linear alignment (affine)

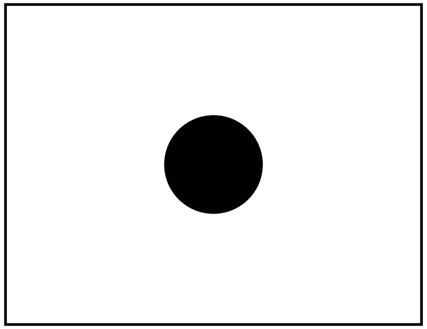


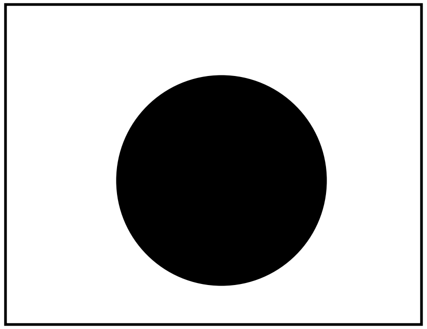
Adult brain MRI atlas (Montreal Neurological Institute):

- 152 adult subjects
- Affine registration
- Superposition
- Serves as probabilistic template for brain mapping
- Blurry, does not look like a real image

Motivation: A Natural Question

Consider two simple images of circles:



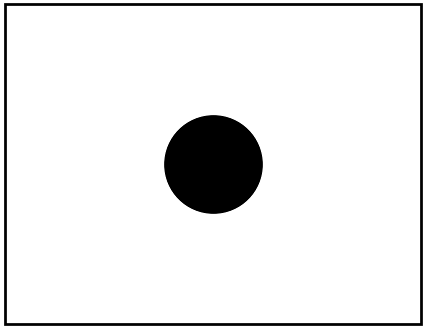


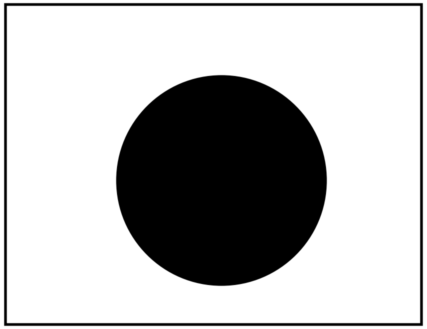
What is the Average?

Courtesy S. Joshi

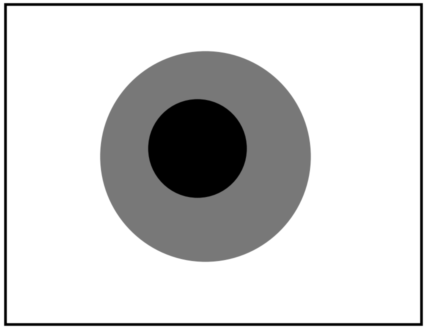
Motivation: A Natural Question

Consider two simple images of circles:





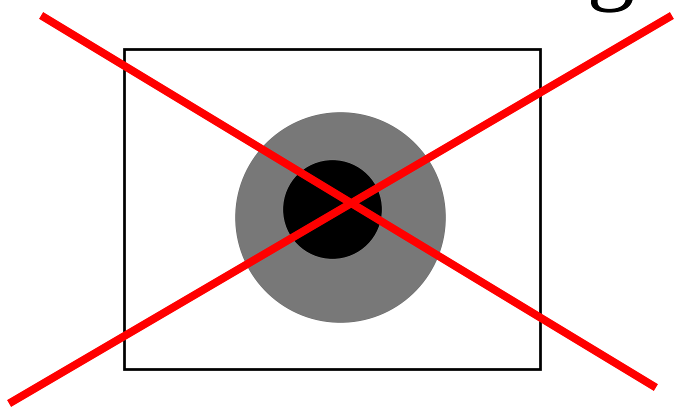
What is the Average?



Courtesy S. Joshi

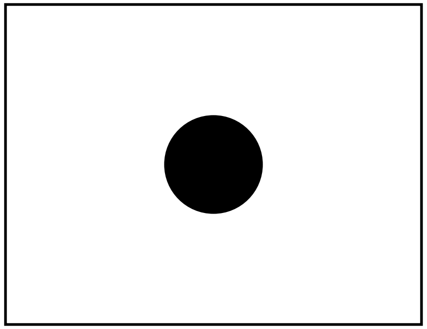
Motivation: A Natural Question

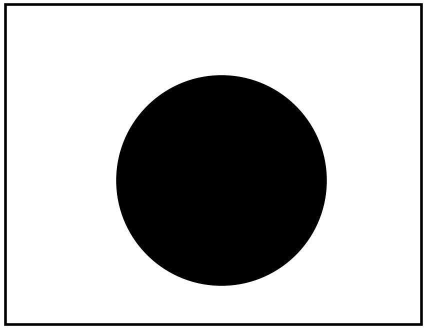
What is the Average?



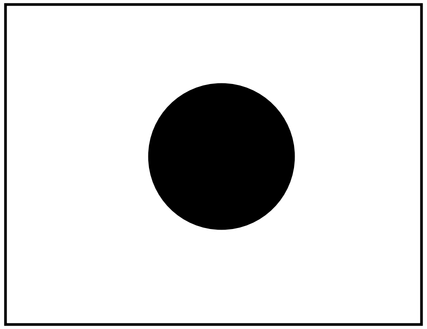
Courtesy S. Joshi

Motivation: A Natural Question





Average considering “Geometric Structure”



A circle with
“average radius”

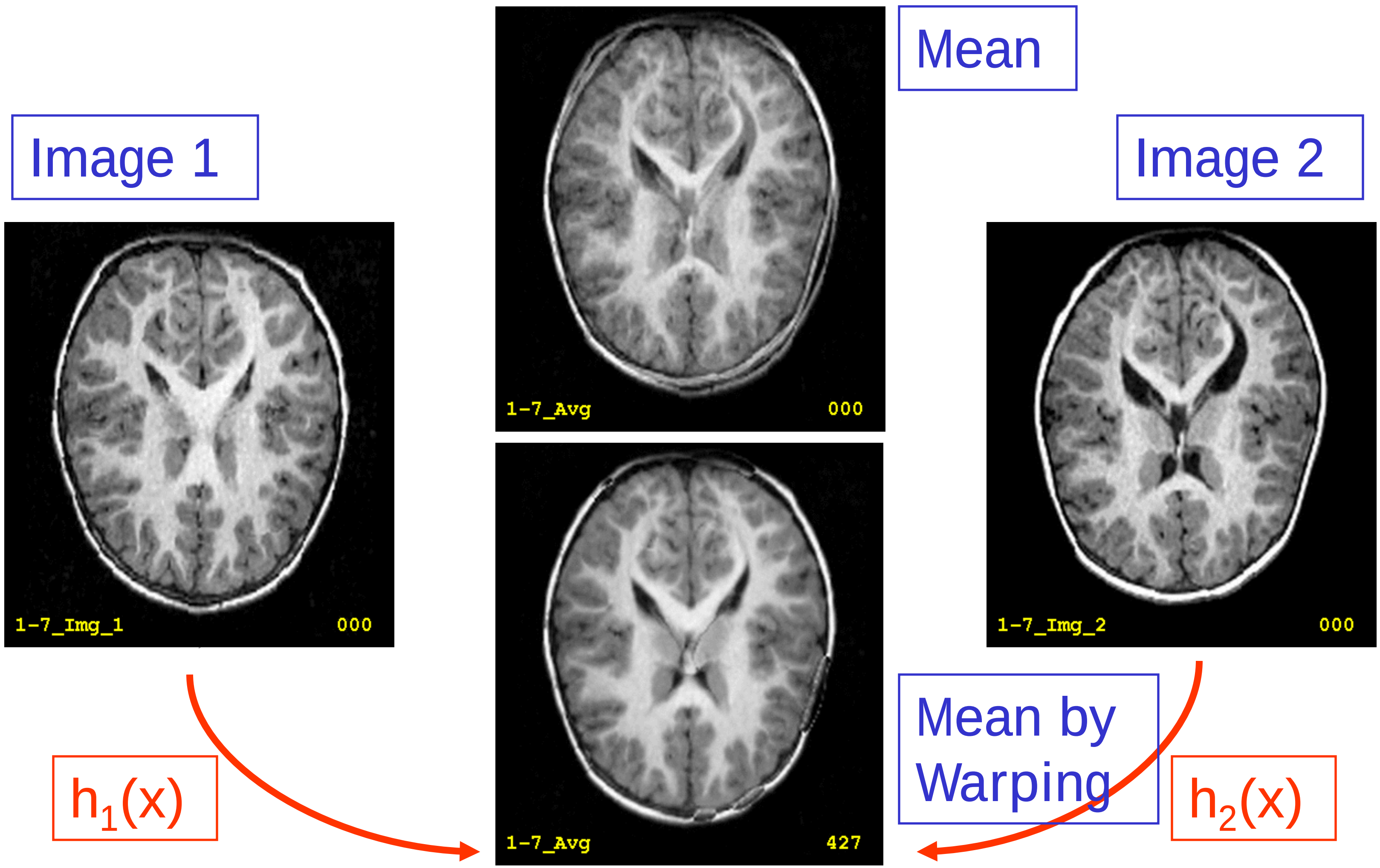
Courtesy S. Joshi

Mathematical Foundations of Computational Anatomy

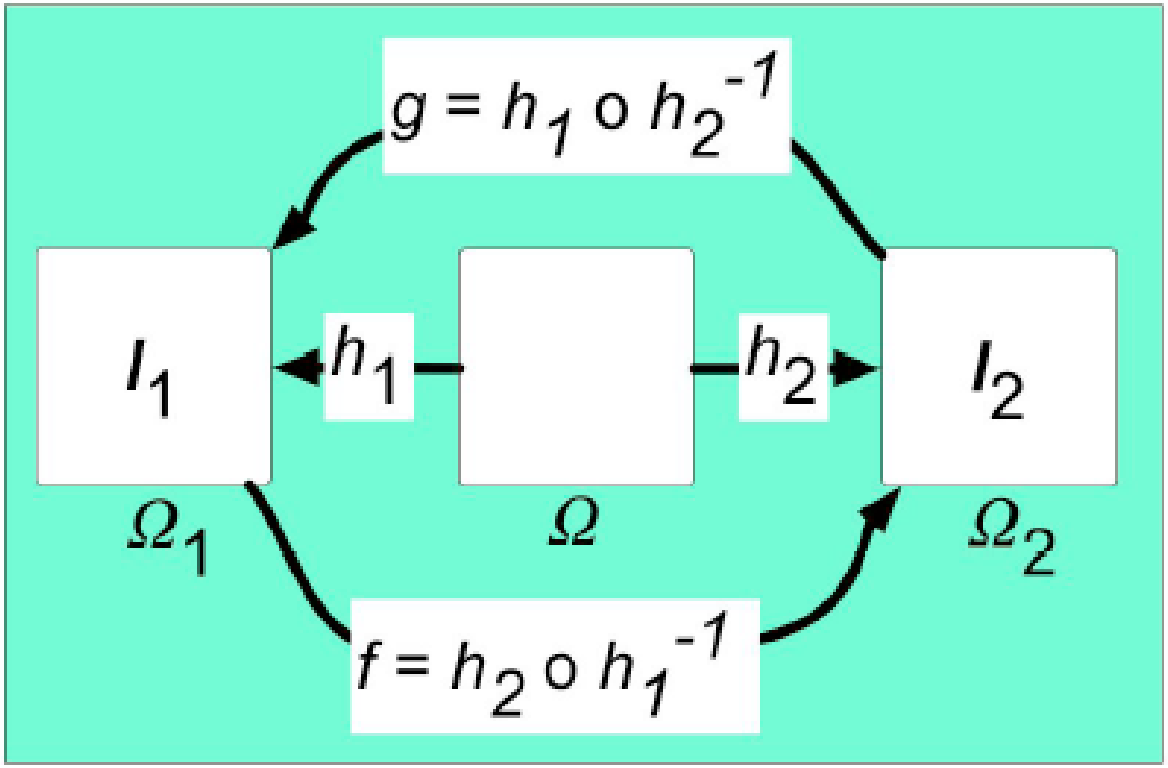
- Structural variation with in a population represented by transformation groups:
  - For circles simple multiplicative group of positive reals (R^+)
  - Scale and Orientation: Finite dimensional Lie Groups such as Rotations, Similarity and Affine Transforms.
  - High dimensional anatomical structural variation: Infinite dimensional Group of Diffeomorphisms.

Courtesy S. Joshi

Unbiased Diffeomorphic Atlas Construction for Computational Anatomy (Joshi, Davis, Lorenzen)



Atlas Formation: Symmetric Registration



Symmetric Registration Framework

$f \circ g = h_2 \circ h_1^{-1} \circ h_1 \circ h_2^{-1} = \mathrm{Id}$

Averaging Anatomies

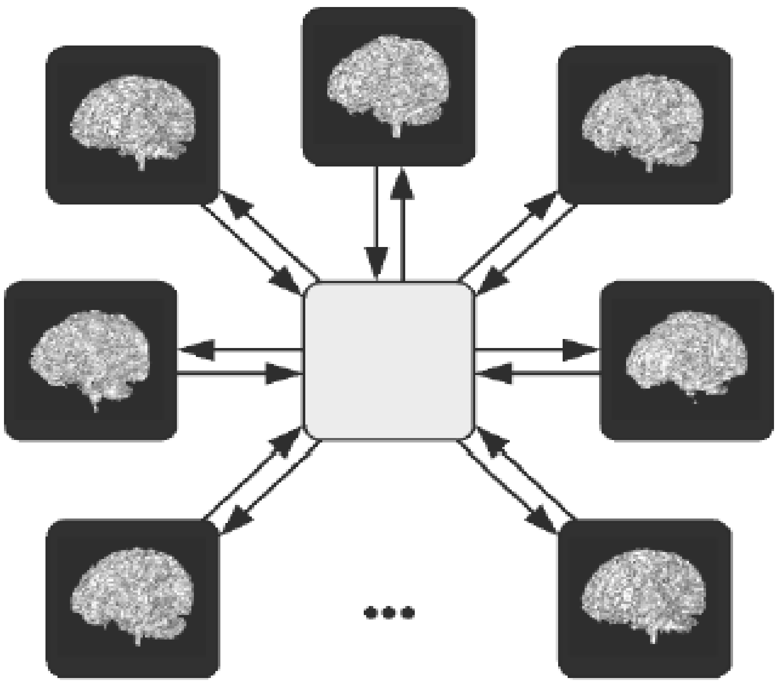


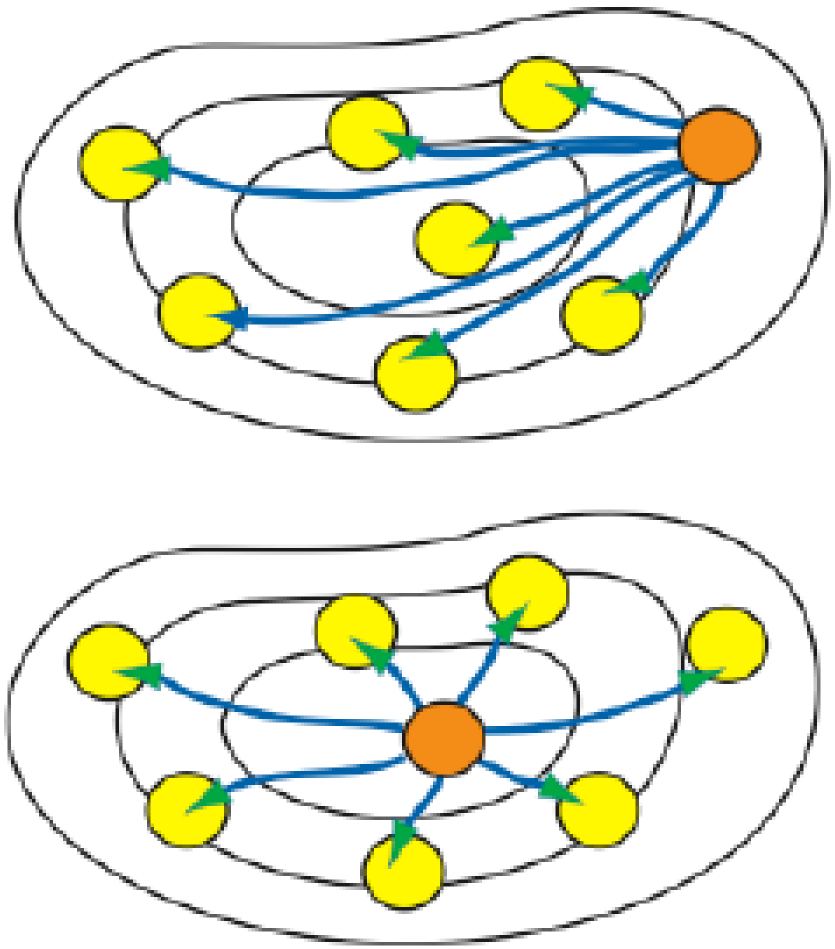
Figure 1. Template Construction Framework

Motivation:

- Map population into common coordinate space
- Learn about normal variability
- Describe difference from normal
- Use as normative atlas for segmentation

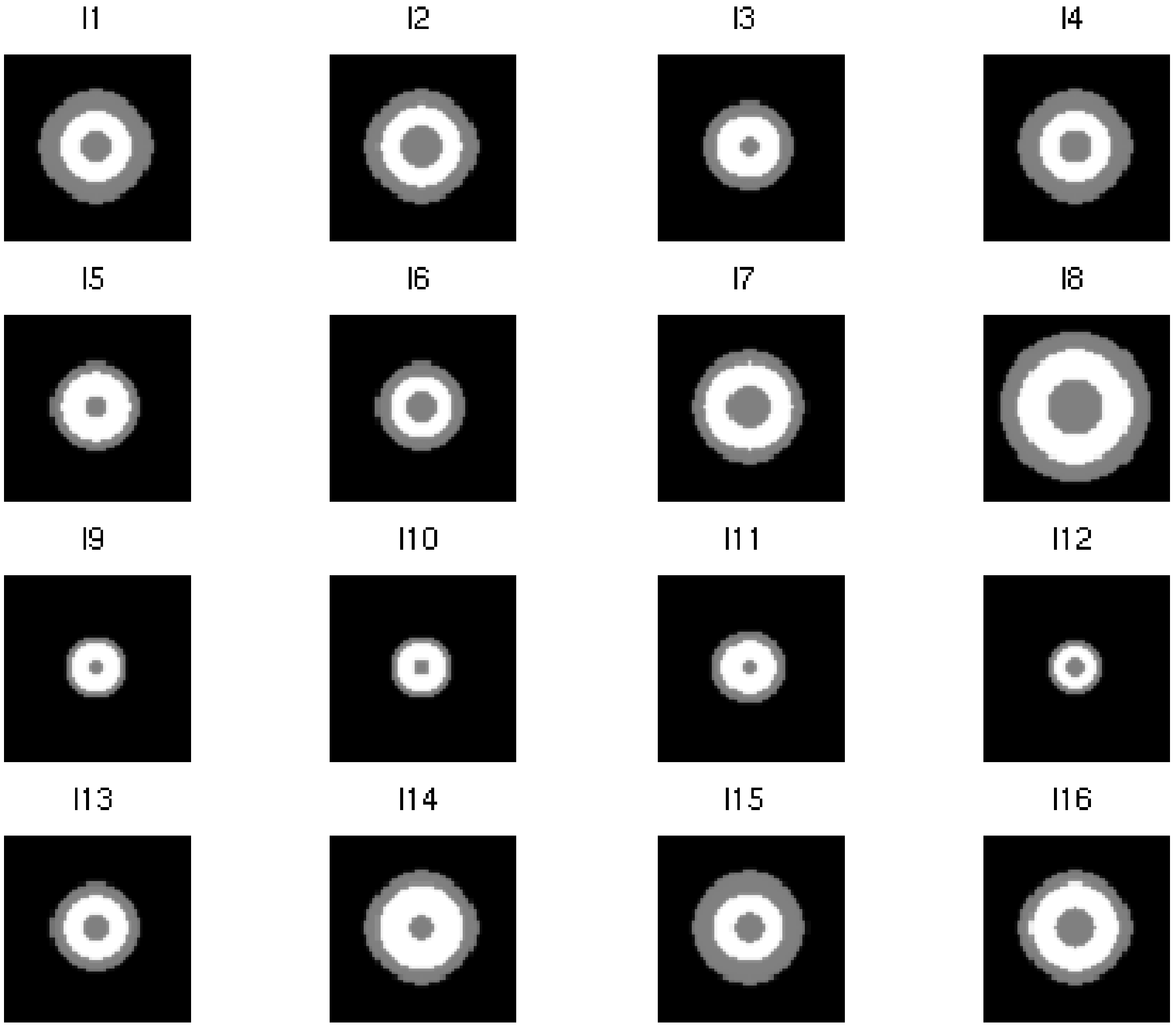
Sarang Joshi, Brad Davis, Matthieu Jomier, Guido Gerig, Unbiased Diffeomorphic Atlas Construction for Computational Anatomy, vol. 23, NeuroImage 2004

Group-wise Atlas Building



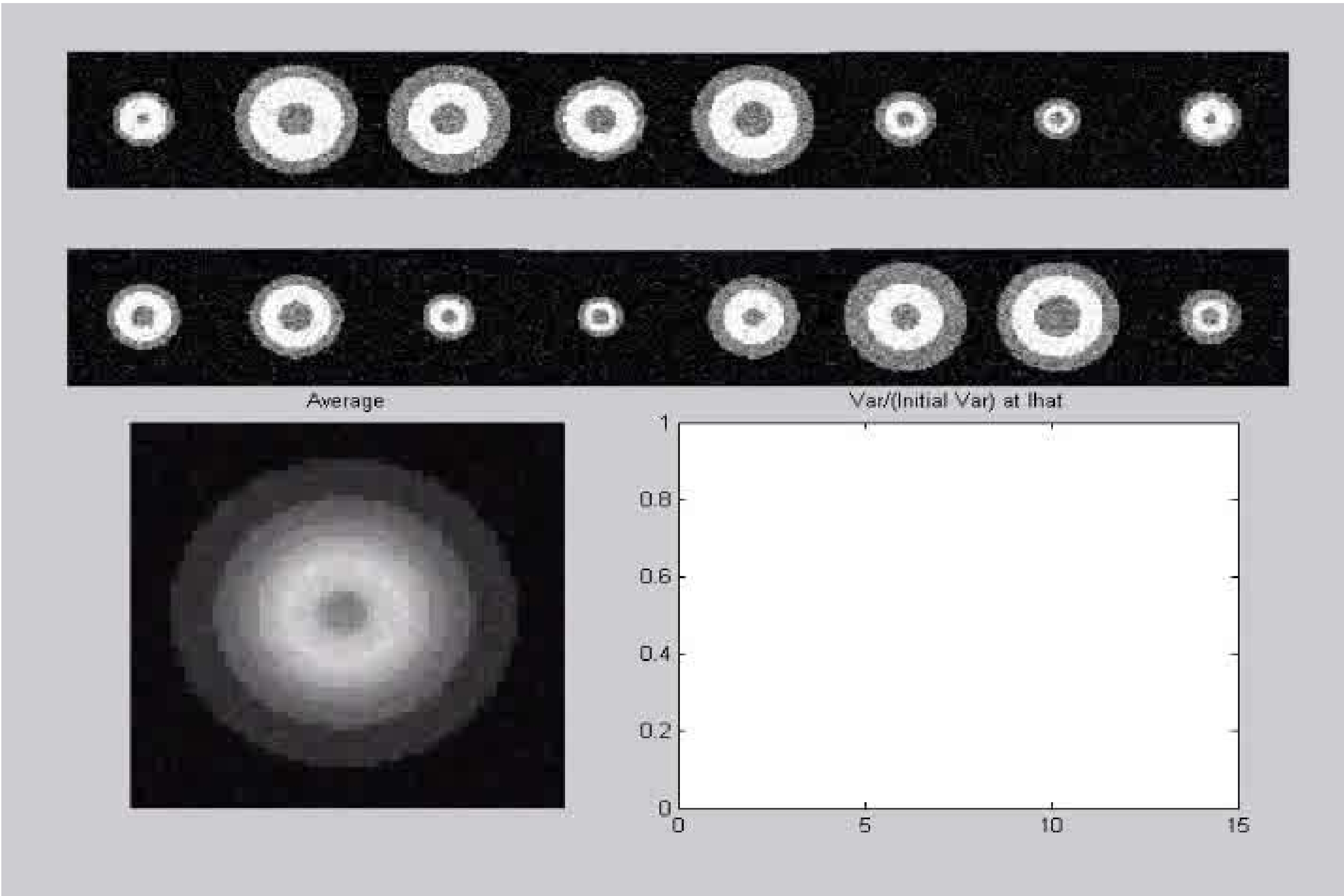
Minimize total distance beetween population and template
(Gee & Avants, Joshi&Fletcher)

More than Pairs: Sample of 16 Bull's eye Images



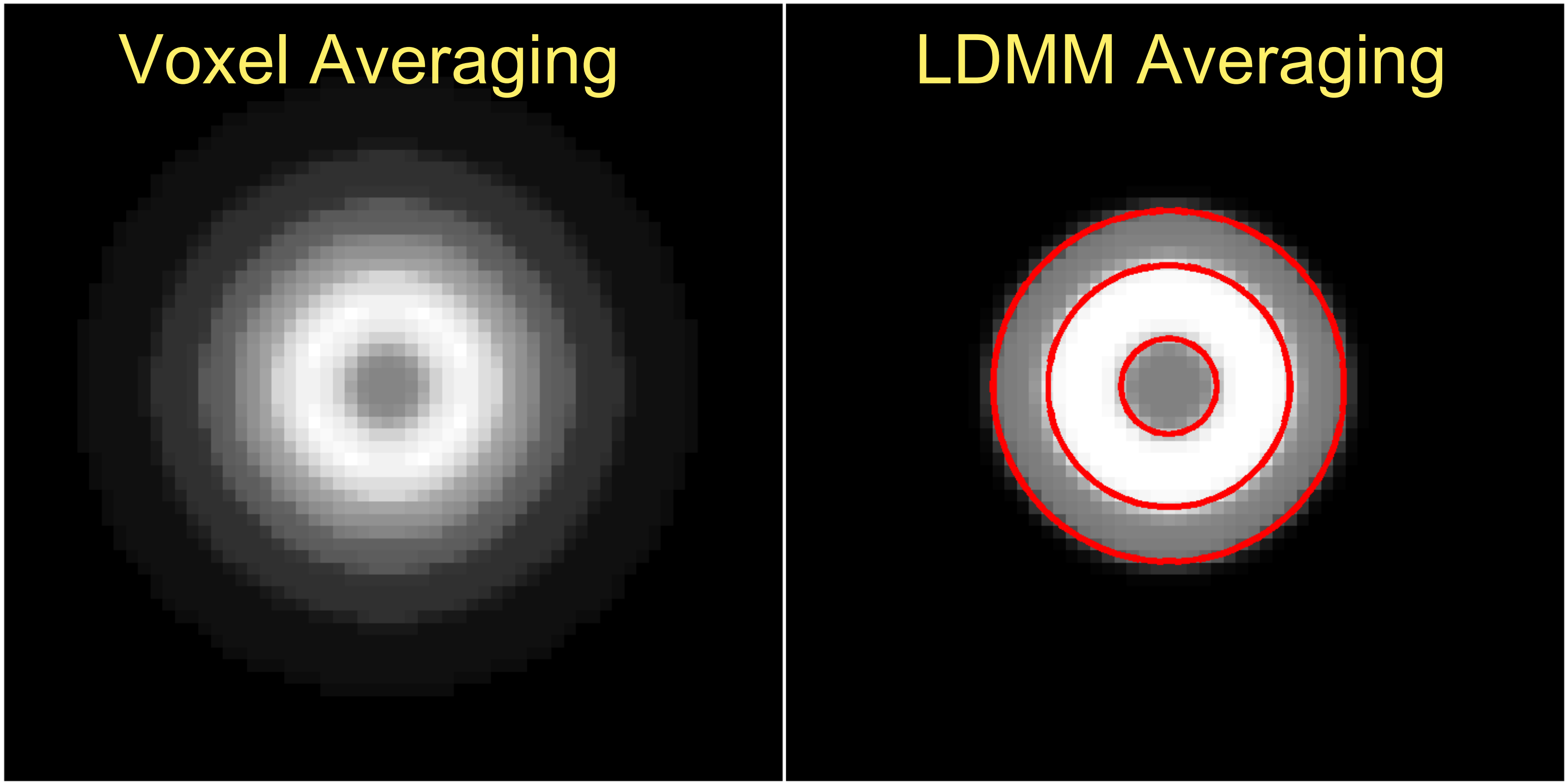
Courtesy S. Joshi

Group-wise Image Averaging



Courtesy S. Joshi

Averaging of 16 Bull's eye images



Numerical geometric average of the radii of the individual circles forming the bulls eye sample.

Courtesy S. Joshi

Averages in Metric Spaces

- Recall the linear average:

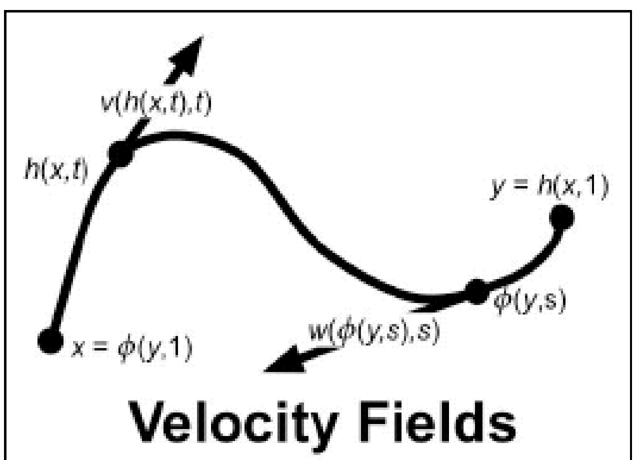
$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i$$

- The space of diffeomorphisms is not a vector space
- Need a more general notion of "average"
- Frechet mean: $\mu = \operatorname*{argmin}_{x \in \mathcal{M}} \sum_{i=1}^{N} d(x, x_i)^2$

Large deformation diffeomorphisms.

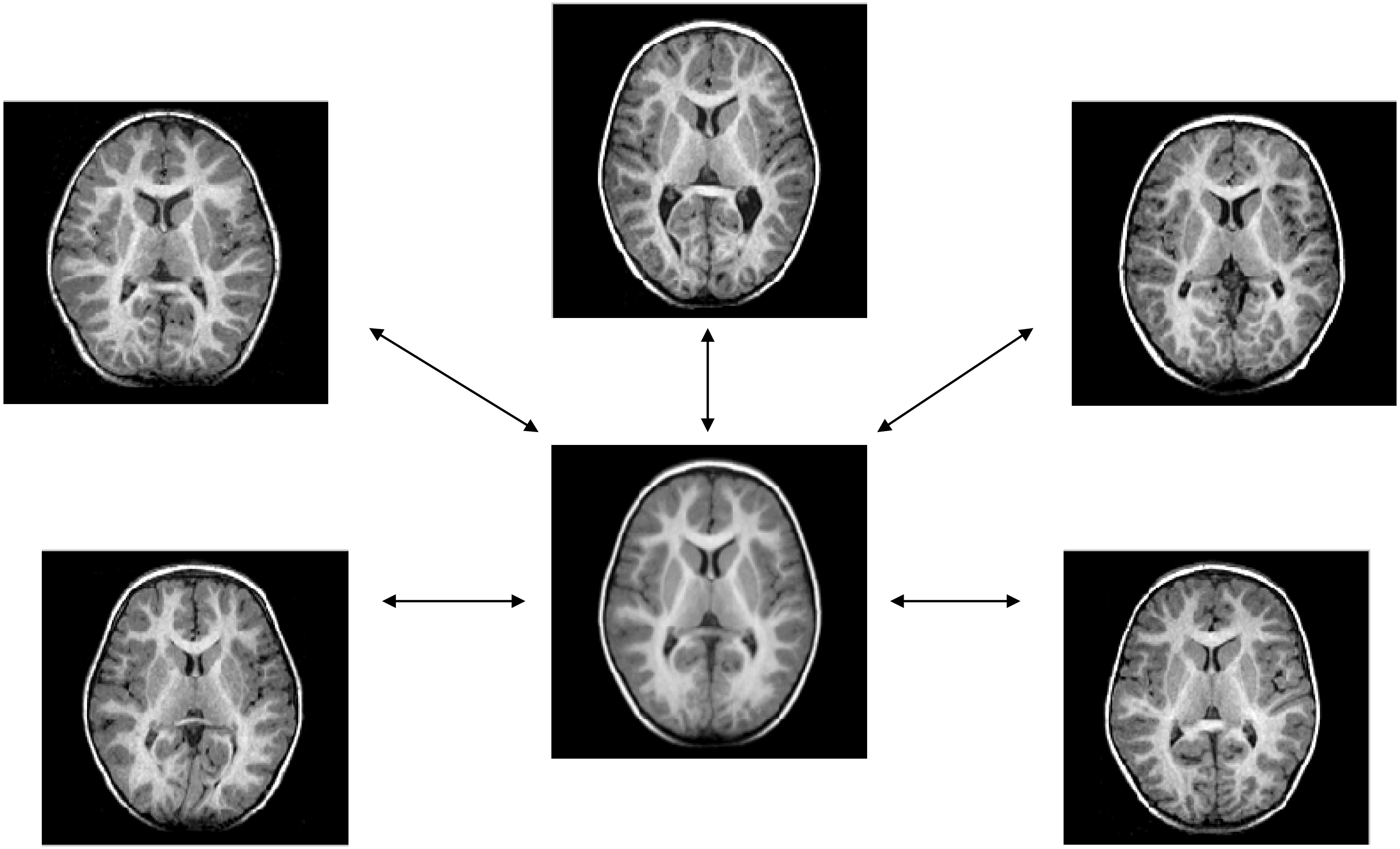
- $Diff\,(\Omega)$ infinite dimensional “Lie Group”.
- Tangent space: The space of smooth vector valued velocity fields on Ω .
- Construct deformations by integrating flows of velocity fields.
- Induce a metric via a differential norm on velocity fields.

$$\frac{d}{dt}h(x,t) = v(h(x,t),t) \quad h(x,0) = x.$$

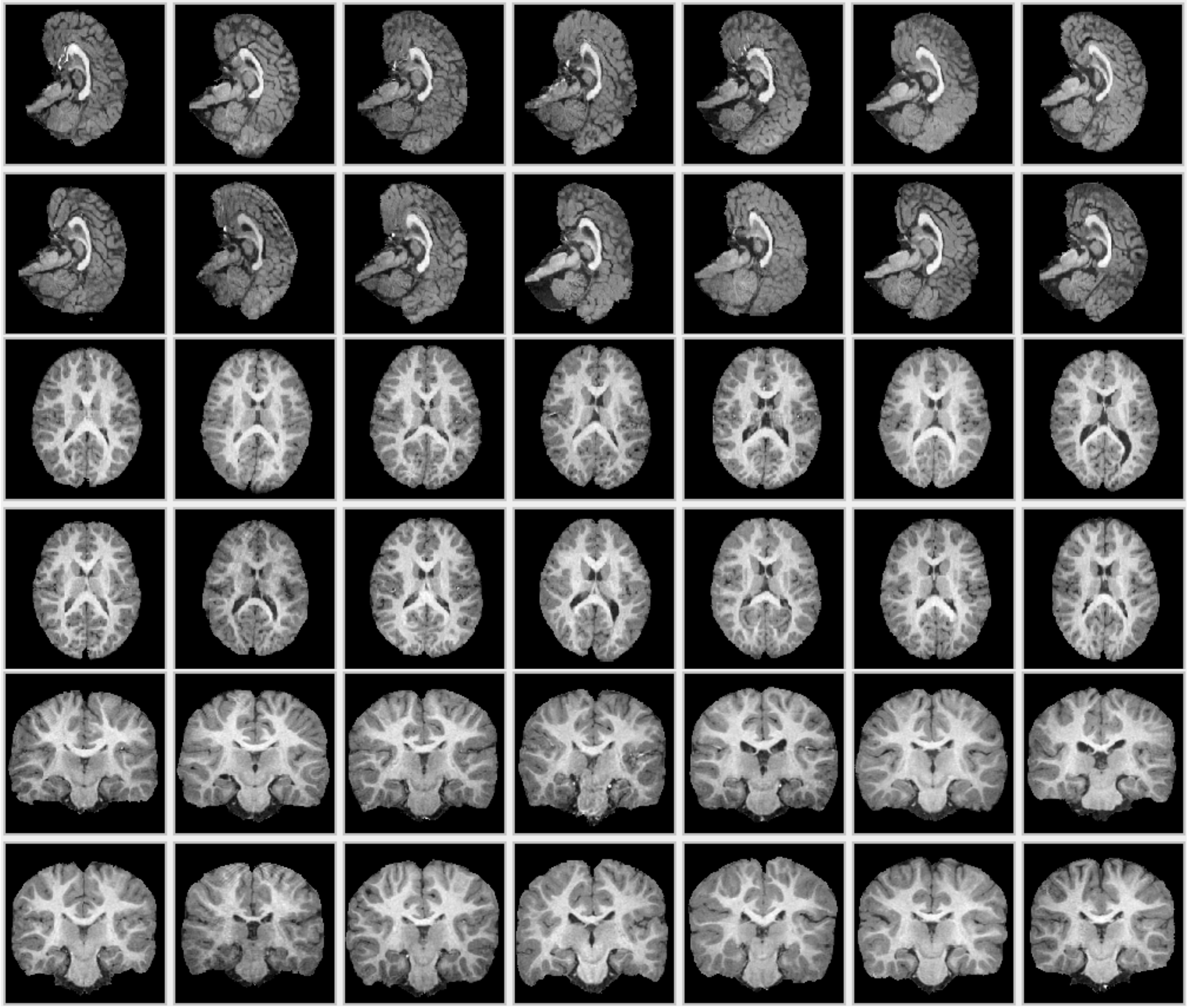


$$\begin{aligned} y &= h(x,1) = x + \int_0^1 v(h(x,\tau),\tau)d\tau \\ x &= \phi(y,1) = y + \int_0^1 w(\phi(y,\tau),\tau)d\tau \end{aligned}$$

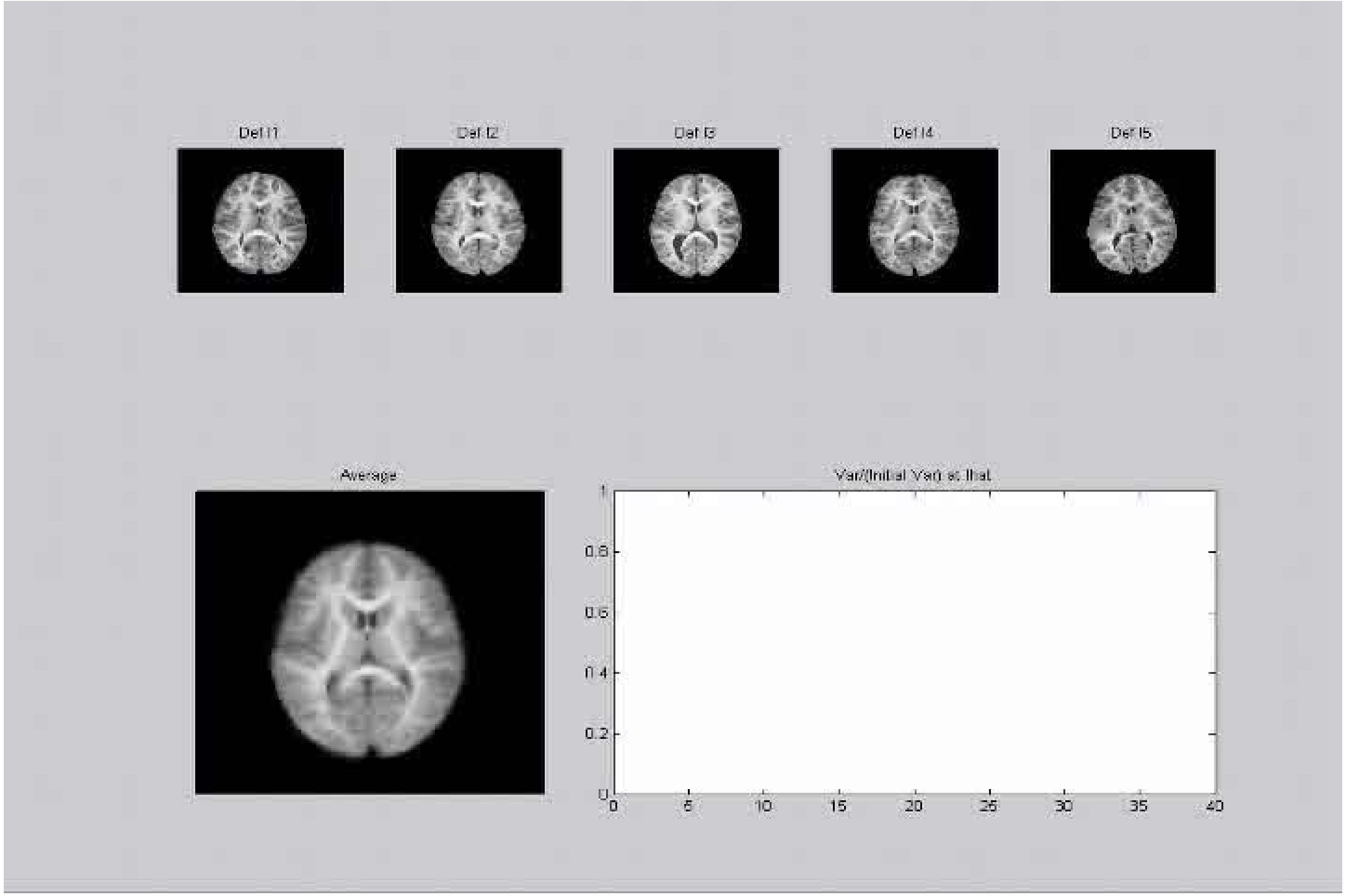
Atlas Building – Population Average (Infant 2 yr)



Atlas Builder – Atlas with 14 images

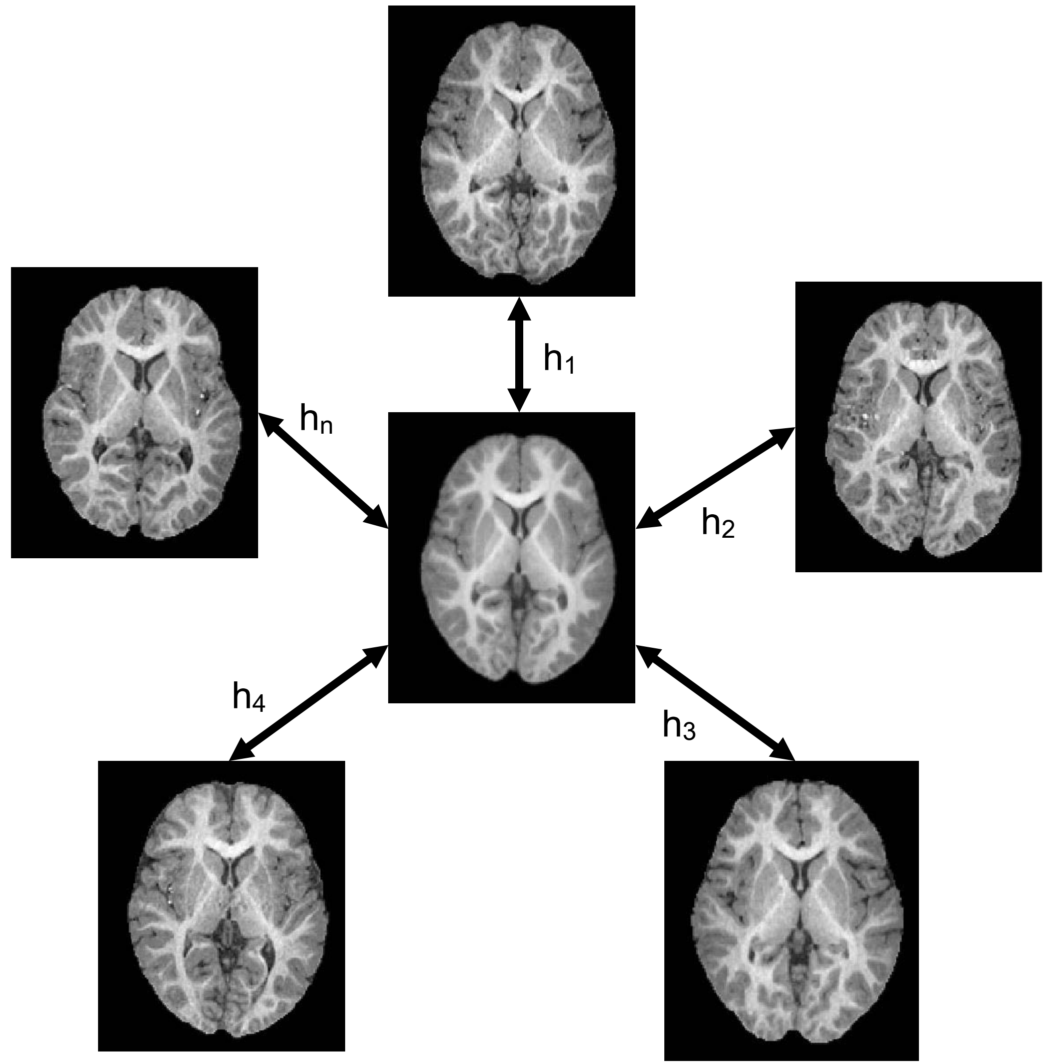


Averaging Brain Images



Motivation Atlas Building: Statistics of embedded Shapes

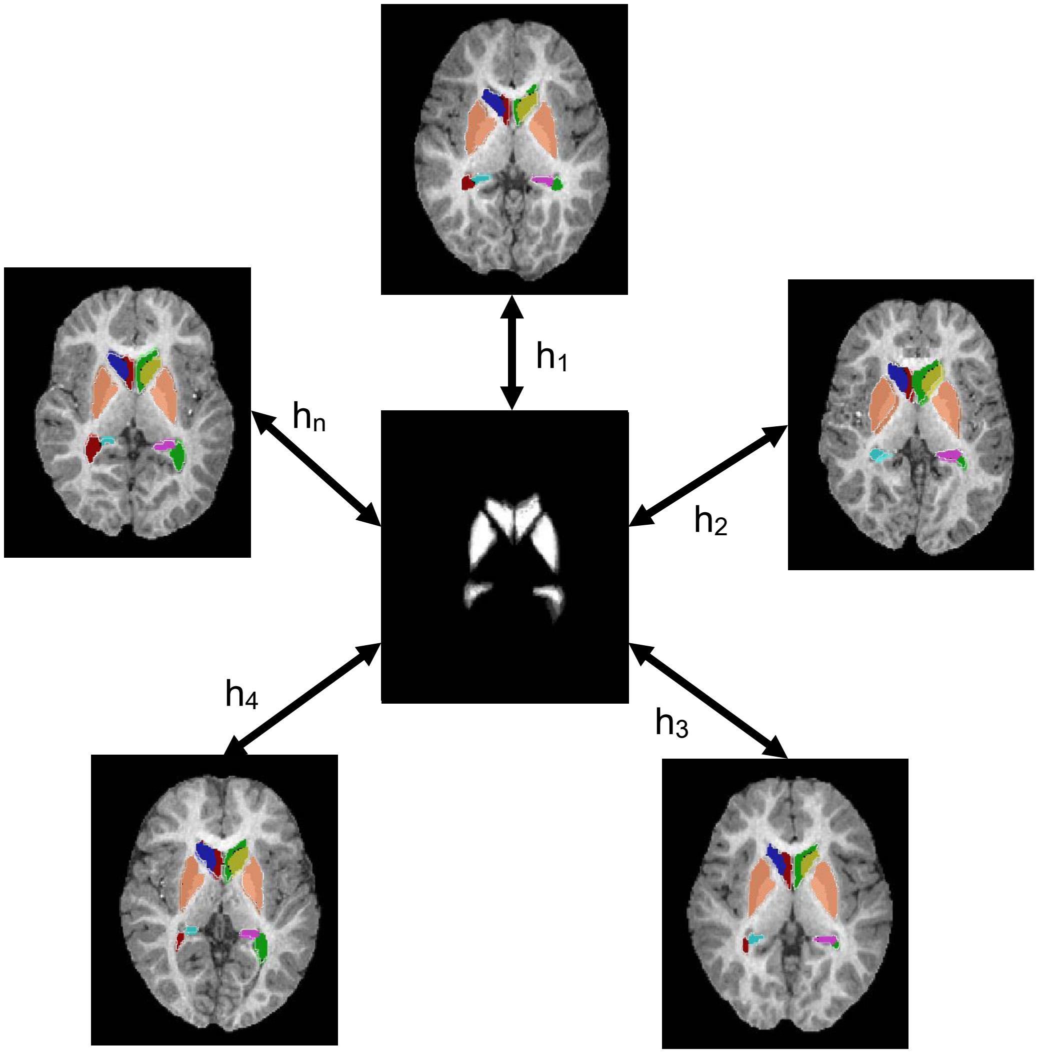
- Brain atlases is central to the understanding of the variability of brain anatomy.
- How to study statistical shape properties from nonlinear deformation fields of atlases?



Embedded Objects: Voxel Representation

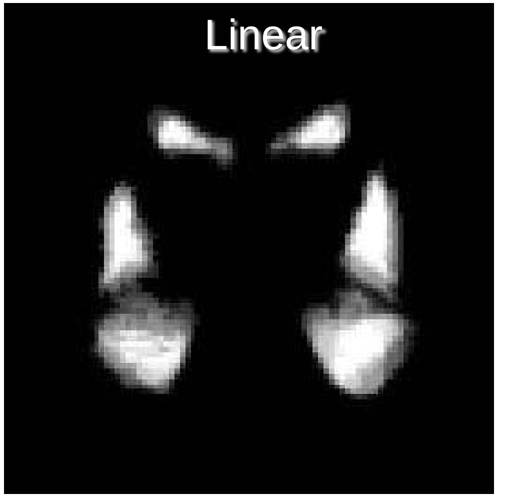
To evaluate shape variability

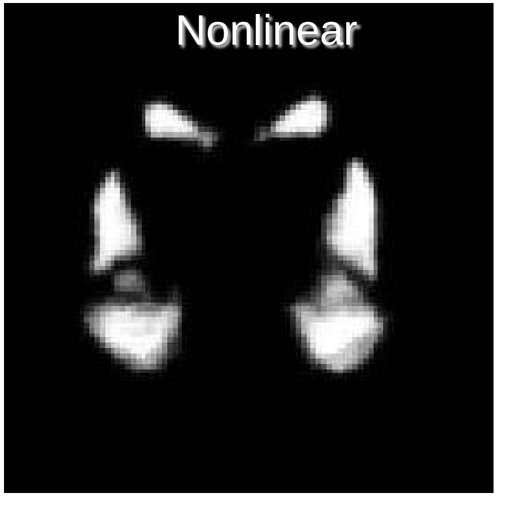
- reliable user-supervised voxel segmentations by geodesic snakes
- probability map in atlas space



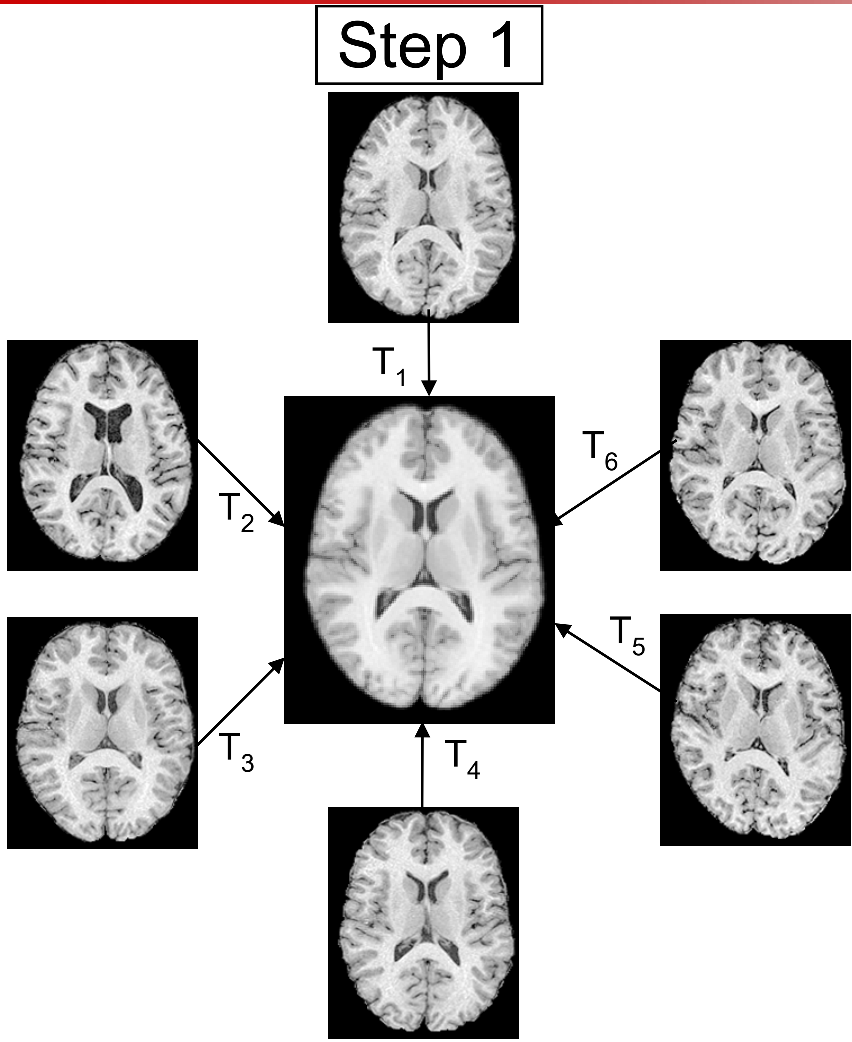
Voxel-based Representation: Linear vs. Nonlinear Atlas

- Single population
- Linear averaging of voxel objects — blurry probability maps
- Nonlinear average appears sharper
- Notion of probabilistic label atlas: centered & population-based

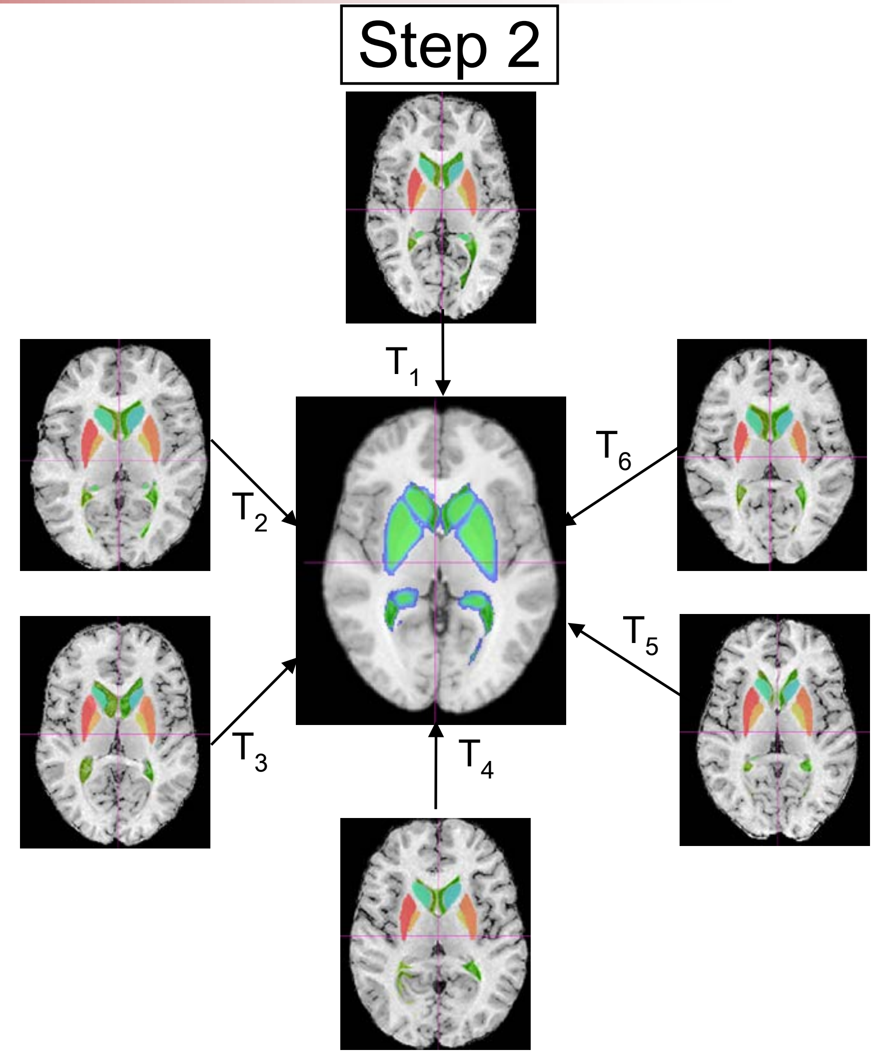




Atlas-based segmentation: Atlas Building

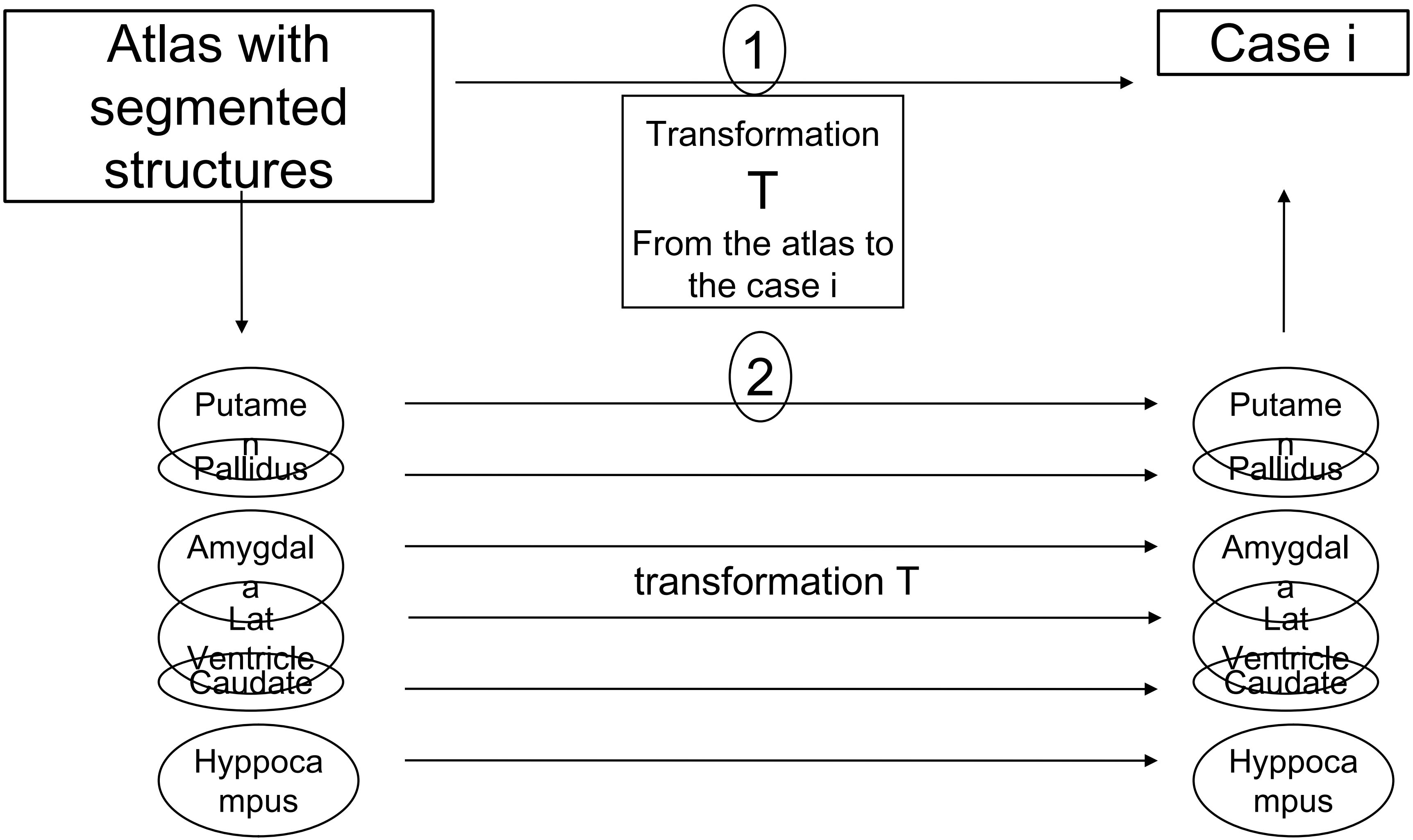


Template image created from several cases



Probabilistic maps of the 12 ROIs

Pipeline


Atlas with segmented structures
1
Case i
Transformation
T
From the atlas to the case i
2
Putame
n
Pallidus
Amygdal
a
Lat
Ventricle
Caudate
Hyppoca
mpus
transformation T
Putame
n
Pallidus
Amygdal
a
Lat
Ventricle
Caudate
Hyppoca
mpus

Segmented ROIs

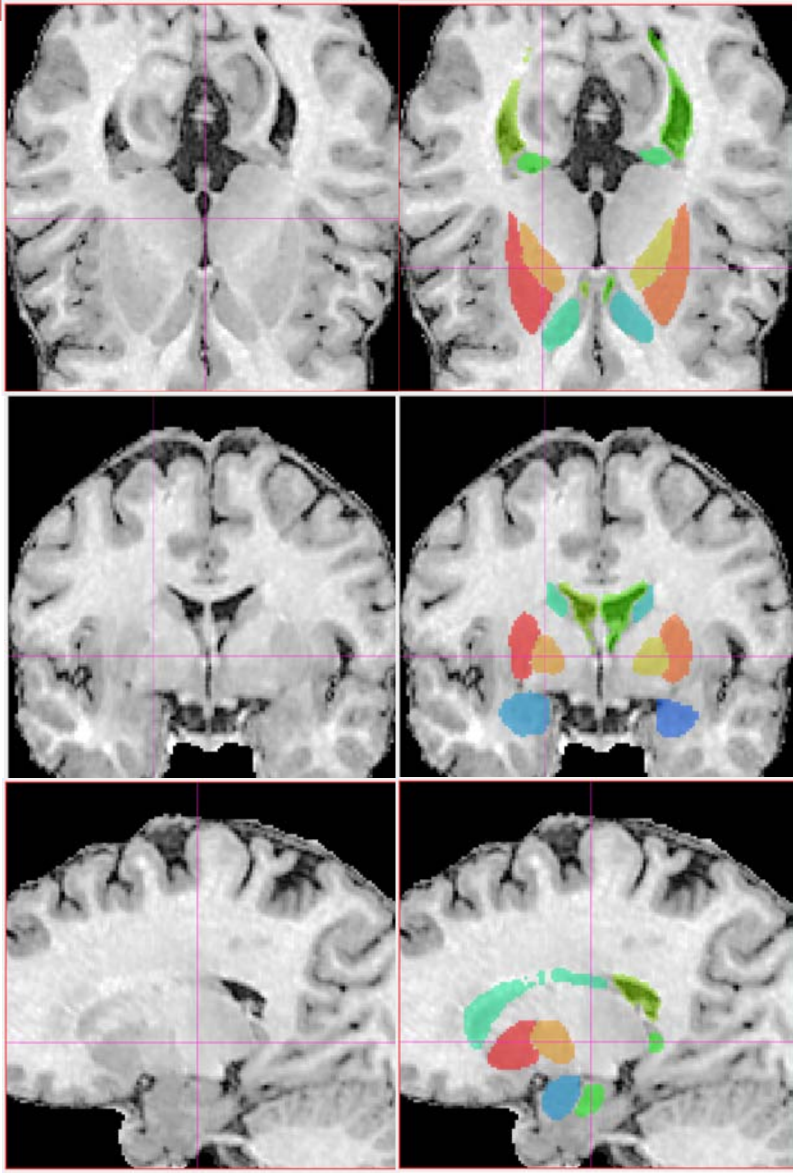
Segmented case

Without ROIs With ROIs

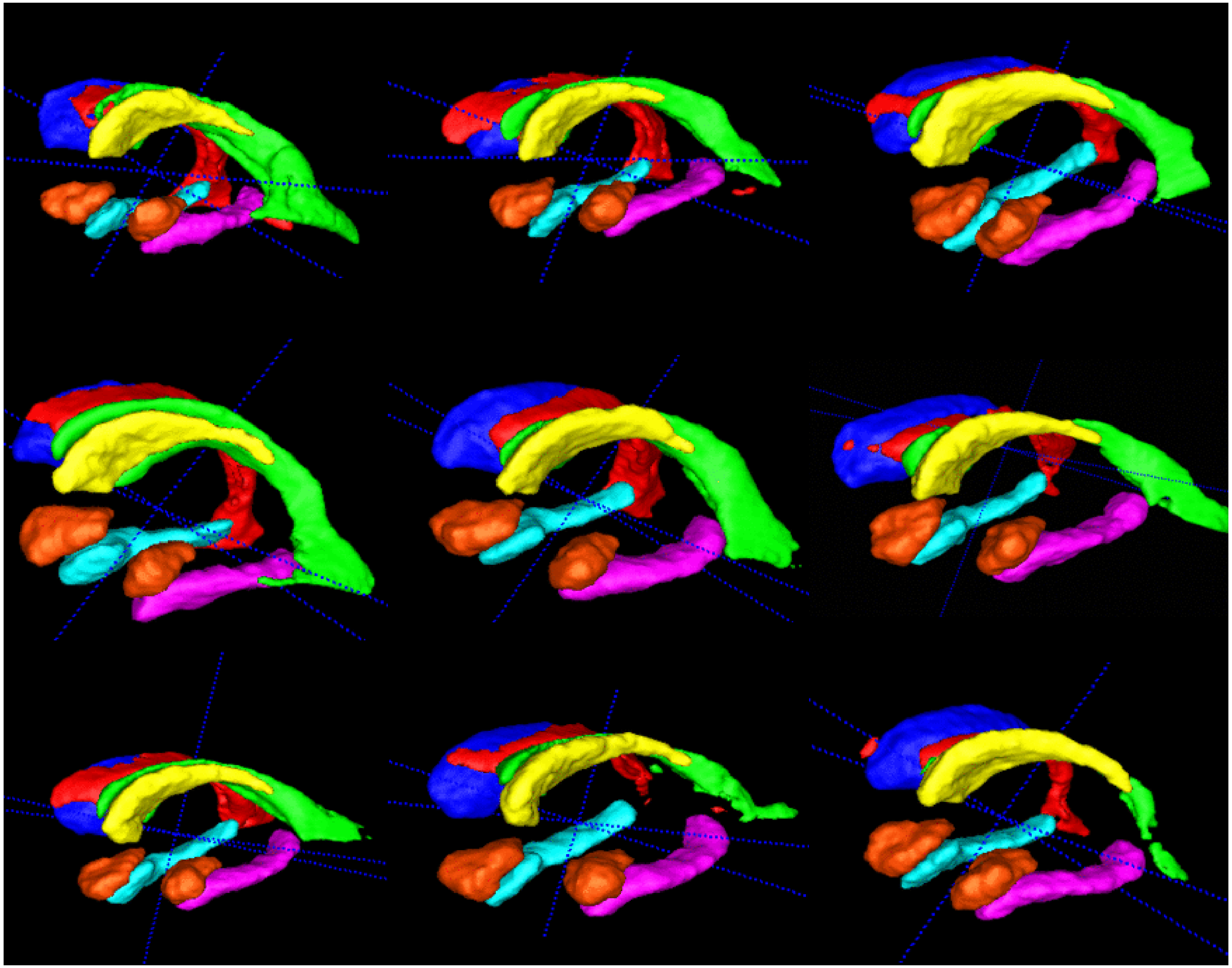
Axial View

Coronal View

Sagittal View



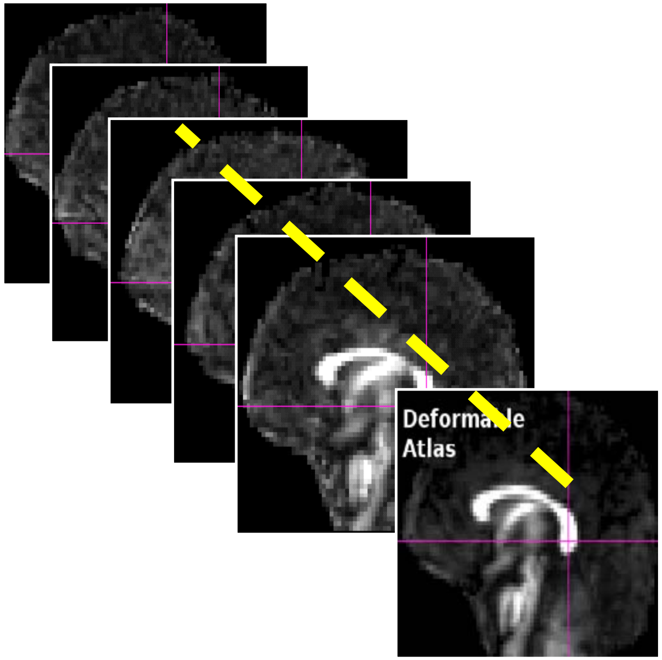
Automatic segmentation (N=130)

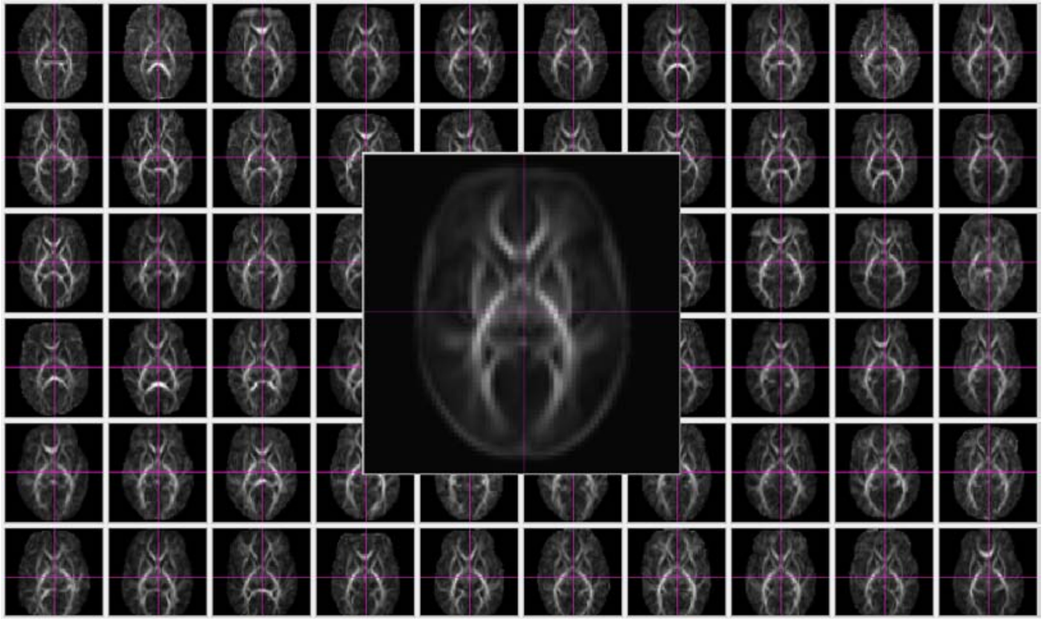


UNC Chapel Hill pediatric autism study (J. Piven, H. Cody, G. Gerig et al.)

DTI: Population-based analysis of fiber tracts

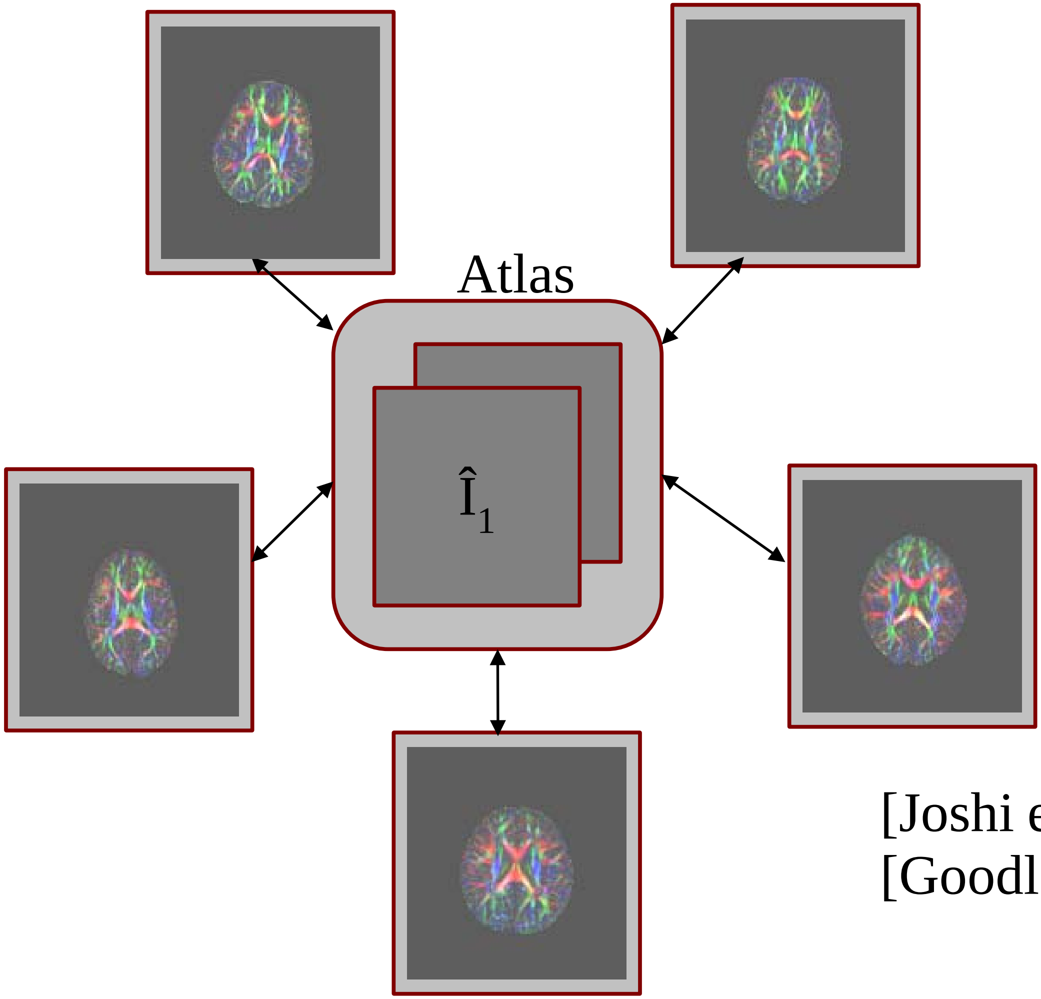
Example: 150 neonate DTI mapped to unbiased atlas





Casey Goodlett, Sarang Joshi, Sylvain Gouttard, Guido Gerig,
(MICCAI'06, MICCAI'08, NeuroImage 2009

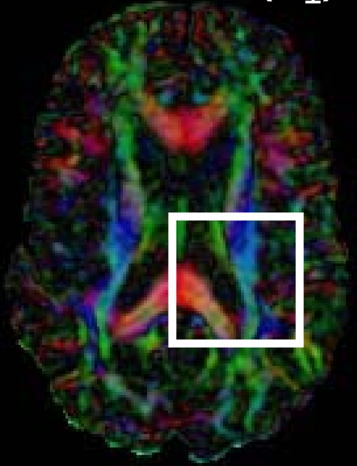
Atlas Building for DTI Tensor Fields



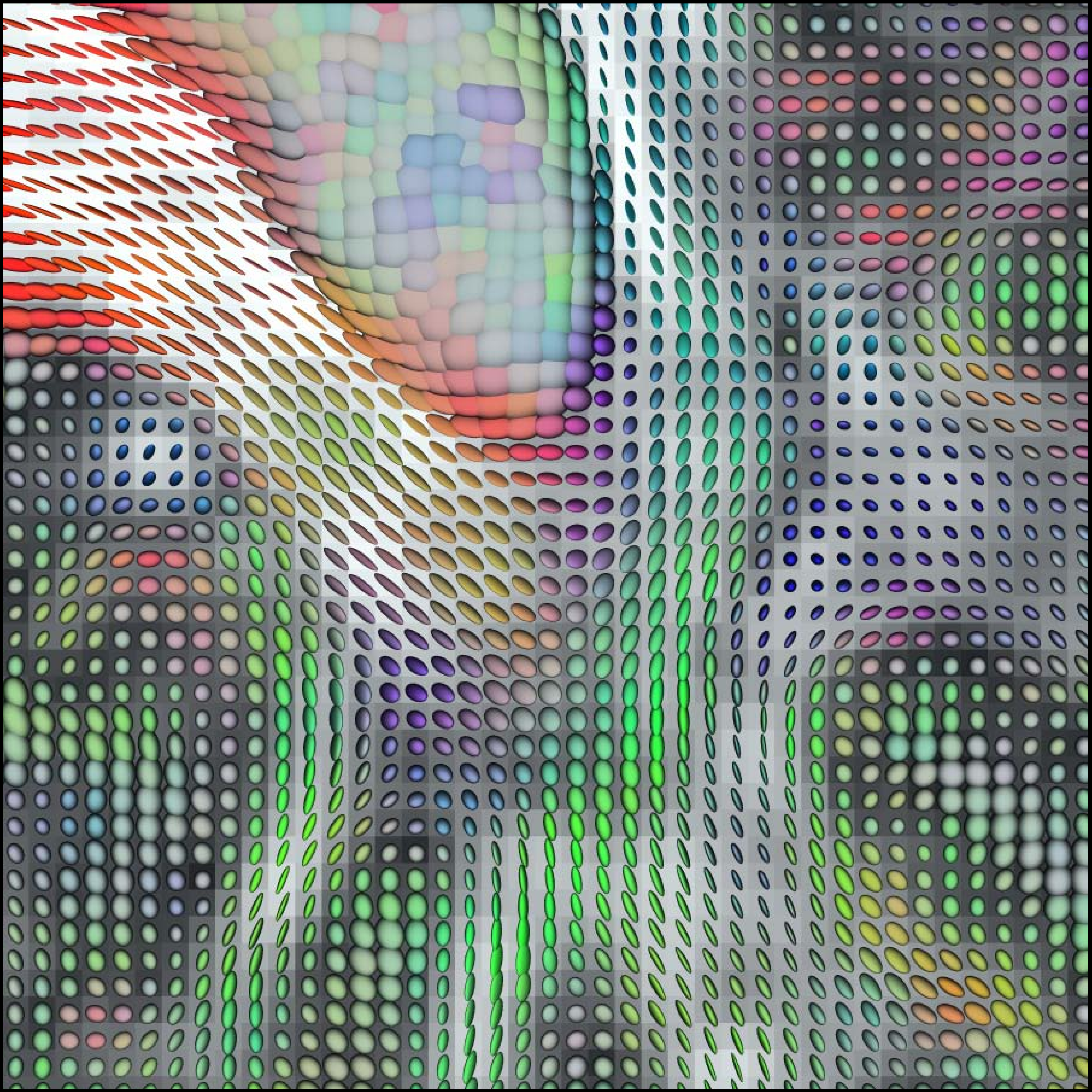
[Joshi et al 2004]
[Goodlett et al 2006, 2009]

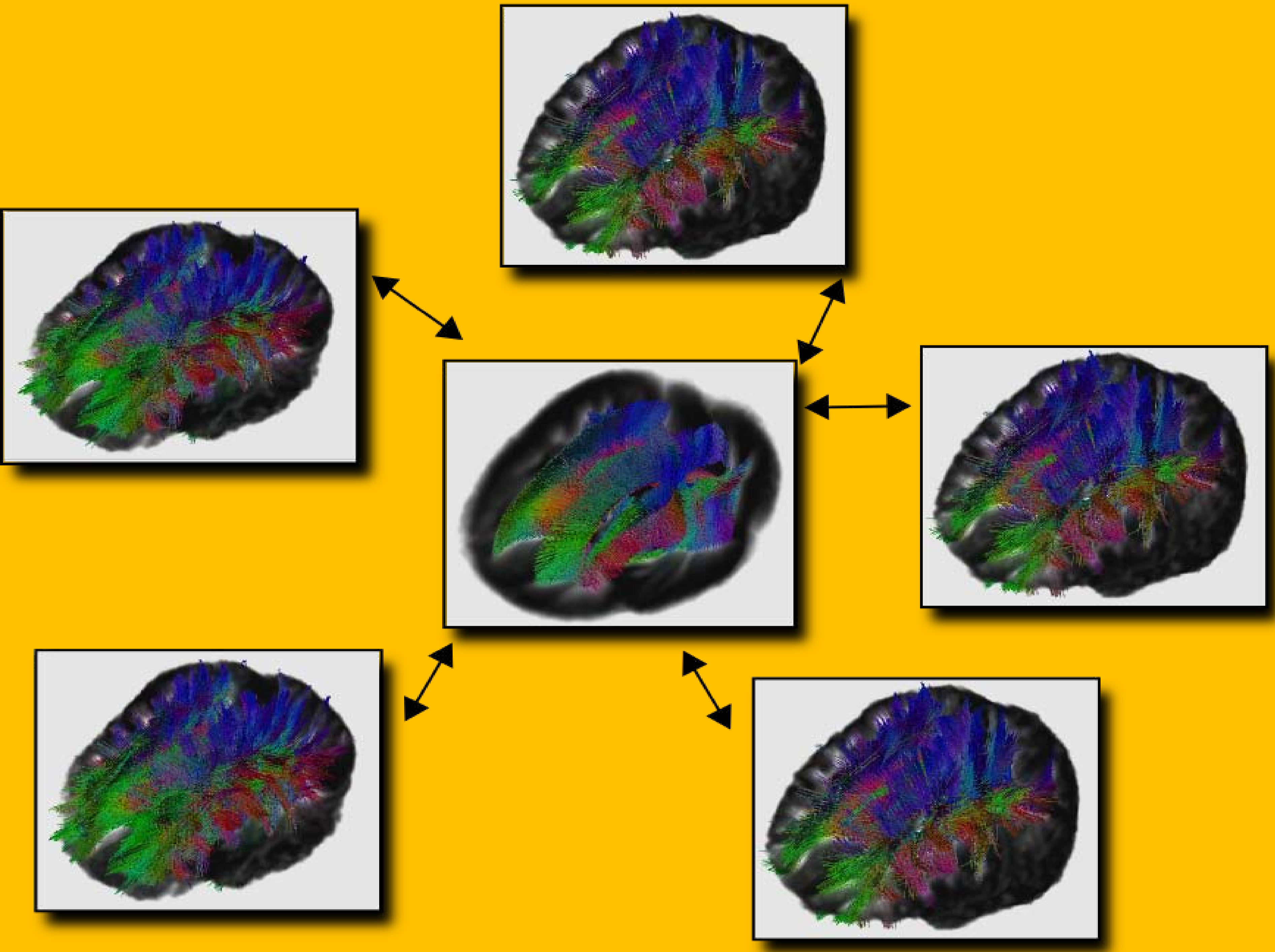
Backdrop: FA

Color: RGB($\mathbf{e}_1$)

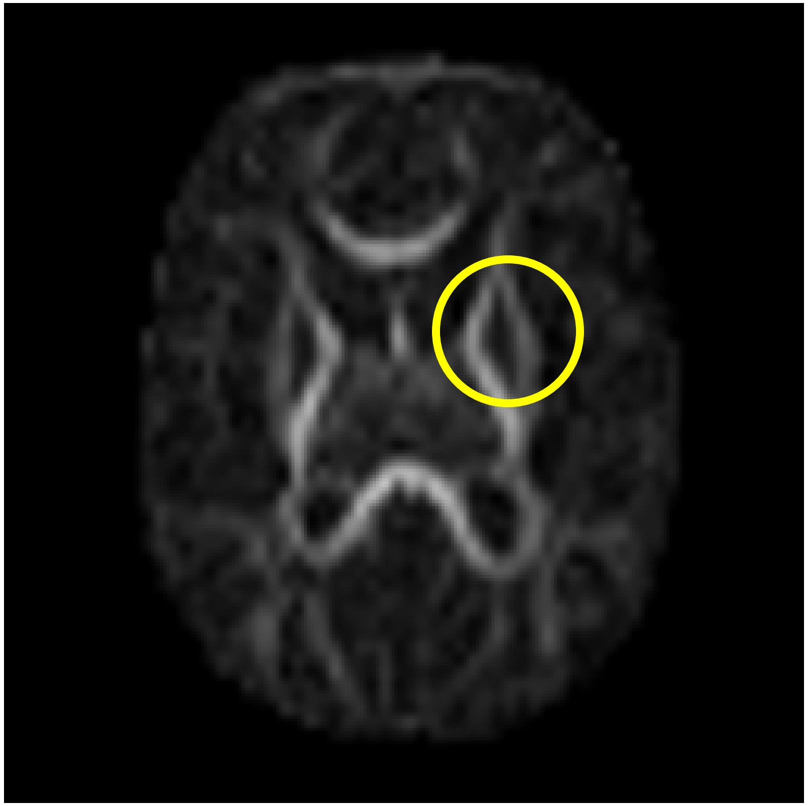


G. Kindlmann

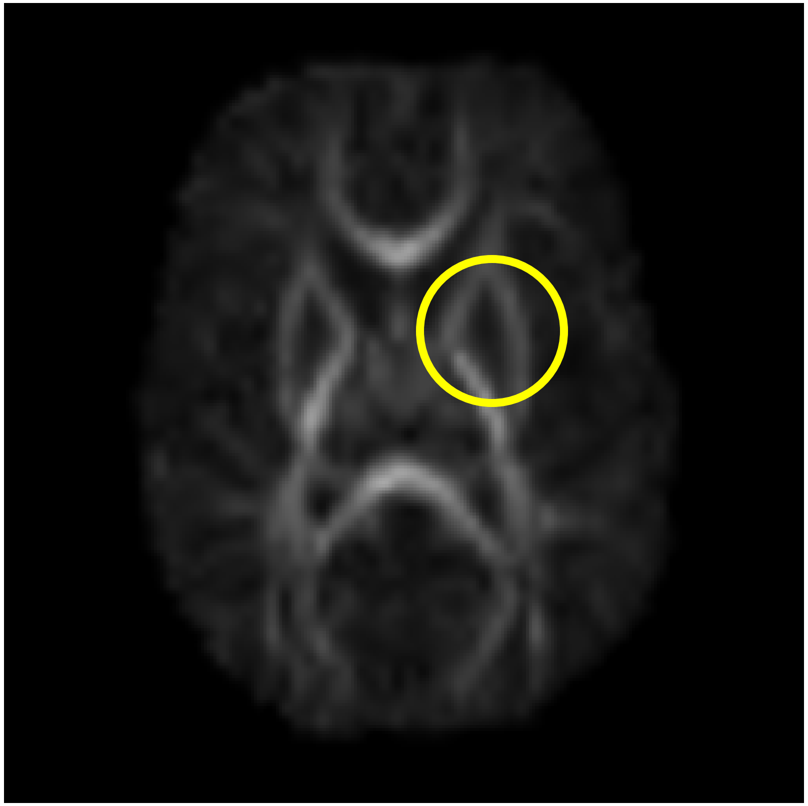




Co-registration: From linear to nonlinear

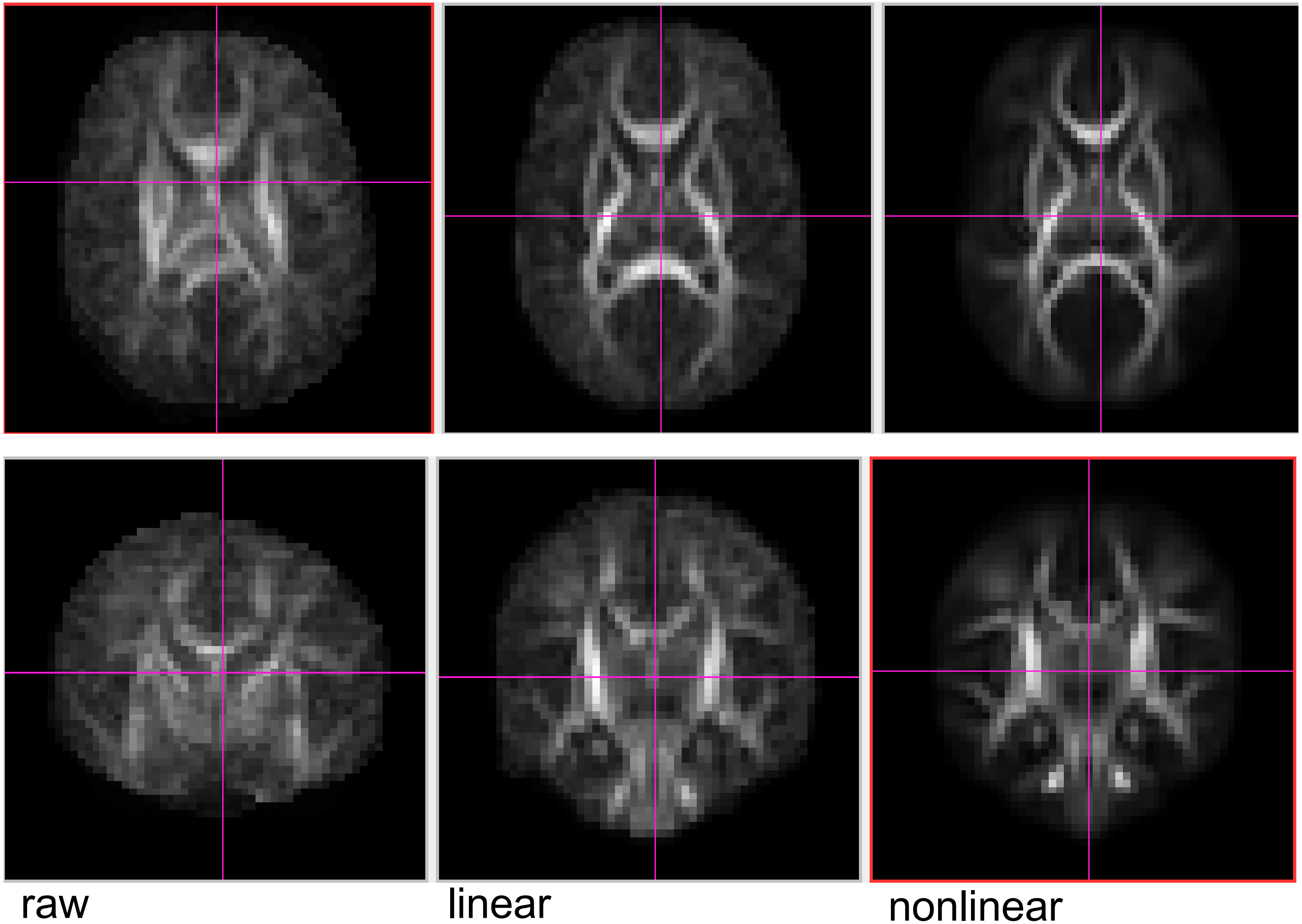


Linear registration (affine)

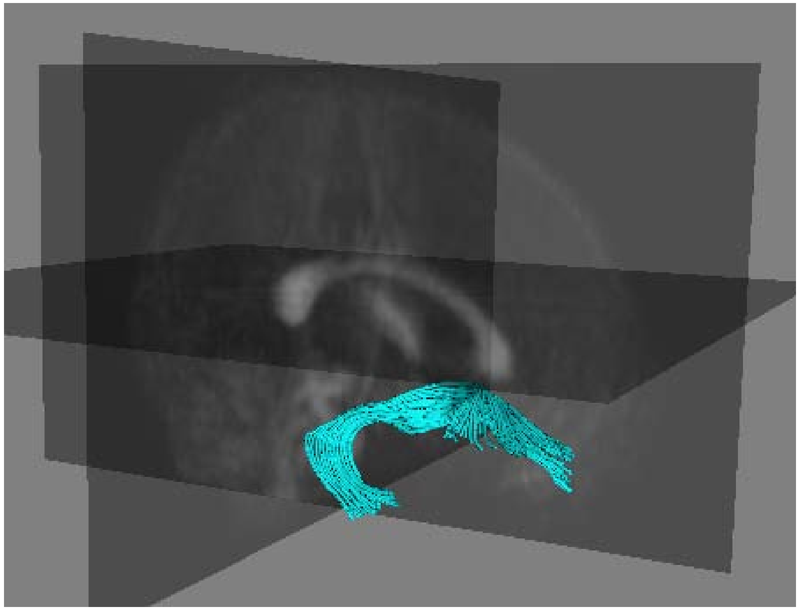


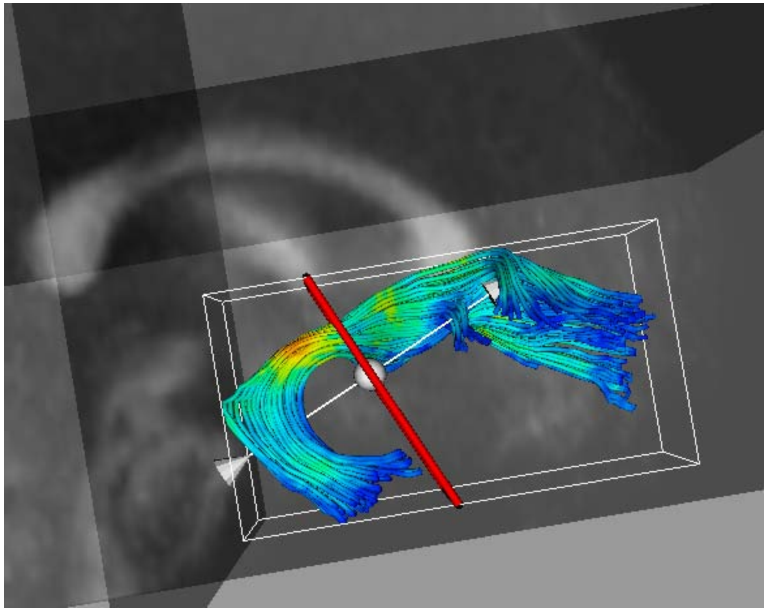
Nonlinear registration (fluid)

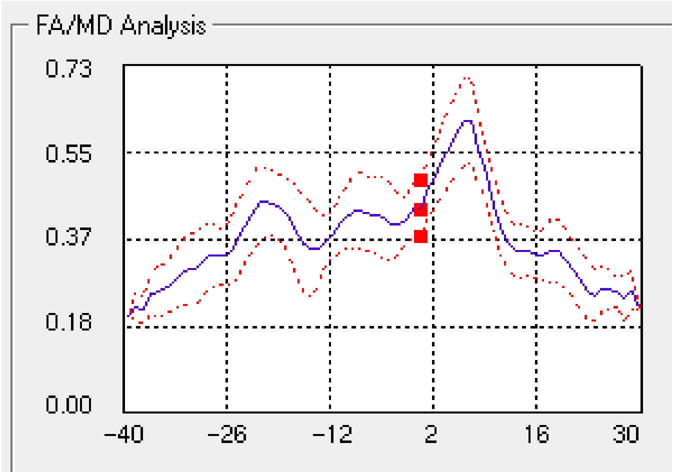
Atlas Building: FA of average tensor field



Quantitative Fibertracking: Example Uncinate Fasciculus

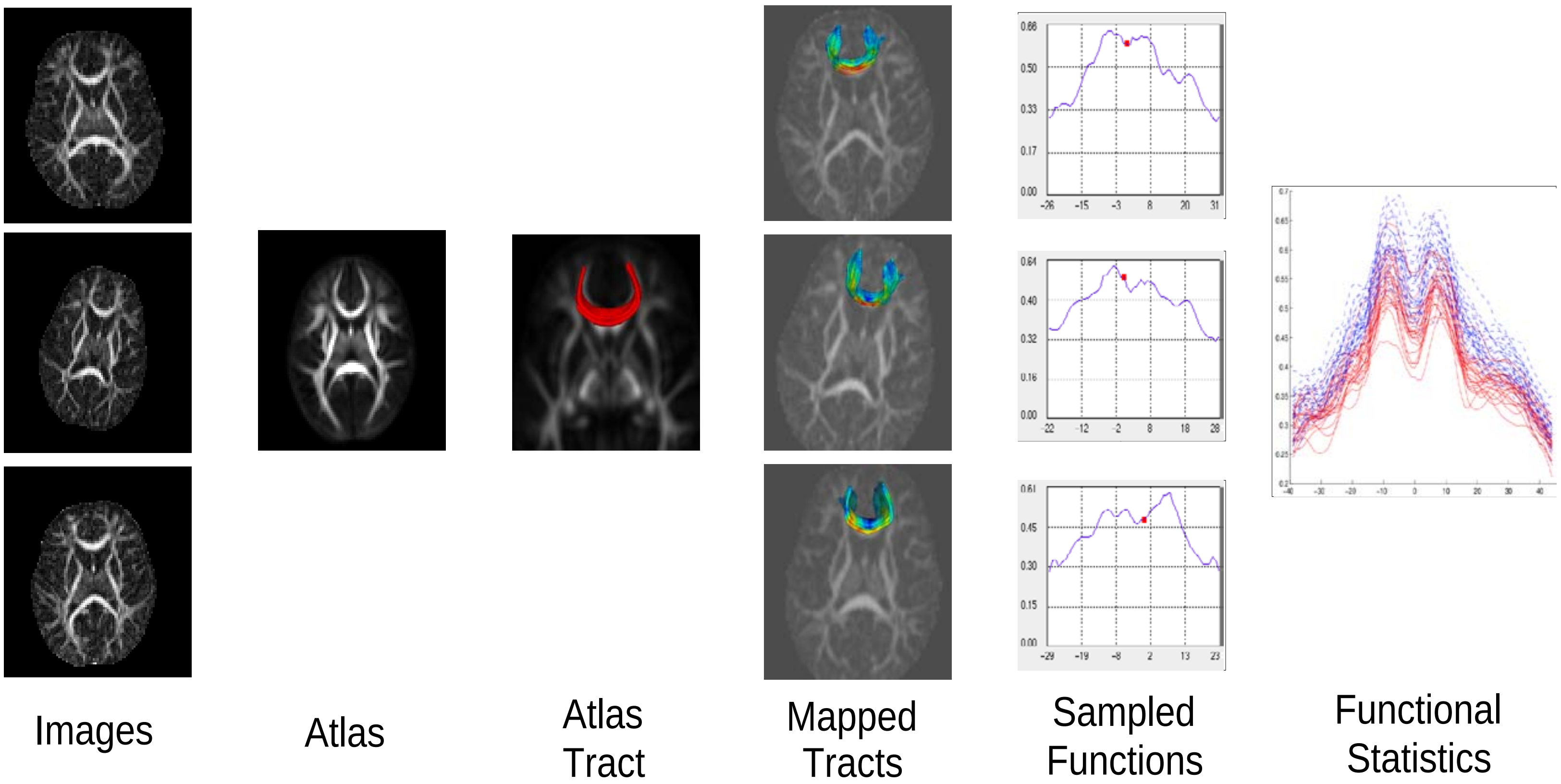






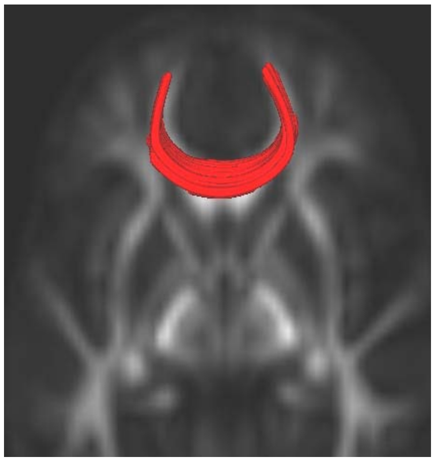
Corouge et al. *Fiber tract-oriented statistics for quantitative diffusion tensor MRI analysis*. Medical Image Analysis 2006.
FiberViewer software - http://www.ia.unc.edu/dev/

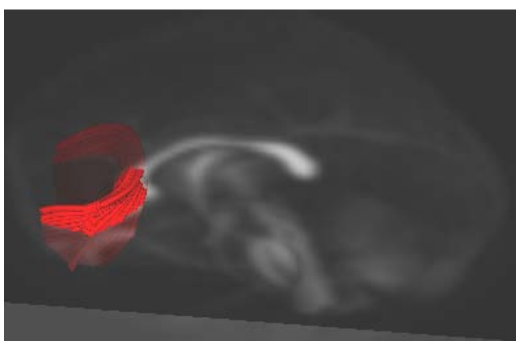
Concept: Group statistics of fiber tracts

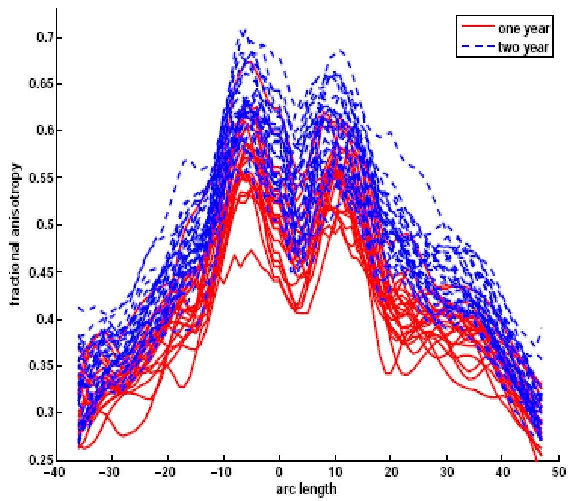


Goodlett et al., NeuroImage March 2009

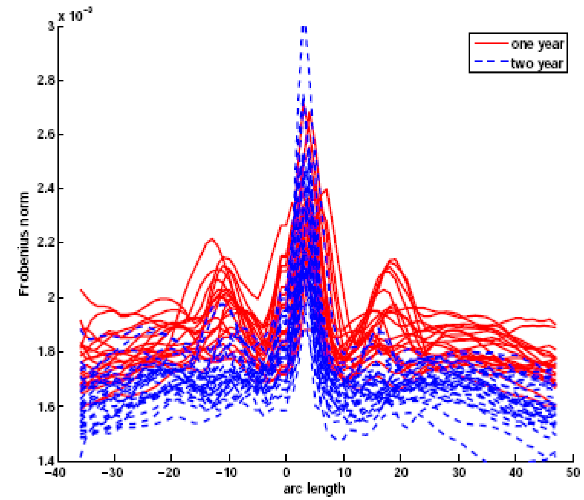
Pediatric Example: Genu Tract 1-2yrs







(b) All FA curves



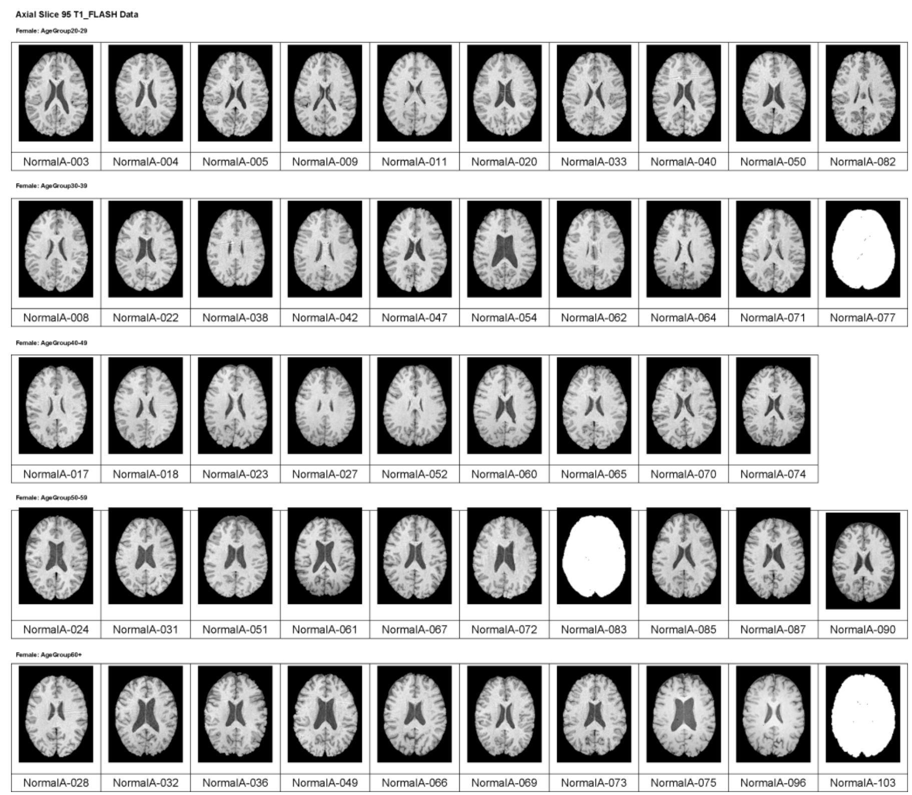
(c) All norm curves

- Working example of 1 year vs. 2 year subjects
- Significance expected
- Discrimination provides interpretation

Towards 4D Atlases: Study of Healthy Aging

Elizabeth Bullitt, UNC

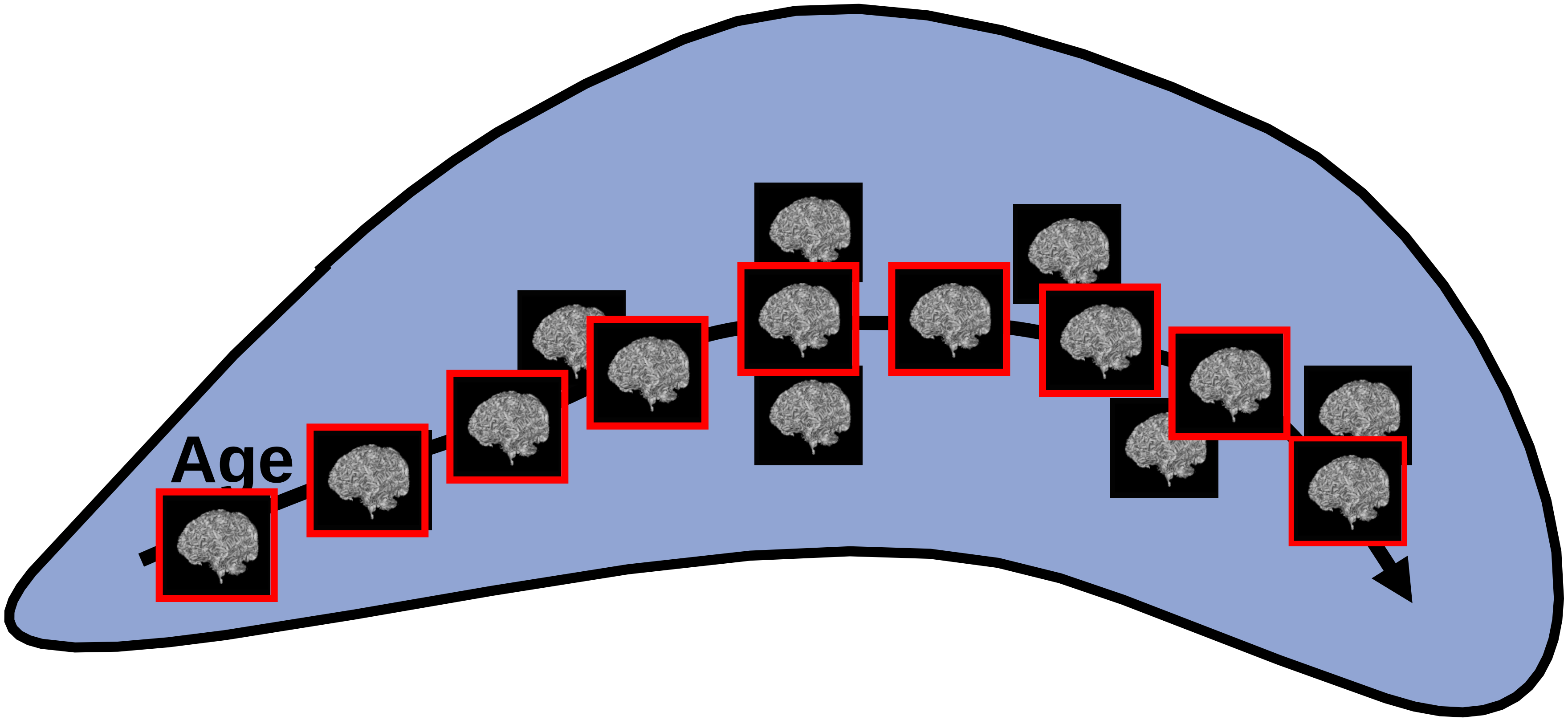
- MRI Aging Study
- 100 volunteers (50 male, 50 female). 20 subjects, equally divided by sex, were imaged by decade (20-29, 30-39, 40-49, 50-59, and 60-72).
- Images (T1 and T2 sequences) 3T MR
- Automatic EM Segmentation (**Marcel Prastawa, Gerig**)
- Atlas formation (**Peter Lorenzen, Sarang Joshi, Brad Davis**)



T1 of female subjects, per decade

Manifold Kernel Regression (B. Davis)

- What are we looking for: A weighted Fréchet mean image as a function of age!
- Weights depend on the age



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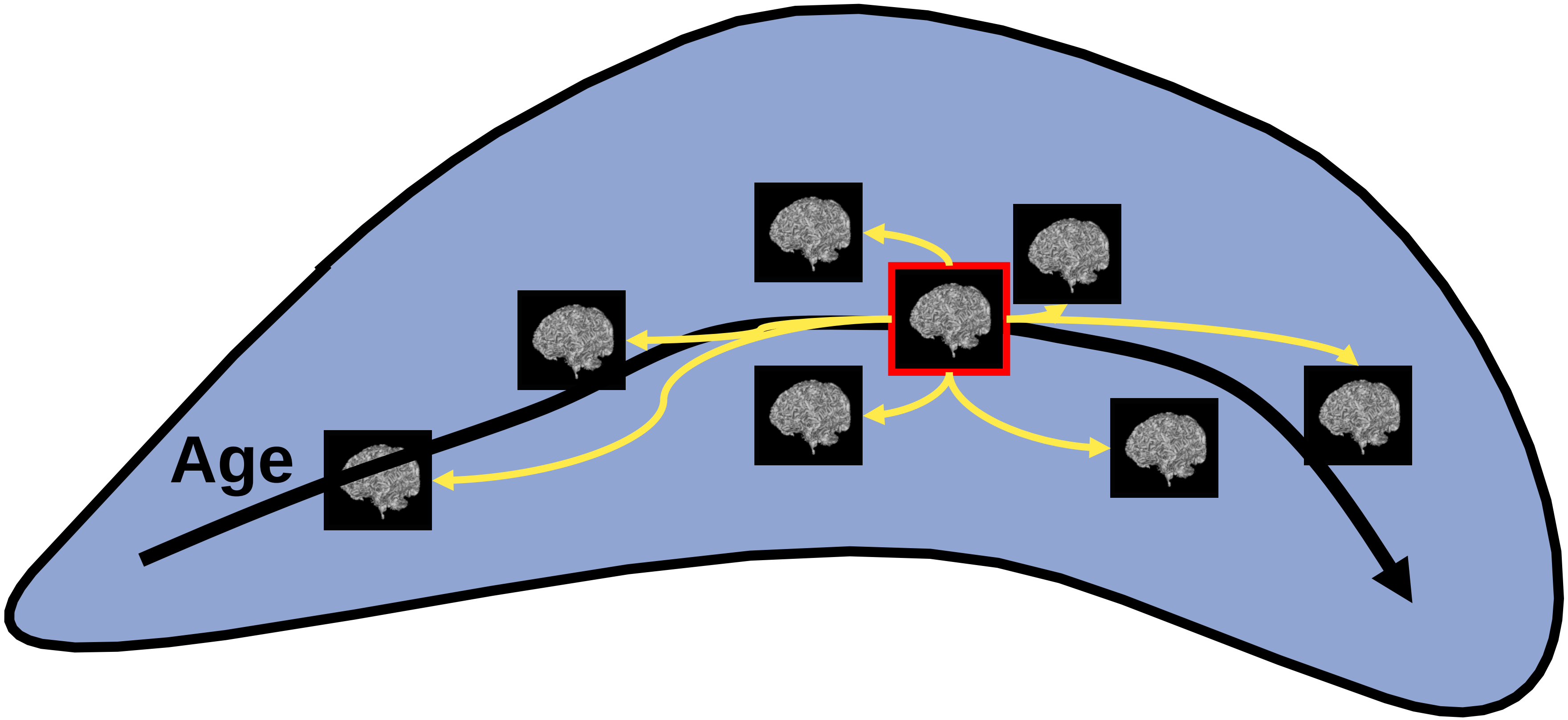
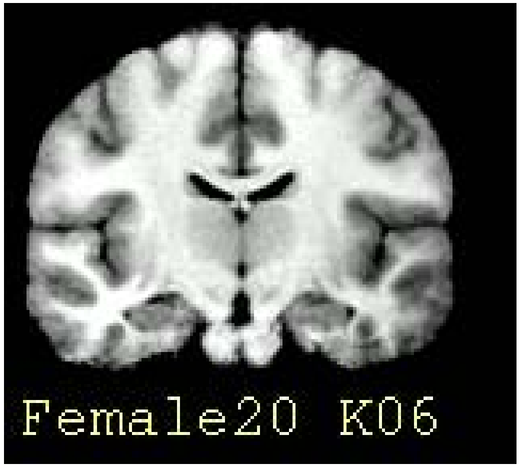
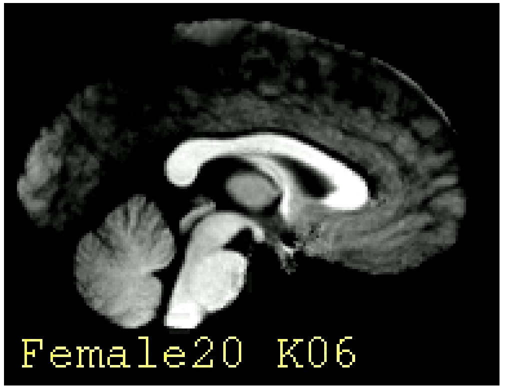


Aging Brain via Population Shape: Manifold Kernel Regression





- B. Davis, E. Bullitt, (UNC)
- S. Joshi, T. Fletcher (Utah)
- D. Marr Prize, ICCV'07 best paper award

Bibliography

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- "Mutual-Information-Based Registration of Medical Images: A Survey"
  - Pluim et al, IEEE-TMI, 22(8), 2003
- IEEE Transaction of Medical Imaging Special Issue
  - November 2003

Conclusions

- Image registration has become one of the most important tools for medical image analysis
- Powerful packages available to the scientific community:
  - RVIEW, ITK, Demons, SPM, AIR, FSL,FreeSurfer, SLICER-3, etc.
- Important issue: Choice of appropriate methodology (linear versus nonlinear, type of nonlinear method, image match metric, cascading of transformations)
- Community needs: Platform for validation and cross-method comparison -> Users can choose most appropriate, best techniques