The Anatomy of Reading

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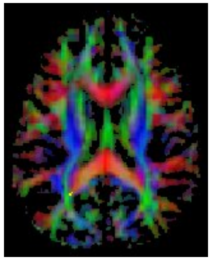
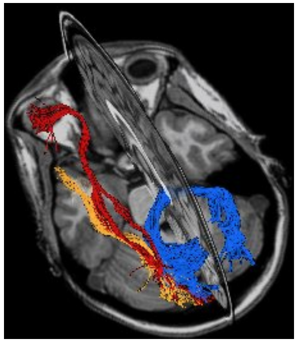
Reading and Learning

SIRL Longitudinal Study of Reading Development





- Behavioral assessment
- Anatomical + Diffusion Tensor Imaging
- Functional MRI
- 50 7-11 yr olds
- 3 years (4 measurements)
  - Completed 1st and 2nd measurement (1yr)

Overview

- Proficient reading is an impressive skill
- Garden-variety brains
- The anatomy of reading
    - Key cortical regions
    - Connected by important white matter pathways
    - But- some brains aren't optimized for reading
- Conclusions

Name the ink colors:

XXXXXX

XXXX

XXXXX

XXX

XXXXXX

Name the ink colors:

red

green

blue

orange

purple

Reading Numbers

Typical reading rate:	250 words/minute
Fixation duration:	225 ms (skewed distribution)
Saccade distance:	7-10 letters (2 deg)
Duration of 2 deg saccade:	30 ms
Regressive saccades:	10-15%, ↑ with difficulty
Minimal saccade latency:	150 ms
Probability of fixation:	2-3 letter words: 0.25
	> 7 letter words: ~1.0

Sensory Aspects of Reading

- Maintain fixation
  - Identify currently fixated word
  - Preprocess parafoveal words
- Program saccades
- Execute saccades
- Ignore irrelevant retinal motion

Visual Processing of Words is *Fast*

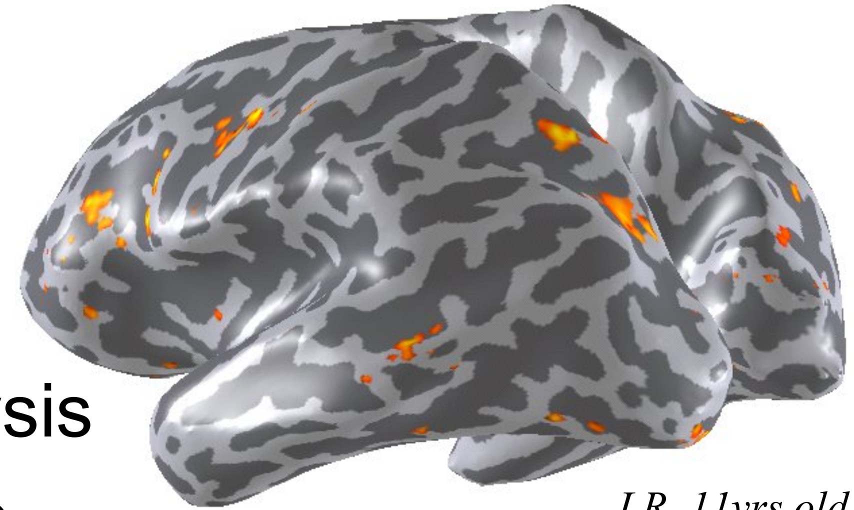
- ~150 ms to program a saccade
- Visual info influences fixation duration and subsequent saccade target
- Relevant info extracted and processed within ~75ms (+ overlap w/ saccade program?) during fluent reading

Explaining Reading Development

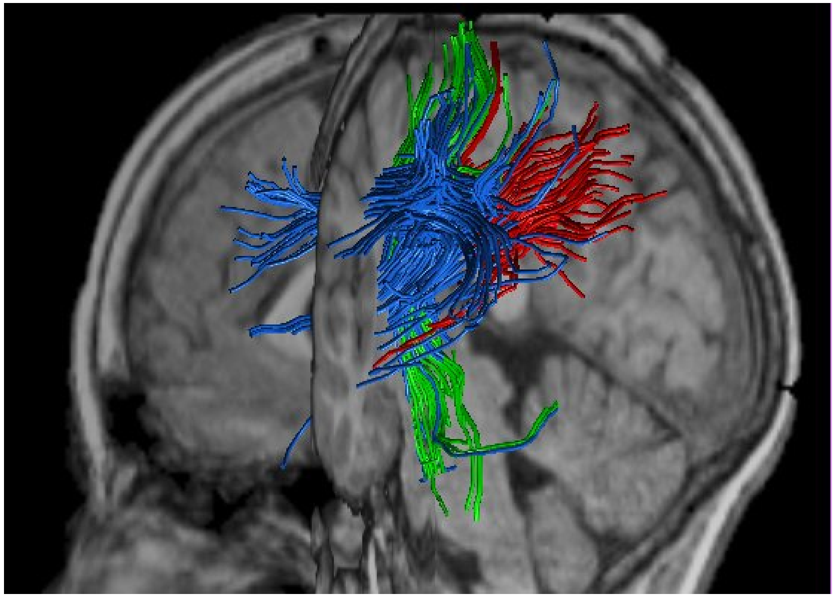
- Most variance is explained by social factors and general cognitive ability
- Significant variance remains...
  - What are the neurological factors?
- Identify biological correlates
  - Explain individual differences in reading development with variation in anatomy and physiology
  - Predict & intervene before reading failure

Neural Basis of Reading

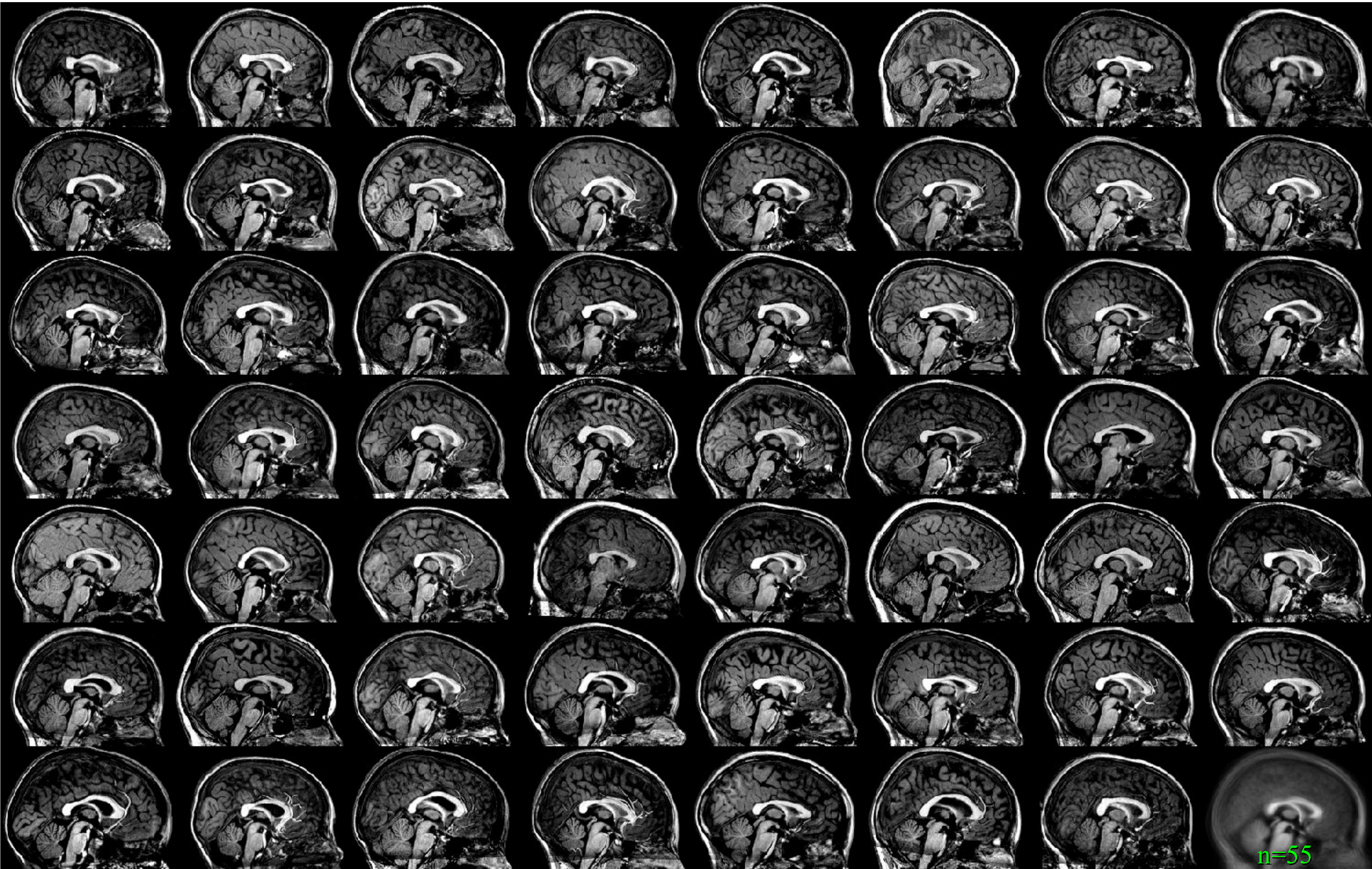
- Behavior
- Gross Anatomy
  - Brain shape/size analysis
- White matter structure
  - Diffusion imaging
- Cortical activity
  - Functional MRI



LR, 11yrs old



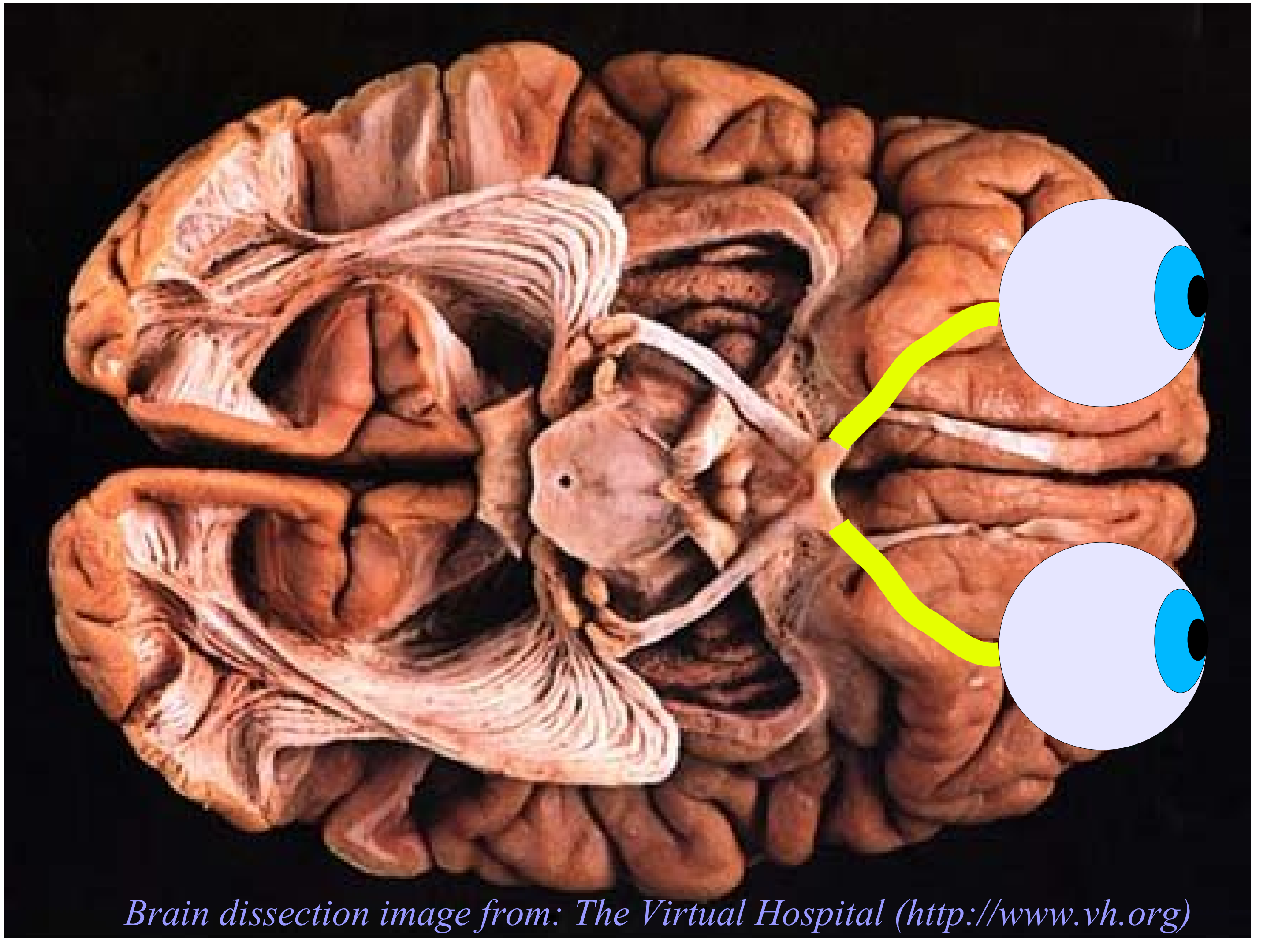
Every Brain is Different...



What's the Matter?

- Gray matter: the connections (synapses)
  - Site of functional activity (EEG, MEG, fMRI)
- White matter: the wiring (myelinated axons)
  - Looks white due to high lipid content (myelin)
  - Long-range connections
  - Connections develop early and limit plasticity
  - Connections *define* cortical modularity (Müller's law of specific nerve energies)

Why You See with the Back of Your Brain



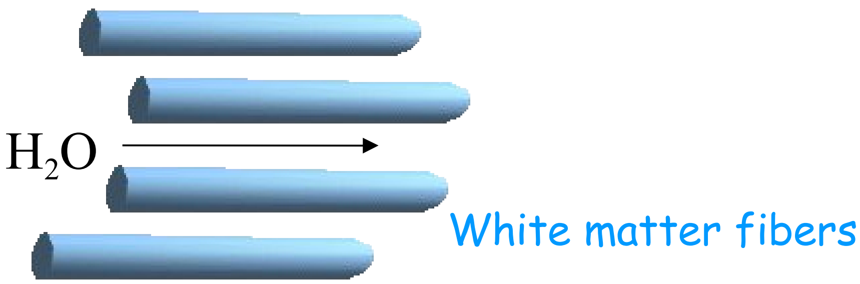
Brain dissection image from: The Virtual Hospital (http://www.vh.org)

Diffusing Water Probes Microscopic Tissue Structure

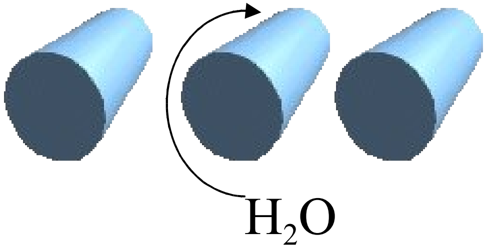
- Tissue structures affect water diffusion
- Diffusion through white matter probes:
  - Axon density & myelination, principal fiber direction and directional coherence
- MR Diffusion weighting measures diffusion
- Fiber tracking in diffusion data
  - Hints at axonal connectivity

Water Diffusion in the Brain

Unimpeded direction- higher diffusion rate

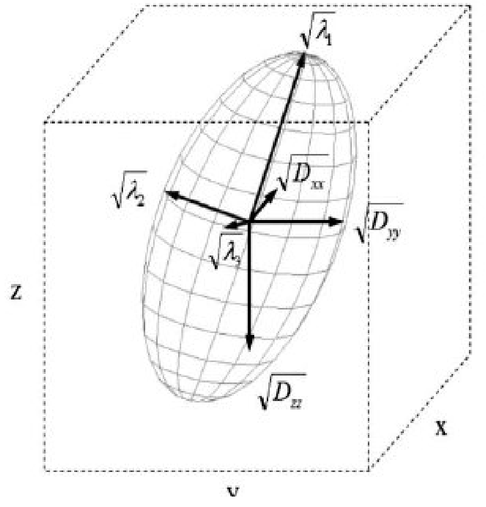


Impeded direction- lower diffusion rate



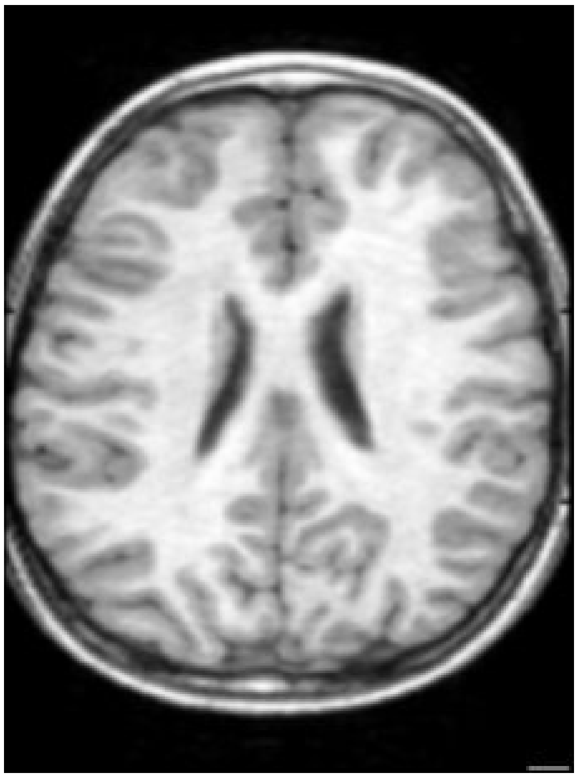
The Diffusion Tensor: 3x3 Covariance Matrix (Ellipsoid)

- Water molecules move in Brownian motion
- 3D Gaussian (3x3 covariance matrix) model
  - Eigenvalues & vectors define ellipsoidal isodiffusion surface

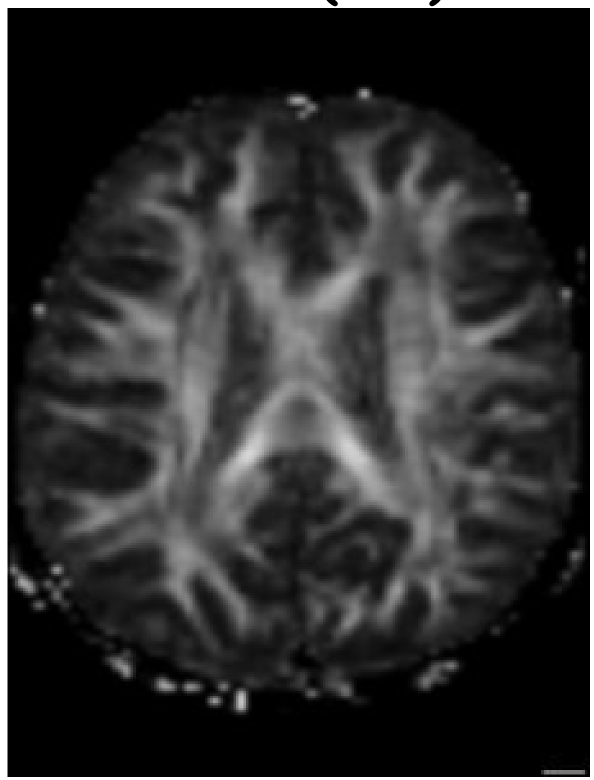


DTI Reveals White Matter Structure

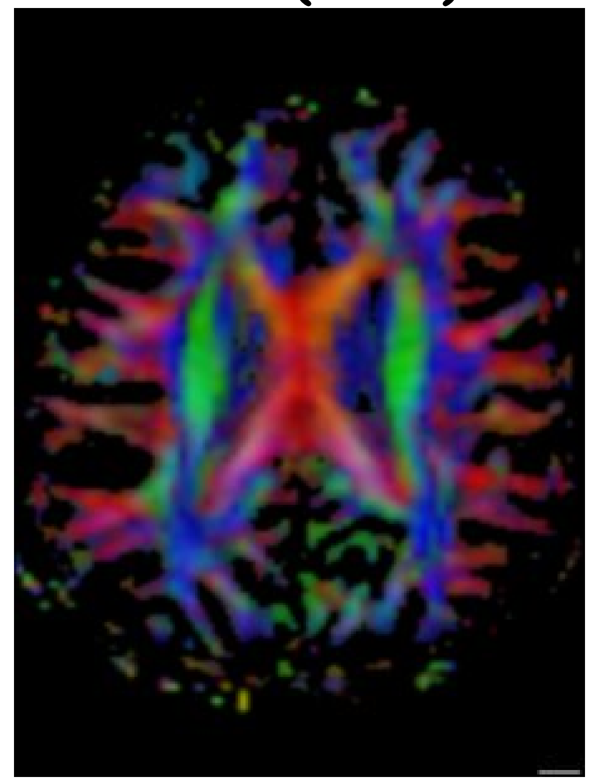
T1

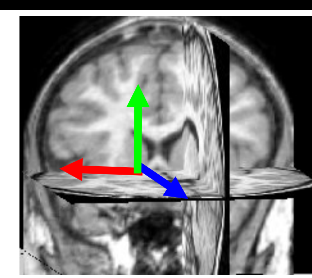


DTI (FA)



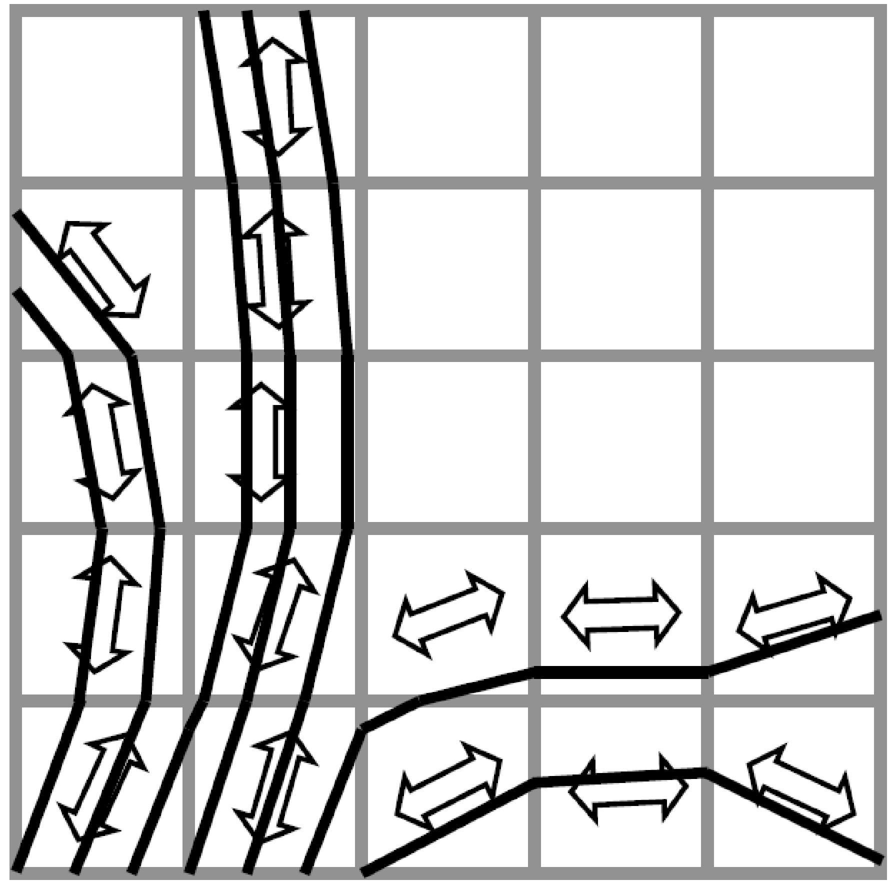
DTI (PDD)





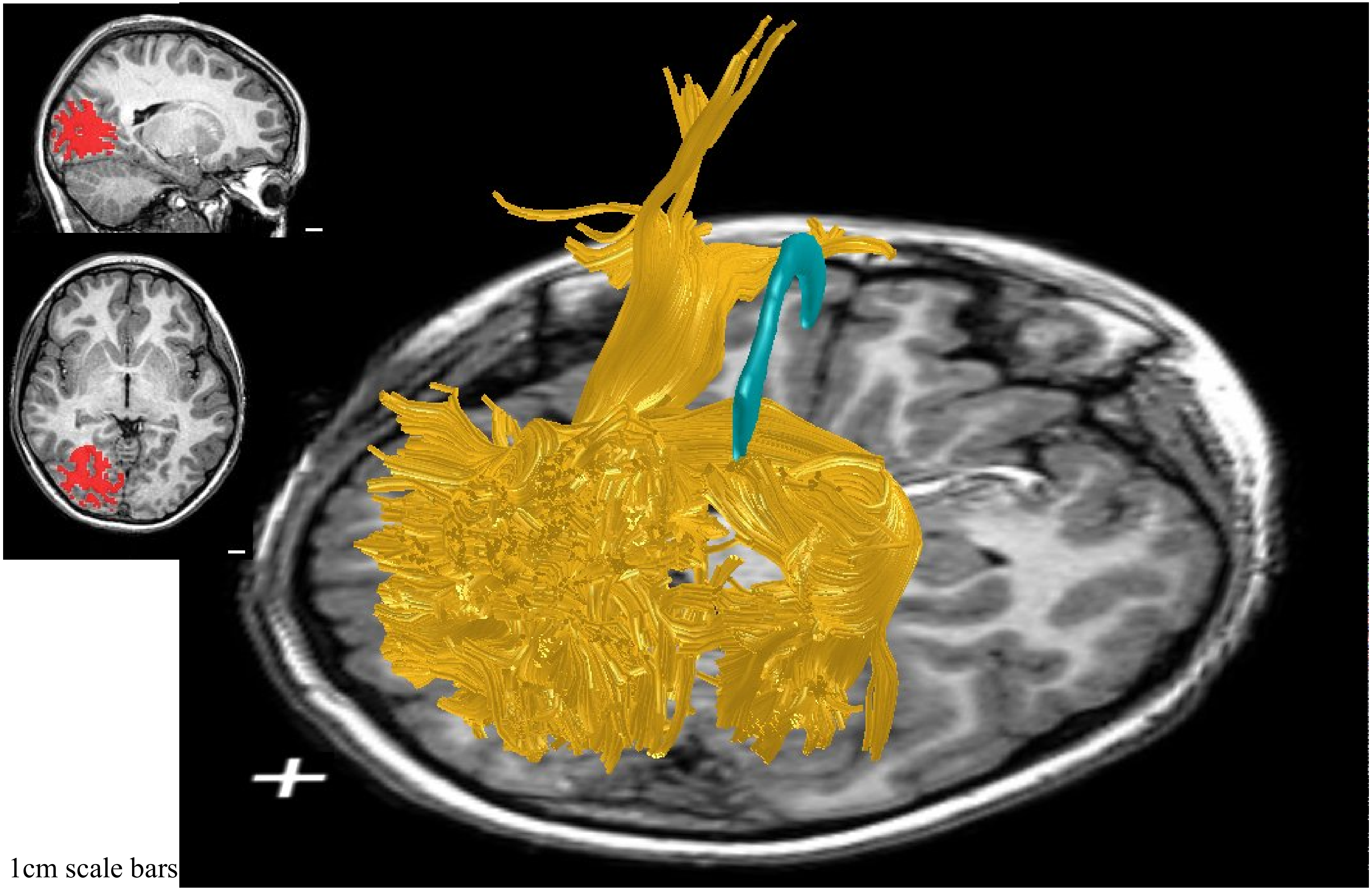
Trace Paths Through Tensor Field

- Connecting the dots to make fiber tract estimates
- Stream-tubes tracking (STT)
  - Assume PDD is tangent to fiber tract estimate
  - Go where PDD leads (Runge-Kutta path integral)
  - Tri-linear interpolation of tensors
  - 1 mm step size
  - Stop at FA<0.15 or angle > 30°



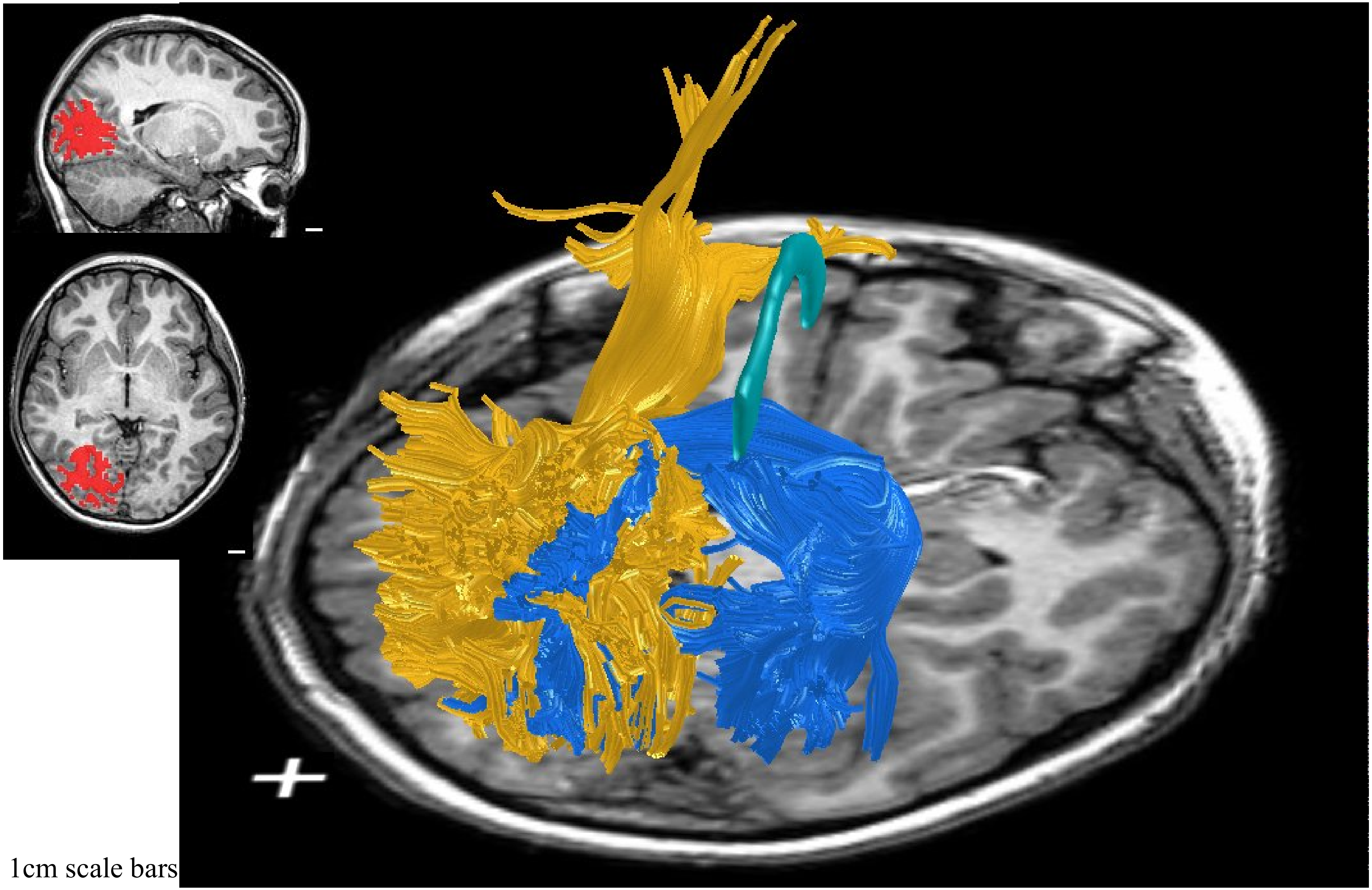
From Watts et. al. (Cornell)

Occipital Fibers



1cm scale bars

Occipital Callosal Fibers



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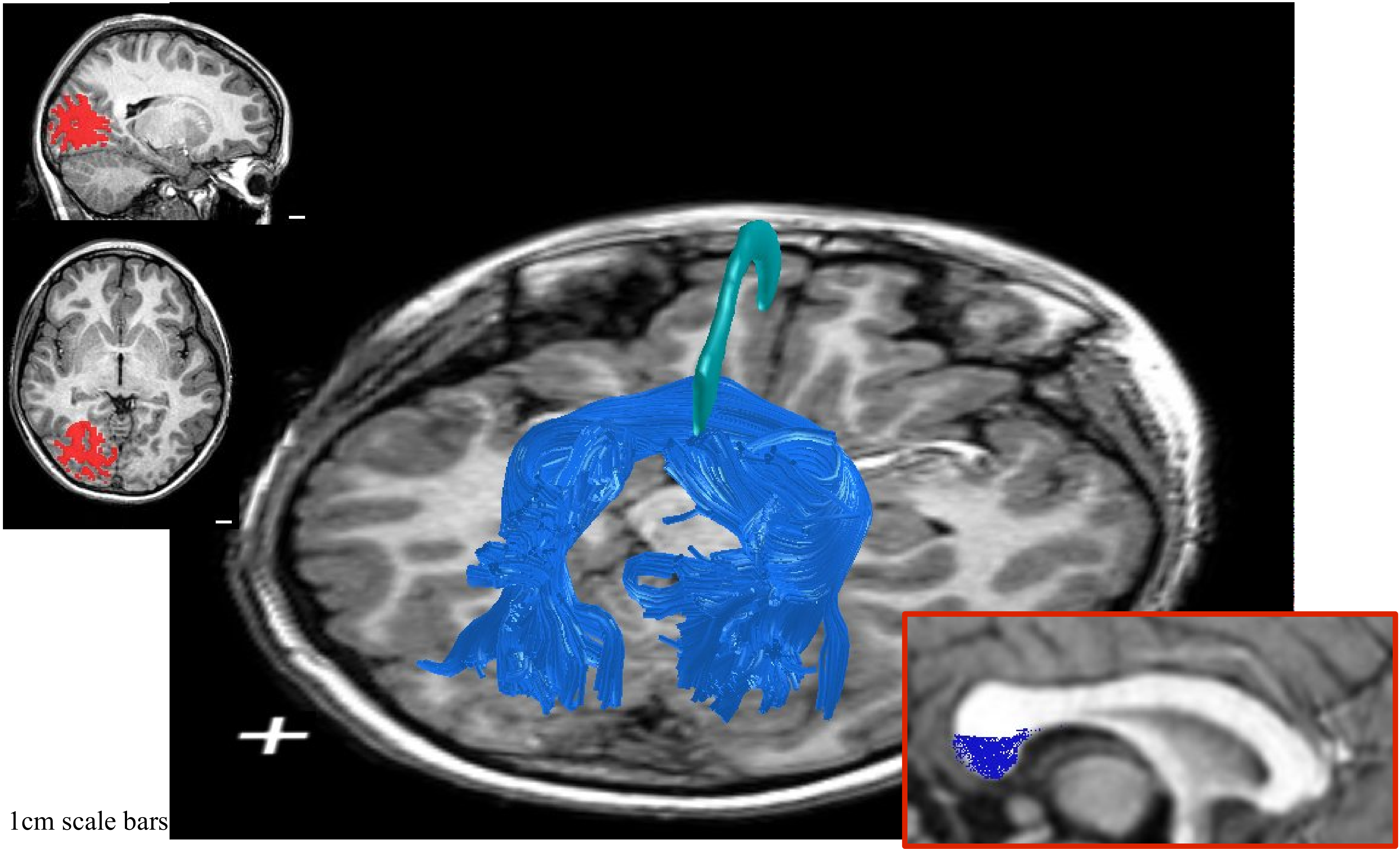
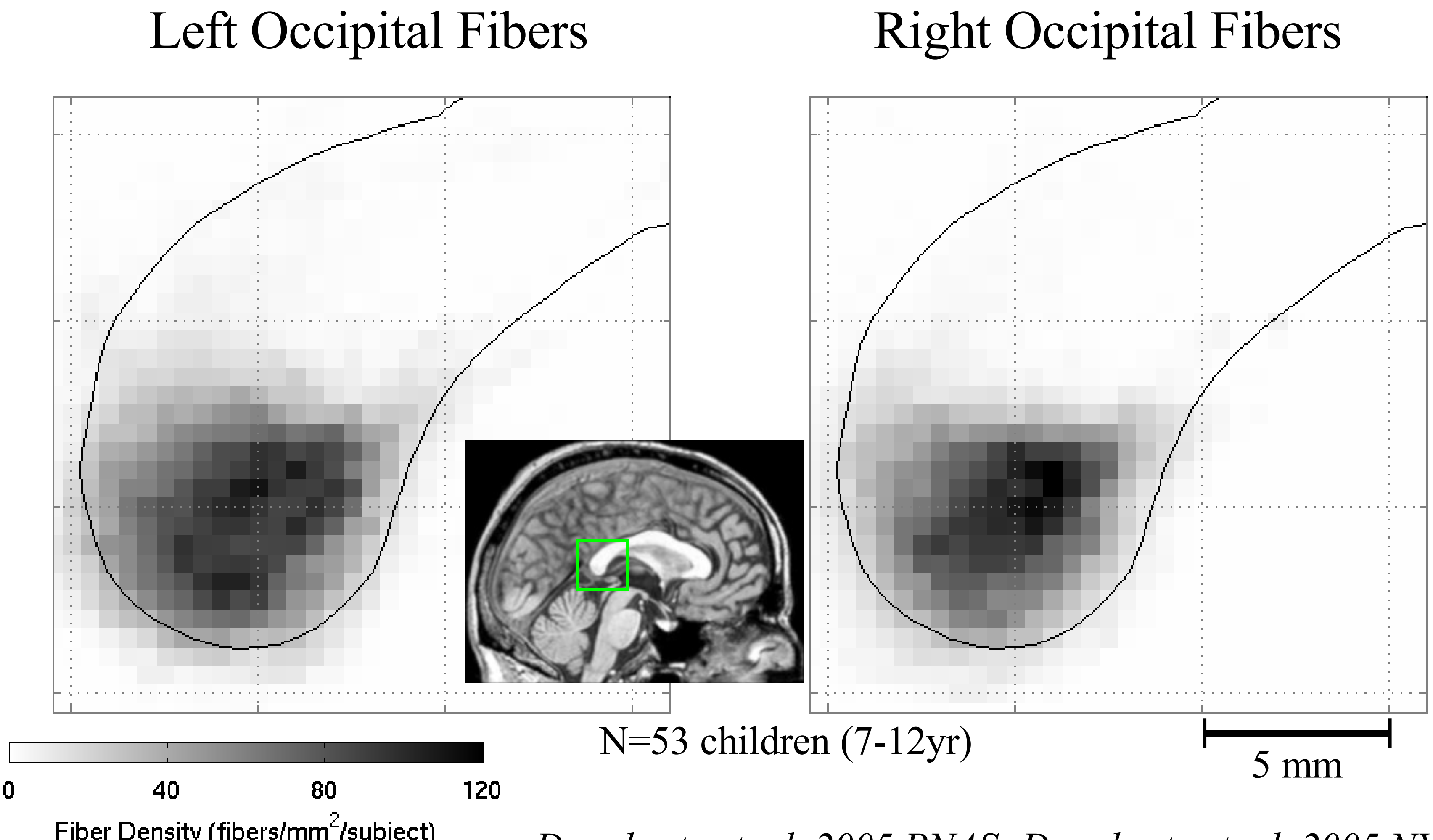


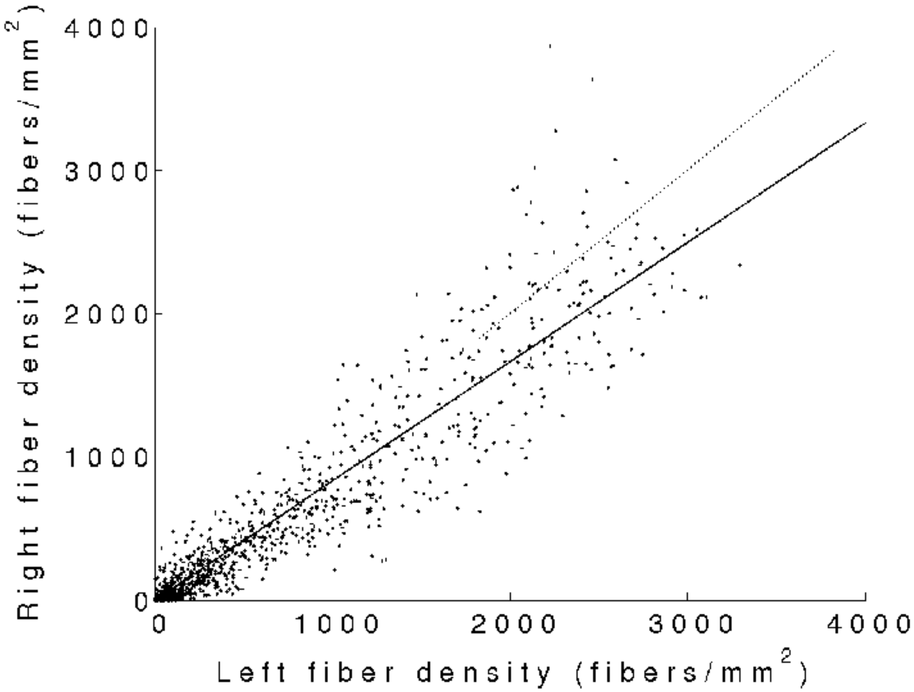
Left-Right Convergence: Mean-Centered Density



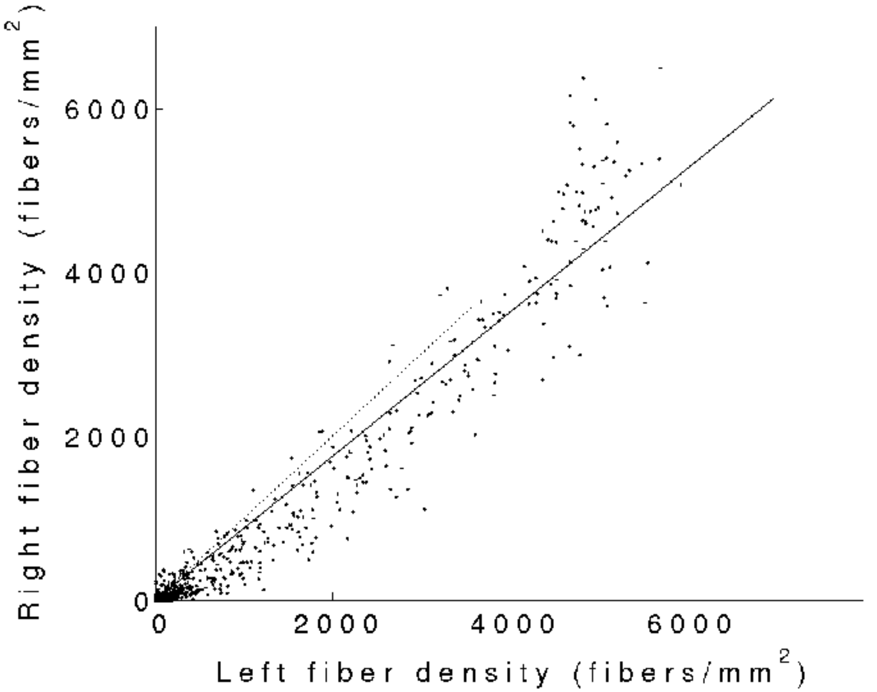
Dougherty et. al. 2005 PNAS; Dougherty et. al. 2005 NYAS

Left and Right Fibers Converge

Unshifted ($r^2 = 0.88$)



Mean-shifted ($r^2 = 0.94$)



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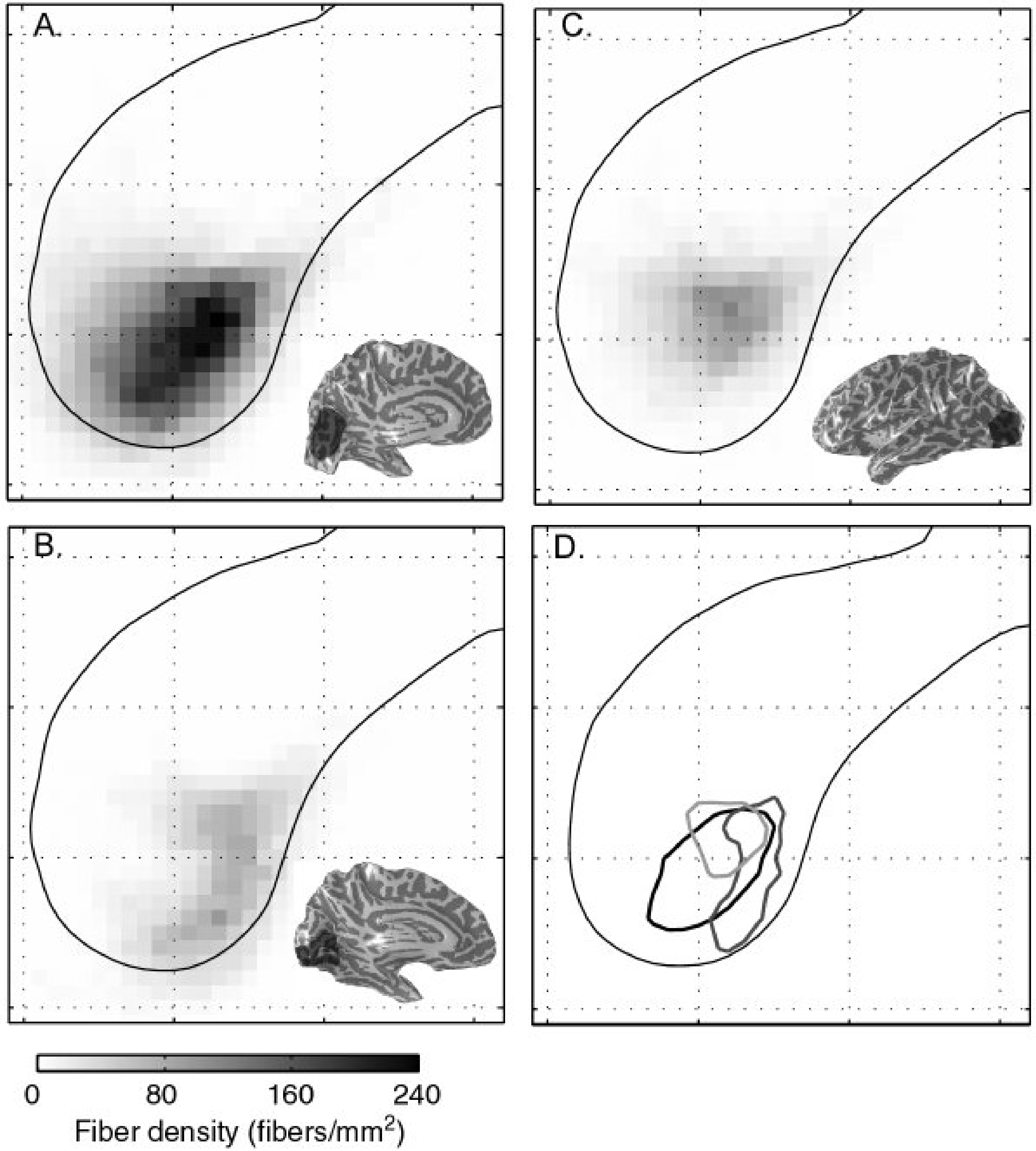
Splenium Map in 53 Children

left/right convergence (r^2):

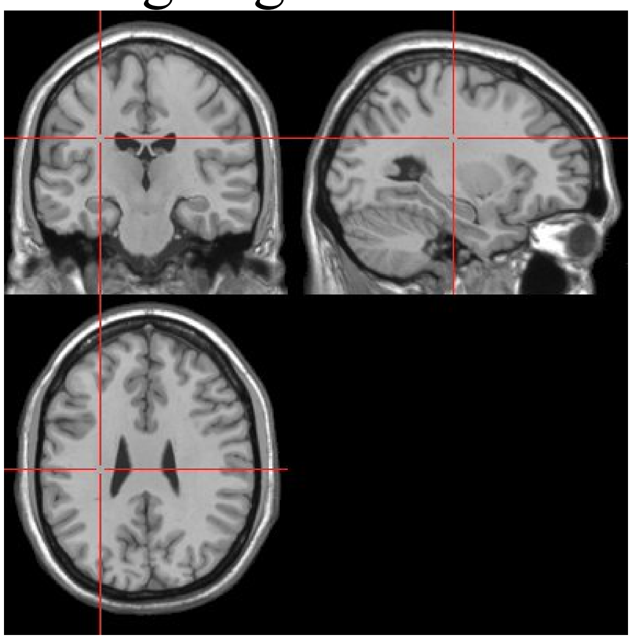
	LD	LV	LL
RD	0.87	0.73	0.21
RV	0.47	0.89	0.38
RL	0.37	0.50	0.77



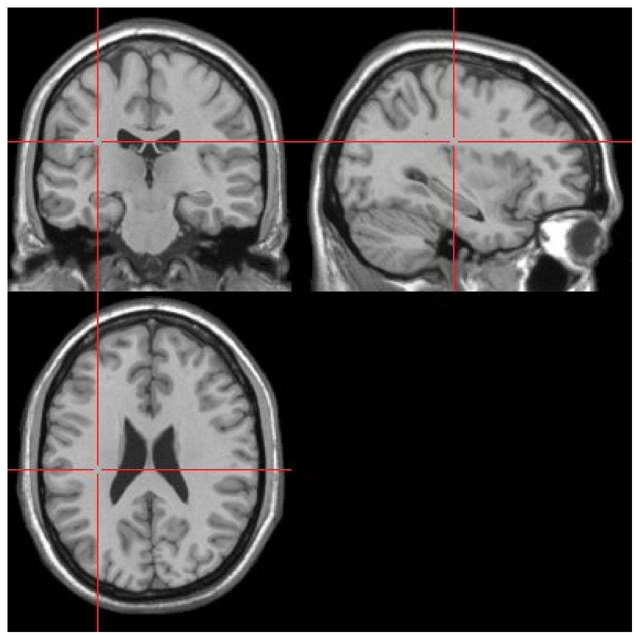
Previous WM Findings in Reading

- Decreased FA in low readers in temporal-parietal WM region (esp. on left)

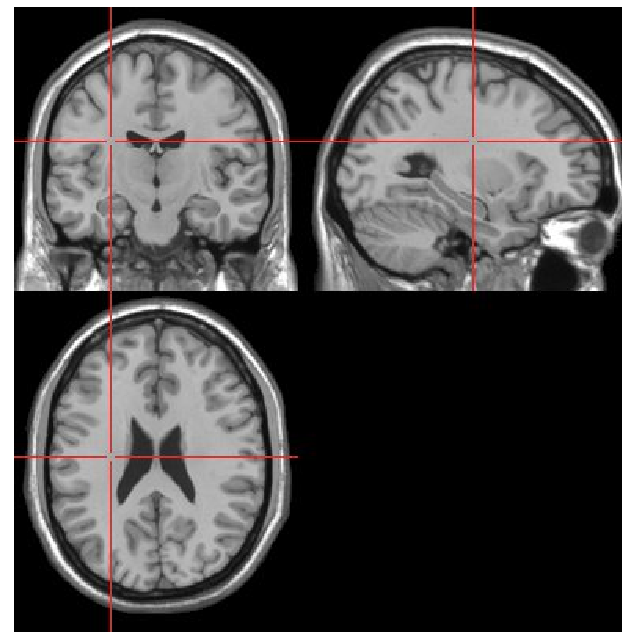
Klingberg et. al. 2000



Deutsch et. al. 2005



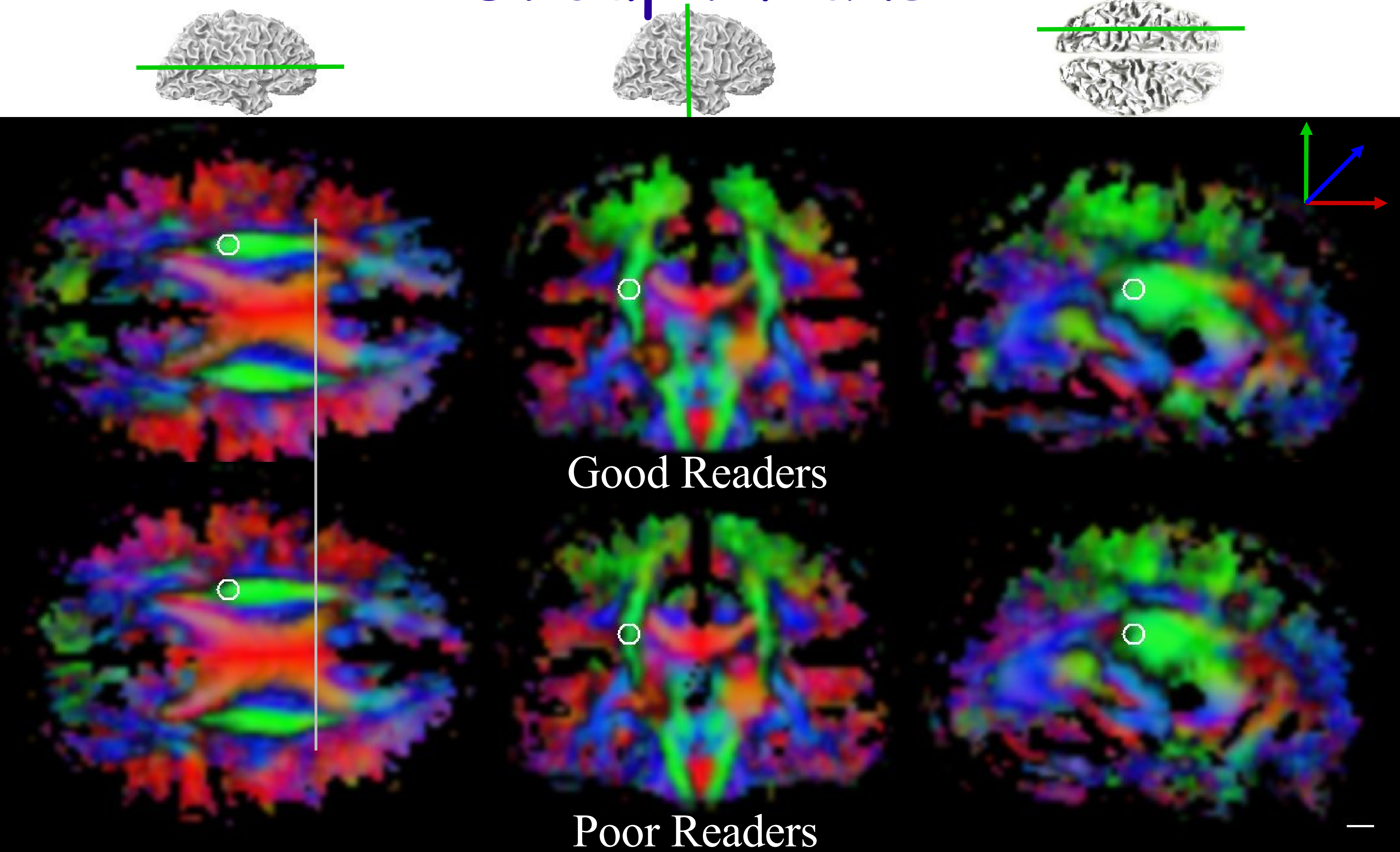
Beaulieu et. al. 2005



adults *children*

Some overlap in extent; voxels of maximal difference <1cm apart

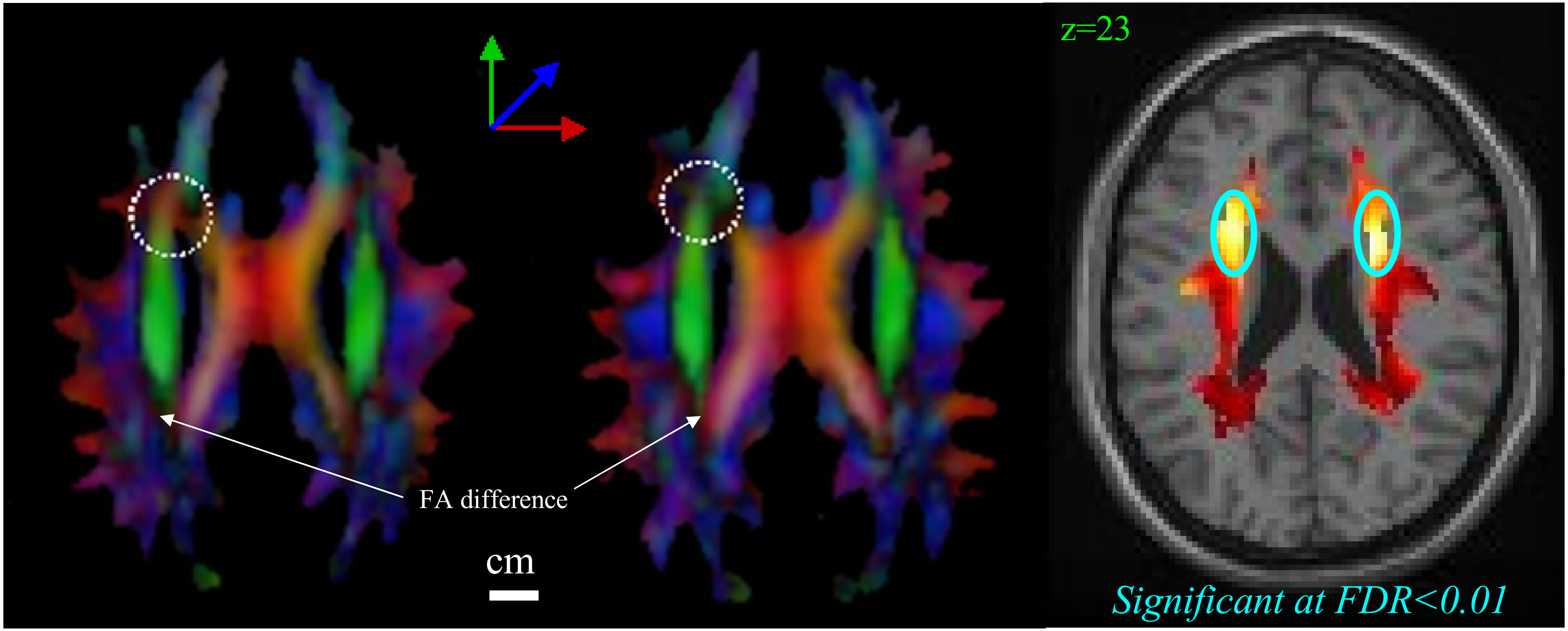
Principal Diffusion Direction: Group Means



A PDD Difference in Anterior WM

(Schwartzman, Dougherty, Taylor, 2005, MRM)

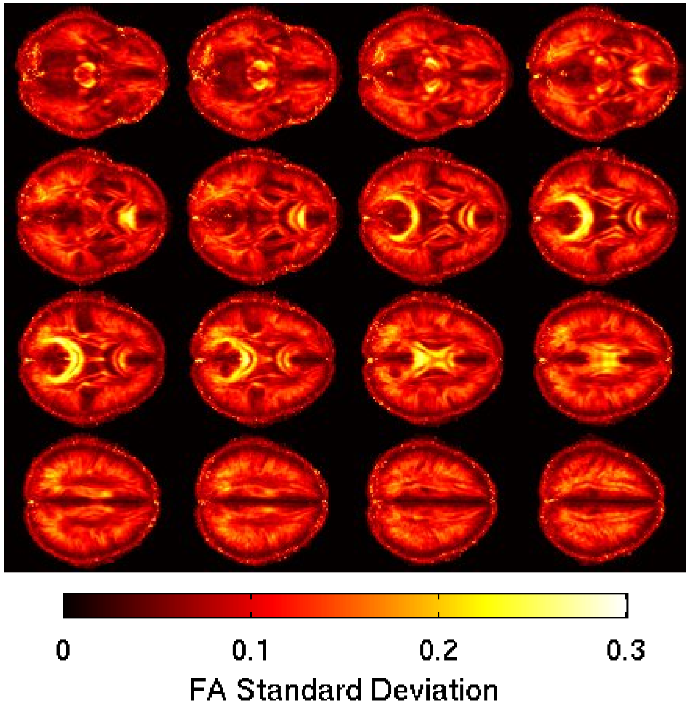
Good Readers *Poor Readers* *Bipolar Watson Distribution*

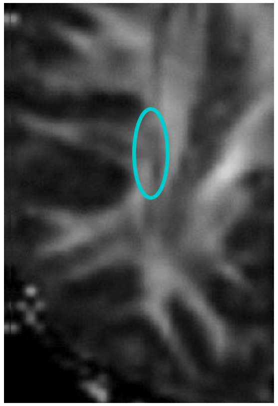


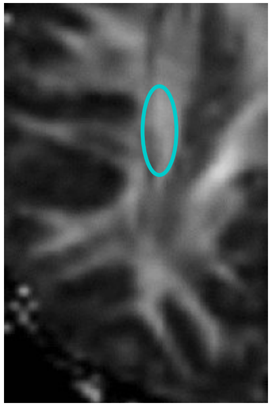
Ages 8-12; N = 14

Limits of the SPM Analysis

- Statistical power varies greatly across brain regions
- Interpretation is often ambiguous
  - Differences may be due to WM properties or structural differences

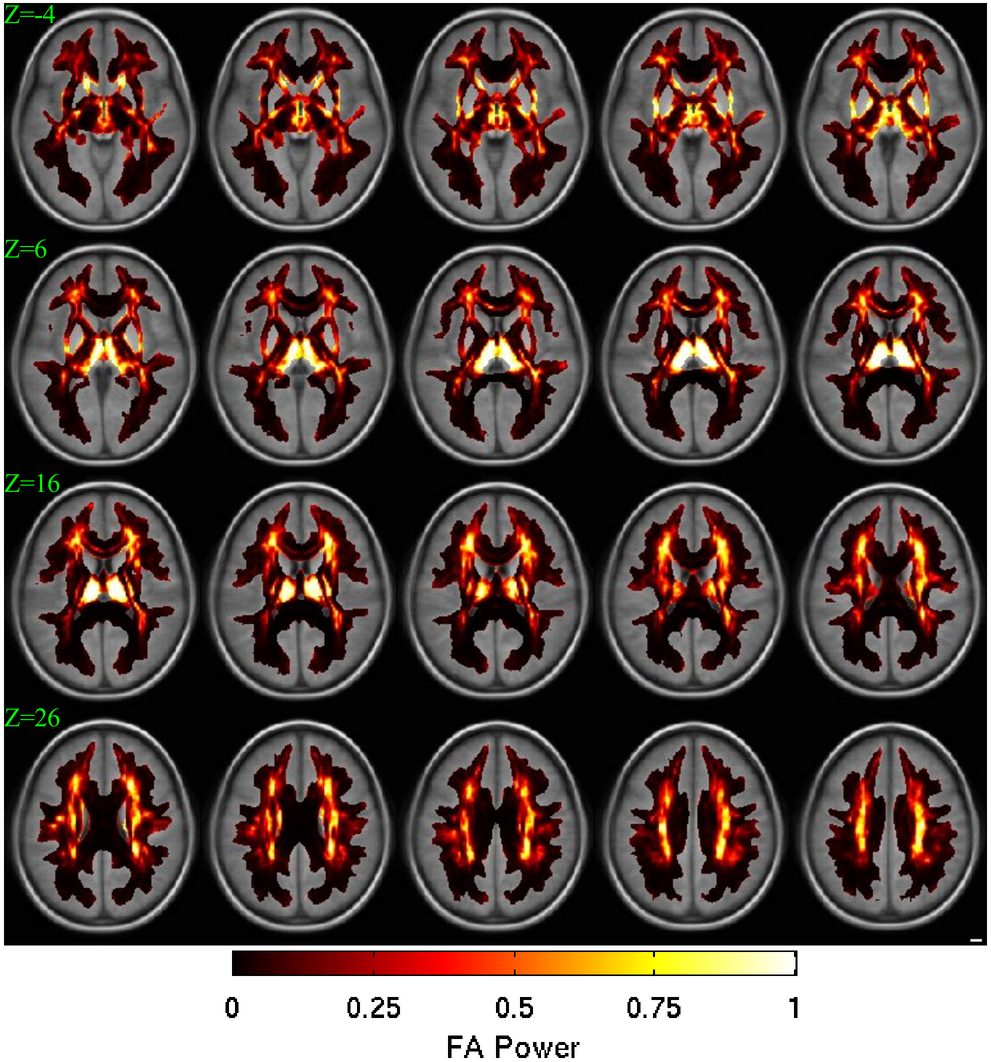






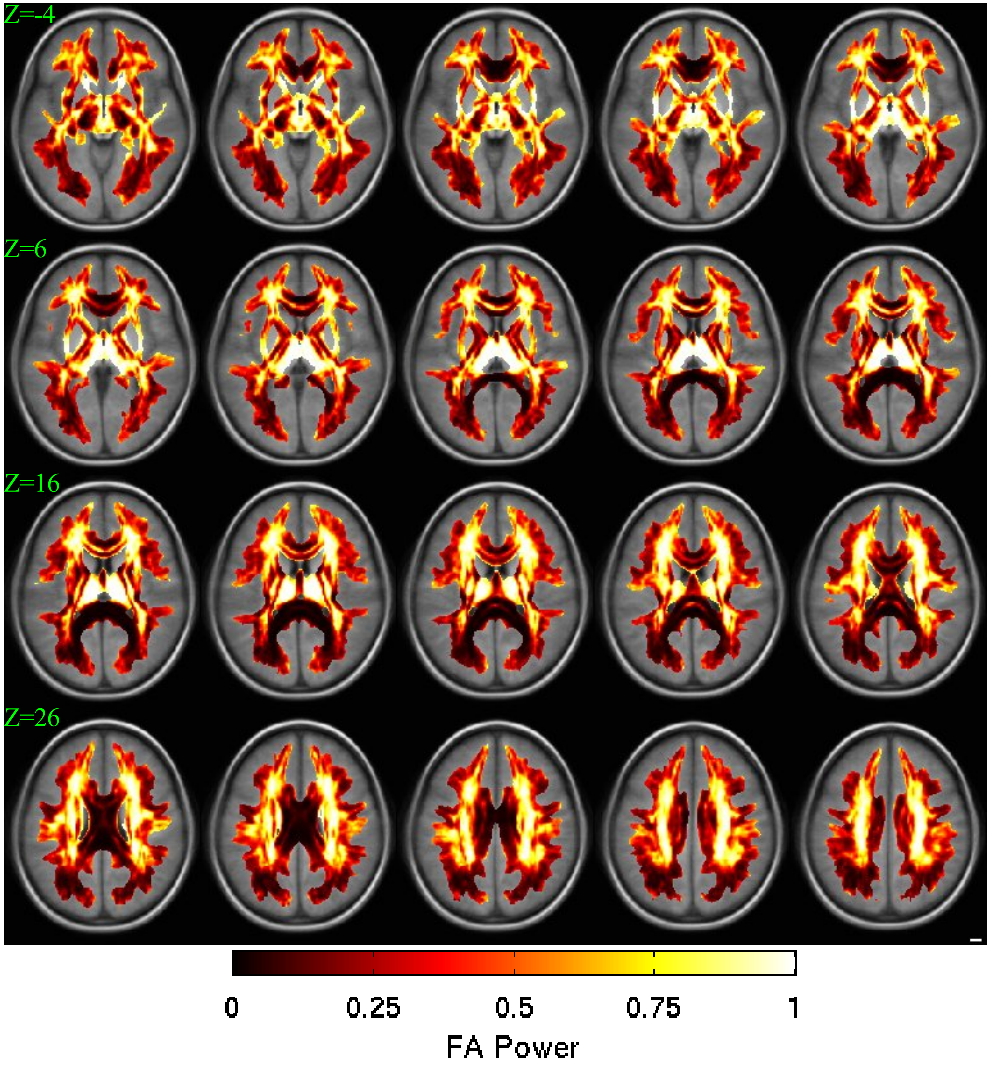
Statistical Power for FA SPMs

- Assumptions:
  - T-test (mean difference between groups)
  - N=10 in each group
  - Mean FA difference = 0.12
  - Uncorrected p=0.001
  - Spatial normalization to MNI T1 template

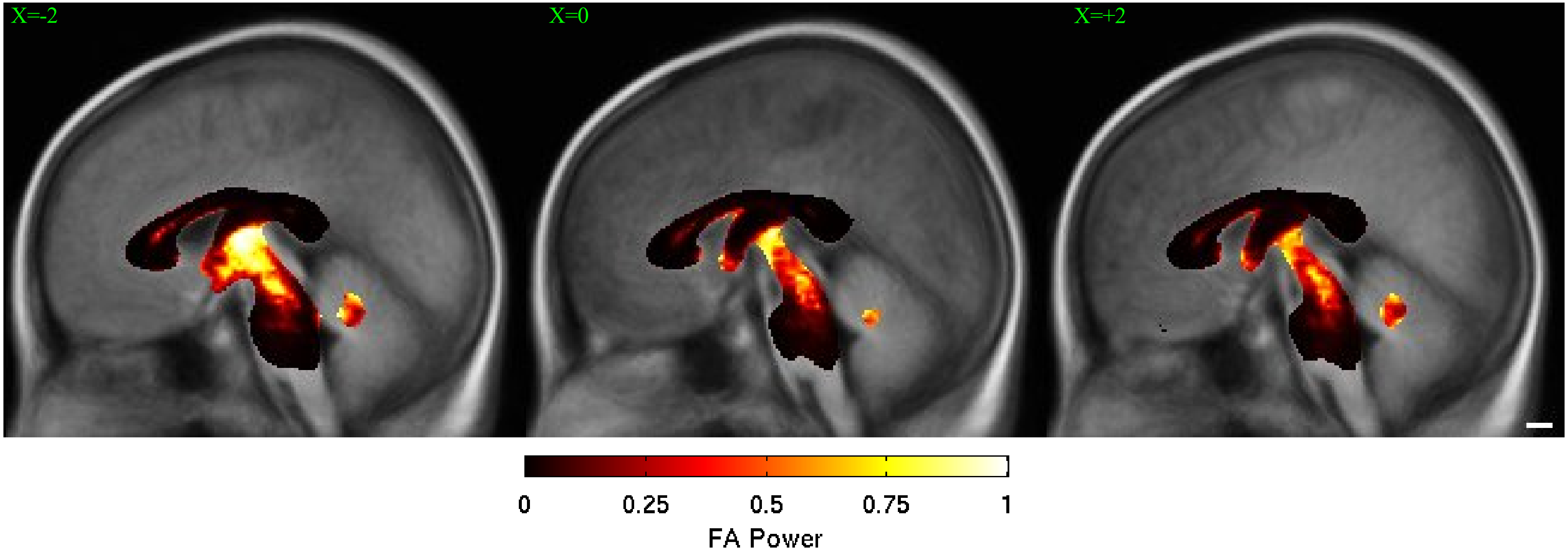


Statistical Power for FA SPMs

- Assumptions:
  - T-test (mean difference between groups)
  - N=15 in each group
  - Mean FA difference = 0.12
  - Uncorrected p=0.001
  - Spatial normalization to MNI T1 template

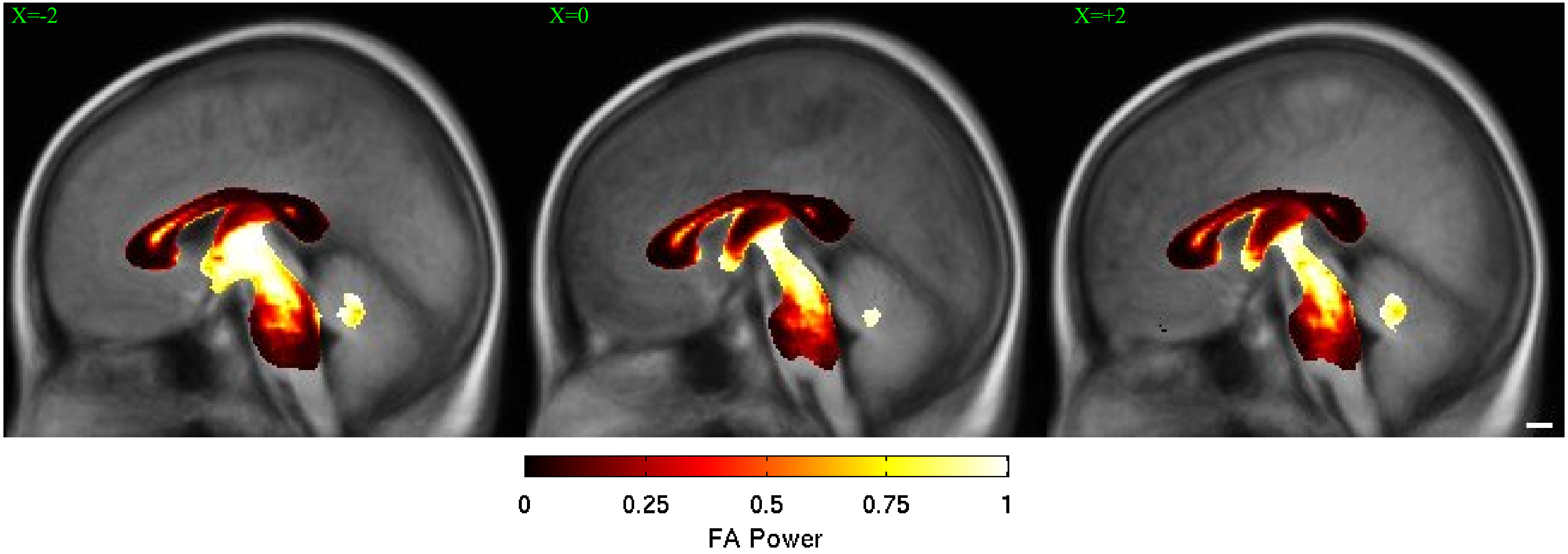


Low Power in CC with FA SPM



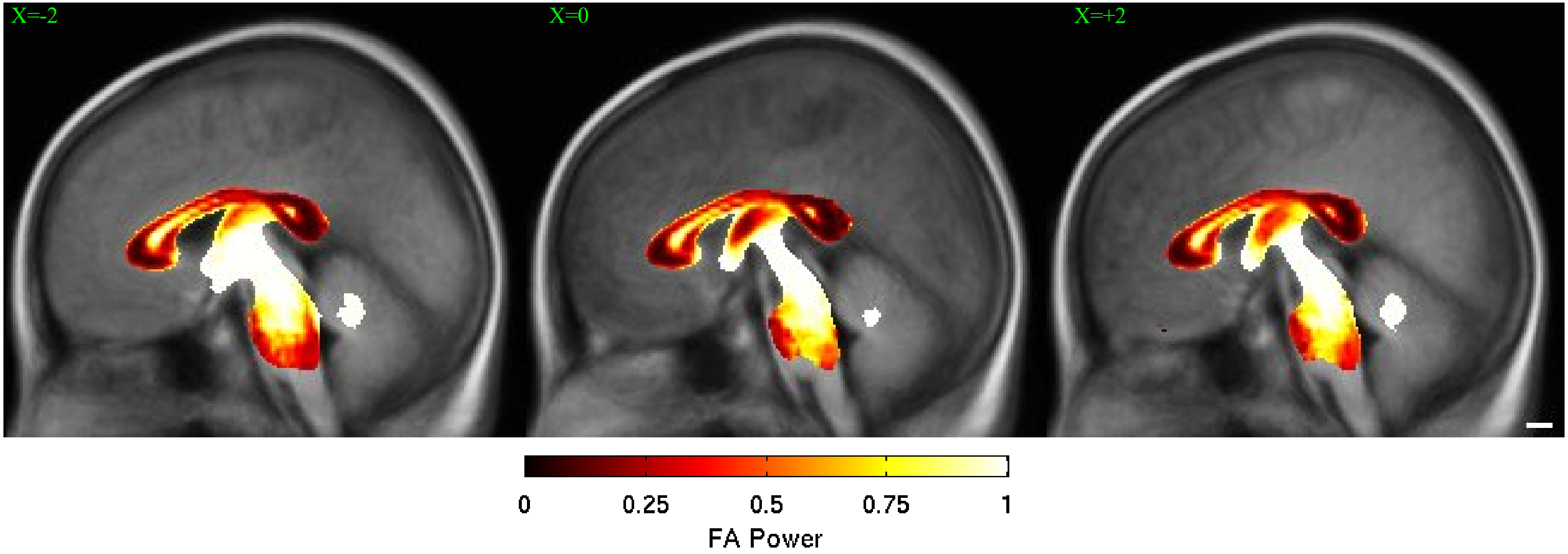
N=10

Low Power in CC with FA SPM



N=15

Low Power in CC with FA SPM

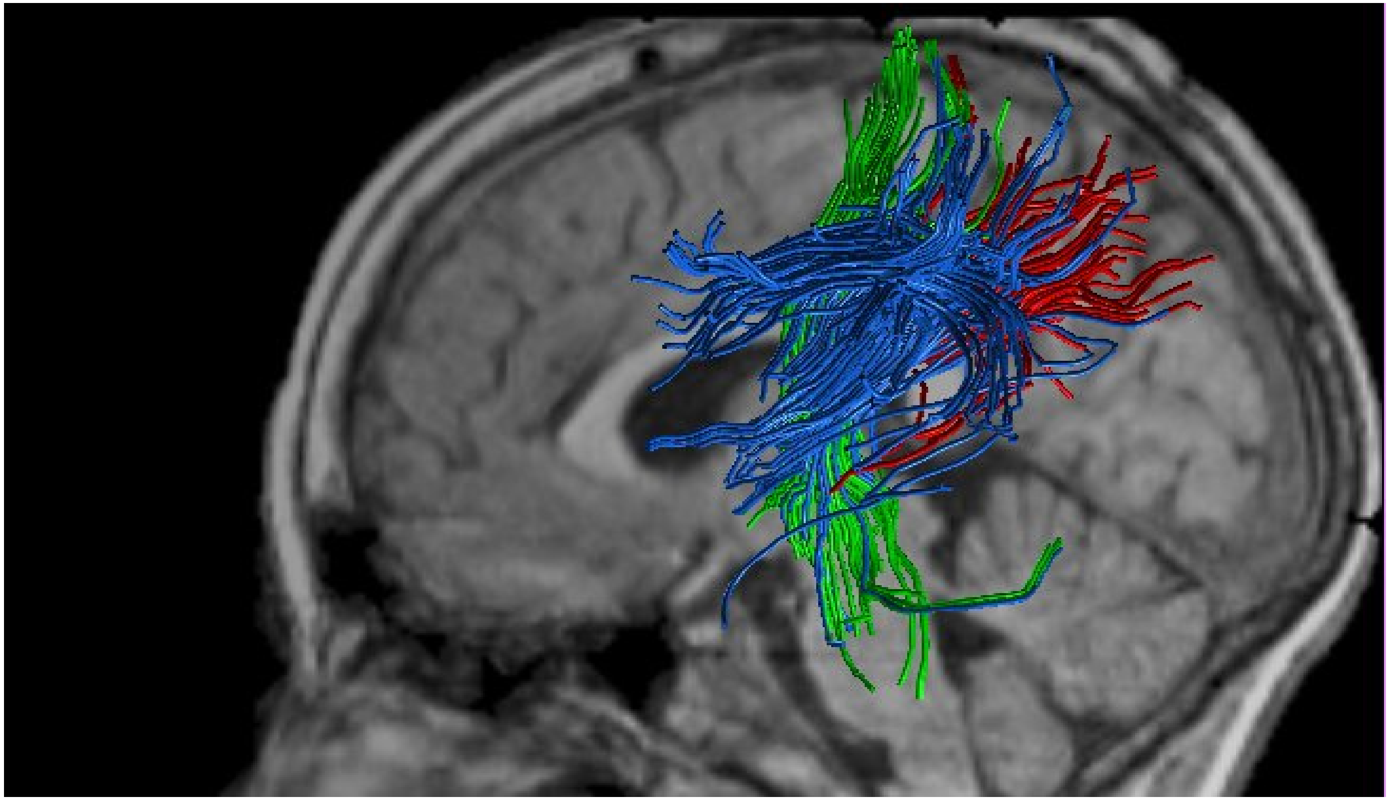


N=25

ROI-based Methods

- More statistical power
  - Eliminate much anatomical variance
  - Many fewer statistical tests
- Easier to interpret
- But:
  - Labor-intensive
  - ROI boundaries are subjective
  - Need a-priori hypostheses

Tracing Virtual Fibers



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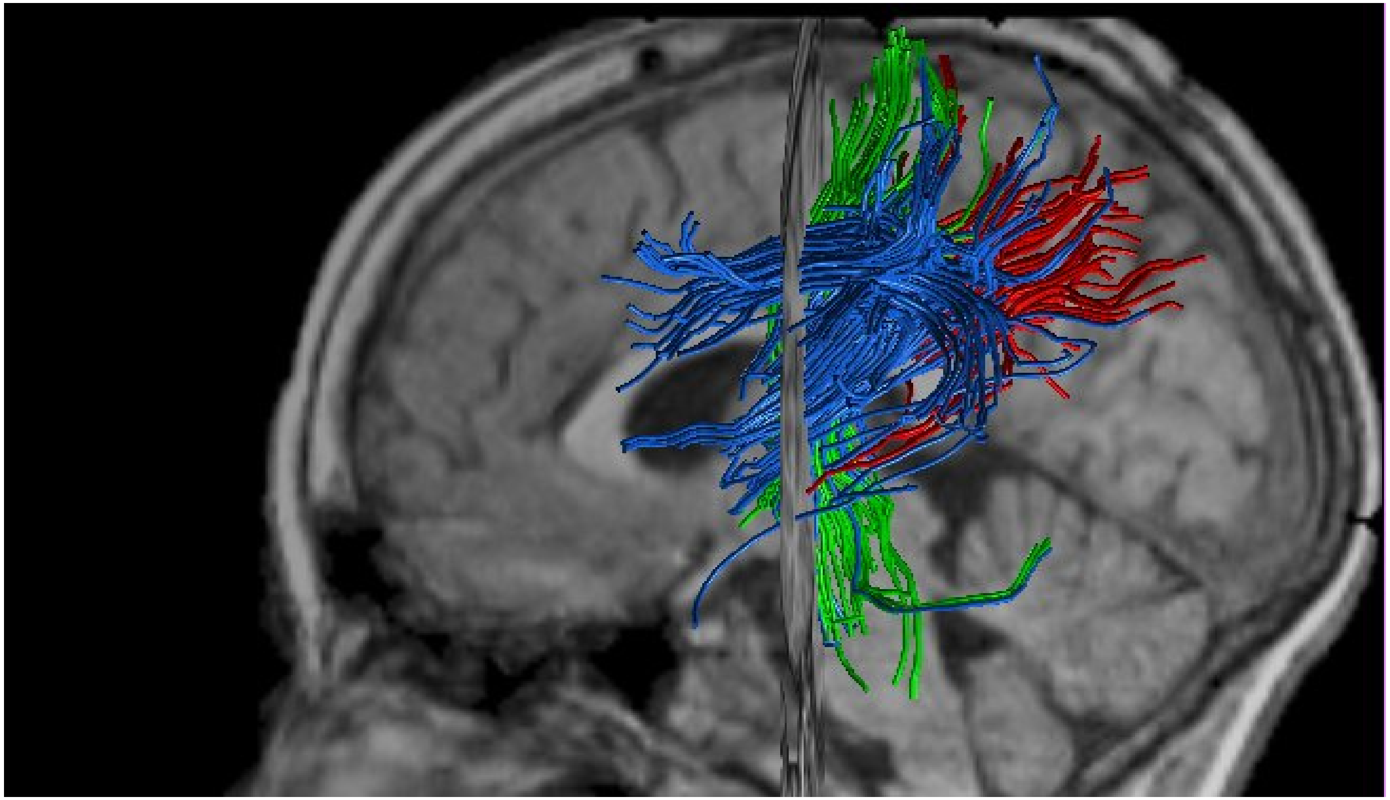

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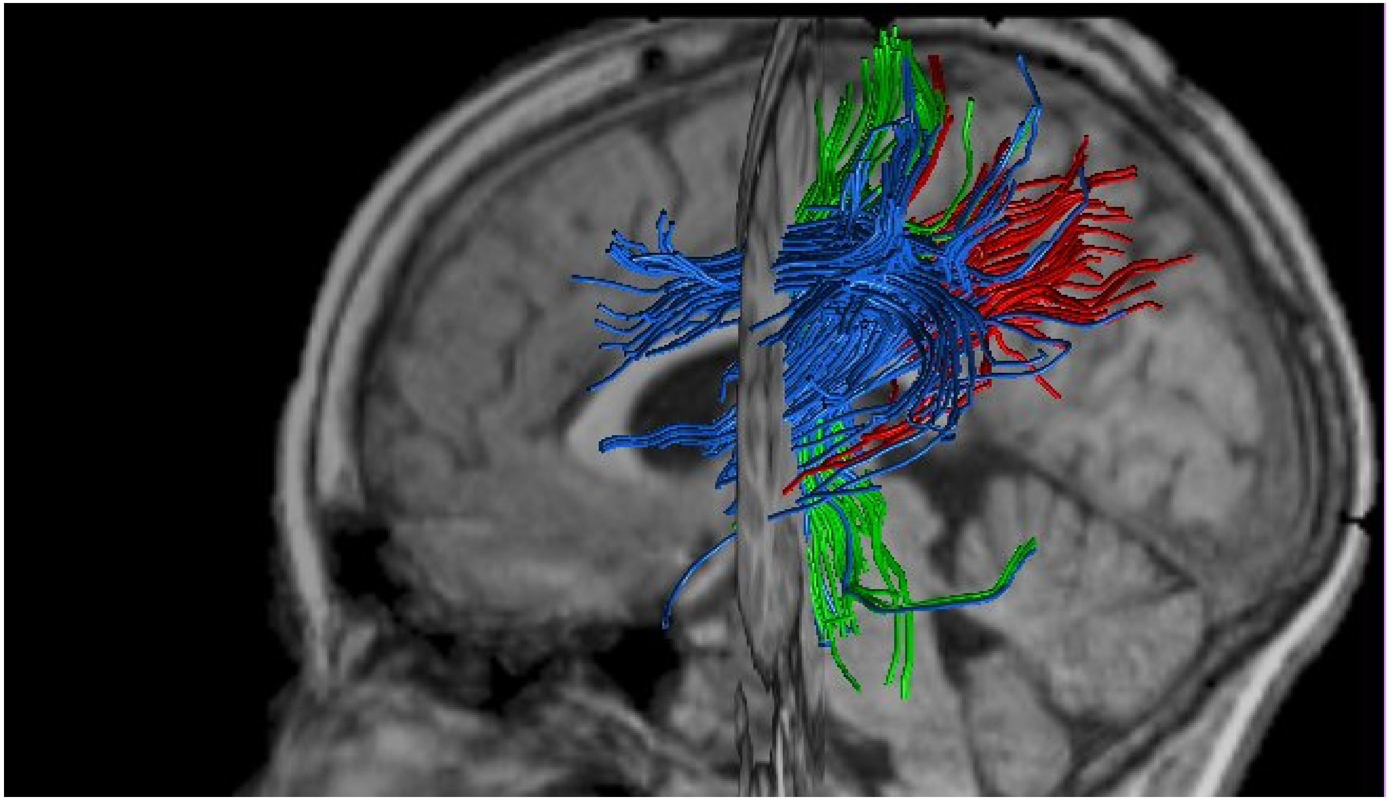

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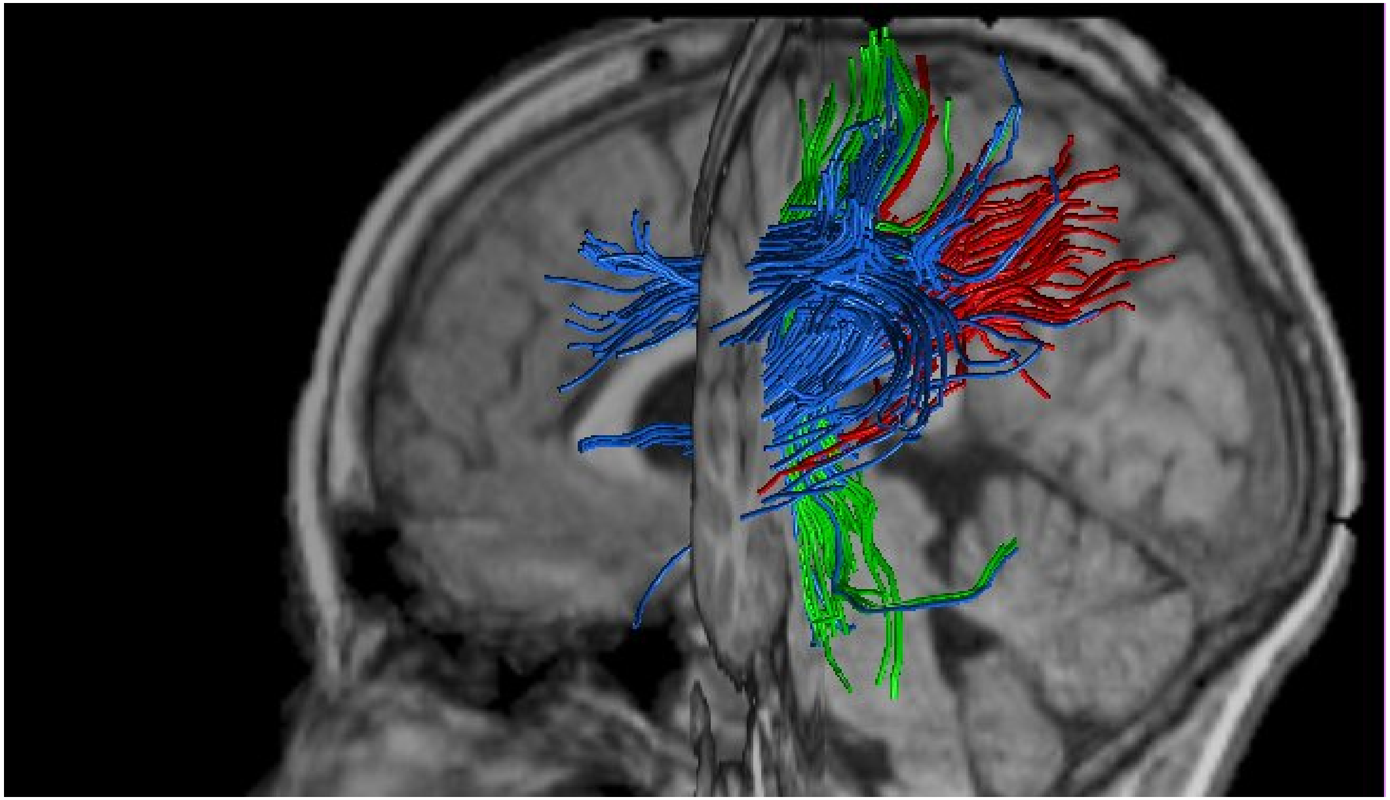

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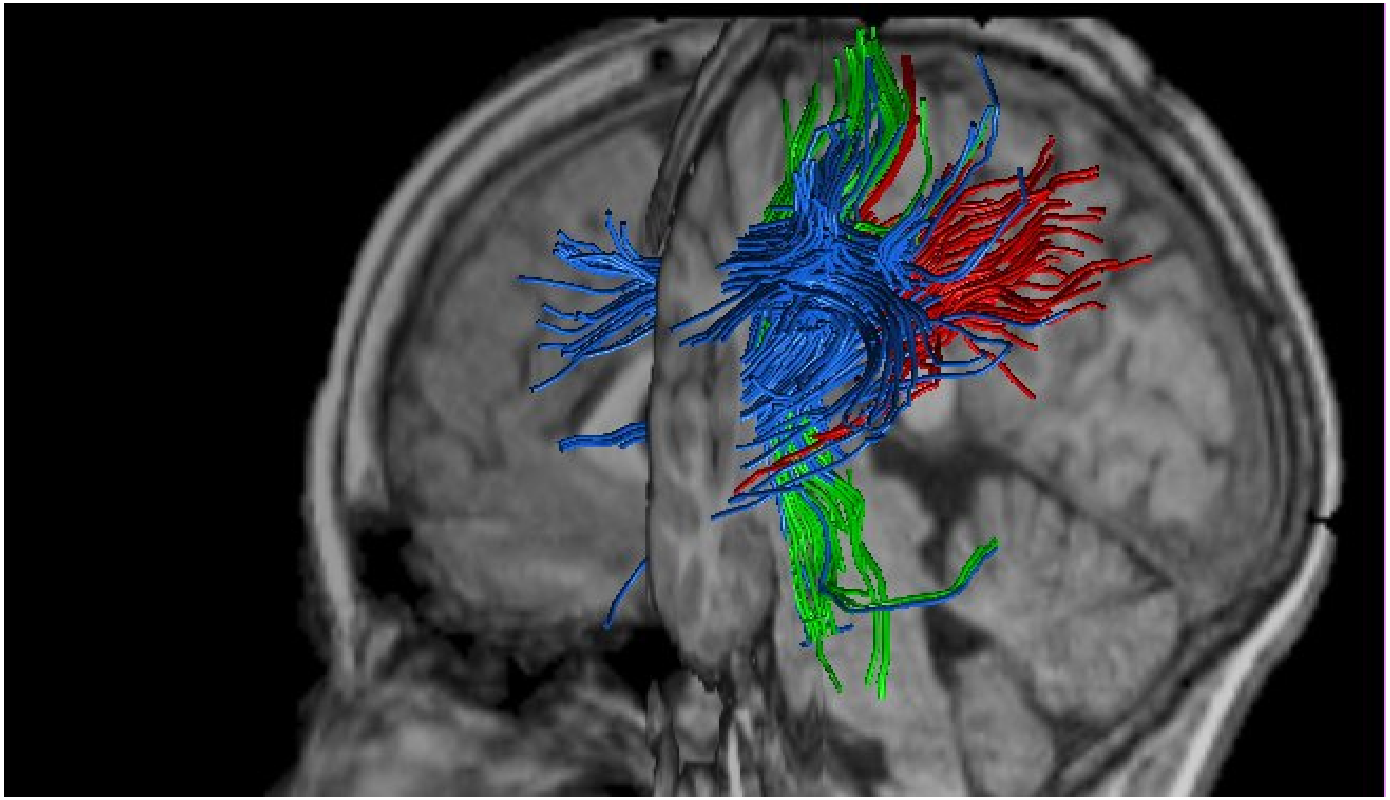

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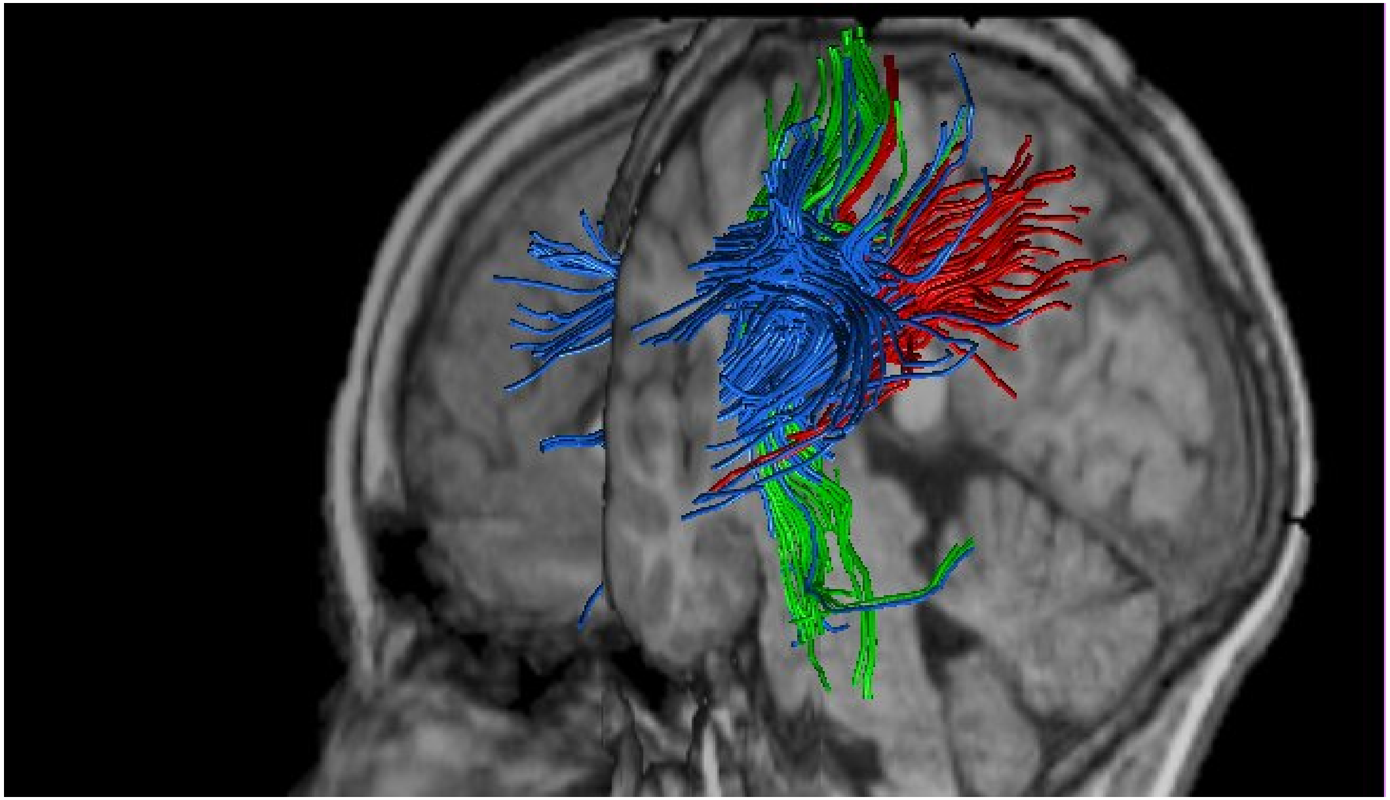

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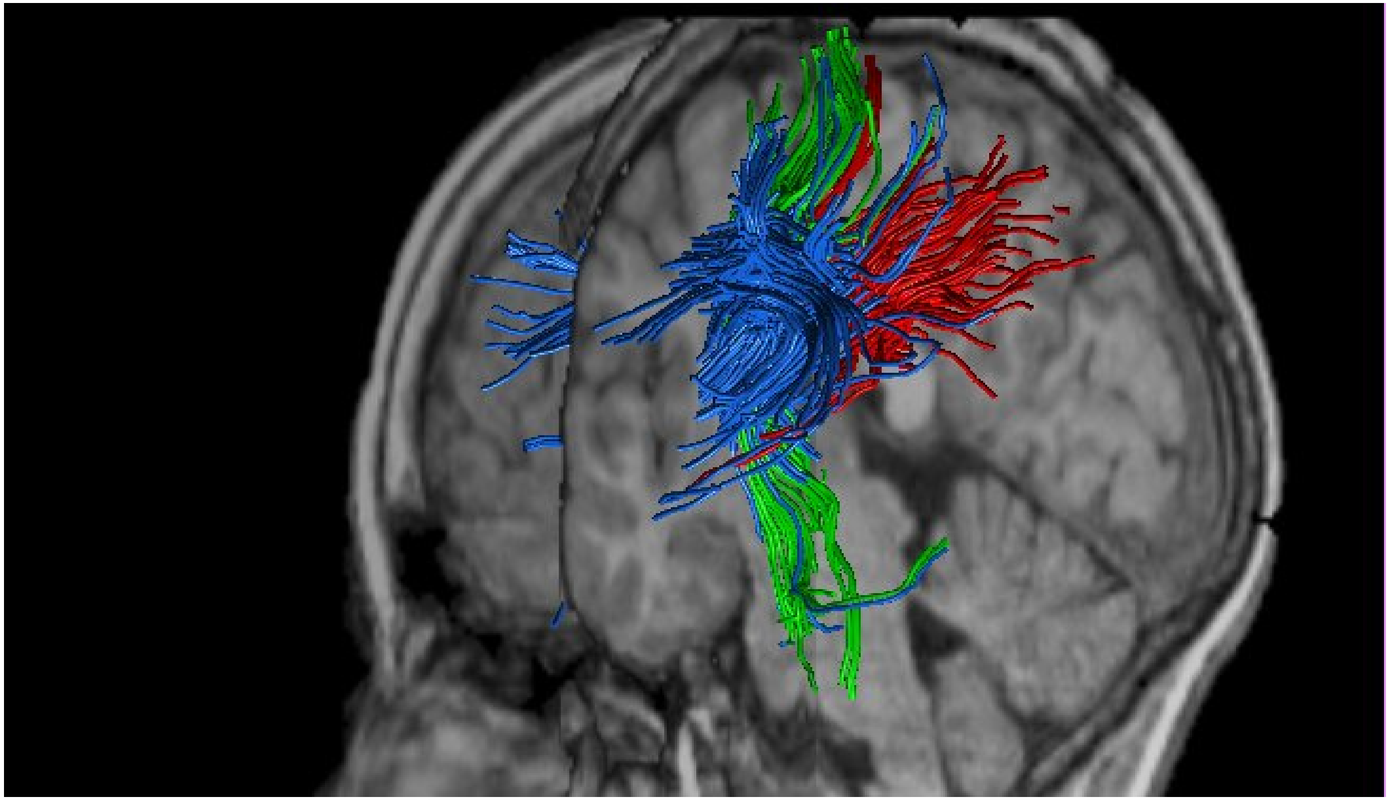

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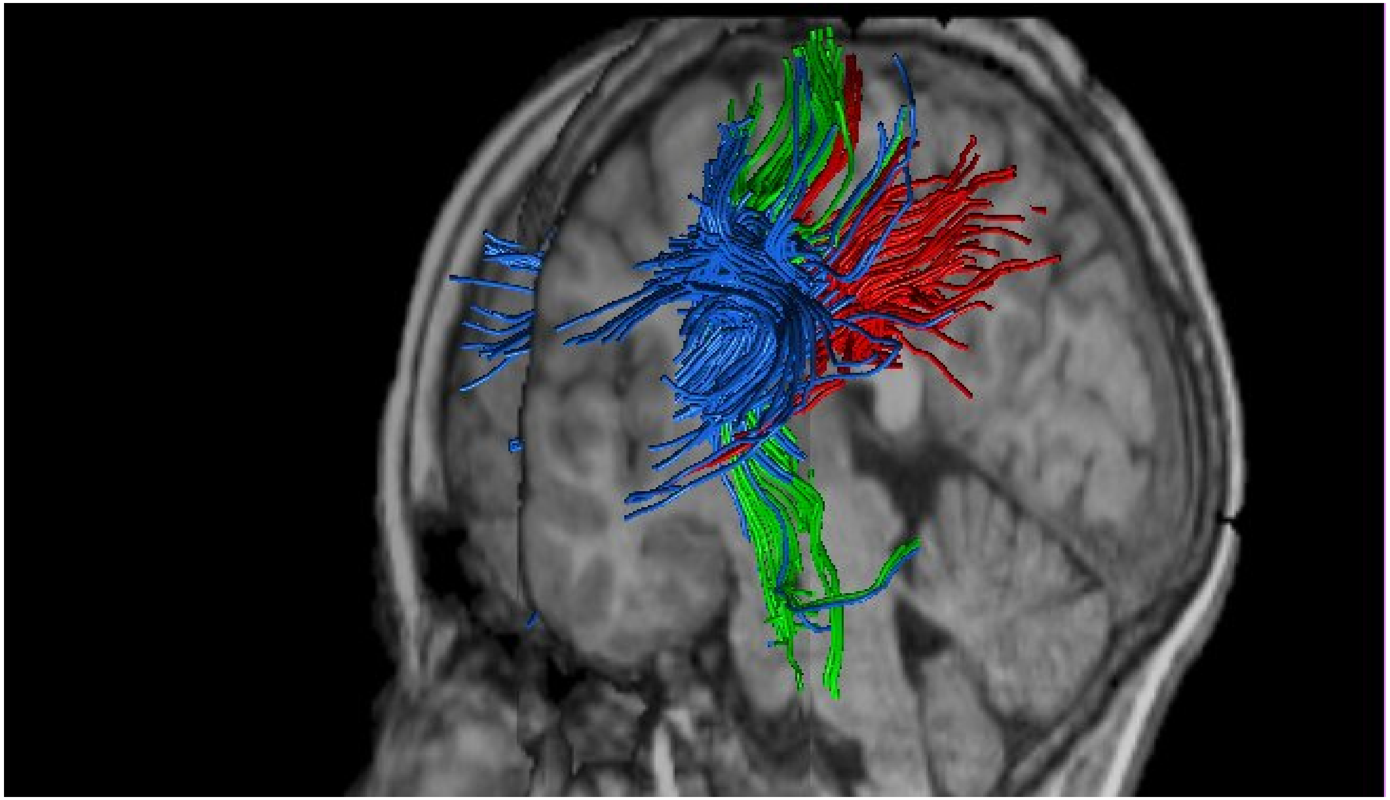

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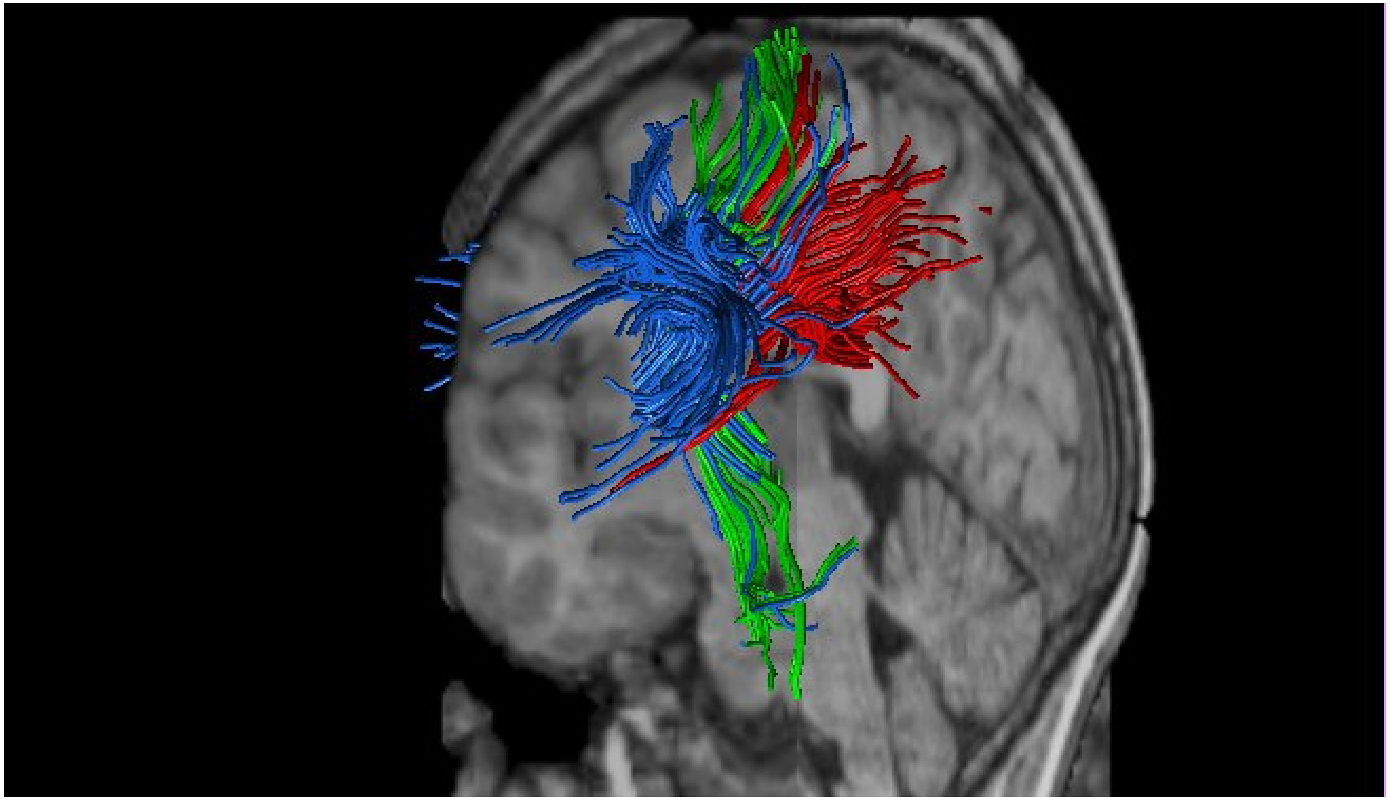

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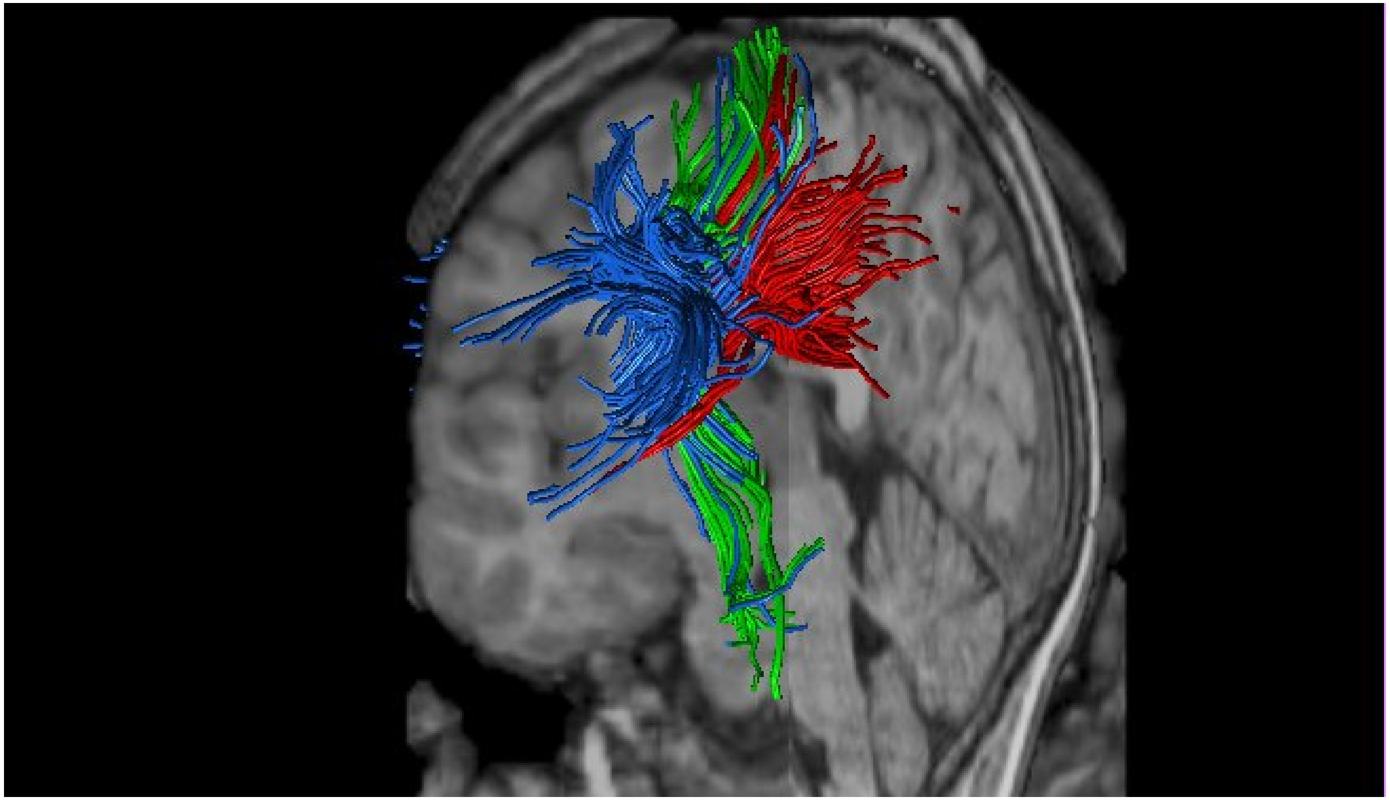

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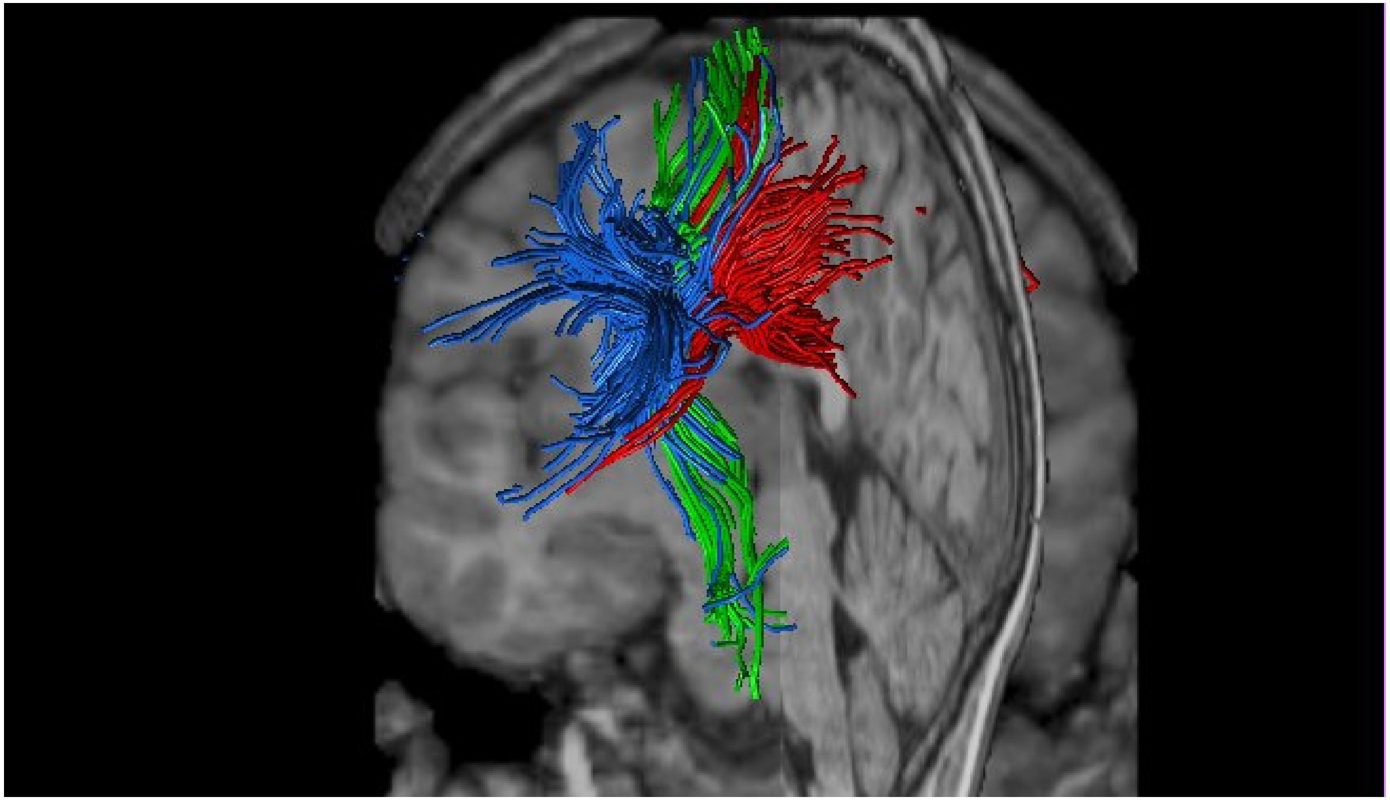

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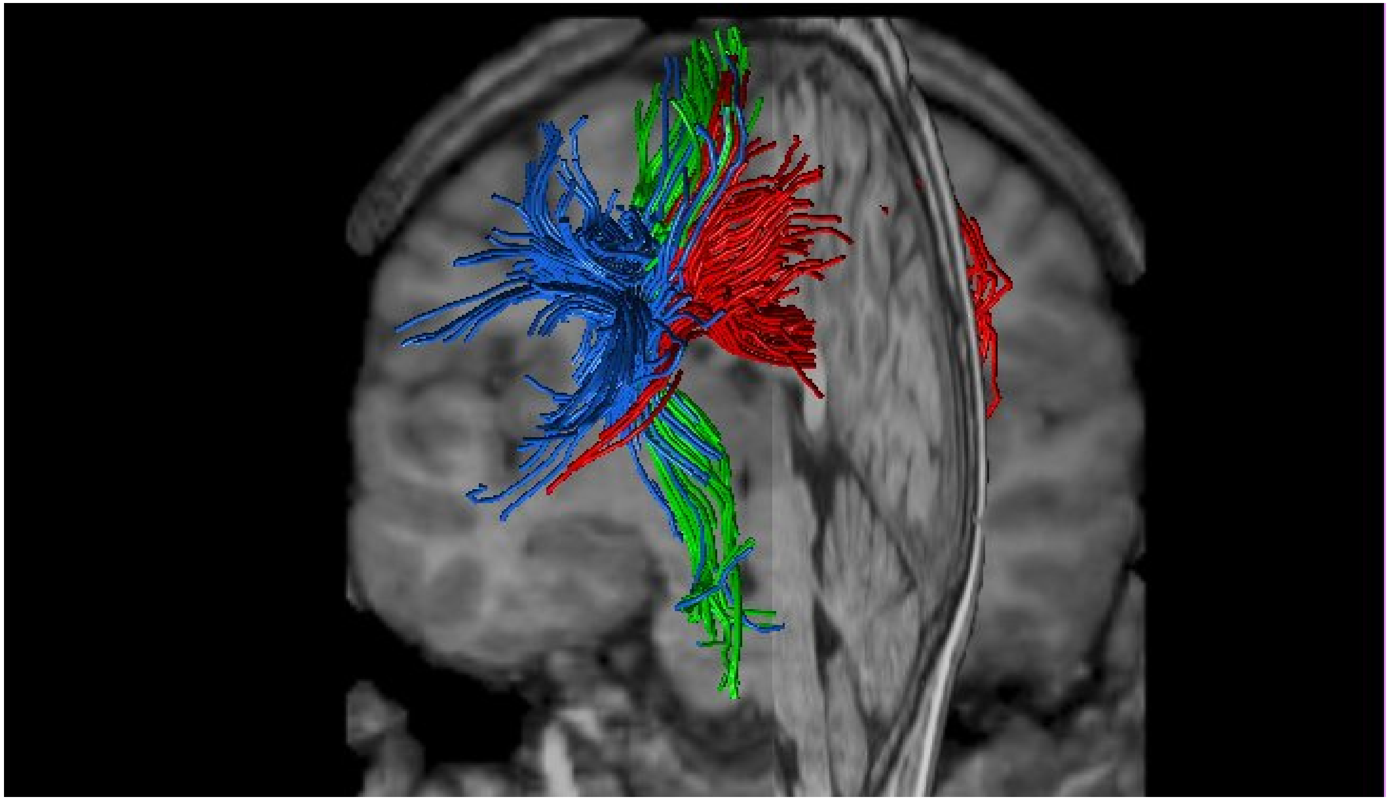

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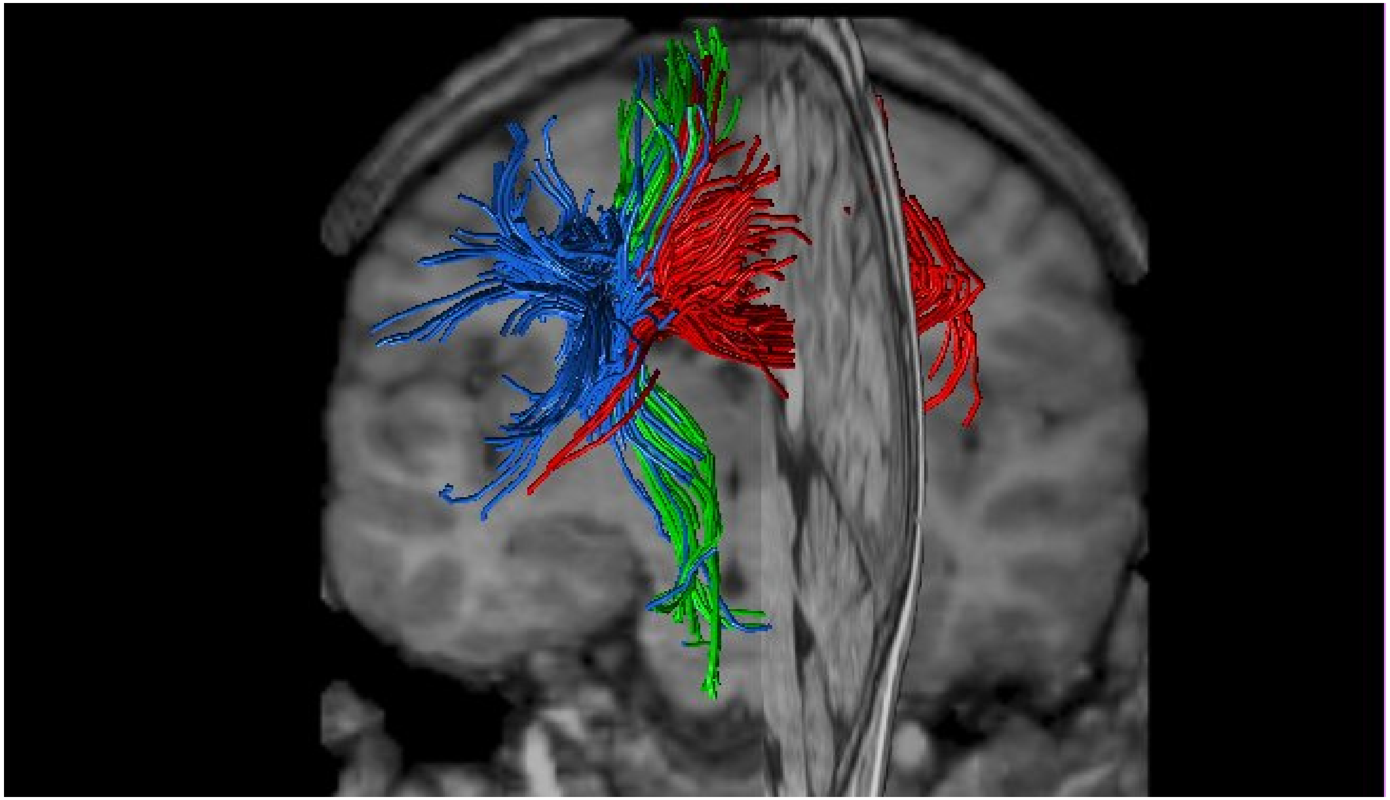

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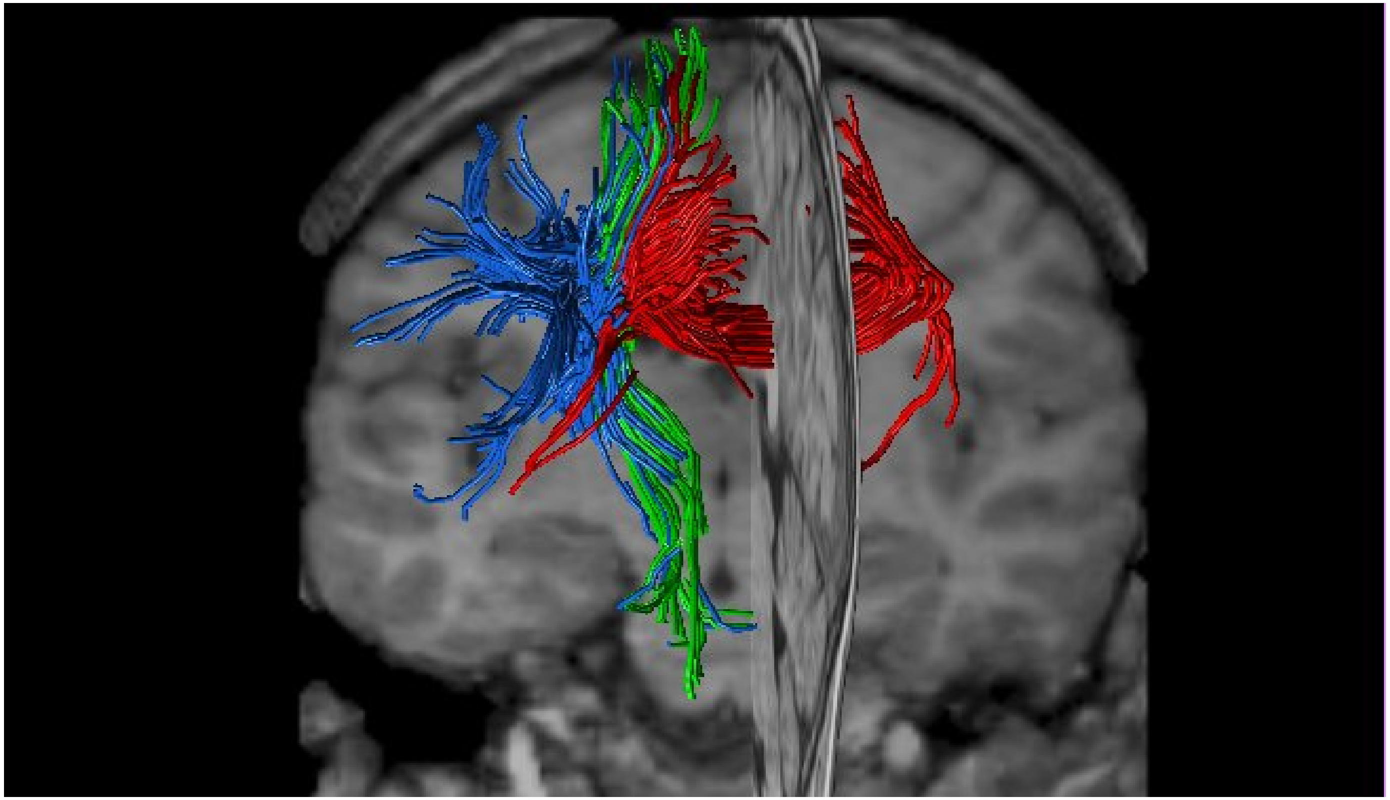

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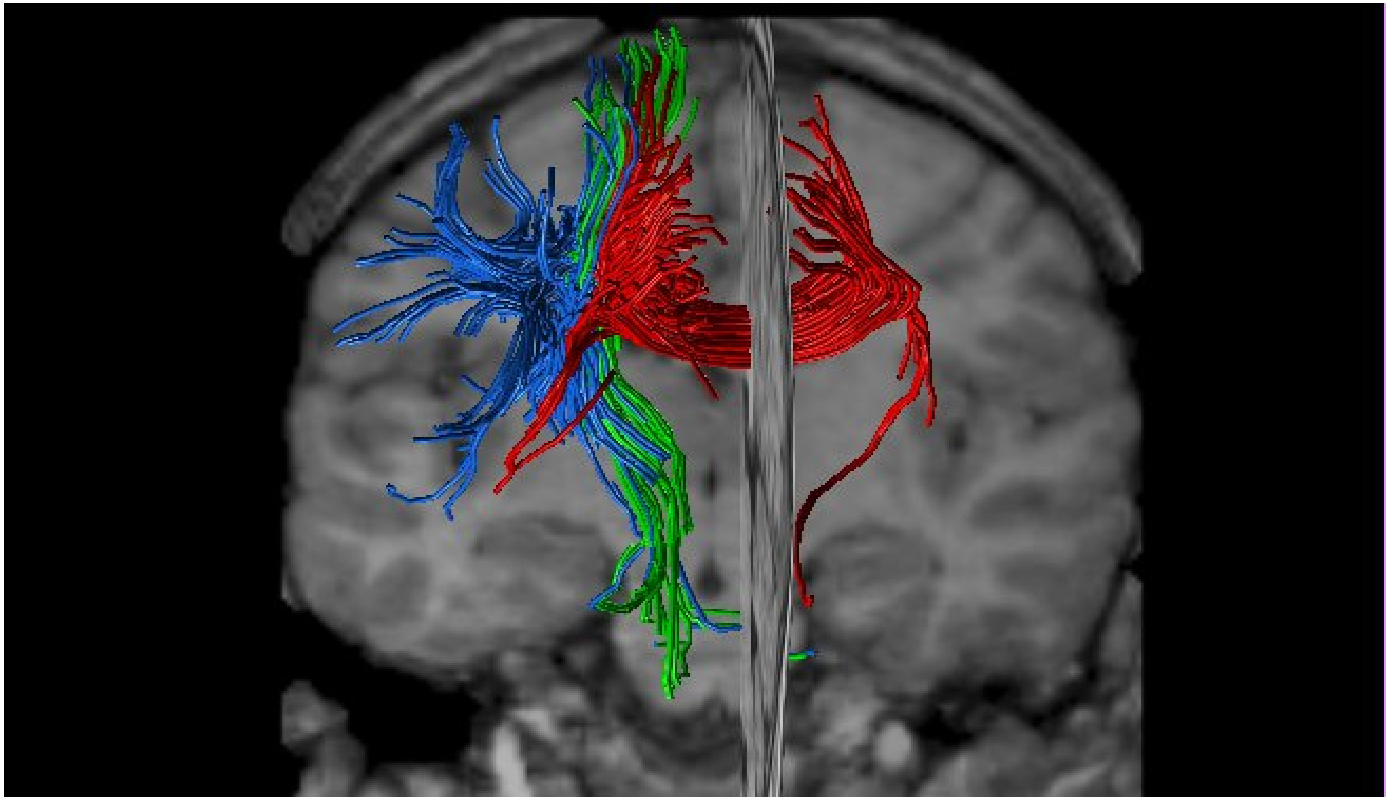

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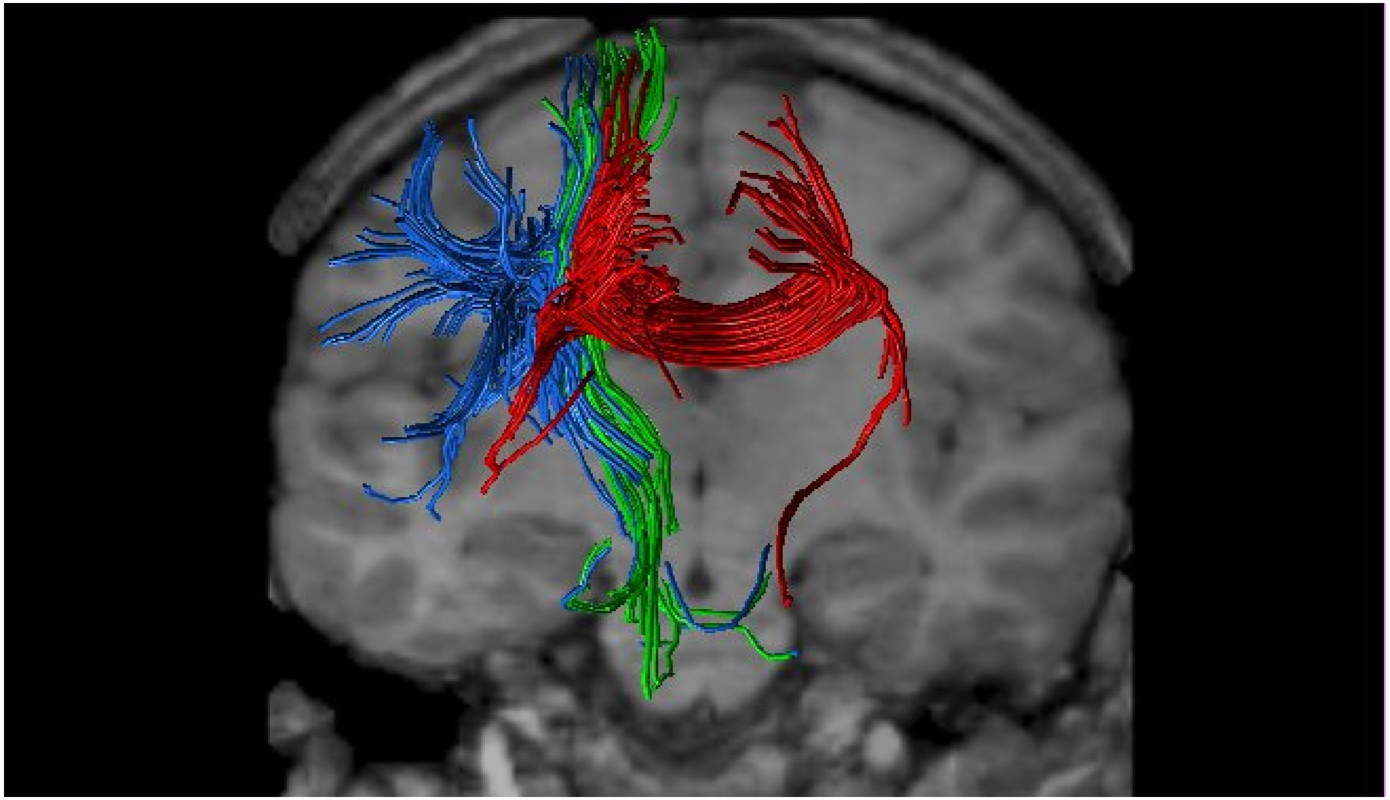
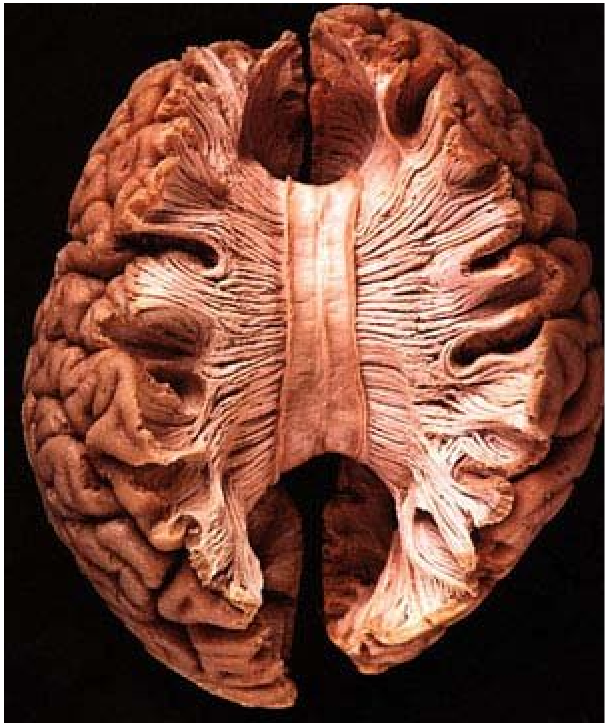
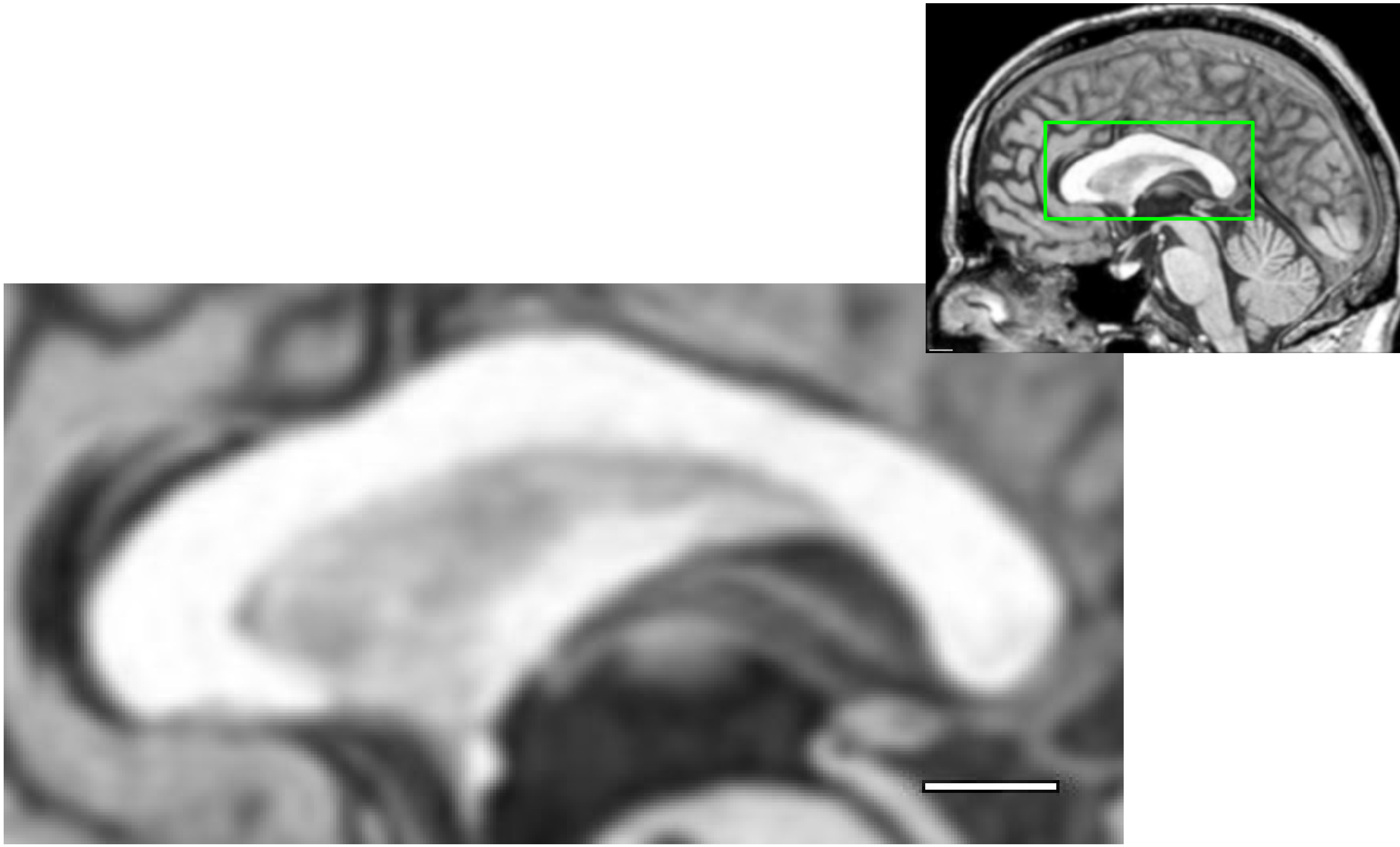


Why The Callosum?

- CC in alexia
  - Mid-splenial lesions can cause alexia
- CC in developmental dyslexia
  - Morphological differences in shape and size
  - Reduced hemispheric asymmetry in anatomy and function



Defining Callosal ROIs



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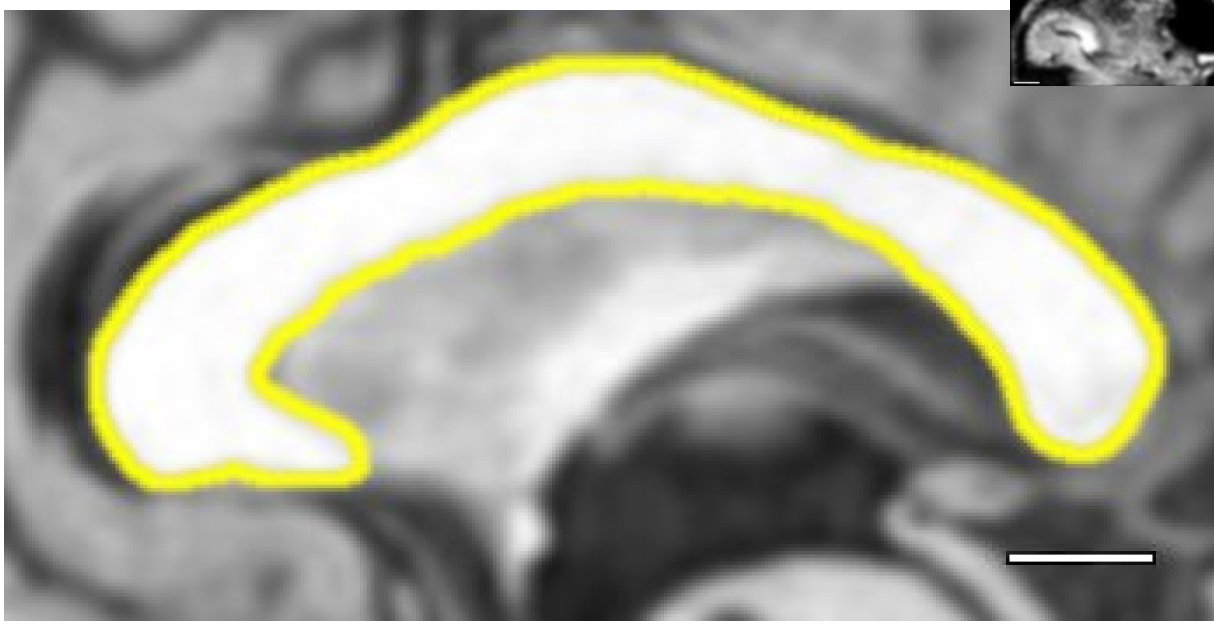

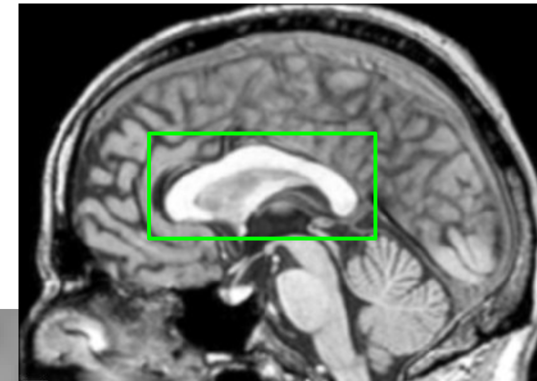

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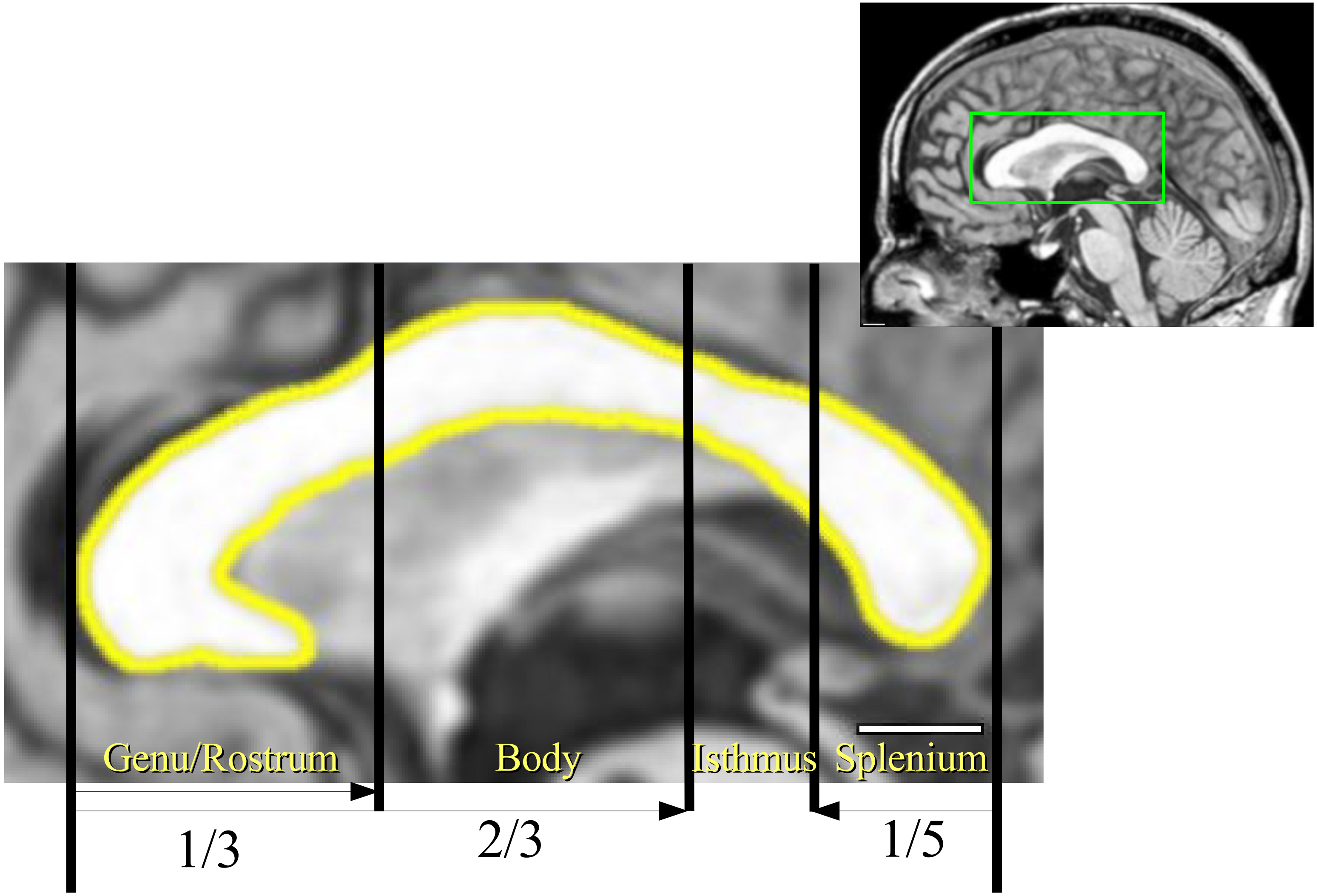
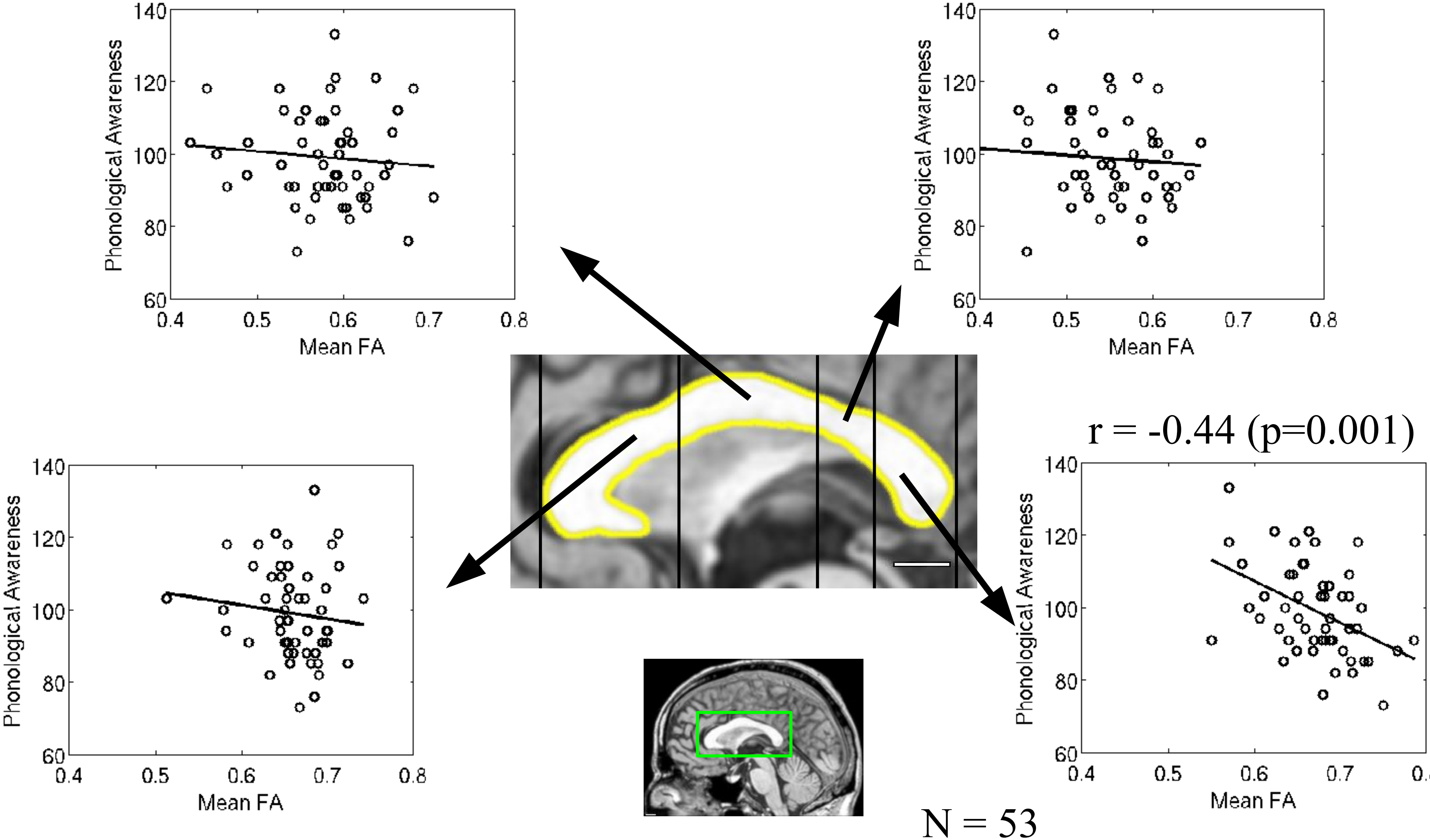


FA Negatively Correlated with Phonological Awareness in Splenium



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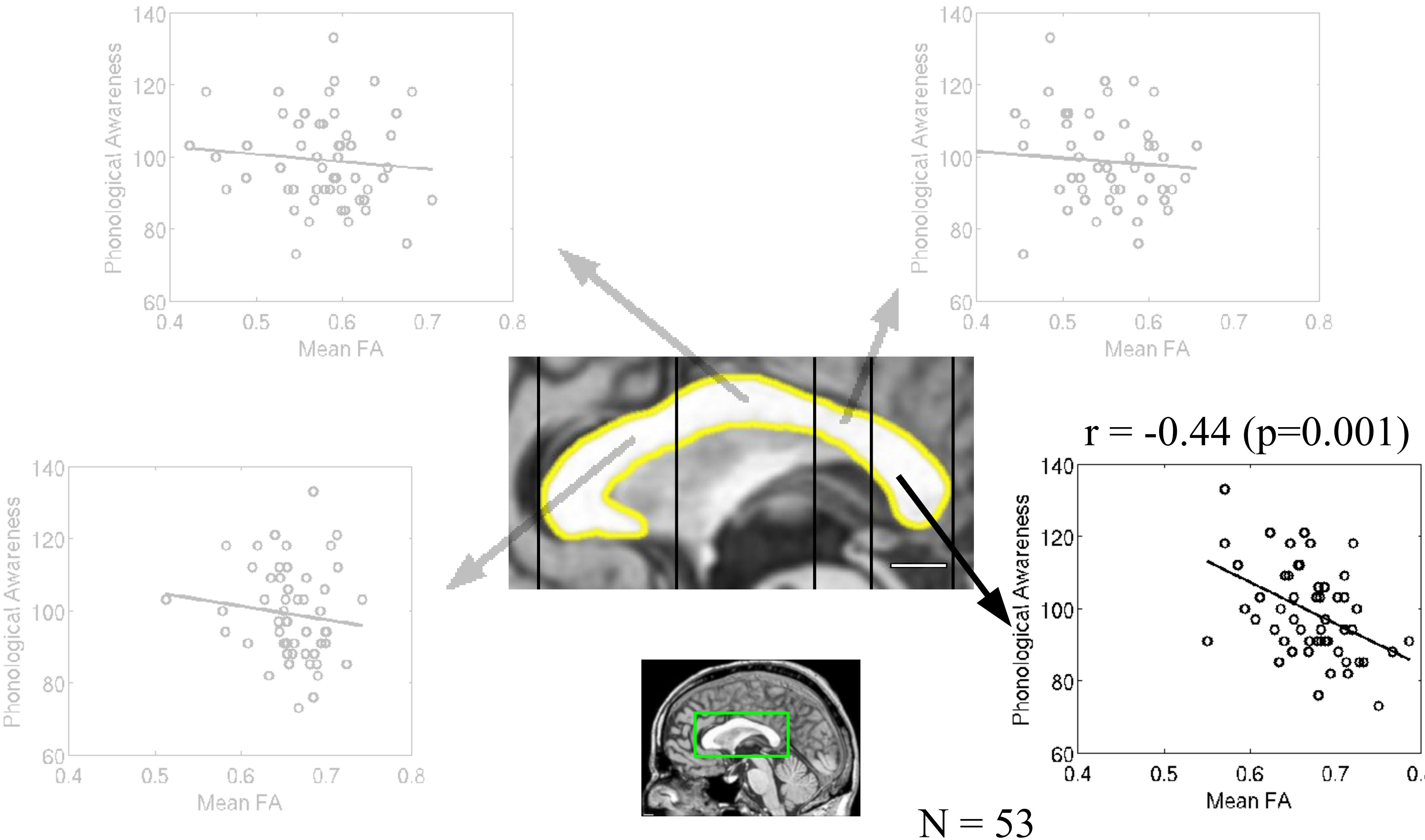
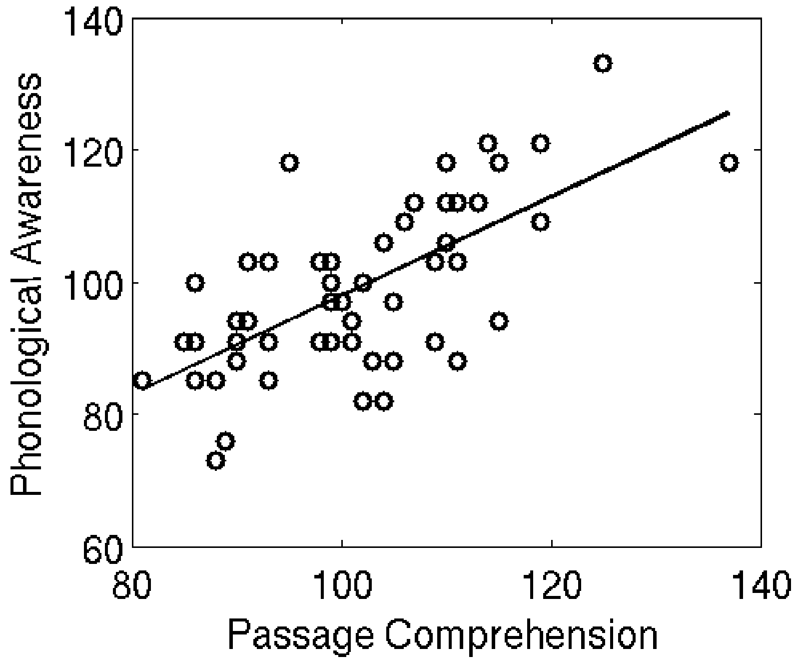
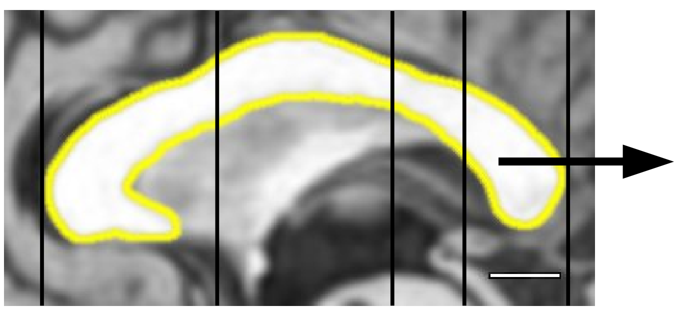


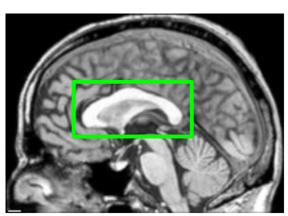
Phonological Awareness is Correlated with Reading

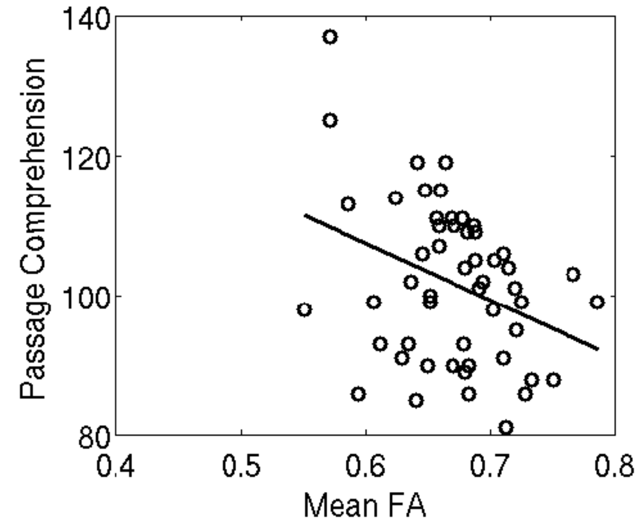
r = 0.67 (p<0.0000001)

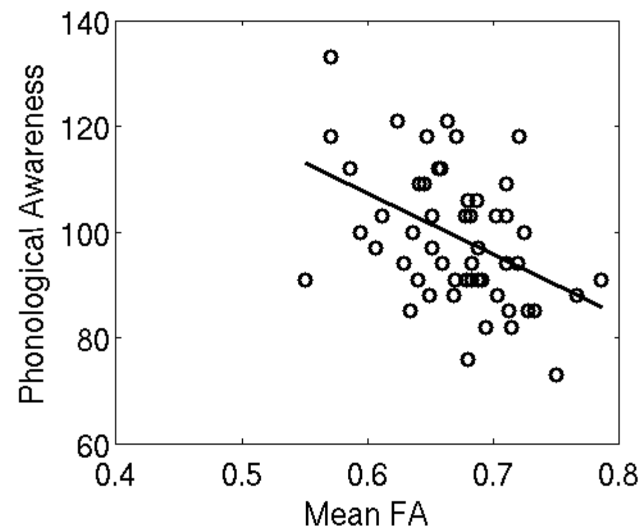


FA and Reading in the Splenium



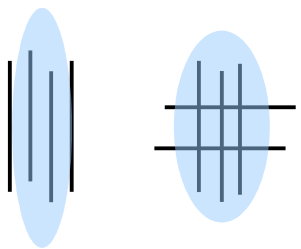






Grand Unification Hypothesis

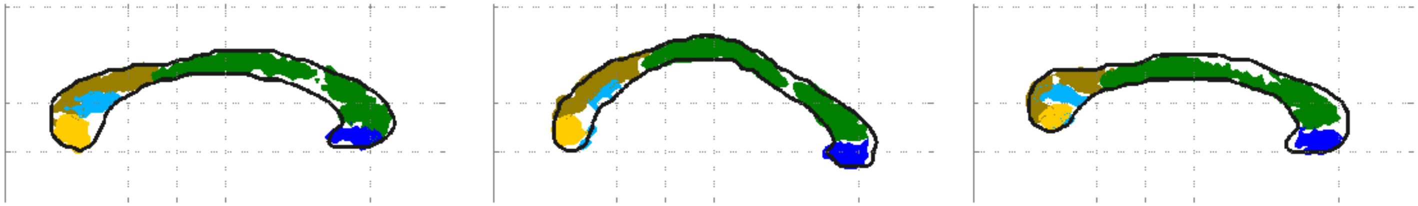
- More left-right connections in low readers
  - larger CC
  - higher FA in CC pathways
- Increased CC connections cause decreased FA in other pathways
  - More crossing fibers, esp. in corona radiata



- Increased hemispheric connectivity causes more anatomical and functional symmetry
- But- is increased hemispheric connectivity a cause or an effect?

Conlcusions

- Splenium FA is *lower* in skilled readers
  - Consistent with previous studies of dyslexia
    - Less lateralized language
    - Enlarged posterior callosum
    - Greater callosal bending angle (?)
- Posterior callosum crucial for skilled reading
  - Lesions there result in alexia
  - But which lobe? Occipital? Parietal? Temporal?
    - Segment callosum by projection zone



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