Head motion in diffusion MRI

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Diffusion contrast

- Basic principle of diffusion MRI: Microscopic motion of water molecules causes attenuation of MR image intensity

- {DW image intensity} = {Baseline image intensity} × {Attenuation factor}

- All diffusion MRI models are based on this, *e.g.*:
  - Tensor:

$$\mu_{ij} = s_{0j} \exp\left(-b_i \mathbf{g}_i^T D_j \mathbf{g}_i\right)$$

Baseline intensity

Attenuation factor

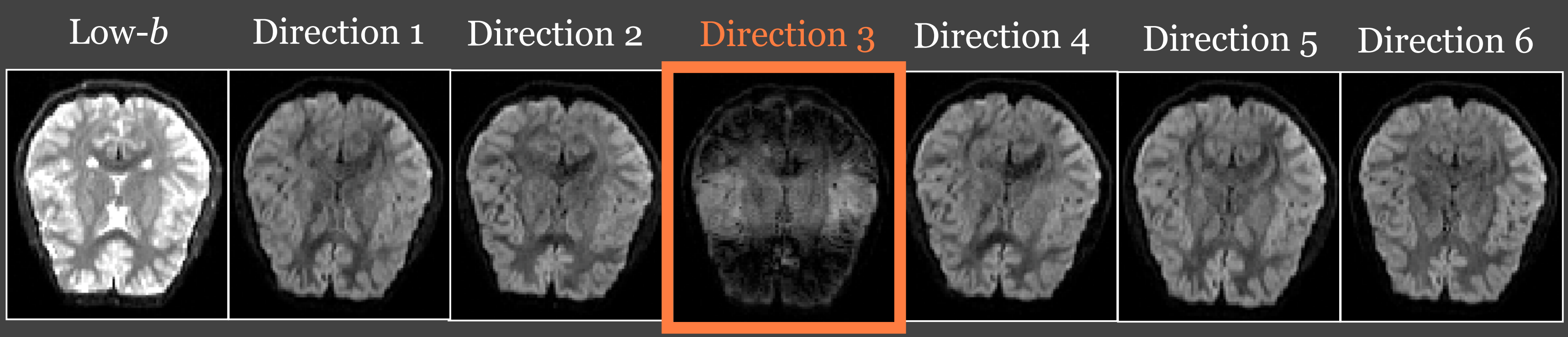
  - Ball-and-stick:

$$\mu_{ij} = s_{0j} \left\{ \left(1 - \sum_{l=1}^{n_F} f_j^l\right) \exp(-b_i d_j) + \sum_{l=1}^{n_F} f_j^l \exp\left(-b_i d_j \mathbf{g}_i^T \mathbf{R}(\theta_j^l, \phi_j^l) \mathbf{A} \mathbf{R}^T(\theta_j^l, \phi_j^l) \mathbf{g}_i\right) \right\}$$

- But macroscopic head motion also acts this way!

Head motion in diffusion MRI

- Head motion during a dMRI scan can lead to:
  - Misalignment between consecutive DWI volumes in the series
  - Attenuation in the intensities of a single DWI volume/slice, if the motion occurred during the diffusion-encoding gradient pulse
  - The former can be corrected with rigid registration, *the latter can't*

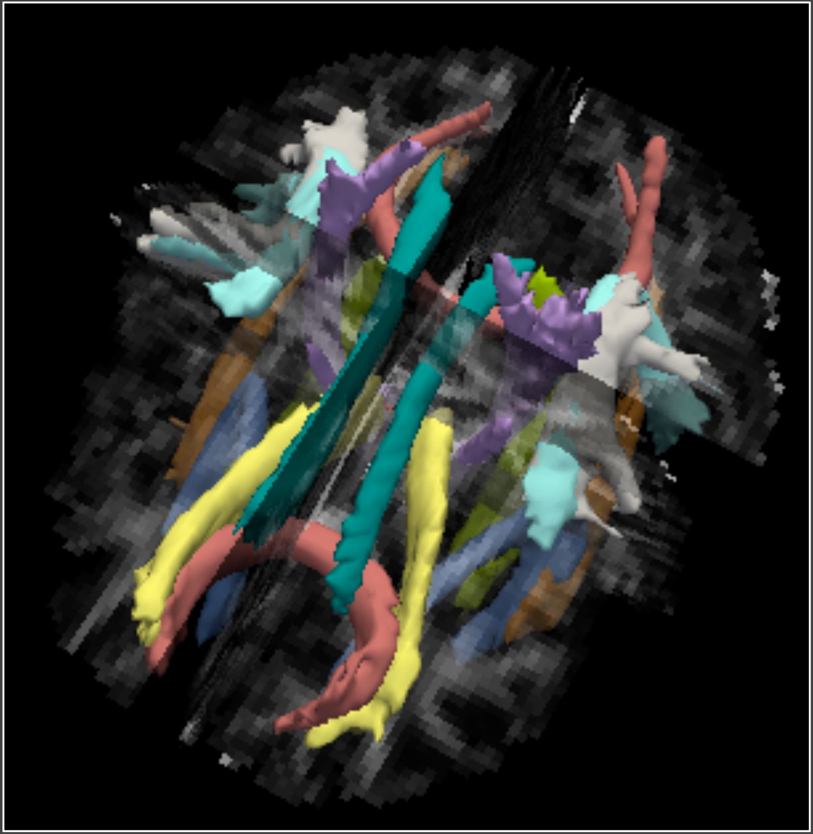


- Conventional EPI sequences for dMRI ignore the problem
  - If motion in several directions ⇒ underestimation of anisotropy
  - False positives in group studies where one group moves more
  - Effects more severe when higher *b*-values, more directions acquired

Motion in a dMRI group study

Yendiki *et al.*, 2013

- 50 children with autism spectrum disorder (ASD) and 62 typically developing children (TD), ages 5-12
- 165 total scans (some retest)
- DWI: 3T, 2mm isotropic, 30 directions, b=700 s/mm^2
- Outlier data sets excluded
- Pathways reconstructed with TRACULA

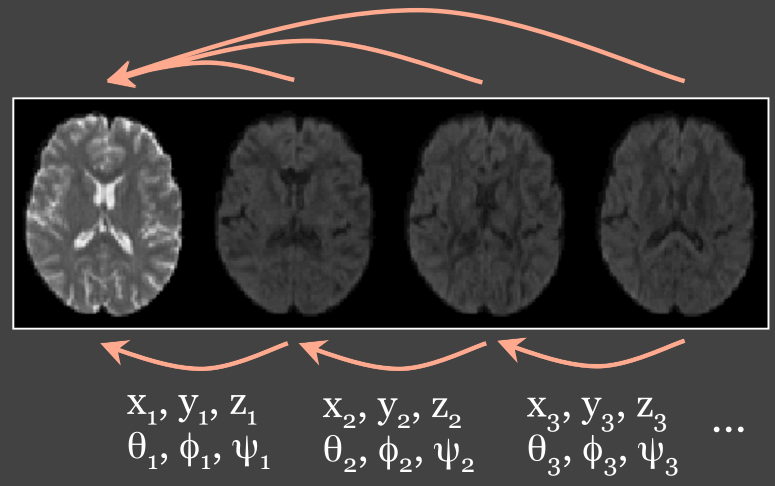


Data courtesy of Dr. Nancy Kanwisher and Ellison autism study

Between-volume motion measures

Yendiki *et al.*, 2013

- From eddy-current correction: affine registration of each volume to the first baseline volume
- Find rotation and translation
- Transform to relative rotation and translation from each volume to the previous volume



- Measure 1: Average volume-by-volume translation
  - $\Sigma_k \operatorname{sqrt}(x_k^2 + y_k^2 + z_k^2) / N_{vol}$
- Measure 2: Average volume-by-volume rotation
  - $\Sigma_k (|\theta_k| + |\phi_k| + |\psi_k|) / N_{vol}$

Within-volume motion measures

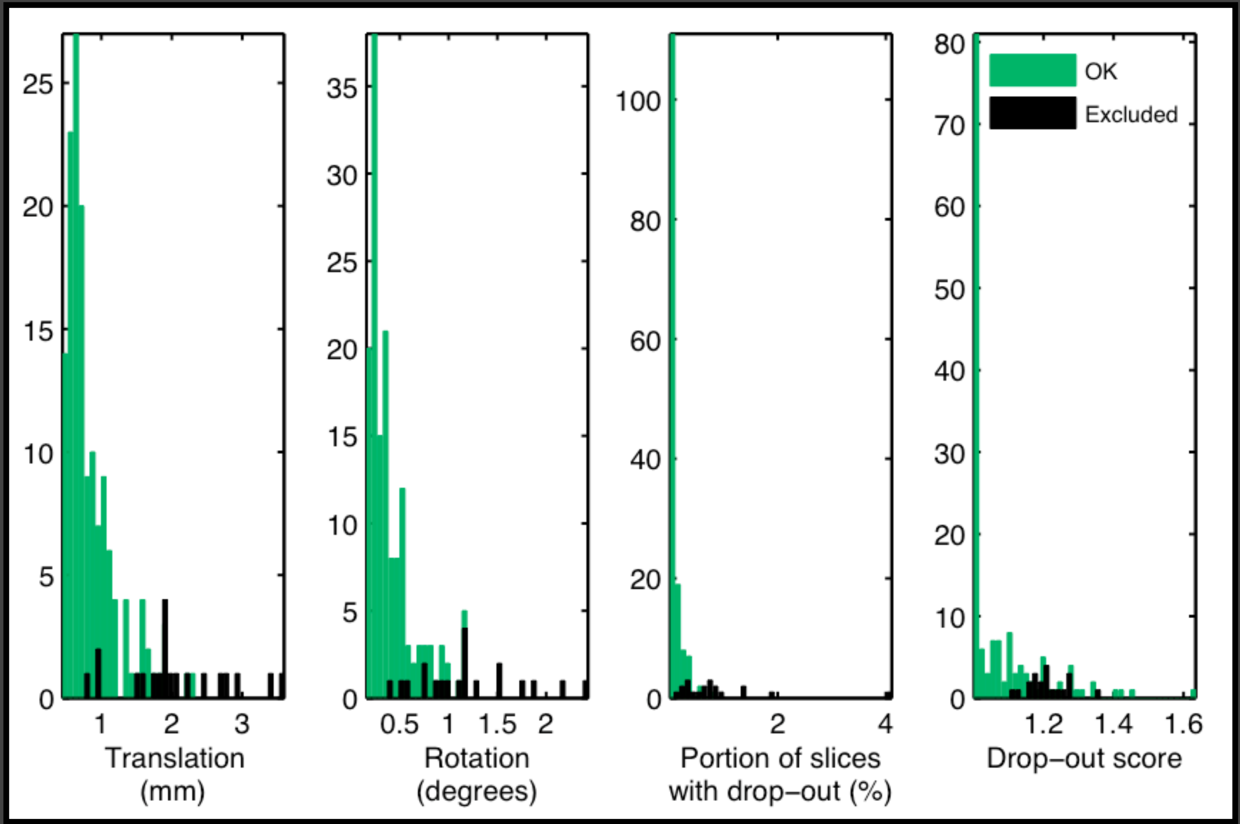
Yendiki *et al.*, 2013

- Score of DWI intensity drop-out [Benner *et al.*, MRM 2011]:
  - For each volume, define an intensity threshold: $I_{min} = T \cdot \exp(-b \cdot D)$
    T the intensity threshold for brain voxels at b=0 (default: T = 100)
    b the b-value of the current volume
    D a nominal value of diffusivity in the brain (default: D = 0.001)
  - Motion score: $S = 2 - r / (0.7 \cdot r_1)$
    r the number of voxels with intensities $I > I_{min}$ in this volume
    r_1 the number of voxels with intensities $I > I_{min}$ in the first volume with the same b-value
  - $S > 1 \;\therefore$ Excessive drop-out
- Measure 3: Percentage of slices with signal drop-out
  - Number of slices with $S > 1$ over the total slices in the data set
- Measure 4: Signal drop-out severity
  - Average score S for slices with $S > 1$

Motion measures histograms

Yendiki *et al.*, 2013

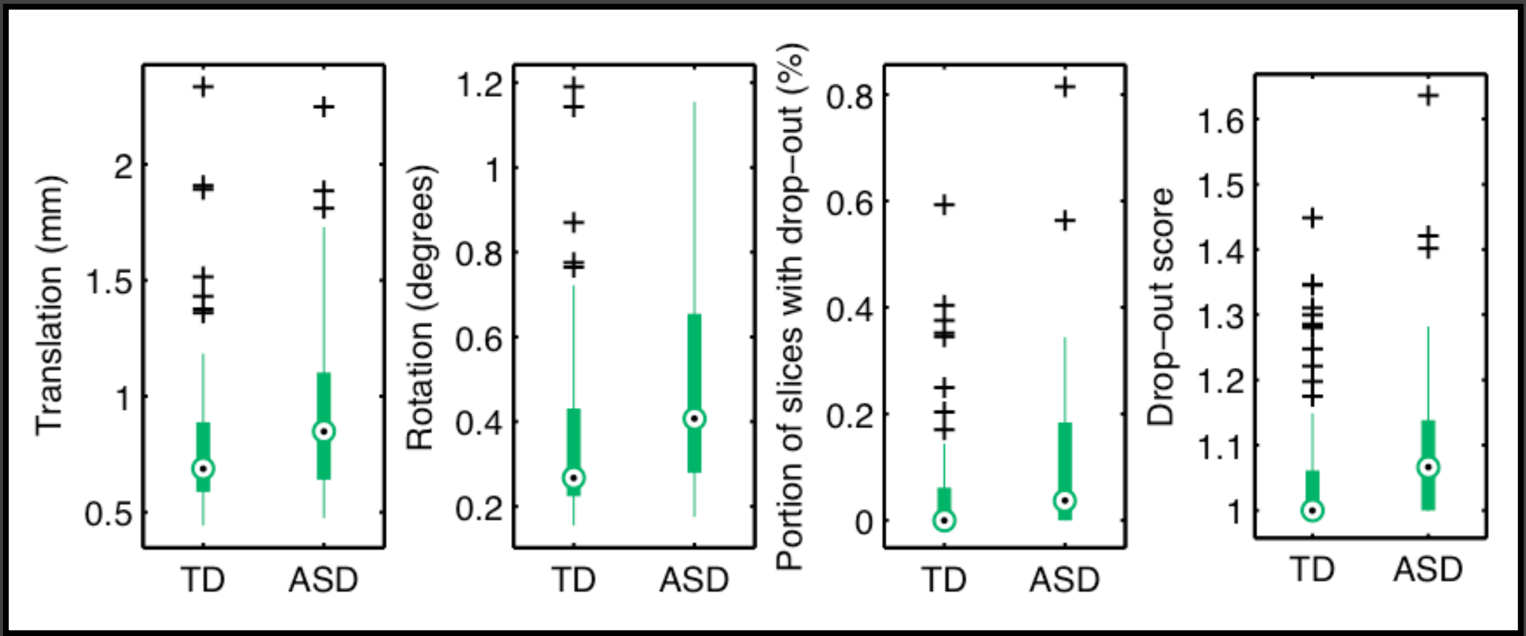
- Qualitative visual inspection to find scans with excessive motion
- Of the 165 scans, 17 were removed after inspection



Motion measures by group

Yendiki *et al.*, 2013

- Significant differences in median measures between groups

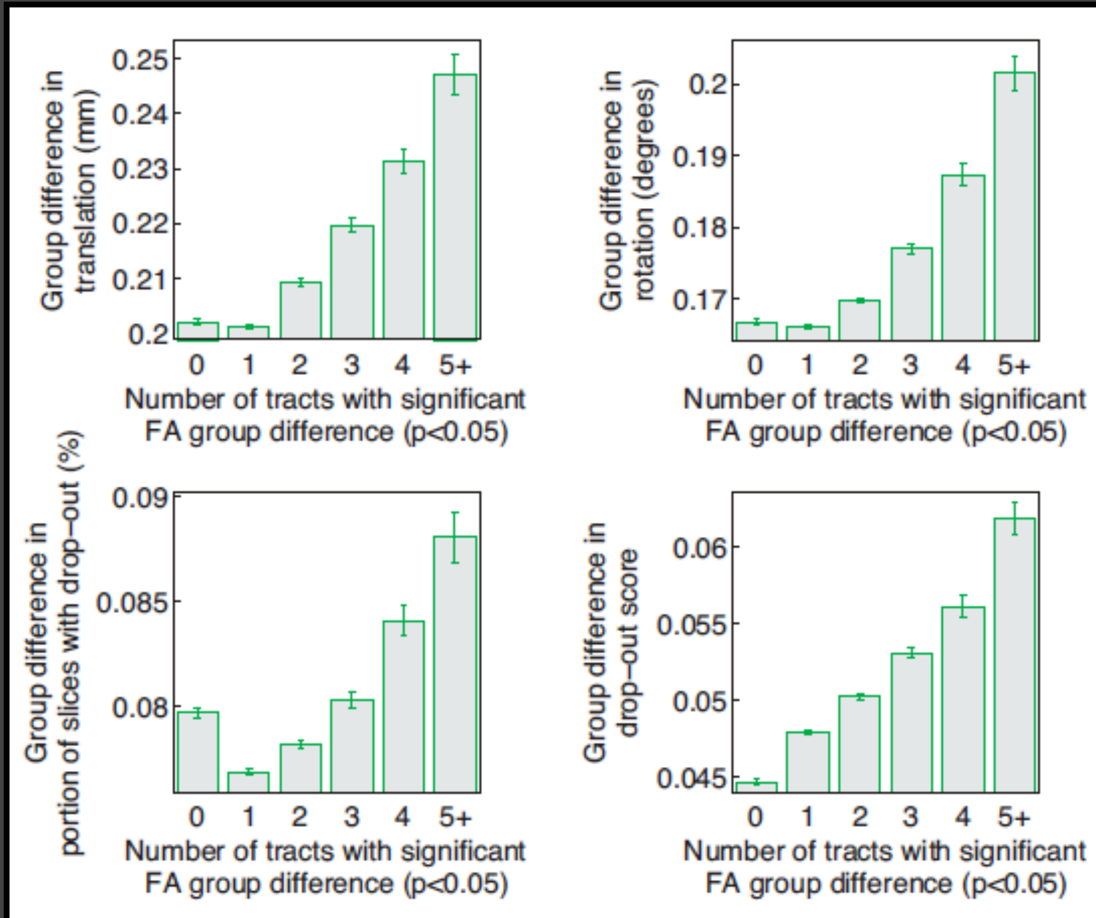


- For ASD children, rotational motion is correlated with ADOS score (ρ=0.31, p=0.04)

ASD vs. TD

Yendiki *et al.*, 2013

- 50,000 random combinations of scans from 30 ASD and 30 TD children, age-matched
- Compute difference in motion measures between ASD and TD
- Count the tracts that have significantly different FA between ASD and TD

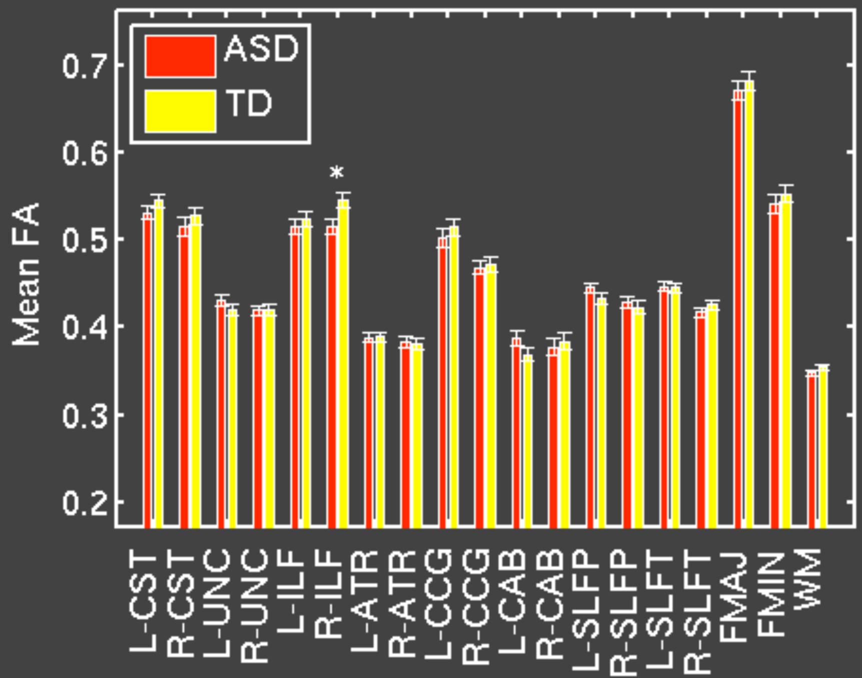


ASD vs. TD

Yendiki *et al.*, 2013

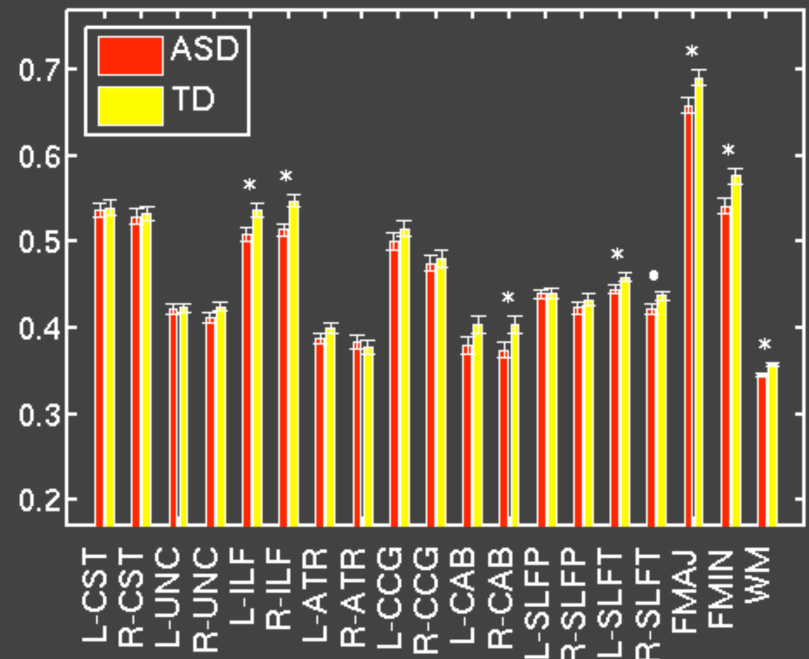
Example trial:

Lower motion difference, one FA finding



Example trial:

Higher motion difference, six FA findings

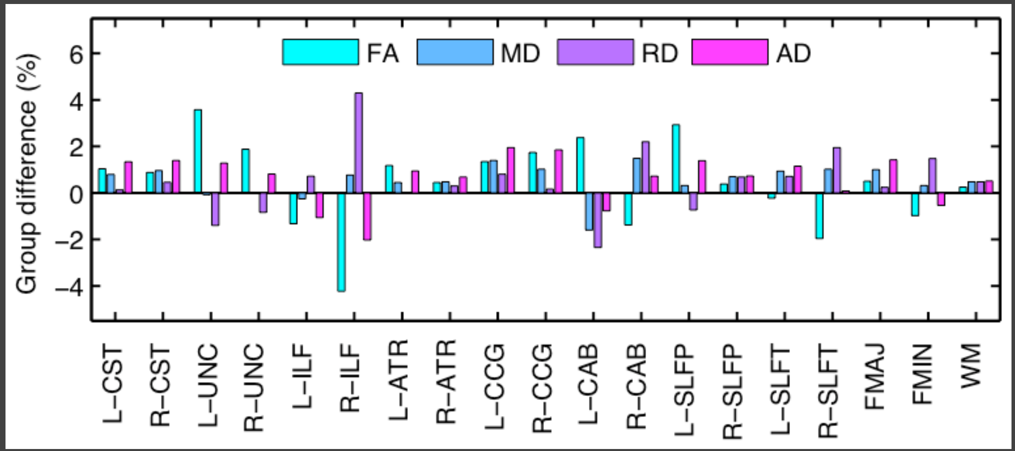


ASD vs. TD

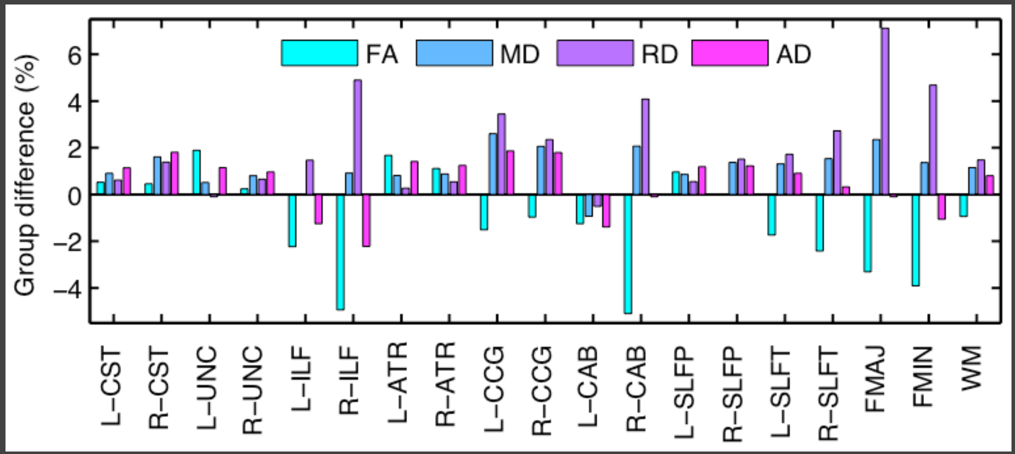
Yendiki *et al.*, 2013

Differences in anisotropy and diffusivity measures between groups

500 groups with lowest differences in head motion:
- Translation 0.04 ±0.03 mm
- Rotation: 0.05 ± 0.01 ◦
- Portion of slices with drop-out: 0.04 ± 0.02 %
- Drop-out score: 0.02 ± 0.02



500 groups with highest differences in head motion:
- Translation: 0.36 ± 0.03 mm
- Rotation: 0.28 ± 0.01 ◦
- Portion of slices with drop-out: 0.11 ± 0.02 %
- Drop-out score: 0.08 ± 0.02



ASD vs. TD

Yendiki *et al.*, 2013

Frequency of significant ($p < 0.05$) group differences

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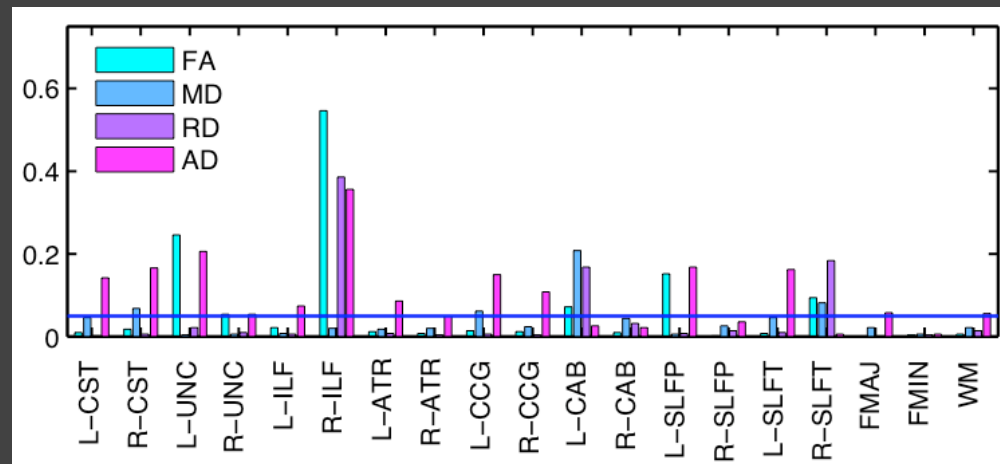

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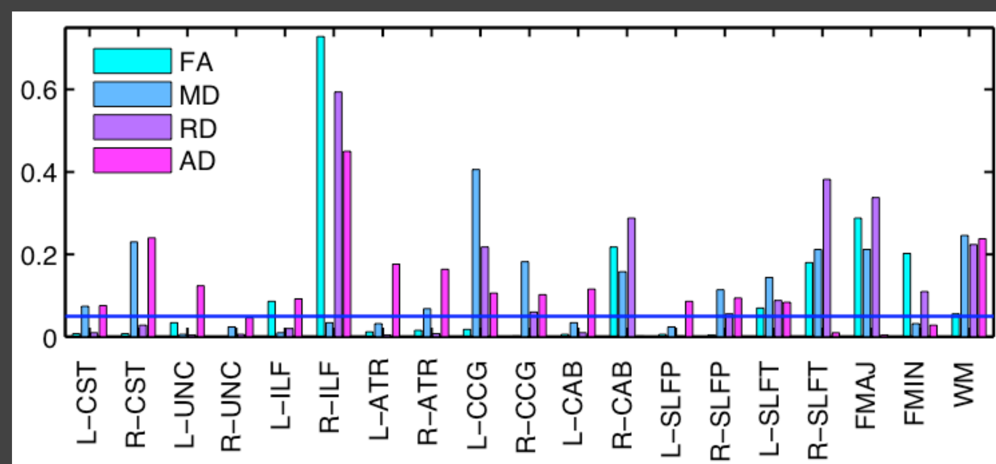

Motion as a nuisance regressor

Yendiki *et al.*, 2013

- Total motion index (TMI) of the *i*-th scan:

$$\mathrm{TMI}_i = \sum_{j=1,\ldots,4} (x_{ij} - M_j) \,/\, (Q_j - q_j)$$

where: x_{ij} each of the 4 motion measures for this scan
M_j its median value over all scans
Q_j its upper quartile over all scans
q_j its lower quartile over all scans

- Compute the TMI of each scan, include it as a regressor in the group analysis

ASD vs. TD

Yendiki *et al.*, 2013

Frequency of significant ($p < 0.05$) group differences, TMI regressed

500 groups with lowest differences in head motion:
- Translation 0.04 ±0.03 mm
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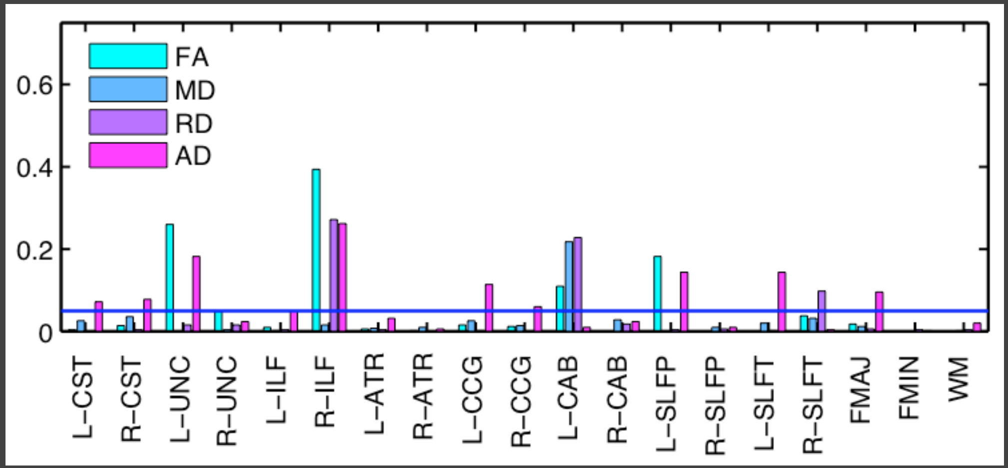

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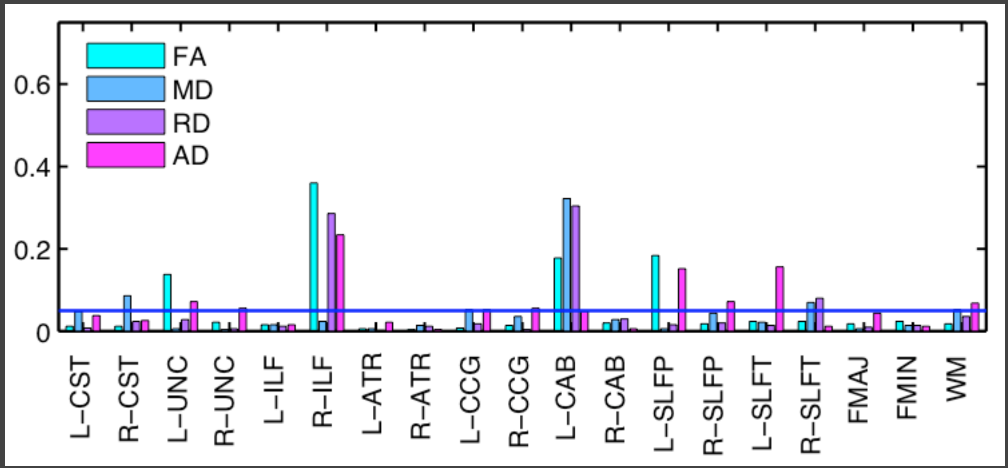
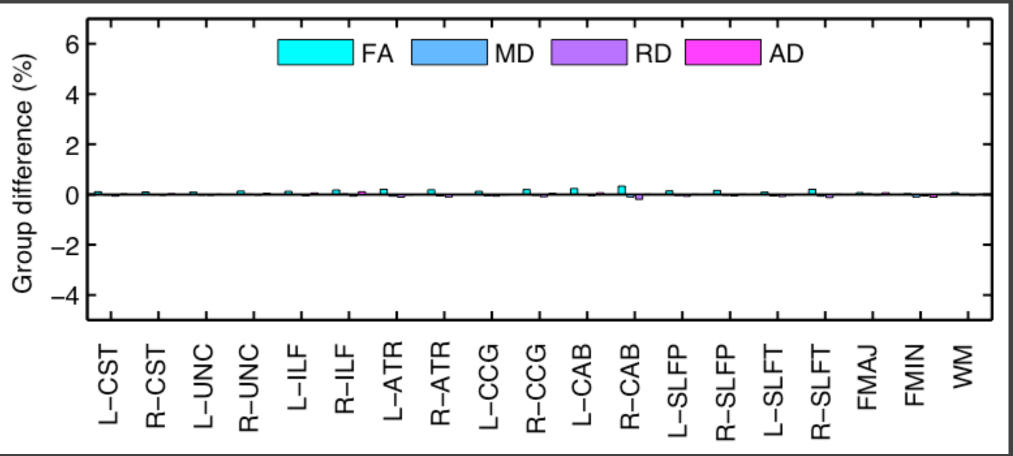


TD vs. TD

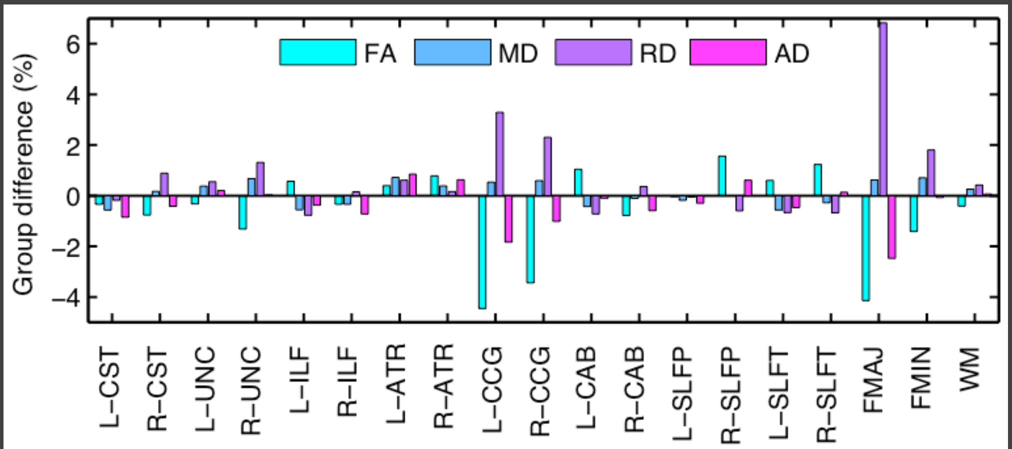
Yendiki *et al.*, 2013

Differences in anisotropy and diffusivity measures between groups

500 groups with lowest differences in head motion:
- Translation 0.04 ± 0.03 mm
- Rotation: 0.0003 ± 0.0002 °
- Portion of slices with drop-out: 0.01 ± 0.01 %
- Drop-out score: 0.02 ± 0.01



500 groups with highest differences in head motion:
- Translation: 0.28 ± 0.05 mm
- Rotation: 0.20 ± 0.01 °
- Portion of slices with drop-out: 0.07 ± 0.01 %
- Drop-out score: 0.07 ± 0.02



TD vs. TD

Yendiki *et al.*, 2013

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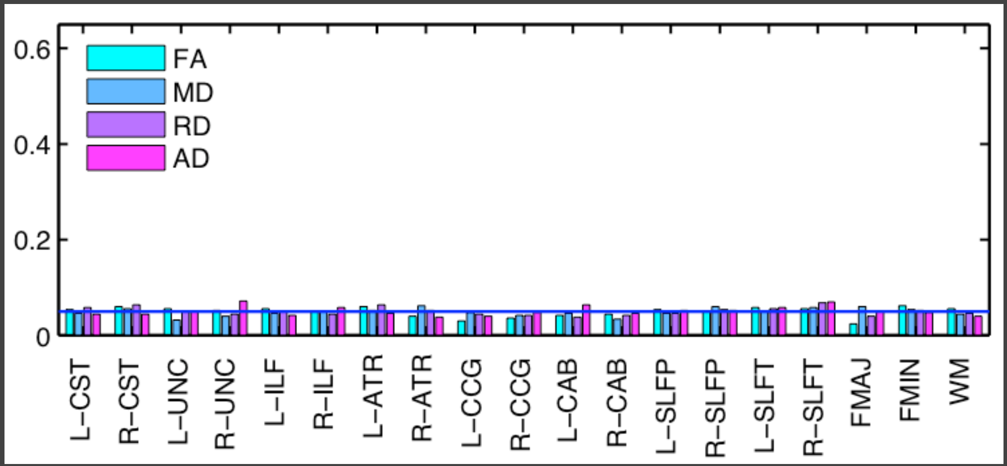

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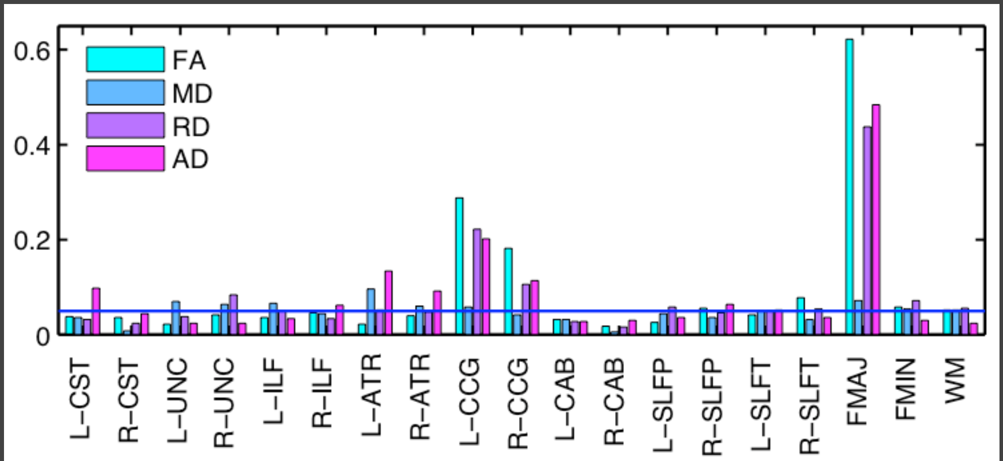

TD vs. TD

Yendiki *et al.*, 2013

Frequency of significant (p < 0.05) group differences, TMI regressed

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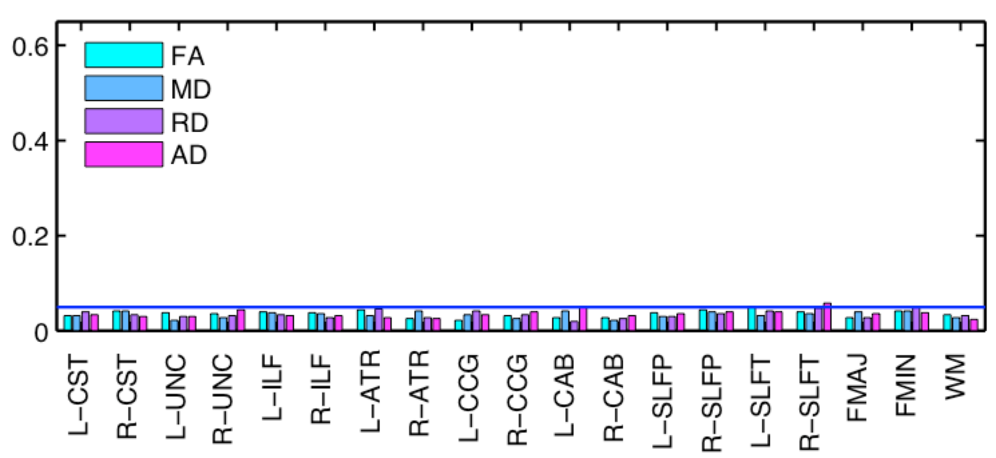

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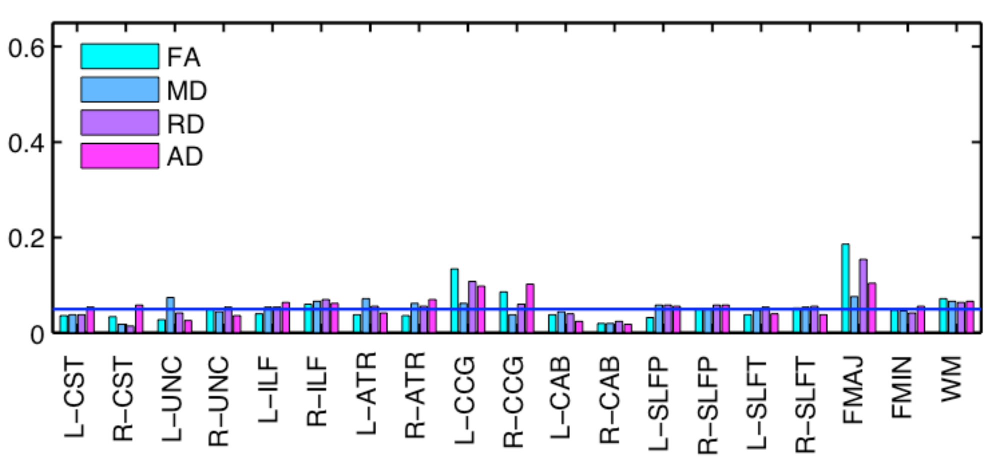
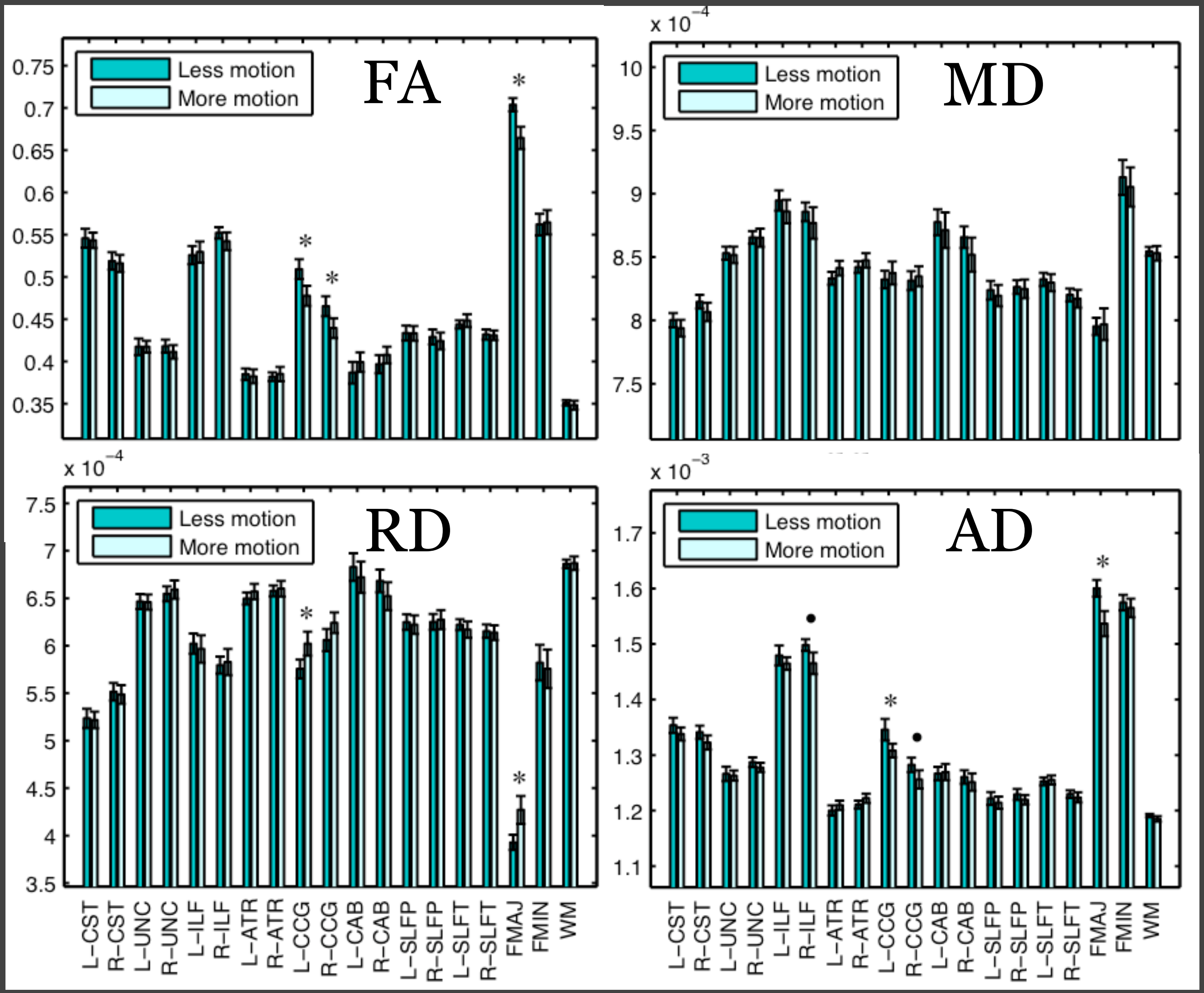


Test vs. retest

Yendiki *et al.*, 2013

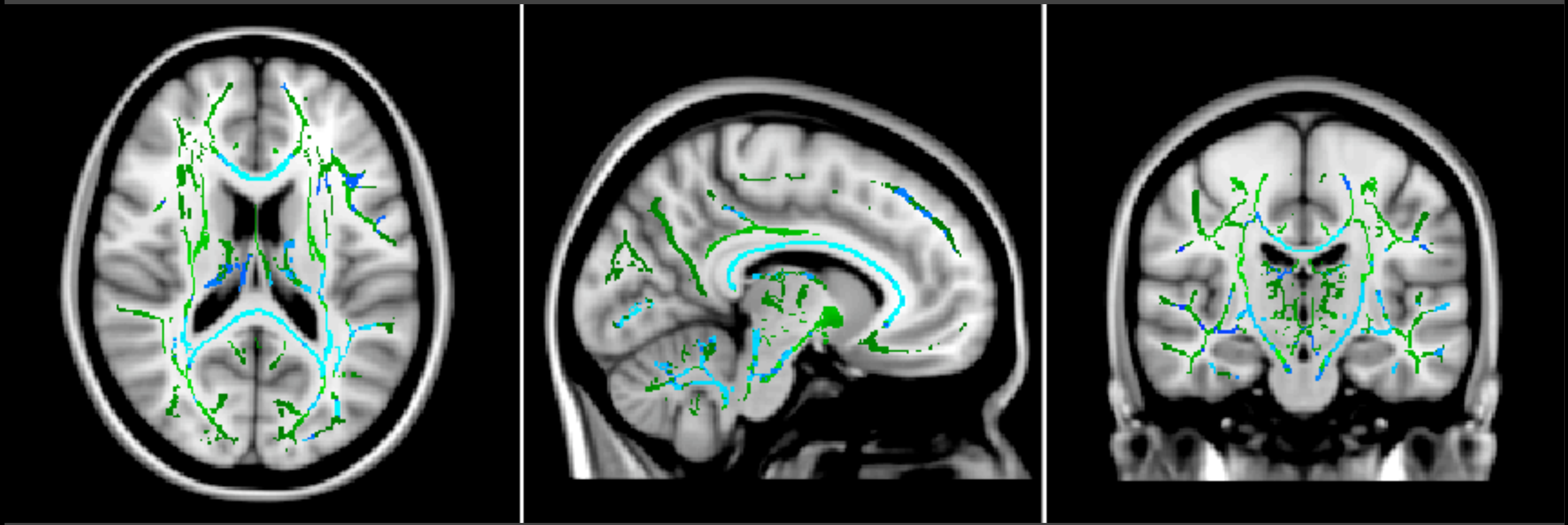
Lower-motion vs. higher-motion scans of *the same* 25 TD children



Voxel-based analysis

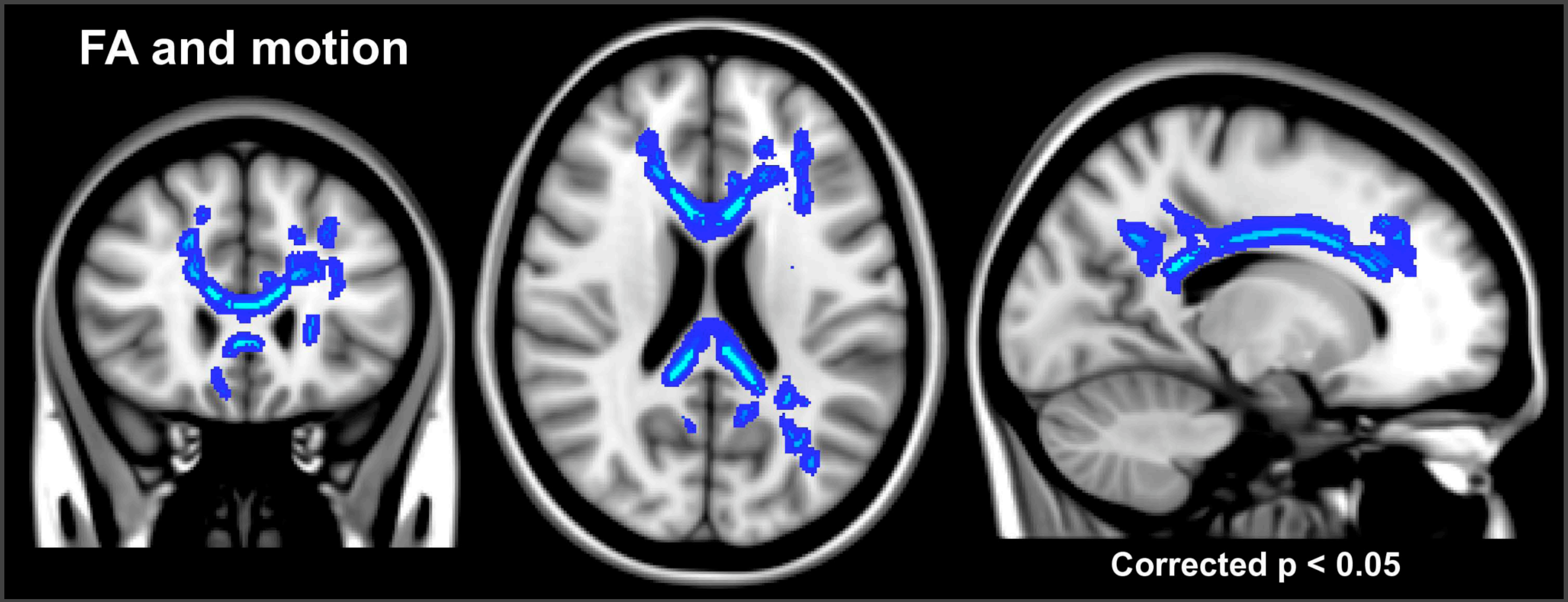
Yendiki *et al.*, 2013

- Test each voxel for association of FA with head motion with TBSS [Smith '06] on all scans



Replication in adult data

- Test each voxel for association of FA with head motion with TBSS on data from a group of middle aged and older adults



Salat, Chapter 12 in: *Diffusion MRI,* 2nd edition (in press)

Motion compensation strategies

- Retrospective:
  - Registration-based [Andersson '02, Rohde '04]
    - Does not correct for intensity drop-out, less robust at high b-values
  - Outlier removal [Chang '05, Zwiers '10]
    - Must have redundancy in data, remove comparably from every group
  - Nuisance regressors
  - Motion matching between groups

- Prospective:
  - Motion-compensated sequences
  - Accelerated sequences

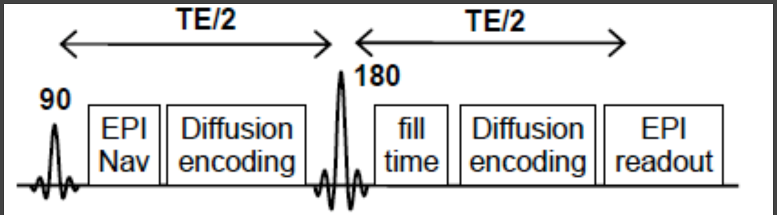
Data acquisition solutions:
Motion-compensated diffusion MRI

Motion-compensated dMRI

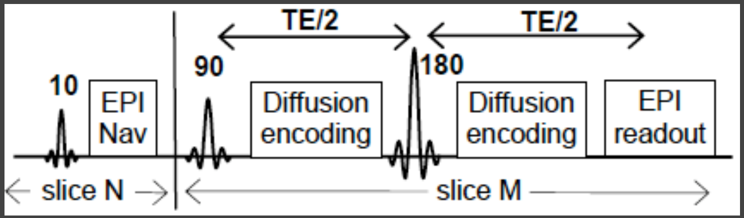
Work by Himanshu Bhat

- Optical tracking systems [Aksoy '11]
- Selective reacquisition [Benner '11]
- Free induction decay navigators [Kober '12]
- Volumetric navigators:
  - Low-res, non-DW EPIs acquired between TRs [Alhamud '12] or between slices throughout each TR [Bhat '12]
  - No external hardware needed
  - Performance independent of b-value
  - Small contribution to TR

Integrated

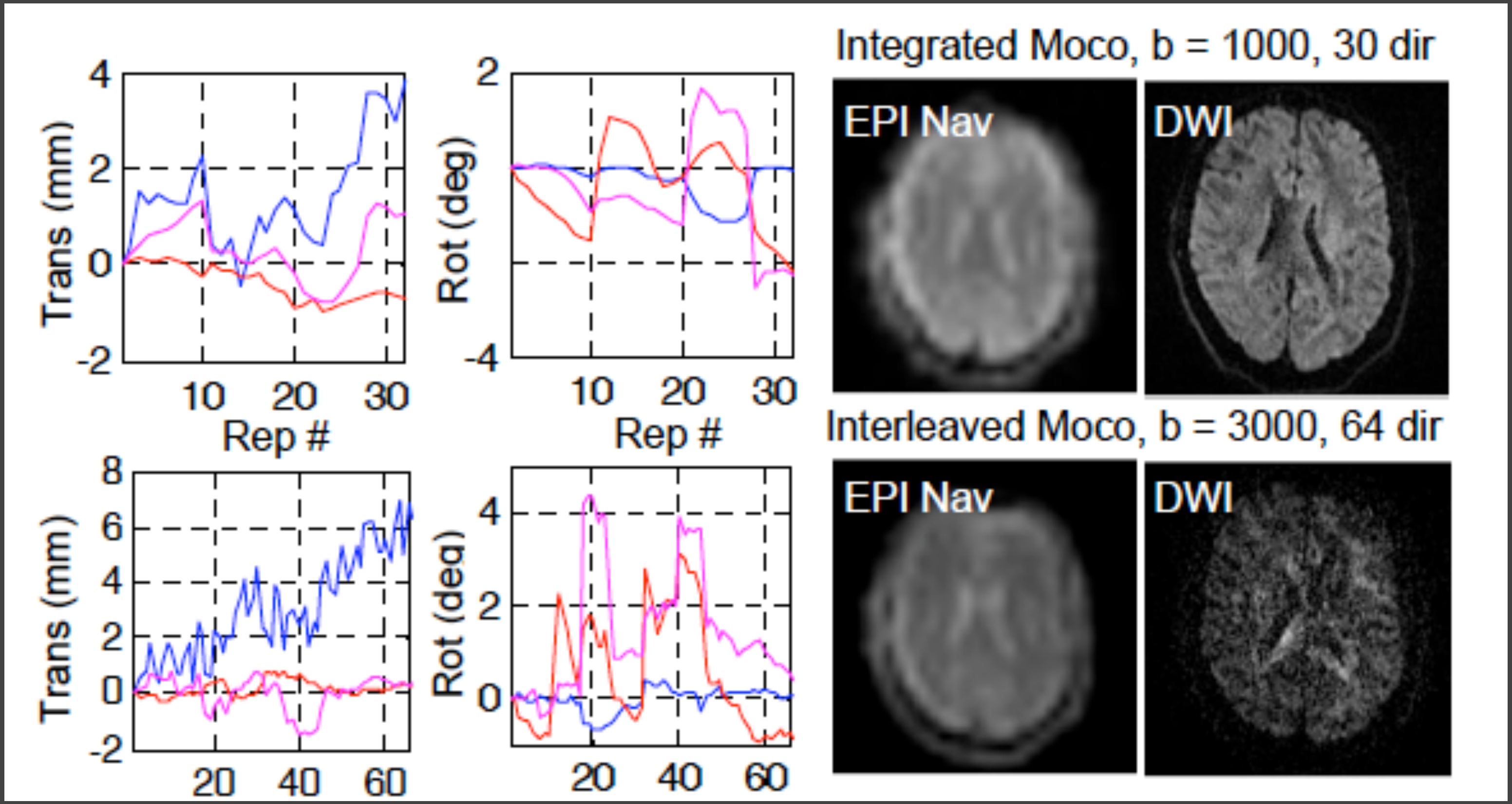


Interleaved



dMRI with volumetric navigators

Work by Himanshu Bhat



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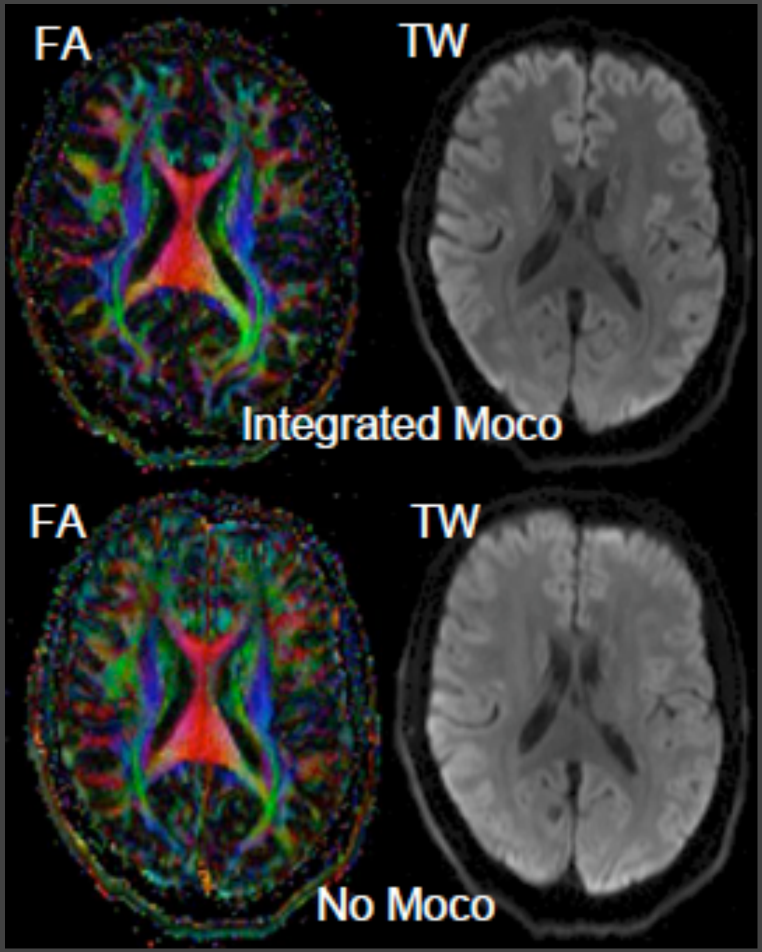
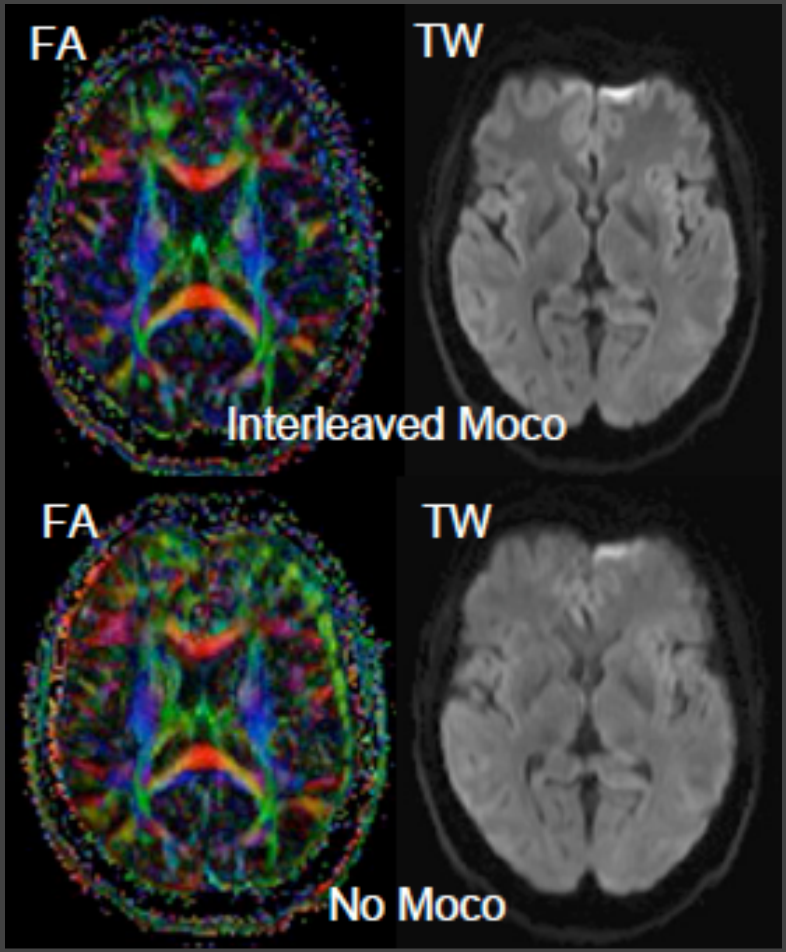


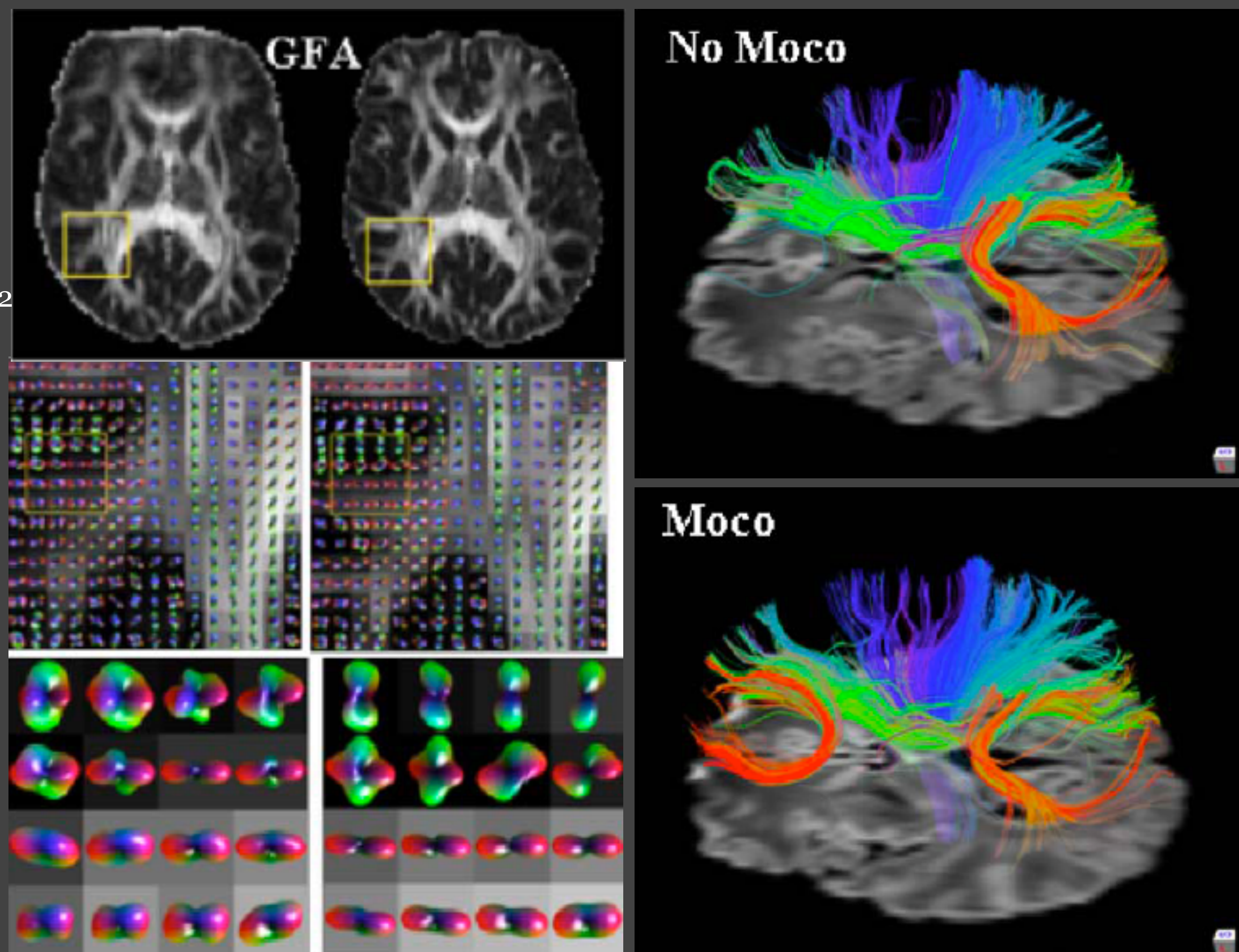


dMRI with volumetric navigators

Work by Himanshu Bhat

- Resolution 2mm isotropic
- TR = 7.3 s
- TE = 69 ms
- 100 directions
- b=1000 s/mm²

No Moco   Moco



Data acquisition solutions:
Accelerated diffusion MRI

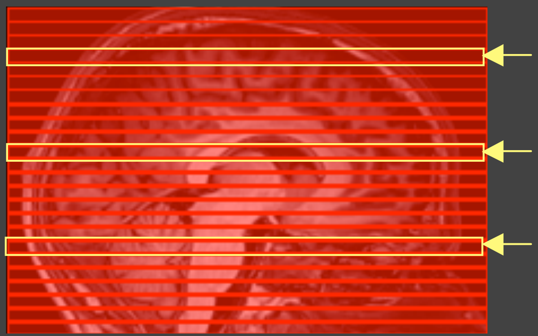
Simultaneous multi-slice EPI

Work by Kawin Setsompop

- Motivation: Increase efficiency of EPI for dMRI and fMRI
  - Whole brain acquisition with thin slices leads to long TR
  - TR >> T1 $\Rightarrow$ inefficient SNR/time
  - Long acquisition time makes EPI with high spatial resolution (or, for dMRI, high angular resolution) impractical

- Conventional parallel imaging: Undersample data in *k*-space
  - For R-fold speedup, SNR drops by $g\sqrt{R}$
  - Shorter read-out train but efficiency gain smaller for EPI

- Simultaneous multi-slice (SMS): Excite and acquire multiple slices in each readout period
  - For R-fold speedup, SNR drops only by g
  - Reduces TR significantly

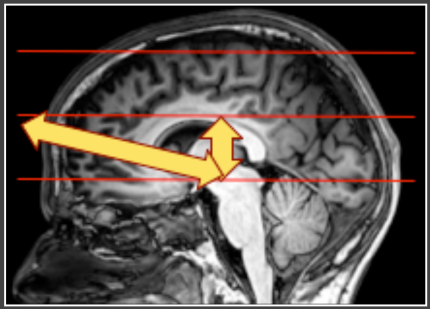


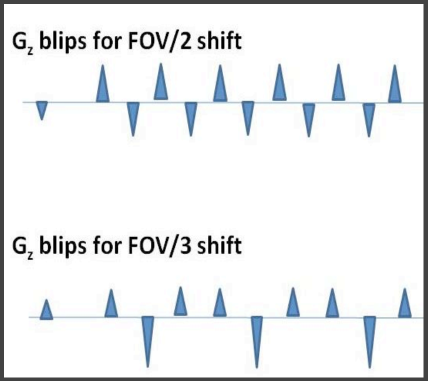
Teasing apart the slices

Work by Kawin Setsompop

- Parallel imaging with simultaneous acquisition of multiple slices:
  - High *g*-factor when slices are close to each other [Larkman '02]
- CAIPIRINHA:
  - Fix this for multi-slice parallel FLASH with FOV/2 shifts b/w slices by phase cycling of excitation pulses [Breuer '05]
  - Not relevant to EPI
- Extension to EPI:
  - Use blips in slice-select direction to shift slices to get benefits of CAIPIRNHA [Nunes '09]
  - Constant slice-select blips with every phase-encode blip cause through-plane dephasing

    ⇒ "tilt" voxels in phase-encode direction
- Blurring solved by blipped-CAIPI:
  - Back-and-forth jumps in slice-select blips to unwind dephasing of previous blip [Setsompop '12]



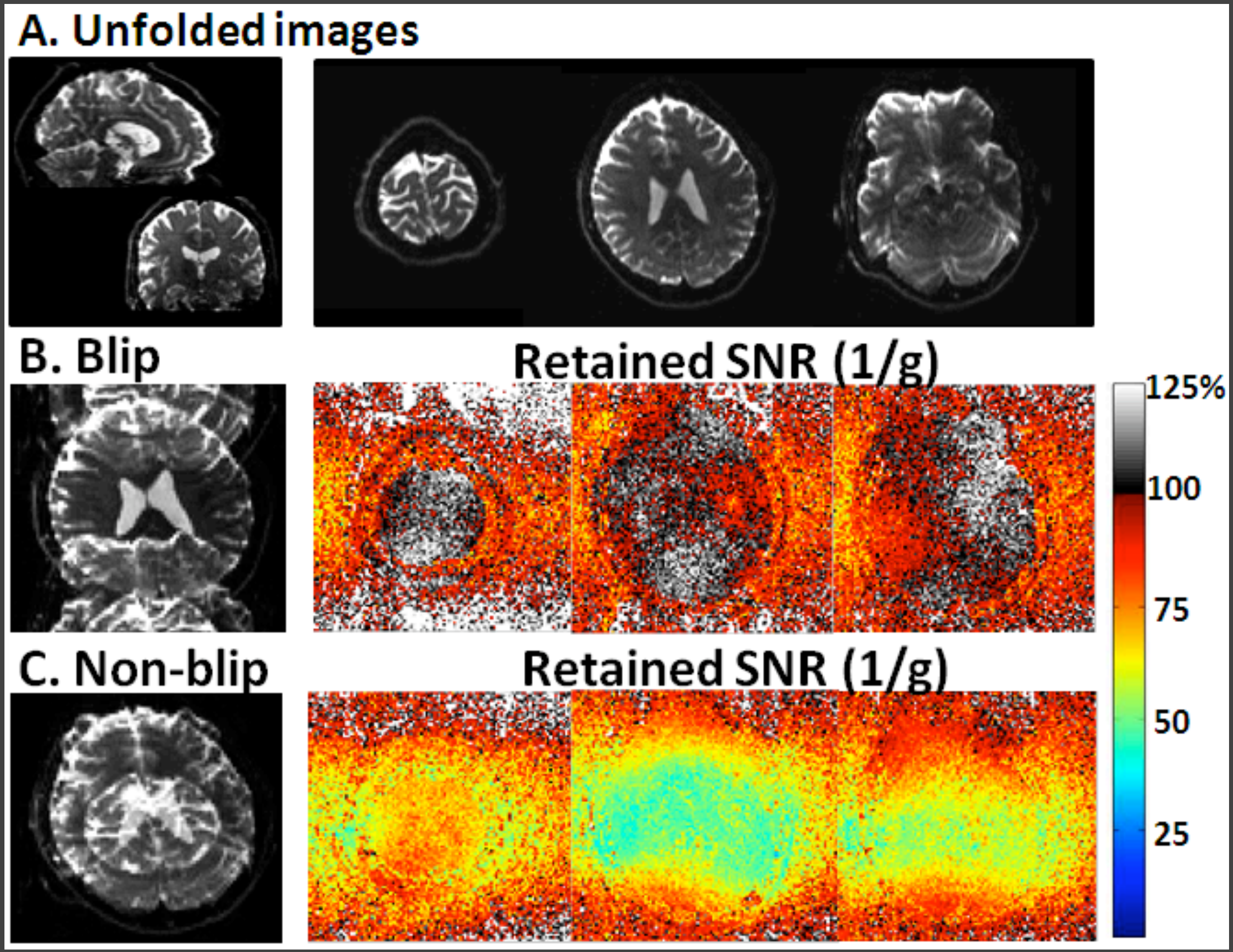


Simultaneous multi-slice dMRI

Work by Kawin Setsompop

- Multi-slice SE-EPI for diffusion imaging with 3-fold speed-up

- Resolution 2mm isotropic
- 32-channel head coil
- Inter-slice gap 40mm
- FOV 208 x 208 x 120mm
- TR = 3s
- TE = 96 ms
- Partial Fourier ¾
- Matrix 104x78x20
- Slice GRAPPA

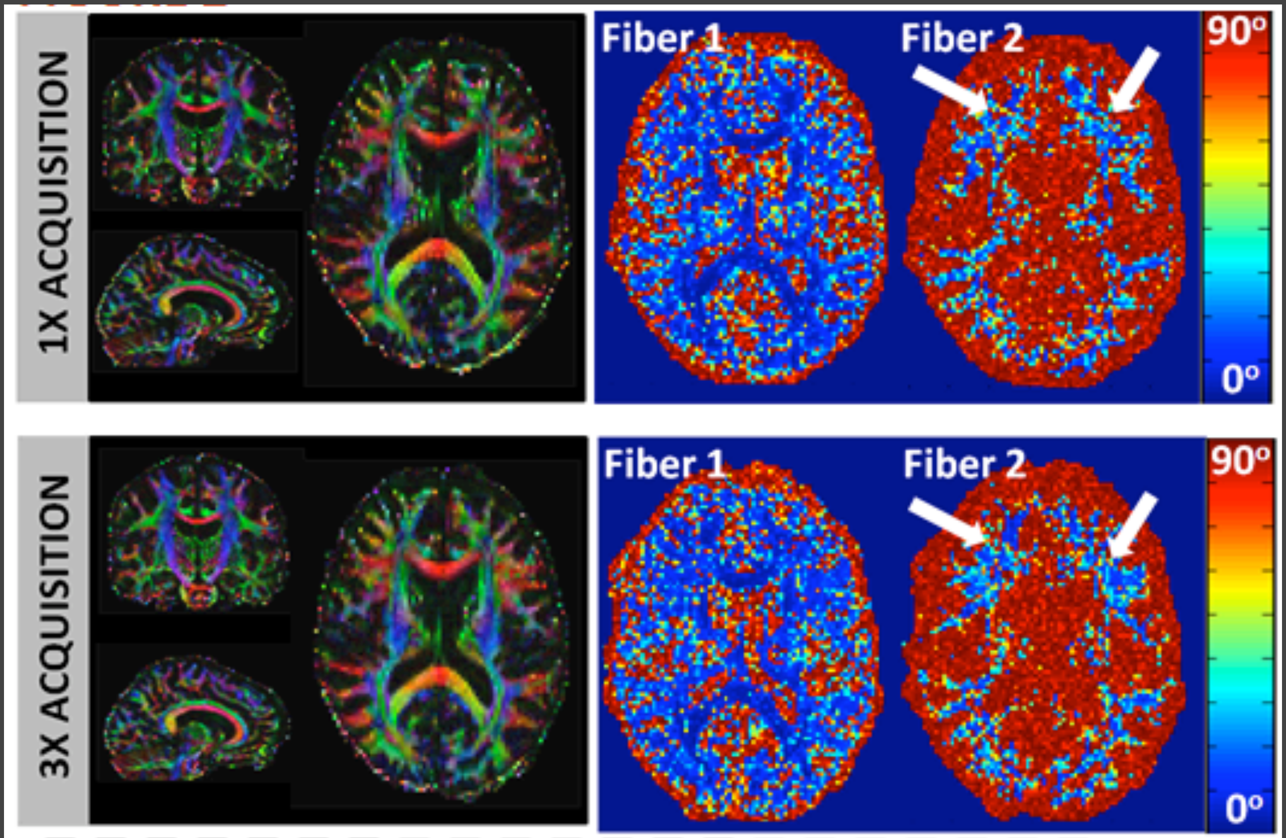


Simultaneous multi-slice dMRI

Work by Kawin Setsompop

- DTI (64 directions, b=1000 s/mm², 2 mm isotropic)
  - Conventional acquisition: 10 min
  - 3-fold SMS acquisition: 3 min

Tensor map   Angle of uncertainty from bedpostX

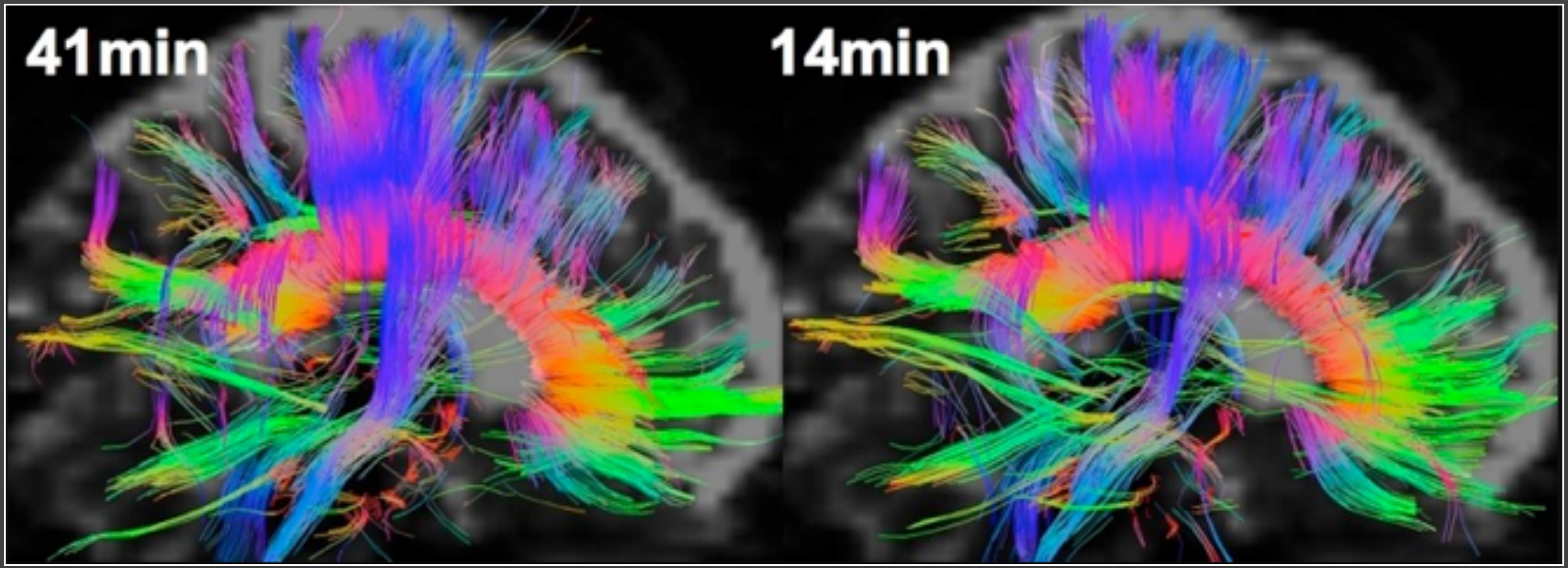


Simultaneous multi-slice dMRI

Work by Kawin Setsompop

- DSI (257 directions, b_{max}=7000 s/mm², 2.5 mm isotropic)
  - Conventional acquisition: 41 min
  - 3-fold SMS acquisition: 14 min

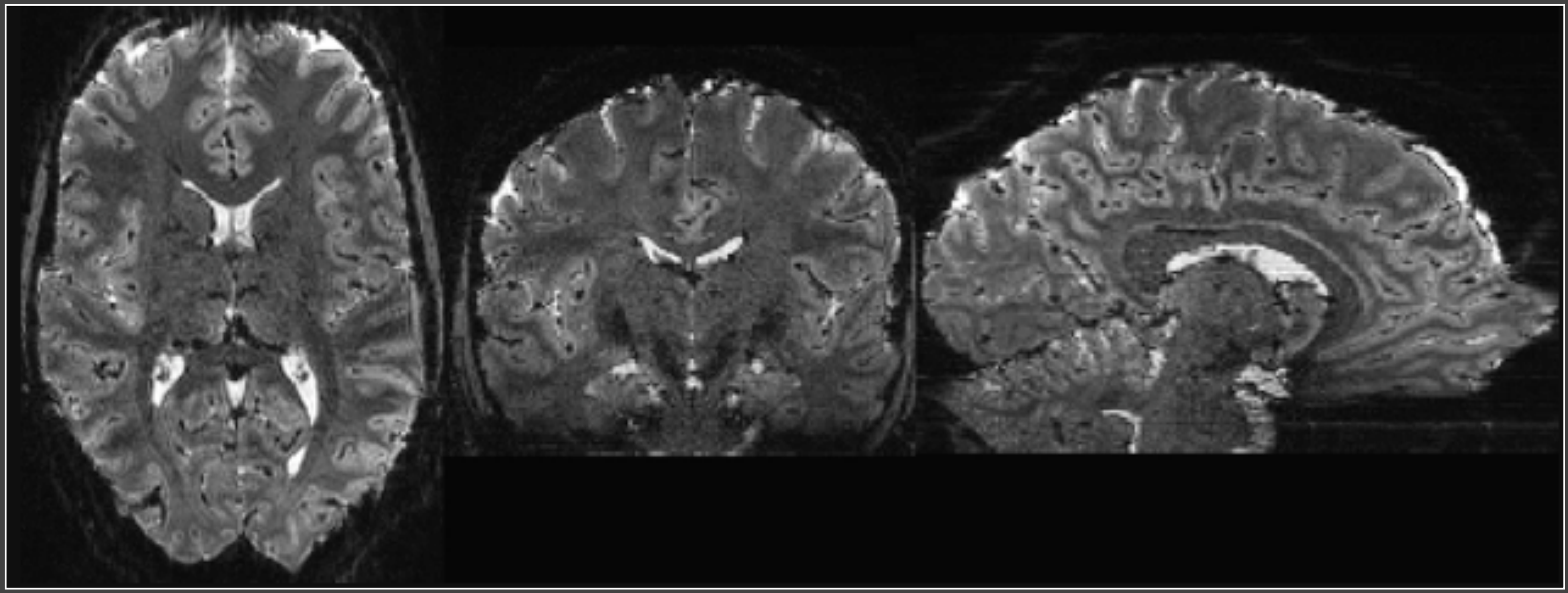
1x acquisition 3x acquisition



Simultaneous multi-slice fMRI

Work by Kawin Setsompop

- 7T fMRI, 1mm isotropic, 120 slices (whole head), R=2 in-plane GRAPPA, 32 channel coil
- TR=2.88s with 3x simultaneous multi-slice acquisition



Conclusions

- Differences in head motion between groups can induce spurious group differences in diffusivity and anisotropy
- General trend: Head motion$\uparrow$ $\Rightarrow$ RD$\uparrow$, AD$\downarrow$, MD –, FA$\downarrow$
- This is *after* registration-based motion correction
- Match motion between groups and/or use a motion score as a nuisance regressor
- Note that all this will address *false positives,* but not *false negatives* due to head motion in the data
- Methods for tackling the problem during data acquisition are important