The Literate Brain
A Neuroscience Perspective on Reading Development
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Fundamental Questions

• Why is reading difficult to learn for everyone?
• Why do some individuals struggle more than others?

Now, the Star-Belly Sneetches
Had bellies with stars.
The Plain-Belly Sneetches
Had none upon thars.

Those stars weren’t so big. They were really so small
You might think such a thing wouldn’t matter at all.
Why Don't Infants Learn to Read?

- Interactive language (oral/sign)
  - Learned early
  - Without explicit training
  - Most children achieve proficiency
- Reading acquired late
  - Learned late
  - Requires explicit training
  - Many (5-10%) struggle to achieve proficiency
Interactive Languages

• Production & reception learned together
  • Powerful motivator- get what you want!
• Long evolutionary history for brain adaptation
  • Build upon early social systems- calls & signs
Compared to Interactive Languages, Reading is...

• Much less social

• Less motivation, since production (writing) is hopeless before fine motor skills develop

• Lacking the specialized, early maturing brain modules
  • Baby's brains are wired for acquiring interactive language right from birth
  • Reading leverages late-maturing high-level visual areas, e.g. contour analysis and object identification
Learning to See: The “Molyneux Problem”

“If a man born blind, and able to distinguish by touch between a cube and a globe, were made to see, could he now tell by sight which was the cube and which the globe, before he touched them?”

A question posed by William Molyneux to John Locke, discussed in Locke's Essay Concerning Human Understanding.
Learning to See

Virgil- regained sight after 45 years:

“On the day he returned home after the bandages were removed, his house and its contents were unintelligible to him, and he had to be led up the garden path, led through the house, led into each room, and introduced to each chair. ... As Virgil explored the rooms of his house, investigating, so to speak, the visual construction of the world, I was reminded of an infant moving his hand to and fro before his eyes, waggling his head, turning it this way and that, in his primal construction of the world."

*Oliver Sachs, To See and Not See (New Yorker 1993-05-10)*
Restored Vision: Mike May

- Chemical accident at age 3 yrs
- One eye lost; other cornea destroyed
- Blind from age 3 through 46
- Stem cell replacement in right eye for both epithelium and stem cells
Restored Vision: Mike May

I took my first flight since the operation on March 7. It was very bumpy and I was keeping my mind off this by working. After about 30 minutes, I suddenly realised that I could look out of the window, so I did. I could see some white lines in the distance and brown and green patches sliding by on the ground. I was so excited and eager to find out what I was looking at that I asked the person sitting next to me: "Excuse me, I just got my sight back last week after being totally blind for 43 years. Could you help me figure out what I am seeing?" There was a long pause as she decided whether I was a lunatic or a miracle. I broke the silence by asking if the white lines I could see were mountains. She said: "No, honey, that's haze." From then on, she and her husband gave me a play by play commentary on the central valley, fields, channels, roads, Tehachapi mountains and, finally, the Los Angeles coastline. I could see the water and even the waves. I picked out white dots, which must have been sailboats.

Visual Pathways
Perception is an Inference
3D Shape is Inferred
The Inference is Often Wrong
from A. Kitaoka: http://www.ritsumei.ac.jp/~akitaoka/
Purple in front, Yellow in back

Yellow in front, Purple in back

Monnier and Shevell
Lightness Perception
(Lotto and Purves)
Sensory Aspects of Reading

• Maintain fixation
  • Identify currently fixated word
  • Cognitive processing of narrative
  • Preprocess parafoveal words
• Program & execute saccades
• Ignore irrelevant retinal motion
• Stabilize fixation
• Repeat
Visual Processing of Words is Fast

- 250 words/min, ~4 words/sec
- 225 ms fixation duration
- ~30 ms saccade duration (2 deg)
- Visual info influences fixation duration and subsequent saccade target
- ~150 ms to program a saccade
- Fixated text must be processed very quickly (~100 ms) during fluent reading
Name the ink colors:

xxxxxxx

xxxxx

xxxxxx

xxx

xxxxxxx
Name the ink colors:

red
green
blue
orange
purple
Reading Prerequisites

• Motivation- a lot of work before the pay-off
• Attention- visual and auditory
• Cognitive ability to follow narrative
• Precision eye movement system
• Maturation of visual system components
  • Reading leverages late-maturing visual areas:
    • Contour analysis and object identification
    • Motion processing
    • Visual attention
    • Breaking bilateral symmetry bias
Brain Matters

• Gray matter: the connections (synapses)
  • Functional activity (EEG, MEG, PET, fMRI)
• White matter: the wiring (myelinated axons)
  • High lipid content (myelin)
  • Connections develop early and limit plasticity
  • Connections *define* cortical modularity
Cortical Maturation
(Distribution of gray matter loss)

Gogtay, Giedd, Lusk, Hayashi, Greenstein, Vaituzis, Nugent, Herman, Classen, Toga, Rapoport, Thompson, 2004, PNAS.

13 subjects scanned ~ every 2 years
White Matter Growth

Maturation of white matter in the human brain:
A review of magnetic resonance studies

T. Paus, D. L. Collins, A. C. Evans, G. Leonard, B. Pike and A. Zijdenbos

Age (years)
Callosal Growth Maps

Local growth: -20% 0%+20%+40%+60%+80%

Years:
- 3
- 6
- 7
- 8
- 9
- 11
- 12
- 13
- 15

Four-year interval
7–11 years (boy)
6–7 years (girl)
8–12 years (girl)
9–13 years (girl)
11–15 years (boy)

Two-week interval
3–6 years (girl)

Tensor map
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Explaining Reading Development

• Most variance explained by social factors and general cognitive ability
• Significant variance remains
  • Explained by variation in anatomy and physiology
  • We hope to eventually predict & guide intervention before reading failure
SIRL Longitudinal Study of Reading Development

- Behavioral assessment
- Anatomical Imaging
- Diffusion Tensor Imaging
- Functional MRI
- 50 7-11 yr olds
- 3 years (4 measurements)
  - Completed 3 measurements
Every Brain is Different...
Consensus: Phonology and reading

“… the specification of the role of phonological processing in the earliest stages of reading acquisition is one of the more notable scientific success stories of the last decade.” (Stanovich, 1991, p. 78)

“To my mind, the discovery and documentation of the importance of phonemic awareness … is the single most powerful advance in the science and pedagogy of reading this century.” (Adams, 1990).
Phonemic awareness and reading

• Hearing, distinguishing and manipulating the sounds in words
• Claimed to be the chief causal factor in early reading achievement
• Hope: If we train phonemic awareness, children will become better readers (also skills-training, decoding)

Example Tasks

• **Deletion:** Remove the /r/ from rat. What do you have left?

• **Add a /b/ to rat.** What do you have?

• **Rhyming**

• **Oddity:** bud, bun, bus, rug

• **Pronouncing pseudowords** (dif, giz, dop, blif)
Word reading correlates with phonological awareness
(Ben-Shachar, Deutsch, Dougherty, Wandell)

Reading (Word ID)
read aloud: ‘..together,.. enough, ..’

Phonological Awareness (elision, blending)

elision (strain-/r/ = stain)
blending (/t/+/oi/ = toy)

\[ r = 0.719 \]
\[ p < 0.0001 \]
The Astonishing Hypothesis
(Francis Crick; Braitenberg and Schutz, 1991)

Neurons are the computational elements
White matter connects the neurons via axons
The connection is called the synapse

Neurons: $10^{11}$
Synapses: $10^{14}$
Synapses/neuron: 1000
Surface area of each hemisphere: 25 x 30 cm²
Most connections are local (10-100 um); some span many cm
Neurons/mm³: 104-106
Axon length/mm³: 3 km
Localized cortical damage produces very specific visual dysfunction
Neurology of word reading
(Cohen et al, 2003; Cerebral Cortex)

• Dejerine described a patient with a left occipito-temporal lesion who could see, but not process letters and words

• Callosal patients have a visual field loss of reading
Magnetic Resonance Imaging

GE 1.5T and 3.0T MR scanner
Gray/white surface boundary
There Is An Increase In Oxygenated Blood Flow To Active Regions of Cortex  
J.F. Fulton, M.D. (1928)

Operation
On turning down a left occipital bone flap, a large angry-looking angioma arteriale racemosum of the left occ. Lobe was disclosed which extensively involved the visual cortex. The haemorrhage occasioned by the bone flap was so excessive that the operation had to be abandoned without touching the tumour. A decompression, however, was made. The patient was discharged … with greatly improved vision.

Subject noted that “the noise in the back of his head increased in intensity when he was using his eyes.” There was no increase for hearing, touch or smell.
Functional MRI

Stimulus → Neural response → Hemodynamics → MRI scanner → fMRI response + Noise

fMRI linear transform

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Using magnetic resonance imaging, we can measure responses in human visual cortex
Phonological Processing in the Brain

Locations where dyslexics had decreased activity relative to normal readers during phonological processing.

Temple, 2001, CONB
Visual cortex is about 20% of human neo-cortex
The Development of Skilled Reading Relies on:

• A network of brain regions
  • Early visual processing
  • Ventral 'What' stream
  • Motion processing and attention
  • Temporal and frontal language areas
• Interconnected by white matter pathways
  • Optic radiations, occipital & temporal U-fibers
  • Arcuate fasciculus (lat. temporal to lat. frontal)
  • Posterior corpus callosum
  • Posterior corona radiata? (cerebellar-parietal?)
Motion responses in children's MT+
MT+ activation reduced in poor readers (Eden et al.)

Replicated by Demb et al., Ben-Shachar et al.
MT+ Contrast Responsivity Predicts Phonological Awareness

\[ r^2 = 0.41 \ p < 0.0001 \]

\[ r^2 = 0.12 \ p = 0.06 \]

\[ r^2 = 0.04 \ p > 0.2 \]

Ben-Shachar, Dougherty, Deutsch, Wandell (under review & SFN 2006)
Responsivity to Words and Letters

- Task: Judge fixation color (maintaining attention throughout)

Ben-Shachar et al., Cerebral Cortex 2006
The "Contour Processing" Area

Ben-Shachar et al., Cerebral Cortex 2006

Cohen, Dehaene et al. (2000, 2002)
Word Visibility in pOTS Develops with Age and Reading Skill

Ben-Shachar et al., SFN 2005
Word Visibility in pOTS Develops: Cross section and Longitudinal

Ben-Shachar et al., SFN 2005
Conclusions: pOTS

• Increasing contour visibility produces increasing pOTS response
  • Words, line-drawings & false fonts have similar tuning, but stronger response to words
• pOTS responsivity to words develops with age and reading skill
• Likely a result of reading acquisition
  • But may be a necessary condition of proficient reading (acquired dyslexia)
Brain Matters

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White Matter is Crucial for Understanding Brain Development

• Connections form early (genetic program)
• Myelin limits new long-range connections
  • Exuberant connectivity before myelination
  • Experience can:
    • Prune existing connections
    • Strengthen existing connections
• Long-range connections limit adult plasticity
  • Neighboring regions can densely connect
  • Distant regions can increase direct connections only if some connections already exist
Why You See with the Back of Your Brain

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

Courtesy Professor Ugur Ture
Human fiber tracts

From: The Virtual Hospital (www.vh.org); TH Williams, N Gluhbegovic, JY Jew
Diffusing Water Probes
Microscopic Tissue Structure

Unimpeded direction- higher diffusion rate

Impeded/tortuous direction- lower diffusion rate

At 30 ms diffusion time, RMS diffusion in tissue is \( \sim 10\mu m \)
**H₂O Diffusion Probes Membrane Properties in the Brain**

In regions of high axial coherence, the cytoplasm within the axon limits diffusion and there is a large Apparent Diffusion Coefficient (ADC).
H$_2$O Diffusion Probes Membrane Properties in the Brain

In all other directions the bi-lipid cell membranes and myelin limit diffusion; perpendicular to the axon the ADC is smaller.
Tracking the entire network of signals
Reading and the Corpus Callosum

• CC in developmental dyslexia
  • Morphological differences in CC
  • Abnormal language lateralization
• CC in acquired dyslexia (alexia)
  • Mid-splenial lesions

Mao-Draayer & Panitch (2004), Alexia without agraphia in multiple sclerosis...
Reading and Lateriazation

- Orton (1939)- incomplete lateralization
- Geschwind & Galaburda (1985)- greater hemispheric symmetry
- Corpus callosum differences
  - Suggesting greater interhemispheric connectivity in dyslexia
  - Rumsey et al. (1992)
  - Robichon & Habib (1998)
Callosal Segments in 49 Children
Good Readers have Higher Radial Diffusivity in Temporal-Callosal Pathways

$r = 0.52 \ (27\%)$

$p < 0.0002$
Increased Radial Diffusivity in Temporal-Callosal Pathways of Good Readers Could Mean...

- Fewer interhemispheric connections
  - Increased language lateralization
  - More efficient interhemispheric transfer of visual information
- More large axons connecting left and right
  - Large axons conduct signals faster

*Dougherty et. al., under review.*
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

adults  children
Factors in Reading Development

- Learning to see
- Phonological awareness
- Network of brain regions
  - pOTS responses develop with reading
  - Motion responses important
  - Interhemispheric communication via corpus callosum

We are making good progress on identifying key locations in the reading pathway using both functional and structural brain measures
What We Would Like to Know

• When is a particular child's brain ready to learn to read?
• What can we do to help those who struggle to learn to read?
  • predict
  • intervene
• How can we make reading easier to learn for all children?
  • interactive text?
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