The Anatomy of Reading

Bob Dougherty
Stanford Institute for 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 1\textsuperscript{st} and 2\textsuperscript{nd} 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

xxxxxxx

xxxx

xxxxxx

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
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
Occipital Callosal Fibers

1 cm scale bars
Occipital Callosal Fibers

1cm scale bars
Left-Right Convergence: Mean-Centered Density

Left Occipital Fibers

Right Occipital Fibers

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

N=53 children (7-12yr)
Left and Right Fibers Converge

Unshifted \( (r^2 = 0.88) \)

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

Dougherty et al. 2005 PNAS; Dougherty et al. 2005 NYAS
Splenium Map in 53 Children

left/right convergence ($r^2$):

<table>
<thead>
<tr>
<th></th>
<th>LD</th>
<th>LV</th>
<th>LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD</td>
<td>0.87</td>
<td>0.73</td>
<td>0.21</td>
</tr>
<tr>
<td>RV</td>
<td>0.47</td>
<td>0.89</td>
<td>0.38</td>
</tr>
<tr>
<td>RL</td>
<td>0.37</td>
<td>0.50</td>
<td>0.77</td>
</tr>
</tbody>
</table>
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

Some overlap in extent; voxels of maximal difference <1cm apart
Principal Diffusion Direction:
Group Means

Good Readers

Poor Readers
A PDD Difference in Anterior WM
(Schwartzman, Dougherty, Taylor, 2005, MRM)

Good Readers

Poor Readers

Bipolar Watson Distribution

FA difference

Ages 8-12; N = 14

Significant at FDR<0.01
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 hypotheses
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
Tracing Virtual Fibers
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
Defining Callosal ROIs
Defining Callosal ROIs

- Genu/Rostrum
- Body
- Isthmus
- Splenium

1/3, 2/3, 1/5
FA Negatively Correlated with Phonological Awareness in Splenium

\[ r = -0.44 \quad (p=0.001) \]

\[ N = 53 \]
FA Negatively Correlated with Phonological Awareness in Splenium

$\text{r} = -0.44 \ (p=0.001)$

$N = 53$
Phonological Awareness is Correlated with Reading

$r = 0.67$ ($p<0.0000001$)
FA and Reading in the Splenium

[Image of brain scans with highlighted areas and scatter plots showing correlation between FA and passage comprehension/phonological awareness vs. mean FA.]
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?
Conclusions

- 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
    - Segment callosum by projection zone
Acknowledgements

Brian Wandell (Psychology)
Gayle Deutsch (Neurology)
Michal Ben-Shachar (Psychology)
Roland Bammer (Radiology)
Polina Potanina (Psychology)
Arvel Hernandez (Psychology)
Armin Schwartzman (Statistics)
Alyssa Brewer (Psychology)
All our subjects (kids and parents)

Funding: Schwab Foundation for Learning & NIH EY015000