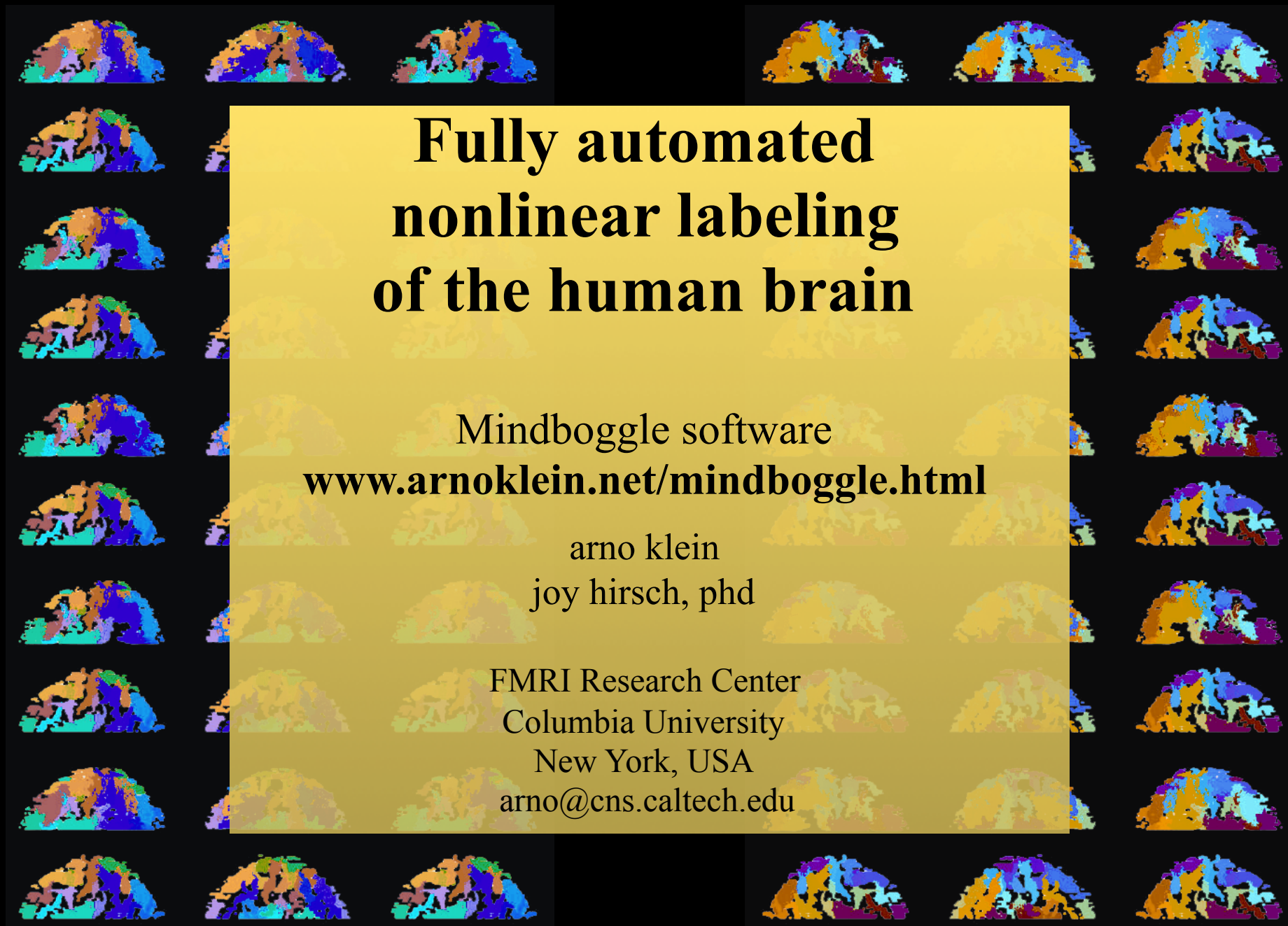

Fully automated nonlinear labeling of the human brain

Mindboggle software
www.arnoklein.net/mindboggle.html

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joy hirsch, phd

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New York, USA
arno@cns.caltech.edu

Scatter-brained approach

Instead of: Global linear registration of brain to atlas, or
Warping of continuous deformable surfaces,

Mindboggle:

(1) Breaks each brain image into pieces

(2) Groups the pieces into combinations

(3) Matches combinations of pieces across brains

(4) Labels structural/functional data

Mindboggle

Fully automated: Matlab code (tested on Linux/Unix platforms)

Feature-based vs. intensity-based matching

Robust to reduced and nonuniform image quality

Labels the entire cortex and can transfer anatomical labels to any regions of interest / activated voxels

Does not assume that different brains:

preserve topology
- gyrii interrupt sulci
- sulcus sequences may vary

have complete homology
- sulci may be present or absent across brains

Mindboggle

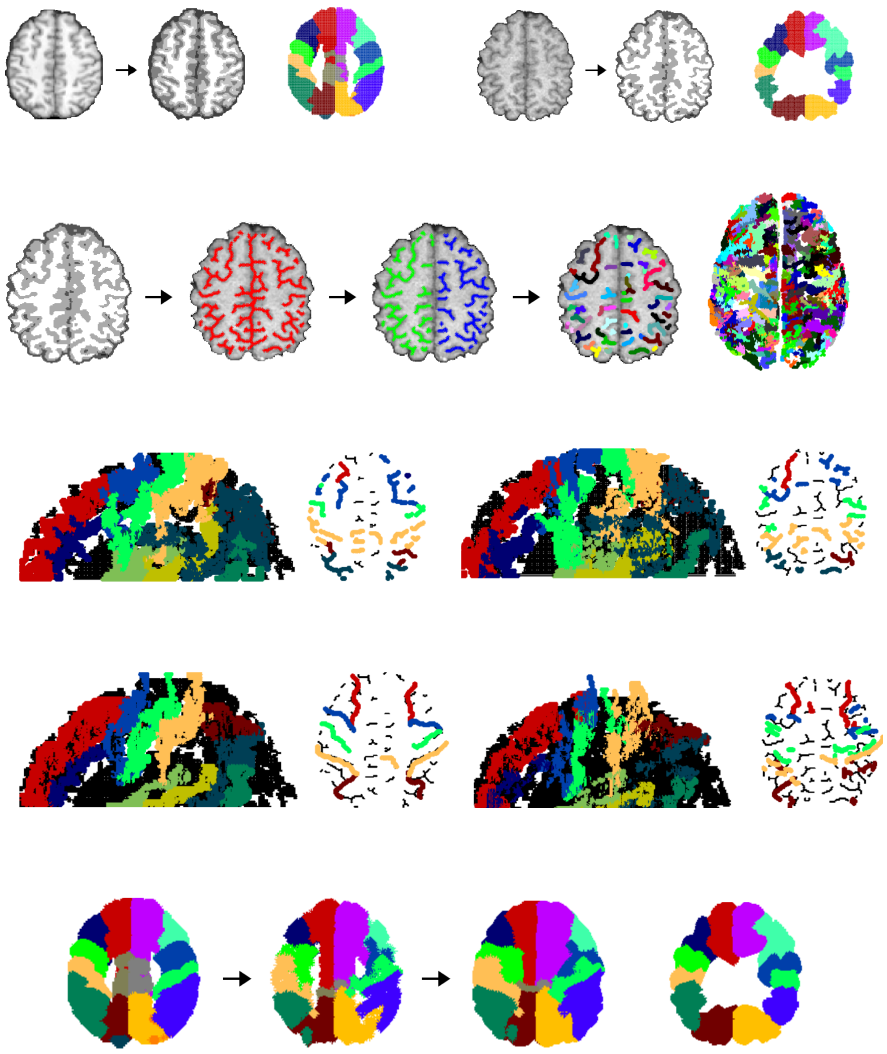
coregister
atlas and subject MRIs

extract 3-D
sulcus **pieces**

combine and
match pieces

transform label
boundaries

warp & interpolate
labels



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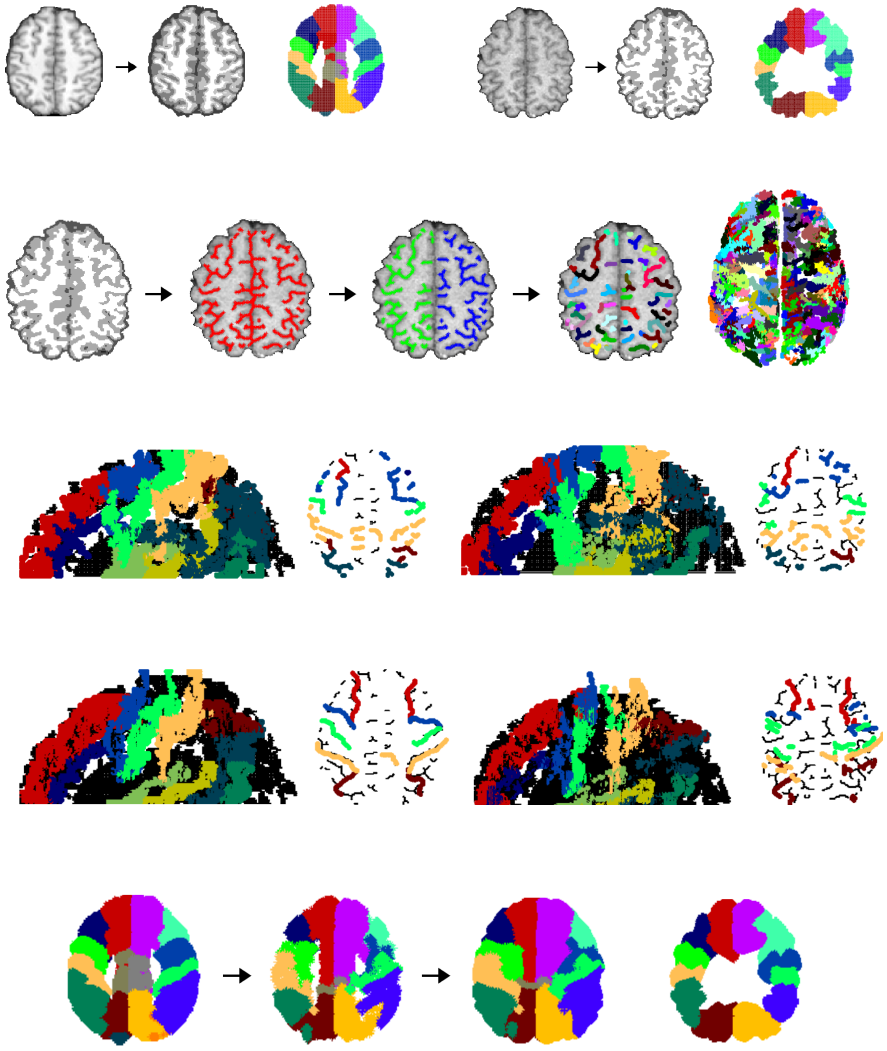
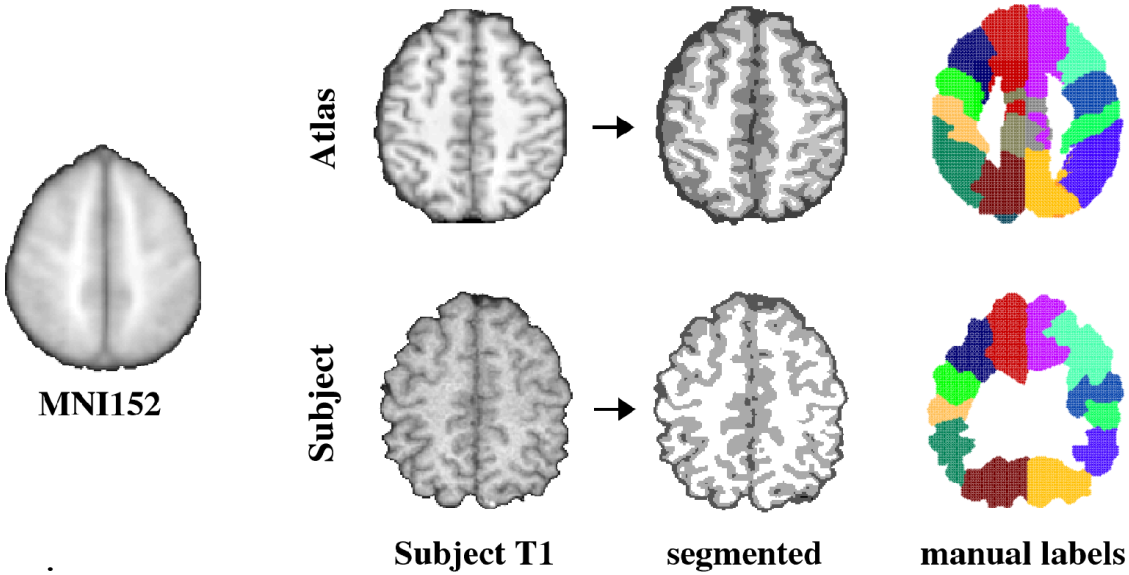


coregister atlas and subject MRIs



Mindboggle requires:
(1) a common space for linear coregistration (**MNI152**),
(2) **Atlas** data (MNI's single-subject Atlas),
(3) skull-stripped, linearly coregistered, and segmented **Subject** MRI data, and
(4) **manual labels** for atlas-labeling and independent evaluation.

[1]Evans, A.C., Collins, D.L., and Milner, B. 1992. An MRI-based stereotactic brain atlas from 300 young normal subjects. In *Proceedings of the 22nd Symposium of the Society for Neuroscience,* Anaheim, 408.
[2]Tzouriuo-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., Mazoyer, B., Joliot, M. 2002. Automated anatomical labelling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single subject brain. *8th Annual Meeting of the Organization for Human Brain Mapping*.
[3]Smith, S. 2000. Robust automated brain extraction. In *Sixth International Conference on Functional Mapping of the Human Brain,* page 625.
[4]Jenkinson, M. and Smith, S. 2001. A global optimisation method for robust affine registration of brain images. *Medical Image Analysis* **5:** 143-156.
[5]Zhang, Y., Brady, M., and Smith, S. 2001. Segmentation of brain MR images through a hidden Markov random field model and the expectation maximization algorithm. *IEEE Transactions on Medical Imaging* **20(1):** 45-57.

Mindboggle

coregister
atlas and subject MRIs

extract 3-D
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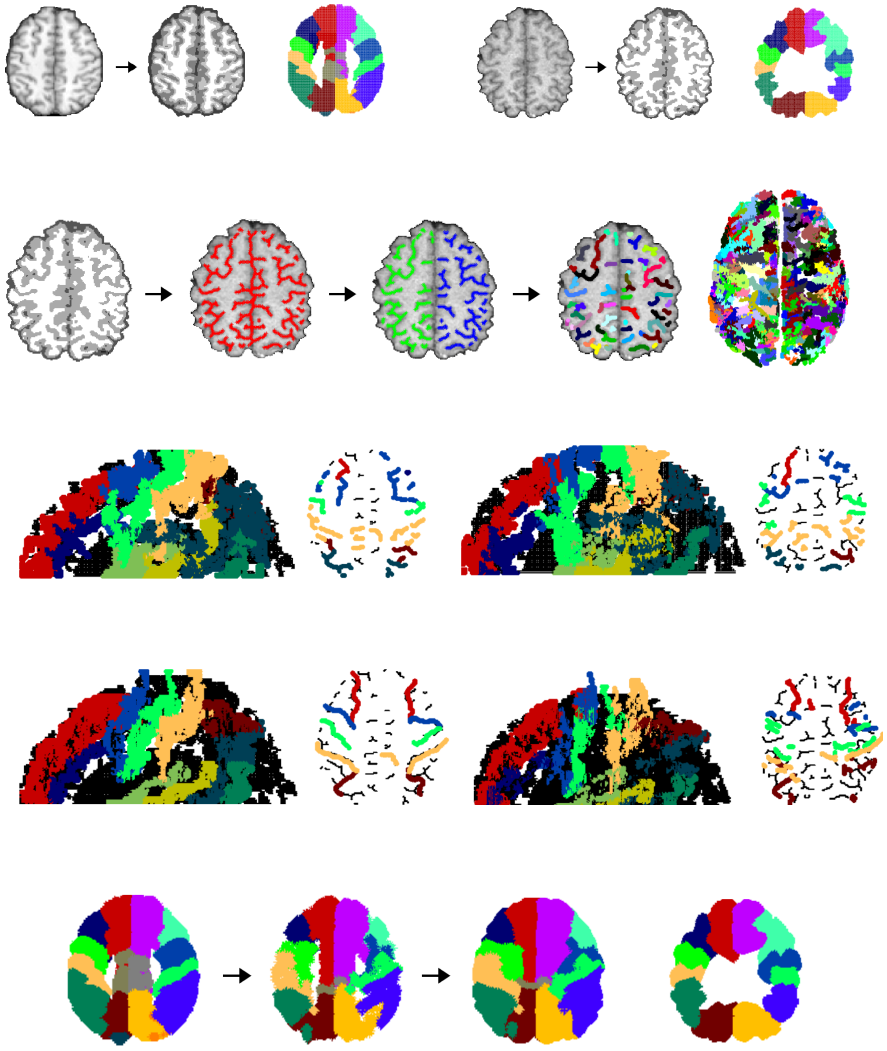
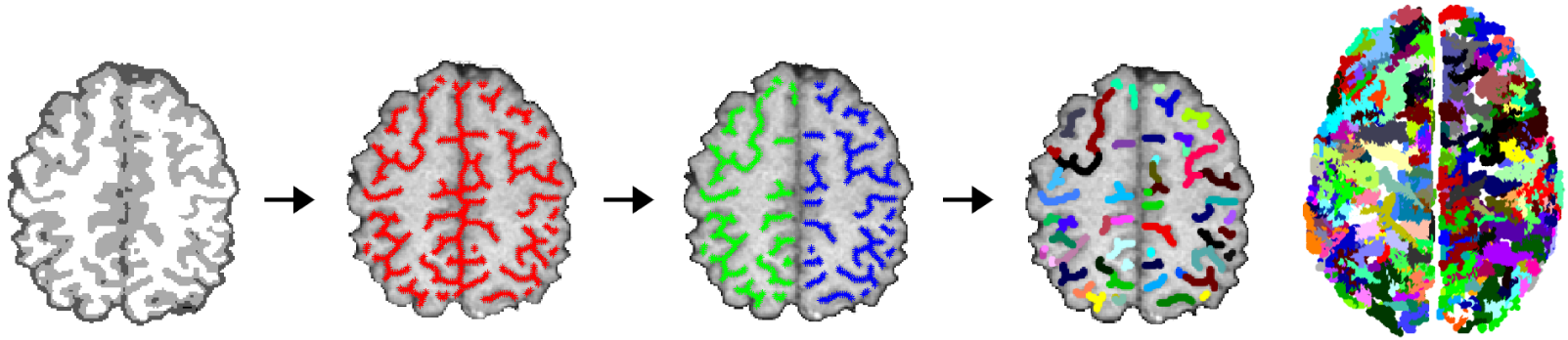
combine and
match pieces

transform label
boundaries

warp & interpolate
labels



extract 3-D sulcus pieces



Thin **segmented** non-white matter to a **skeleton** for each slice (only step in 2-D).

Divide the sulcus skeleton into left and right **hemispheres** by warping a plane to the inter-hemispheric plane.

Combine each 2-D sulcus cross-section with those from adjacent slices,
fragment the resulting 3-D pieces along vertical bifurcations, and
recluster the pieces into 100s of **3-D sulcus pieces** with a modified k-means algorithm.

Mindboggle

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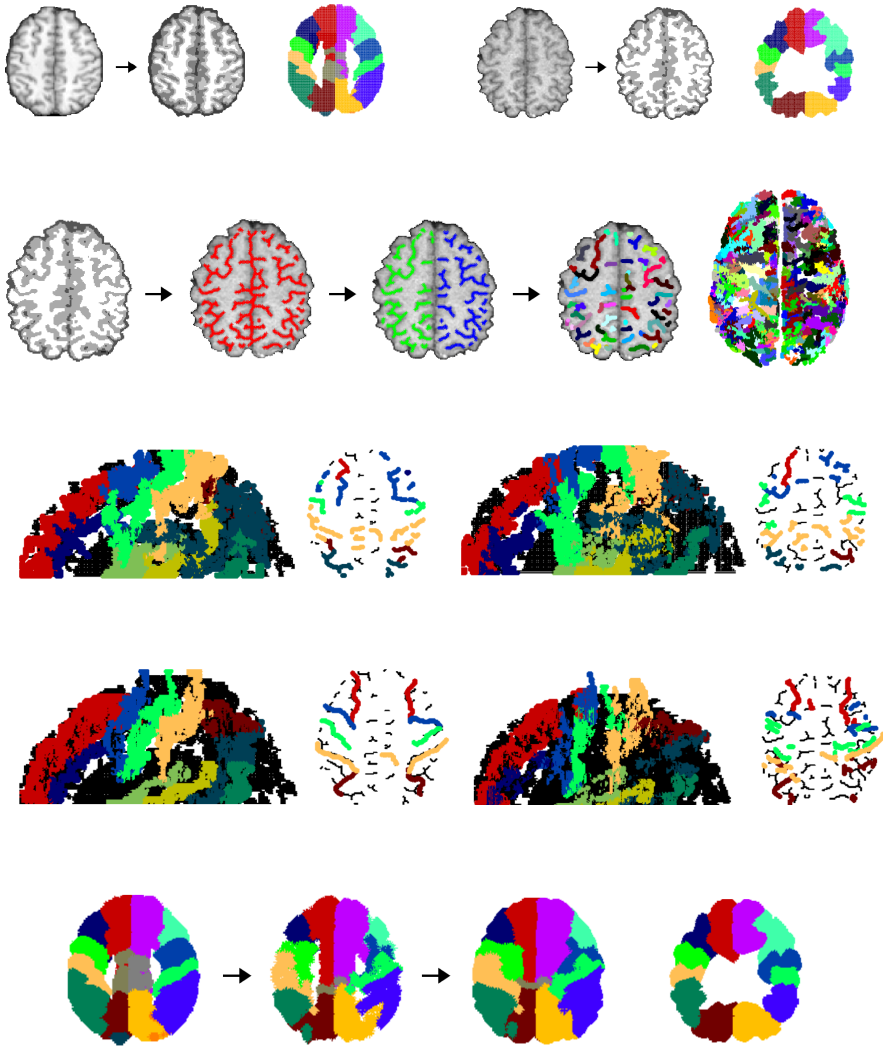
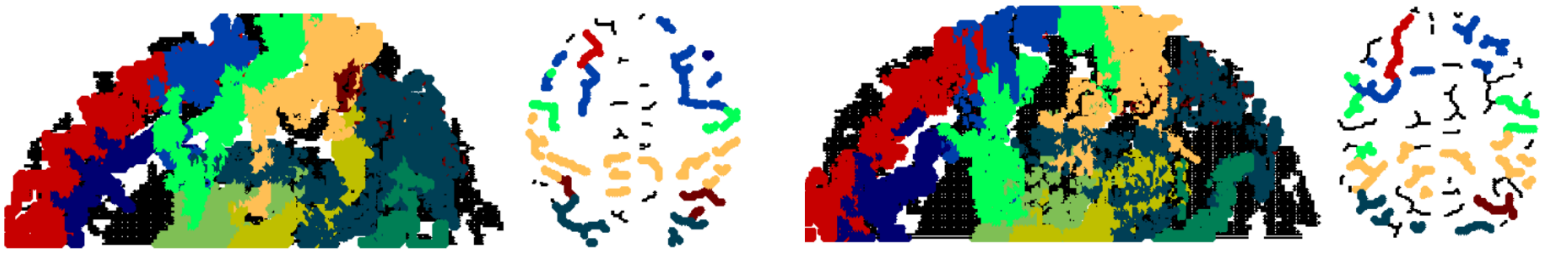


combine and match pieces



Atlas **Subject**

Match combinations of subject pieces to each atlas piece, and order the tentative matches by a simple **cost function**:

$$\mathbf{E_M = w_N N + w_V V + w_P P + w_O O}$$

$$\begin{cases} \mathbf{N} = \Delta \text{ number of points} \\ \mathbf{V} = \Delta \text{ number of subvolumes} \\ \mathbf{P} = \Delta \text{ mean position} \\ \mathbf{O} = \text{degree of non-overlap} \end{cases}$$

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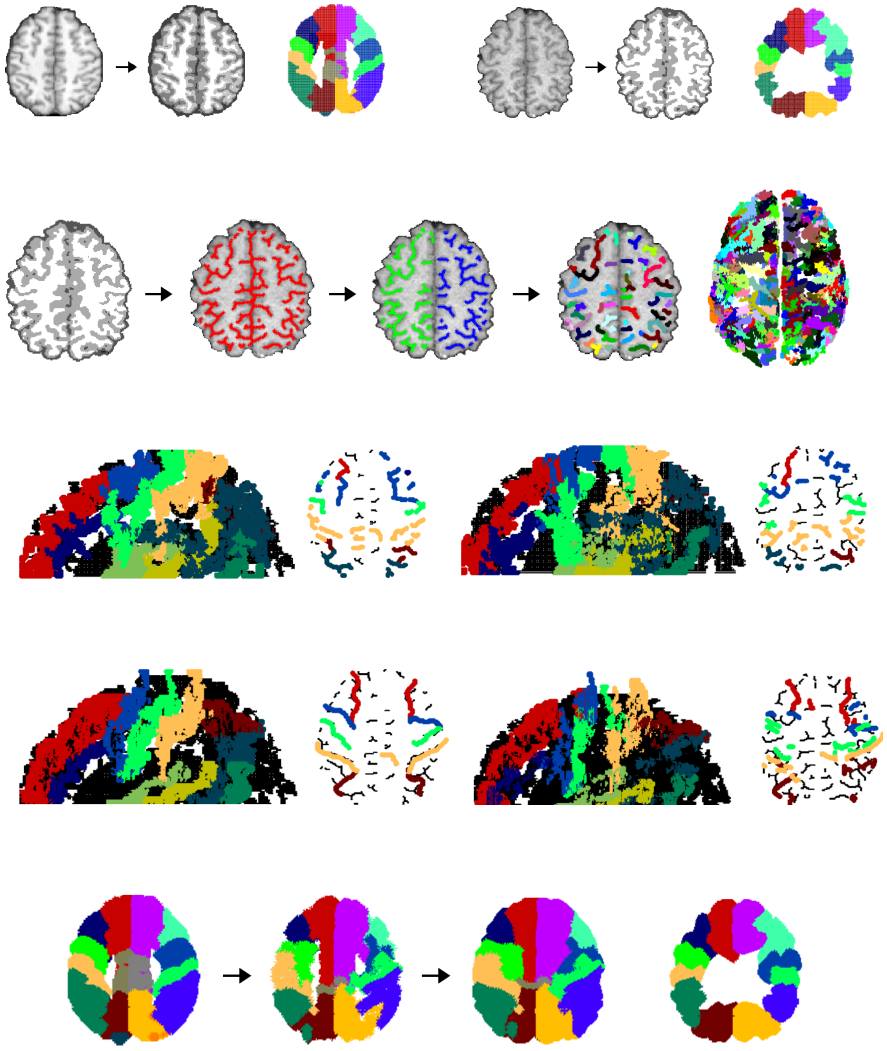
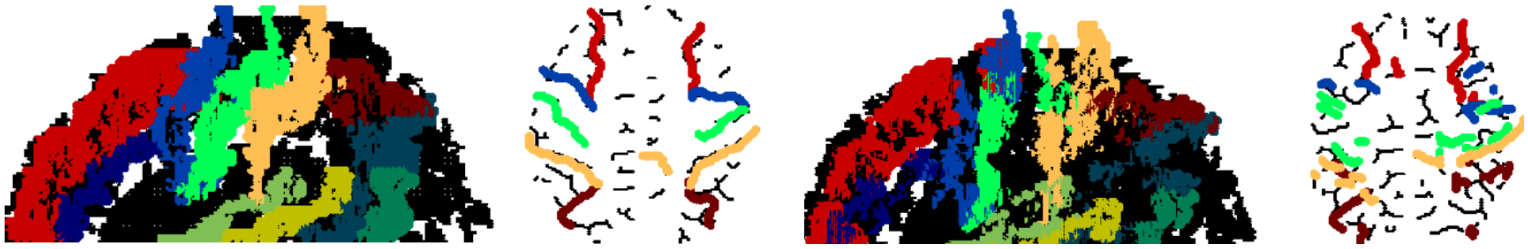


transform label boundaries



Atlas **Subject**

Translate each patch of atlas label boundaries to the matching subject pieces.
(Each patch is defined as the atlas label boundary points nearest to an atlas piece.)

No warping is performed at this stage – only piece-wise linear translation

Mindboggle

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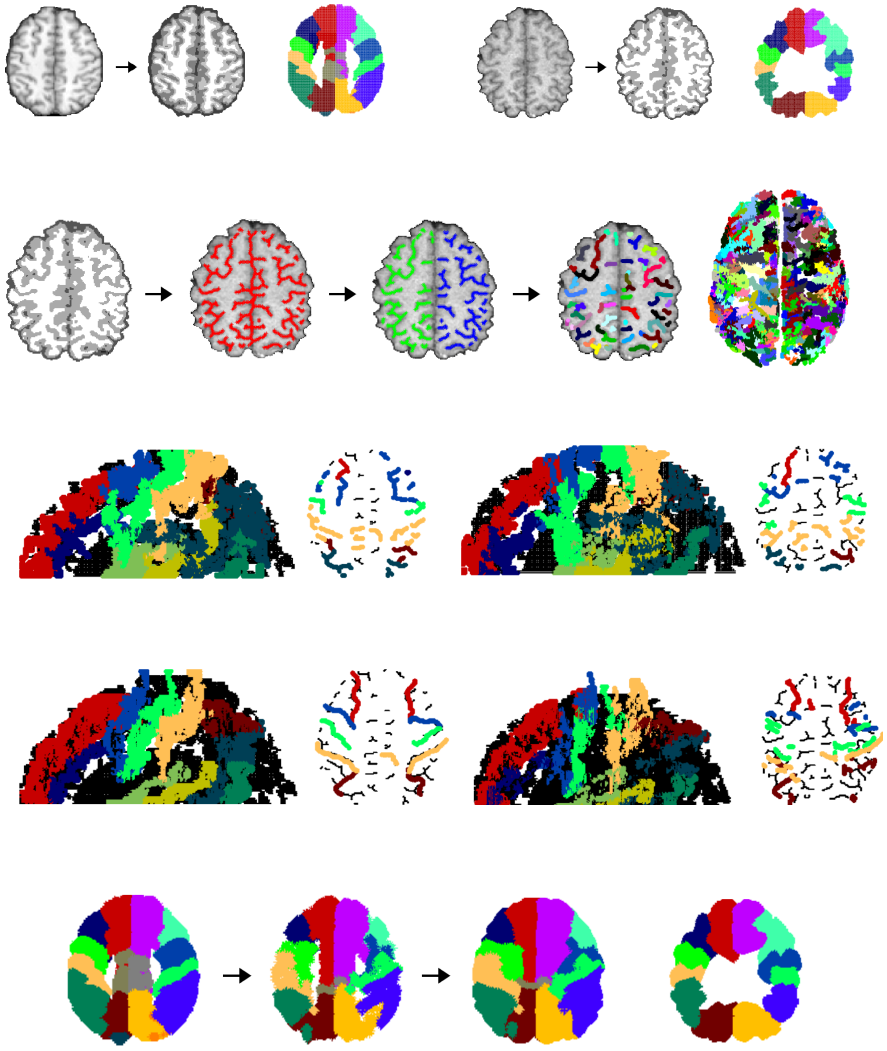
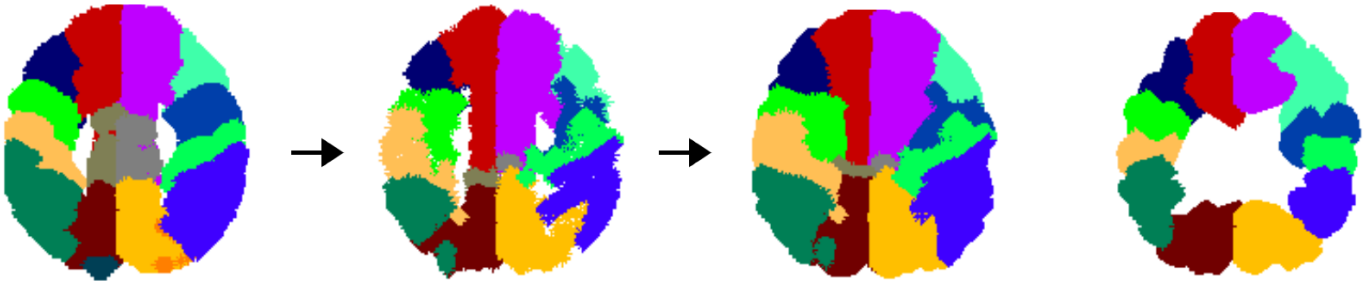


warp and interpolate labels

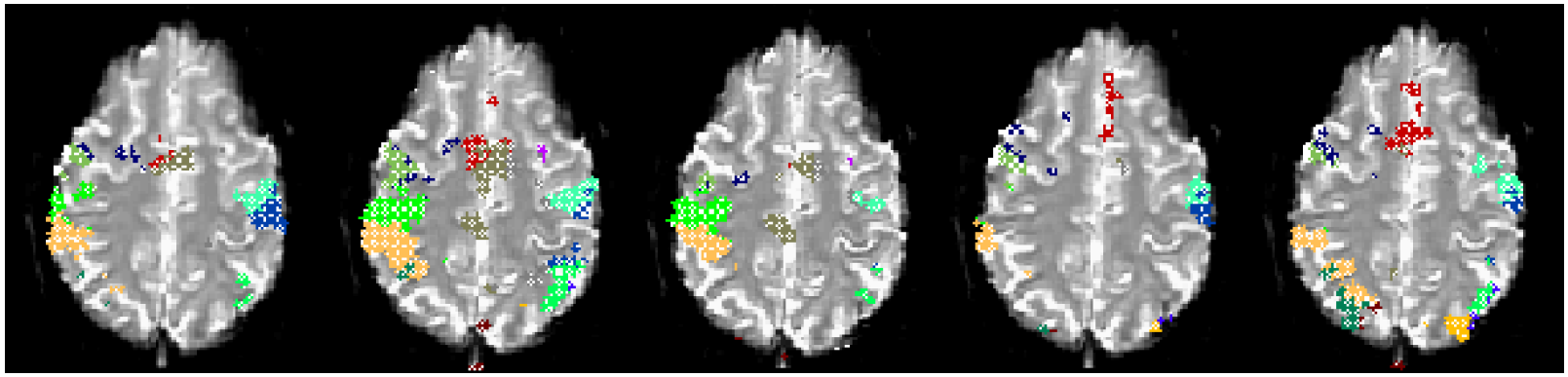


Warp Atlas labels (with a modified Self-Organizing Map) to smoothly fill the Atlas label boundaries that have been broken up and transformed to the subject sulcus pieces. Label unlabeled voxels by the majority label in a new neighborhood.

From left:

(1) Atlas labels,
(2) Atlas labels after deformation to the subject,
(3) the interpolated result, and
(4) subject manual labels.

transfer labels to activity data



Motor tongue **Motor hand** **Tactile hand** **Listening** **Picture-naming**

The resulting labels may be transferred to a coregistered volume of activity data.

In this example, 5 standard tasks elicited BOLD activity in expected regions.

Evaluation of Mindboggle

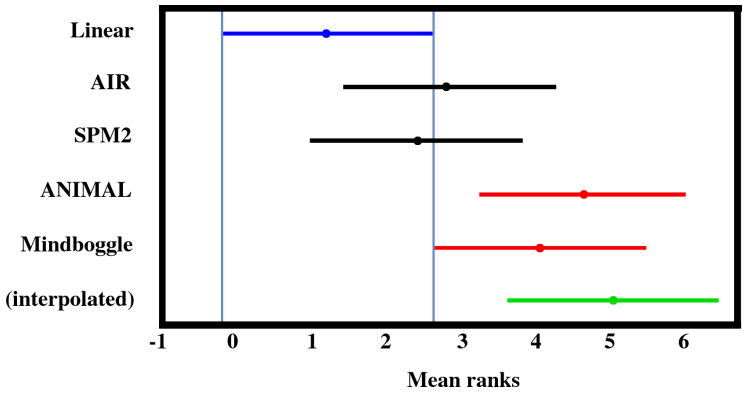
Label agreement metric

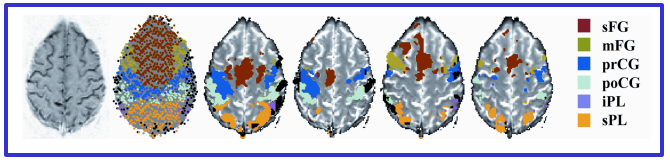
↓

Compare with
Linear
AIR
SPM2
ANIMAL

↓

Functional mapping tests





Evaluation of Mindboggle

Label agreement metric

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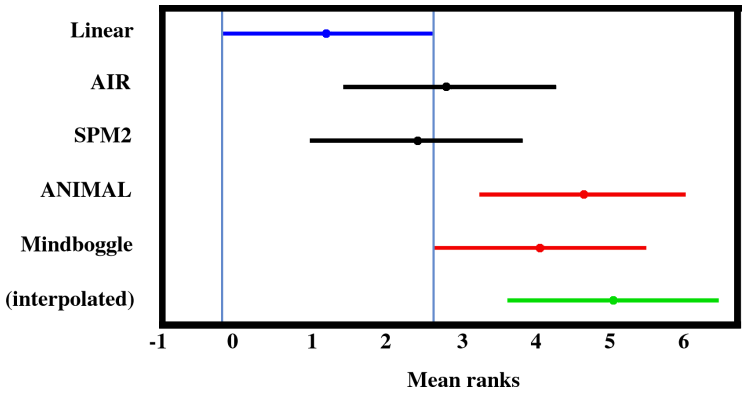

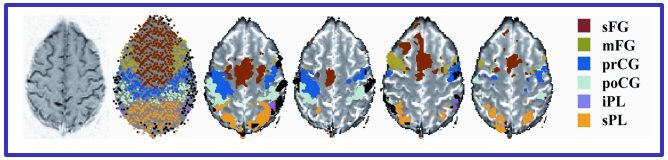

Label agreement metric

$$\frac{V_a}{V_i} = \frac{\text{intersecting voxels with the same label}}{\text{intersecting voxels}}$$

Evaluation of Mindboggle

Label agreement metric

↓

Comparison with
Linear
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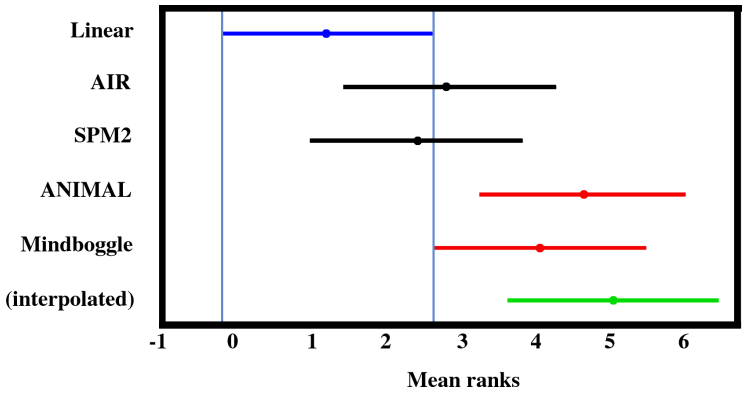
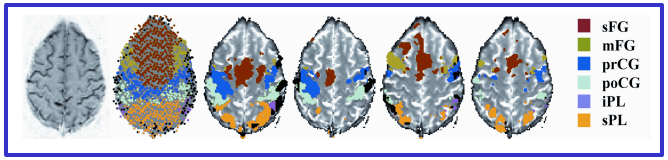
SPM2
ANIMAL

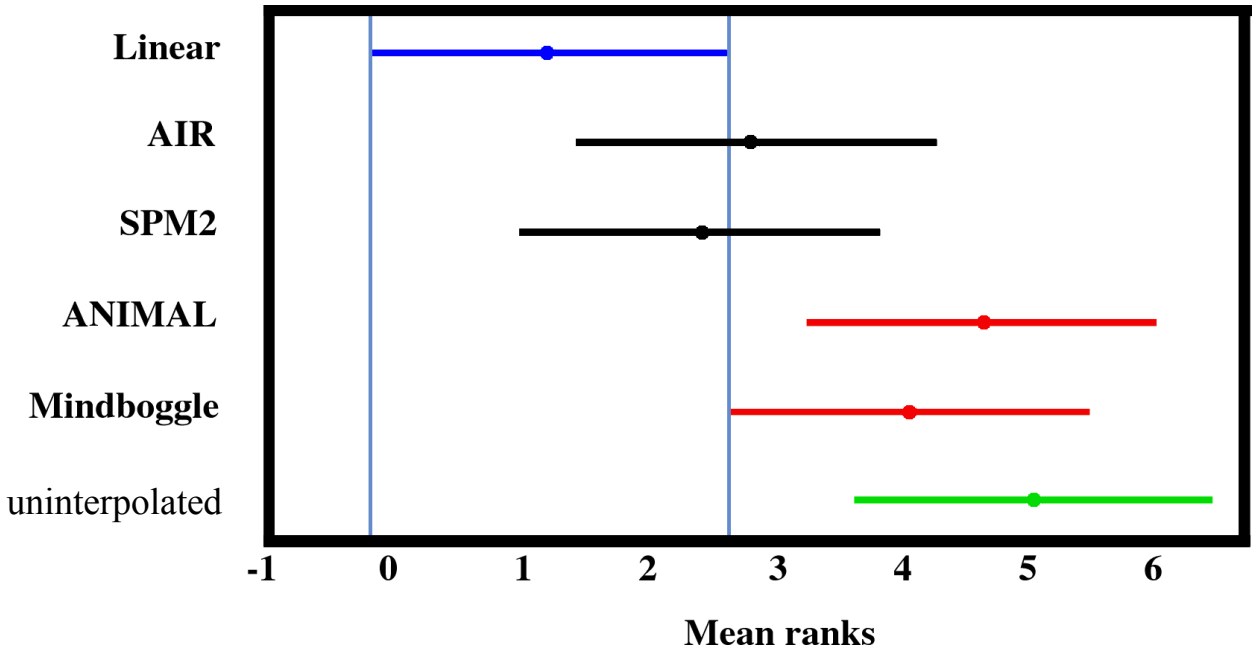
↓

Functional mapping tests





Comparison of label agreements



A nonparametric Friedman's ANOVA test (with Dunn-Sidak critical values) was used to compare the percent label agreements between manual and automated labels obtained by each of the methods. Mindboggle and ANIMAL were found to have mean ranks significantly higher than that obtained by linear registration ($p < 0.05$). When uninterpolated Mindboggle labels are tested, its mean rank is significantly greater than that of SPM2 as well.

Evaluation of Mindboggle

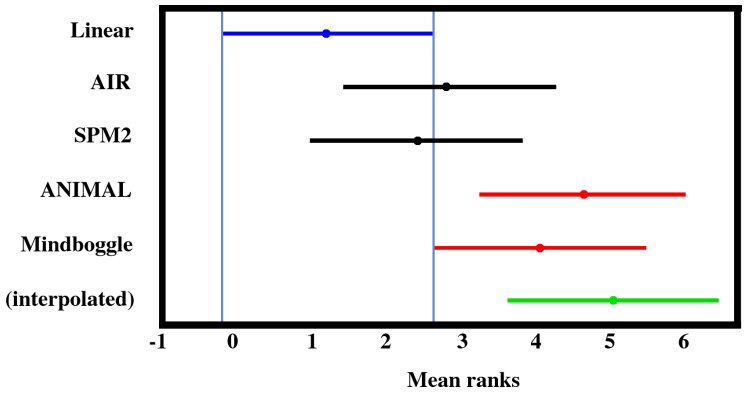
Label agreement metric

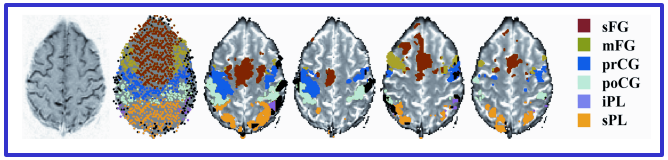
↓

Comparison with
Linear
AIR
SPM2
ANIMAL

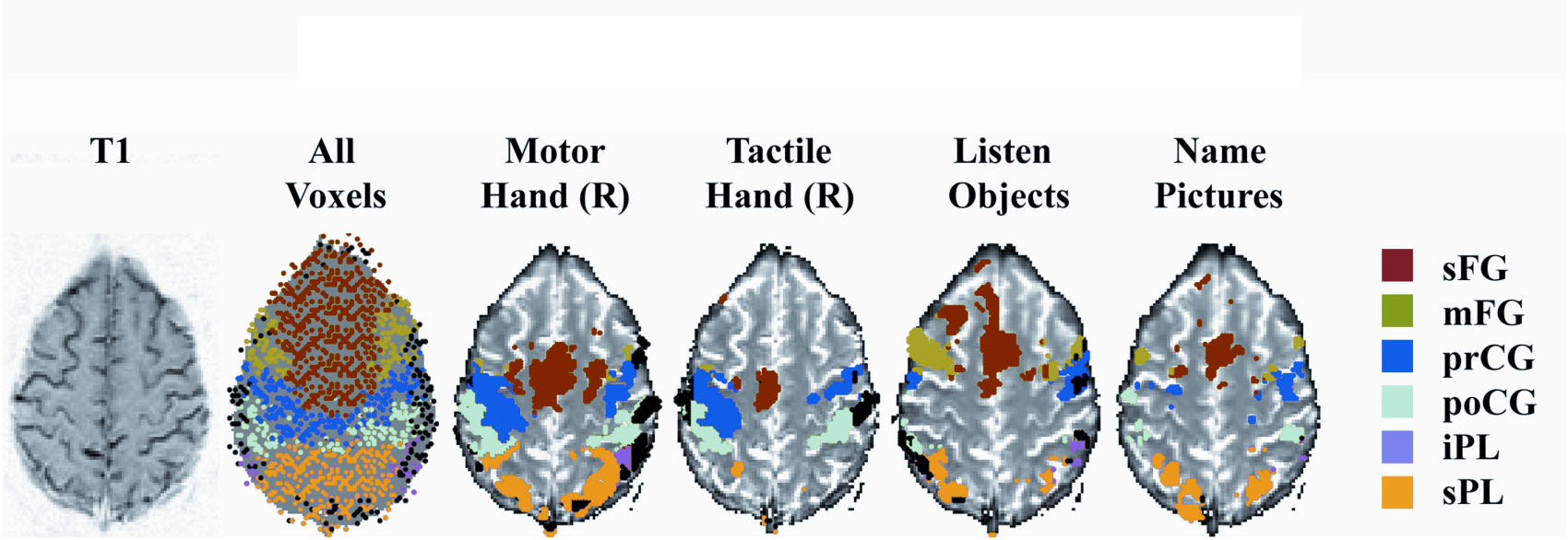
↓

Functional mapping tests





Functional mapping tests



Mindboggle labeled activity from 5 subjects undergoing 4 standard tasks that are known to elicit activity in specific regions (Hirsch, 2000). We determined whether Mindboggle's labels included those regions. According to Mindboggle, of the 45 gyrii expected to be activated (9 gyrii distributed across 4 tasks performed by 5 subjects), 44 were activated, well within expected variance of the subject pool.

Conclusions

Mindboggle is an alternative tool to fully automate cortical anatomical labeling that outperforms other methods such as linear coregistration, AIR, and SPM2 nonlinear registration. Mindboggle performs comparably with ANIMAL, with fewer assumptions.
We hope that it will find its place as a useful tool for brain imagers.

Mindboggle:

Fully automated

Does not assume that different brains preserve topology or have complete homology

Feature-based vs. intensity-based registration

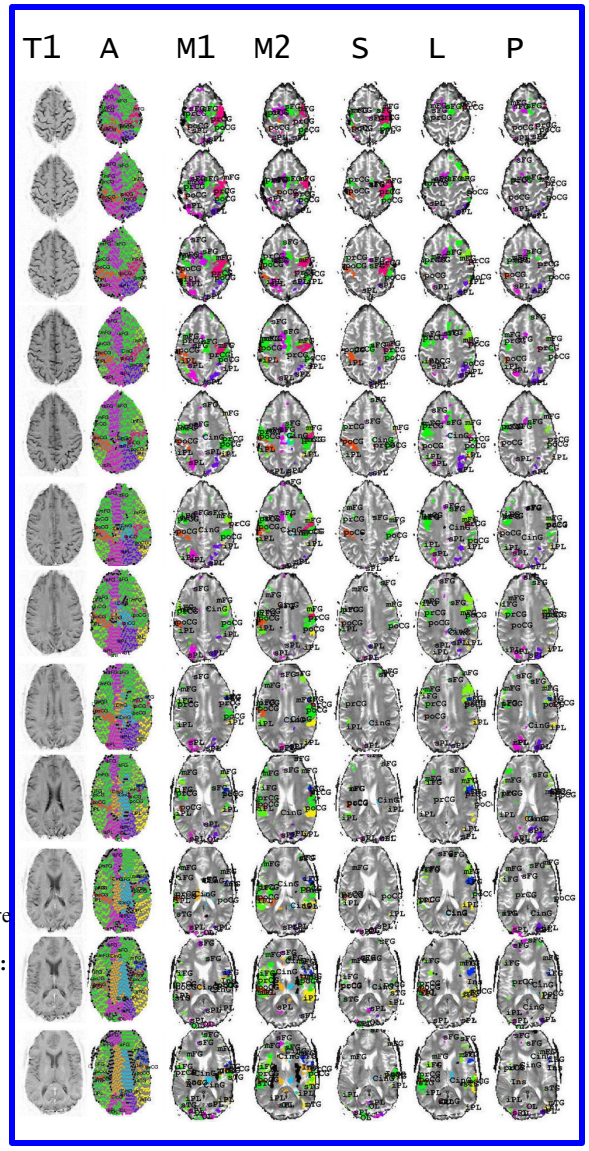
Robust to reduced and nonuniform image quality

May apply mask to transfer labels to any regions of interest / activated voxels

Please visit: www.arnoklein.net/mindboggle.html

Label BOLD activity for 5 tasks

(1 of 5 subjects)



Tasks

T1 = original T1 slices
A = everything labeled
M1 = motor hand task
M2 = motor tongue task
S = tactile hand task
L = listening task
P = picture-naming task

Clinical battery:

Hirsch, J., et. al. 2000.
An integrated functional magnetic resonance imaging procedure for preoperative mapping of cortical areas associated with tactile, motor, language, and visual functions. *Neurosurgery* **47:** 711-721.

Labels

sFG = superior Frontal Gyrus
mFG = middle Frontal Gyrus
iFG = inferior Frontal Gyrus
sTG = superior Temporal Gyrus
mTG = middle Temporal Gyrus
iTG = inferior Temporal Gyrus
prCG = preCentral Gyrus
poCG = postCentral Gyrus
sPL = superior Parietal Lobe
iPL = inferior Parietal Lobe
OL = Occipital Lobe