The typical and atypical reading brain:

How a neurobiological framework of reading development can inform educational practice and policy

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Boston Children’s Hospital
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Laboratories of Cognitive Neuroscience

www.thegaablab.com
www.babymri.org
Overview

- Typical and atypical reading development and its neurobiology
- Remediating the atypical reading brain
- The ‘Dyslexia Paradox’
- Early pre-markers of reading difficulties before reading onset
- Compensatory mechanisms, resiliency and protective factors
- Detecting children at risk for reading difficulties in infancy?
- Educational and Clinical Implications
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Timeline of typical reading development

- Sound and Language Processing
- Phonological Processing
- Visual Processing
- Grapheme-phoneme Mapping
- Reading of single words
- Reading sentences and connected text
- Reading complex text
- Reading Fluency
- Reading Comprehension
Key predictors of reading ability before reading instruction starts:

- Phonological/Phonemic awareness
- Speech perception/production
- Syntax production and comprehension
- Receptive/expressive vocabulary
- Rapid automatized naming abilities
- Letter name knowledge
- Verbal short-term memory

(e.g., Schatschneider et al., 2004; Georgiou et al., 2008; de Jong & van der Leij, 1999; Scarborough, 1998; Pennington & Lefly, 2001).
Home Literacy Environment (HLE)

Aspects of HLE that are most predictive of future language and literacy skills include (e.g., Hamilton, 2013; Payne, Whitehurst, & Angell, 1994; Bus et al., 1995; Rodriguez et al., 2011):

- Age of onset of shared reading
- Frequency and quality of book reading
- Frequency of library visits
- Parental knowledge of storybook titles
- Parental mediating style during shared reading
- Parental language during shared reading
- ...
The typical reading network with its key components

[Dehaene, 2009]
The development of basic reading skills is one of the primary goals of elementary education...but

- 66% of U.S. fourth graders are not reading at grade level
- Among students from low socio-economic backgrounds, 80% are reading below grade level

Factors contributing to atypical reading development

- Genetics
- Brain
- Perception & Cognition
- Environment

Atypical Reading Development
What is Developmental Dyslexia?

- Affects 10-12% of children.
- Specific learning disability characterized by difficulties with speed and accuracy of word/text decoding and poor spelling and poor comprehension performance.
- Cognitive difficulties may further include:
  - Speech perception
  - Accurate representation and manipulation of speech sounds
  - Verbal memory
  - Rapid automatized naming
  - Letter sound knowledge
- Cannot be explained by poor vision or hearing, lack of motivation or educational opportunities.
- Strong psychological and clinical implications that start long before reading failure.
- Familial occurrences as well as twin studies strongly support a genetic basis for DD.
Genetics

- Studies of families with DD suggest that DD is strongly heritable, occurring in up to 68% of identical twins and up to 50% of individuals who have a first degree relative with DD [Finucci et al., 1984; Volger et al., 1985; Grigorenko, 2008].

- Several genes (e.g.; ROBO1, DCDC2, DYX1C1, KIAA0319) have been reported to be candidates for dyslexia susceptibility and it has been suggested that the majority of these genes plays a role in early brain development. [e.g.; Galaburda et al., 2006; Hannula-Jouppi et al., 2005; Meng et al., 2005; Paracchini et al., 2006; Skiba et al., 2011].
A tentative pathway between a genetic effect, developmental brain changes and perceptual/cognitive deficits in DD has been proposed based on studies in animal and humans (Galaburda et al., 2006).

Variant function in any number of genes involved in cortical development

Subtle cortical malformation involving neuronal migration and/or axonal growth

Atypical cortico-cortical circuits

Atypical sensorimotor, perceptual and cognitive processes critical for learning (to read)

Giraud & Ramus, 2013
Impaired reading

Deficient phonological representations

Grapheme-phoneme mapping

Left hemisphere peri-sylvian dysfunction

Current Opinion in Neurobiology

[ after Ramus, 2003]
Structural and functional brain alterations in DD

(A) Gray matter (volumetric analyses)

[B] Gray matter (functional analyses)

[e.g. see Meta-analyses: Richlan et al., 2013; Linkerdoerfer et al., 2012, Martin et al., 20015]

[e.g. see Meta-analyses: Richlan et al., 2011; Temple et al., 2002]
White matter alterations in DD

(C) White matter

- Left Superior Longitudinal Fasciculus
- Left Arcuate Fasciculus
- Left Inferior Frontal-Occipital Fasciculus
- Left Inferior Longitudinal Fasciculus
- Corpus Callosum
  (forceps minor - genu and major - splenium)
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Brain Changes After Remediation

Midway through the exam, Allen pulls out a bigger brain.
# Neuroimaging of Reading Intervention: A Systematic Review and Activation Likelihood Estimate Meta-Analysis

Laura A. Barquero¹, Nicole Davis¹,²,³,⁴, Laurie E. Cutting¹,²,³,⁴,⁵

<table>
<thead>
<tr>
<th>Study</th>
<th>RD N</th>
<th>CT N</th>
<th>Age</th>
<th>Intervention</th>
<th>Dosage</th>
<th>Intervention consisted of sight word reading, letter sound practice, decoding practice, and reading for fluency.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simons et al., 2002</td>
<td>8</td>
<td>6</td>
<td>7-12 yrs</td>
<td>Phonographes Read America, (Olanda FL) Lindamood Phonemic Sequencing (LPS)</td>
<td>80 hrs; 5 hr/day over 8 wk</td>
<td></td>
</tr>
<tr>
<td>Ayward et al., 2003</td>
<td>10</td>
<td>11</td>
<td>139.1 (9.8) months, 137.5 (7.9) months</td>
<td>Instruction in linguistic awareness, alphabetic principle, fluency, and reading comprehension</td>
<td>28 hrs; 2 hr/day over 14 session days (3 wk)</td>
<td></td>
</tr>
<tr>
<td>Temple et al., 2003</td>
<td>20</td>
<td>12</td>
<td>8-12 yrs</td>
<td>Fast ForWord Language Scientific Learning Corporation, Oakland, CA</td>
<td>100 min/day, 5 days/wk, average 27.5 days</td>
<td></td>
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<tr>
<td>Eden et al., 2004</td>
<td>19</td>
<td>9</td>
<td>adults, RD 44(8); CT 41.8 (16.7)</td>
<td>Multisensory instruction in phonological awareness, letter-sound association, articulatory feedback administered by Lindamood-Bell Learning Corporation staff</td>
<td>3 hr/day, 8 wks, avg 1123 hr total</td>
<td></td>
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<tr>
<td>Shaywitz et al., 2004</td>
<td>35</td>
<td>37</td>
<td>6.1-9.4 yrs; RD experimental 7.9 (3.5), RD community 8.1 (3.4); CT 8.3 (3.5)</td>
<td>Experimental intervention (125) included sound-syllable associations, blending, timed reading for fluency, and reading differentiation</td>
<td>50 min/day for 8 months</td>
<td></td>
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<tr>
<td>Simons et al., 2005</td>
<td>16</td>
<td>13</td>
<td>responders, 8 non-responders</td>
<td>Phonemic Reading and Responsive Reading (LPS)</td>
<td>40 min/day, 5 days/wk for 8 months</td>
<td></td>
</tr>
<tr>
<td>Richards et al., 2006</td>
<td>21</td>
<td>21</td>
<td>RD 133.8 months, CT 132.6 months</td>
<td>Instruction in alphabetic principle, composition, and other orthographic spelling treatment</td>
<td>28 hr total; 2 hr/day for 14 sessions over 3 wk</td>
<td></td>
</tr>
<tr>
<td>Nestor et al., 2007</td>
<td>64</td>
<td>64</td>
<td>participants received 4 of 4 interventions, but there was no significant effect of intervention on decoding scores</td>
<td>PowerKids Reading Initiative. Many participants received 1 of 4 interventions, but there was no significant effect of intervention on decoding scores</td>
<td>about 6 months during school year</td>
<td></td>
</tr>
<tr>
<td>Richards et al., 2007</td>
<td>20</td>
<td>11</td>
<td>phonological treatment; 9 non-phonological treatment</td>
<td>Phonological treatment included explicit written language instruction using phonological working memory, phoneme-grapheme correspondences in spelling, and science report writing (129)</td>
<td>24 hrs total—8 sessions over 2 wks with 3 h/session</td>
<td></td>
</tr>
<tr>
<td>Simons, Fletcher, Sahakian, Billing, Martin, et al., 2007</td>
<td>15</td>
<td>15</td>
<td>7-9 years</td>
<td>Phonographes [131] and Read Naturally [132]</td>
<td>16 weeks total; 2 hr/day for 8 wks Phonographs, 1 hr/day for 6 wks Read Naturally</td>
<td></td>
</tr>
<tr>
<td>Simons, Fletcher, Sahakian, Billing, et al., 2007</td>
<td>10</td>
<td>8 responders, 7 non-responders (same as Simons, et al., 2007 above)</td>
<td>Phonographes [131] and Read Naturally [132]</td>
<td>16 weeks total; 2 hr/day for 8 wks Phonographs, 1 hr/day for 6 wks Read Naturally</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Menzer et al., 2008</td>
<td>23</td>
<td>23</td>
<td>5th grade</td>
<td>PowerKids project used four programs: Corrective Reading, Wilson Reading, Spell Reading Phonological Auditory Training (PAT), Failure Free Reading</td>
<td>100 hrs total over 6 months</td>
<td></td>
</tr>
<tr>
<td>Odegaard et al., 2008</td>
<td>12</td>
<td>6</td>
<td>10 – 14 yrs</td>
<td>Take Flight: A comprehensive intervention for students with dyslexia (133)</td>
<td>90 min/day, 4 days/wk for 2 school years</td>
<td></td>
</tr>
<tr>
<td>Richards &amp; Benninger, 2009</td>
<td>18</td>
<td>18 as same Richards et al., 2006</td>
<td>RD 133.8 months, CT 132.6 months</td>
<td>Instruction in alphabetic principle, composition, and other orthographic spelling treatment or morphological spelling treatment</td>
<td>28 hrs total—14 sessions over 3 wks with 2hr/session</td>
<td></td>
</tr>
</tbody>
</table>

| Davis et al., 2011 | 10 | 5 responders, 5 non-responders | 7.5 (0.4) yrs | Intervention consisted of sight word reading, letter sound practice, decoding practice, and reading for fluency. | 45 min, 3 days/wk, 17 weeks |
| Farris et al., 2011 | 10 | 5 responders, 5 non-responders (same as Odegaard et al., 2008) | 10 – 14 yrs | Take Flight: A comprehensive intervention for students with dyslexia (133) | 90 min/day, 4 days/wk for 2 years |
| Hoek et al., 2011 | 25 | 20 | RD 14.0 (1.96) CT 11.0 (2.57) | This study did not provide an intervention. 11 participants received some form of intervention, but no differences were observed for intervention. | - |
| Rezaie et al., 2011a | 20 | 10 Adequate Responders (AR), 10 Inadequate Responders (IR) | Adequate Responders 138–7 months, Inadequate Responders 153–11 months, CT 151–11 months | Instruction included word study, fluency, vocabulary, comprehension (134) | 45–50 min/day over 1 schoolyear |
| Rezaie et al., 2011b | 27 | 16 AR, 11 IR (possible overlap with Rezaie et al., 2011a) | Adequate Responders 159–9 months, Inadequate Responders 156–16 months, CT 153–12 months | Instruction included word study, fluency, vocabulary, comprehension (134) | 45–50 min/day over 1 schoolyear |
| Yamada et al., 2011 | 7 | 7 (on-track) | At-risk 3.6 (0.2) yrs, On-track 5.7 (0.3) yrs | Early Reading Intervention (135) | 30 min/day, 3 months |
| Gebauer, Fink, Kargl, et al., 2012 | 20 | 20 total (poor reading and spelling) | 10 Treatment (TG), 10 Waiting Group (WG) | Morpheme: a computer-aided morpheme-based spelling training in German (136) | Daily handwritten and computer homework, 1/wk instructor-guided courses for 2 hr, over 5 wks |
| Bach et al., in press | 6 poor readers (group classification made at follow-up) | Poor Readers 6.3 (0.19) yrs, Normal Readers 6.3 (0.29) yrs | Graphophone: a computerized training game teaching grapheme-phoneme correspondences in German (137–139) | 321.5 ± 124.3 min over 8 wk |
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The dyslexia paradox

Window for most effective intervention

Typical window for a ‘Diagnosis’

‘FAILURE-MODEL’
Early versus late intervention

- A meta-analysis comparing intervention studies offering at least 100 sessions, reported larger effect sizes in kindergarten/1\textsuperscript{st} grade than in 2\textsuperscript{nd} and 3\textsuperscript{rd} grades (Wanzek & Vaughn, 2007).

- When “at risk” beginning readers receive intensive instruction, 56\% to 92\% of at-risk children across six studies reached the range of average reading ability (Torgesen, 2004).

- Overall, converging research points to the importance of early and individualized interventions for at-risk students for improving the effectiveness of remediation (Denton & Vaughn, 2008; Connor et al., 2009; Shaywitz, Morris, & Shaywitz, 2008, Torgesen, et al., 1999; Flynn, Zheng, & Swanson, 2012; Vellutino et al., 1996; Morris, Lovett, Wolf et al., 2012; Morris et al., 1997).
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The Boston Longitudinal Dyslexia Study (BOLD)

Early Identification
children at-risk

- Functional MRI
- Structural MRI
- Behavioral tests
- Psychophysics
- Questionnaires
- DNA

‘Diagnosis’
Dyslexia/
Reading difficulty

Follow up:
- prior to first grade
- prior to second grade
- prior to third grade

- Pre-readers (Word ID <5), reading instruction within next year.
- To date 165 children are enrolled longitudinally
Tasks within MRI scanner:
• Phonological Processing
• Rapid auditory processing
• Executive functioning
• Reading Fluency

Psychometric Measures:
• Clinical Evaluation Language Fundamentals – Preschool 2
• Comprehensive Test Of Phonological Processing
• Grammar And Phonology Screening Test
• York Assessment for Reading for Comprehension
• Rapid Automatized Naming and Rapid Alternating Stimulus Test
• Kaufman Brief Intelligence Test 2
• Year 2: Word reading (timed/untimed), passage comprehension, fluency, spelling, letter knowledge

Psychophysics Measures:
• RAP (tones and environmental sounds)
• Rise Time perception

Questionnaires:
• Development
• Home literacy
• SES

Structural brain differences
(gray matter, DTI)
Control task:
Voice matching
[Raschle et al., 2009; Raschle et al., 2012]
<table>
<thead>
<tr>
<th>YEAR 1  (prereading status)</th>
<th>YEAR 2  (beginning readers)</th>
<th>YEAR 3/4  (readers)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Significant differences in:</strong></td>
<td><strong>Significant differences in:</strong></td>
<td><strong>Significant differences in:</strong></td>
</tr>
<tr>
<td>Expressive and receptive language/content</td>
<td>Expressive language/language content</td>
<td>Core and receptive Language</td>
</tr>
<tr>
<td>Phonological processing</td>
<td>Phonological processing</td>
<td>Rapid automatized naming</td>
</tr>
<tr>
<td>Rapid automatized naming</td>
<td>Rapid automatized naming</td>
<td>Letter knowledge</td>
</tr>
<tr>
<td>Rapid auditory Processing</td>
<td>Single word reading (timed/untimed)</td>
<td>Single word reading (timed/untimed)</td>
</tr>
<tr>
<td></td>
<td>Passage comprehension</td>
<td>Passage comprehension</td>
</tr>
<tr>
<td></td>
<td>Spelling</td>
<td>Spelling</td>
</tr>
<tr>
<td></td>
<td>Reading Fluency</td>
<td></td>
</tr>
</tbody>
</table>

*No differences in* IQ, age, Home Literacy, SES

*all p<0.05*
Functional characteristics of developmental dyslexia in left-hemispheric posterior brain regions predate reading onset

Nora Maria Raschle\textsuperscript{a,b}, Jennifer Zuk\textsuperscript{a}, and Nadine Gaab\textsuperscript{a,b,c,1}

[Image of brain scans comparing FSM > VM, FHD+ and FHD-, and FHD- > FHD+ with statistical information provided.]
Structural brain alterations associated with dyslexia predate reading onset

Nora Maria Raschle, Maria Chang, Nadine Gaab *

[Raschle et al., Neuroimage 2010]
Sulcal pattern (global pattern of arrangement, number and size of sulcal segments) has been hypothesized to relate to optimal organization of cortical function and white matter connectivity (Van Essen, 1997; Klyachko and Stevens, 2003; O’Leary et al., 2007; Fischl et al., 2008).

Individuals with DD may undergo atypical sulcal development. Moreover, global sulcal pattern is determined during prenatal development and may therefore better reflect genetic brain development (Rakic, 2004; Kostovic and Vasung, 2009).
Four groups:
1. Beginning readers FHD-
2. Beginning readers FHD+
3. Developmental Dyslexia
4. Typical developing children

- The pattern of sulcal basin area in the left parieto-temporal and occipito-temporal regions was significantly atypical in children with DD compared to controls.

- Significantly atypical sulcal area pattern was also confirmed in kindergarteners with a familial risk of DD compared to controls.
78 healthy, native English-speaking children (45 FHD+, 33 FHD-)

Among them, 45 children (23 FHD+ and 22 FHD-) had at least two scans and composed a longitudinal cohort.

Three time points: re-reading, beginning reading, fluent reading
Cross-sectional results (n = 78):
Arcuate Faciculus

[Graphs showing fractional anisotropy in different stages of reading development]
Longitudinal Analysis: Development rate of the AF (n=45)

Wang et al., in revision
Linking FA development and individual differences in reading development

\[ r = 0.3386, p < 0.05 \]

Wang et al., in revision
Predicting reading fluency

Outcome measure: WJ-III Reading Fluency ($R^2 = 0.62$); $p<0.0003$
- FA-development rate of left SLF (contributing 27% of $R^2$),
- RAN Objects (contributing 31% of $R^2$),
- KBIT-2 Nonverbal IQ standard scores (contributing 19% of $R^2$)
- Familial risk (contributing 23% of $R^2$).

Wang et al., in revision
The READ Study
(Researching Early Attributes of Dyslexia)


- Invited children with and without risk for dyslexia to participate in a follow-up study including brain imaging with MRI and EEG (n =180 for EEG and n=160 for MRI).

- Following these children to see which measures from kindergarten best predict reading ability at the end of 1st and 2nd grade.
READ at a Glance

• 21 schools: inner-city charter schools, private, suburban district-run schools, and Archdiocese schools
• Free/reduced lunch eligibility from 0% to 80%
• Ethnically diverse student population (49% minority)
• Teacher professional developments and parent presentations conducted in all schools
• Brain awareness days conducted in various schools

“We very much enjoyed everything you and your staff provided. You are warm and professional and certainly put your subjects at ease...It’s exciting to see such cutting-edge research from the inside out!” (Parent, Wheeler School)

“...They were excellent presenters. The students had a wonderful time and were very engaged in the activities.” (Teacher, Lowell Elementary)

“Your whole team was terrific in making the afternoons lots of fun and educational” (Parent, Hosmer Elementary)
Six Distinct Cognitive Profiles of Early Reading

Ozernov-Palchik et al., submitted

Latent Profile analysis model for the Identification of Reading Subgroups: PA-phonological awareness, WM-working memory, RAN-rapid automatized naming, LSK-letter sound knowledge [n = 1,215 children].
Tracking the Roots of Reading Ability: White Matter Volume and Integrity Correlate with Phonological Awareness in Prereading and Early-Reading Kindergarten Children

Zeynep M. Saygin, Elizabeth S. Norton, David E. Osher, Sara D. Beach, Abigail B. Cyr, Ola Ozernov-Palchik, Anastasia Yendiki, Bruce Fischl, Nadine Gaab, and John D.E. Gabrieli

The Journal of Neuroscience, August 14, 2013 • 33(33):13251–13258 • 13251

![Graph showing correlation between white matter volume and blending words raw score.](image)

- $r = 0.38$, $P = 0.015$

- FA
  - 1
  - 0.5
  - 0

- BW score=0
- BW score=3
- BW score=9
- BW score=11
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# Demographics

<table>
<thead>
<tr>
<th></th>
<th>FHD-</th>
<th>FHD+</th>
<th>T-test 2-tailed</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>18</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Age (days)</td>
<td>297.78 ± 99.13</td>
<td>332.64 ± 117.91</td>
<td>p &gt; .100</td>
</tr>
<tr>
<td>Expressive Mullen T-score</td>
<td>48.67 ± 4.77</td>
<td>47.90 ± 10.87</td>
<td>p &gt; .100</td>
</tr>
</tbody>
</table>

Langer et al., in press
White Matter Alterations in Infants at Risk for Developmental Dyslexia

Nicolas Langer\textsuperscript{1,3,†}, Barbara Peysakhovich\textsuperscript{1,†}, Jennifer Zuk\textsuperscript{1,3}, Marie Drottar\textsuperscript{2}, Danielle D. Sliva\textsuperscript{1,2}, Sara Smith\textsuperscript{1}, Bryce L. C. Becker\textsuperscript{1}, P. Ellen Grant\textsuperscript{2,3} and Nadine Gaab\textsuperscript{1,3,4}

FHD+ infants exhibit significantly lower FA values compared to FHD- infants in red regions (all $p < 0.02$, controlled for multiple comparisons)

**Multivariate pattern analysis (MVPA):**

MVPA (using FA at each node of the left AF as input) was performed to determine whether FA can distinguish FHD+ and FHD- infants

- 82% prediction accuracy ($p = 0.001$)

Langer \textit{et al.}, in press
FA values correlate with ‘expressive language Scores’

Langer et al., in press

R = 0.481
p = 0.037
Atypical development of AF from infancy to late elementary school
FA in infancy correlates with language measures at age 4

Relationship between Left Arcuate Fasciculus and Peabody Picture Vocabulary

\[ r = 0.506, \quad p = 0.027 \]

Figuccio et al., in preparation
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Educational and clinical implications

- Early identification may reduce the clinical, psychological and social implications of DD.

- Understanding the complex etiology of specific learning disabilities and their co-occurrences will be essential to underpin the training of teachers, school psychologists, and clinicians, so that they can reliably recognize and optimize the learning contexts for individual learners → personalized medicine/education (Butterworth & Kovas, 2013)

- Development and implementation of early and customized remediation programs (who should get which intervention) → Subtyping and early customized remediation

- Informing (early) diagnostic guidelines

- Changes in educational policies (early IEPs; design and implementation of customized curriculums for children at-risk).

- Evaluation and improvement of existing remediation programs will likely prove cost-efficient as programs are made more effective.

- Improved psycho-social development (reduced child stress, parental stress, improved overall family dynamic).
Grand Challenges...

Develop an understanding of how individual differences in brain development interact with formal education

Adapt learning pathways to individual needs

Butterworth & Kovas, 2013
Collaborators:
John Gabrieli, MIT
Ellen Grant, CHB
Charles Nelson, BCH
April Benasich, Rutgers University
Sandra/Joseph Jacobson, Wayne State
Gennaro Chierchia, Harvard University
Maryanne Wolf, Tufts University
Paulo Andrade, São Paulo
Georgio Sideridis, BCH
Autism Excellence Center

CHB/MIT Staff:
Yingying Wang (Postdoc)
Xi Yu (Postdoc)
Elizabeth Norton (former Post-doc READ)
Nora Raschle (former Postdoc)
Nicolas Langer (former Postdoc)
Jennifer Zuk (Graduate student, HST)
Michael Figuccio (Graduate student, BU)
Ola Ozranov-Palchik (Graduate student, Tufts)
Bryce Becker (former Project Coordinator)
Meaghan Maurer (Project Coordinator, BOLD + Infants)
Talia Raney (RA, BOLD, Infants)
Danielle Sliva (former Data Coordinator, BOLD + Infants)
Barbara Peysakhovich (former RA)
Sara Smith (former RA)
Sara Beach (RA, READ)
Zeynep Saygin (READ)

Current/Past Funding:

- National Institutes of Health
  - BOLD: (1RO1HD065762-05)
  - READ: (1RO1HD067312-05)
  - ACE: (1R01MH100028-04)
  - FASD (1U01AA023503-01)

- Harvard Catalyst (Infants)
- Melinda and Bill Gates Foundation
- Harvard Mind/Brain/behavior Faculty Award
- Charles H. Hood Foundation (BOLD)
- Grammy Foundation
- William Randolph Hearst Foundation (Infants)
- Children's Hospital Boston Pilot Award (BOLD)
- Developmental Medicine Center Young investigator Award
- Victory Foundation
The typical and atypical reading brain:

How a neurobiological framework of reading development can inform educational practice and policy

Nadine Gaab, PhD
Associate Professor of Pediatrics
Harvard Medical School
Boston Children’s Hospital
Developmental Medicine Center
Laboratories of Cognitive Neuroscience

www.thegaablab.com
www.babymri.org