Promise & Pitfalls of Neuroeducation

John Gabrieli
Department of Brain and Cognitive Sciences &
Martinos Imaging Center at the
McGovern Institute for Brain Research, MIT
Science of Learning

NEW SCIENCE OF LEARNING

Psychology

Neuroscience

Machine Learning

Education

Meltzoff et al. Science 2009
Education and the Brain: A Bridge Too Far

John T. Bruer

Brain science fascinates teachers and educators, just as it fascinates all of us. When I speak to teachers about applications of cognitive science in the classroom, there is always a question or two about the right brain versus the left brain and the educational promise of brain-based curricula. I answer that these ideas have been around for a decade, are often based on misconceptions and overgeneralizations of what we know about the brain, and have little to offer to educators (Chapman, 1986). Educational applications of brain science may come eventually, but as of now neuroscience has little to offer teachers in terms of informing classroom practice. There is, however, a science of mind, cognitive science, that can serve as a basic science for the development of an applied science of learning and instruction. Practical, well-founded examples of putting cognitive science into practice already exist in numerous schools and classrooms. Teachers would be better off looking at these examples than at speculative applications of neuroscience.

The teachers' questions arise out of the perennial interest in the brain and neuroscience that has always existed at the margin of educational research and reform discussions. Recently, however, interest in how neuroscience might improve education has moved from the margins to center stage. Educators and education policy experts are the most vocal enthusiasts. Educational writers, likewise fascinated by the brain but puzzled by the mind, have picked up on this enthusiasm. Over the past year, there have been numerous books, journal articles, policy studies, and stories in the media about how our emerging understanding of brain development and neural function could revolutionize educational practice. Neuroscientists, while interested in how their research might find application outside the laboratory and clinic, are more guarded in their claims. Often, they are puzzled by the neuroscientific results educators choose to cite, by the interpretations educators give those results, and by the conclusions educators draw from them.

This article examines those results, interpretations, and conclusions—a set of claims that I will call the neuroscience and education argument. The negative conclusion is that the argument fails. The argument fails because its advocates are trying to build a bridge too far. Currently, we do not know enough about brain development and neural function to link understanding directly, in any meaningful, defensible way to instruction and educational practice. We may never know enough to be able to do that. The positive conclusion is that there are two shorter bridges, already in place, that indirectly link brain function with educational practice. There is a well-established bridge, now nearly 50 years old, between education and cognitive psychology. There is a second bridge, only around 30 years old, between cognitive psychology and neuroscience. This newer bridge is allowing us to see how mental functions map onto brain structures. When neuroscience begins to provide useful insights for educators about instruction and educational practice, those insights will be the result of extensive traffic over this second bridge. Cognitive psychology provides the only firm ground we have to anchor these bridges. It is the only way to go if we eventually want to move between education and the brain.

The Neuroscience and Education Argument

The neuroscience and education argument relies on and embellishes three important and reasonably well-established findings in developmental neurobiology. First, starting in infancy and continuing into later childhood, there is a dramatic increase in the number of synapses that connect neurons in the brain. This synaptic proliferation (synaptogenesis) is followed by a period of synaptic elimination. Second, there are experience-dependent critical periods in the development of sensory and motor systems. Third, in rats at least, complex, or enriched, environments cause new synapses to form.

The argument runs as follows. Starting in early infancy, there is a rapid increase in the number of synapses or neural connections in children's brains. Up to age 10, children's brains contain more synapses than at any other time in their lives. Early childhood experiences fine-tune the brain's synaptic connections. In a process that we might describe as synaptic pruning, childhood experiences reinforce and maintain synapses that are repeatedly used, but snip away the unused synapses. Thus, this time of high synaptic density and experiential fine-tuning is a critical period in a child's cognitive development. It is the time when the brain is particularly efficient in acquiring and learning a range of skills. During this critical period, children can benefit most from rich, stimulating learning environments. If, during this critical period, we deprive children of such environments, significant learning opportunities are lost forever. As one popular article put it, "with the right input at the right
THEORETICAL NOTE

The Practical and Principled Problems With Educational Neuroscience

Jeffrey S. Bowers
University of Bristol

The core claim of educational neuroscience is that neuroscience can improve teaching in the classroom. Many strong claims are made about the successes and the promise of this new discipline. By contrast, I show that there are no current examples of neuroscience motivating new and effective teaching methods, and argue that neuroscience is unlikely to improve teaching in the future. The reasons are twofold. First, in practice, it is easier to characterize the cognitive capacities of children on the basis of behavioral measures than on the basis of brain measures. As a consequence, neuroscience rarely offers insights into instruction above and beyond psychology. Second, in principle, the theoretical motivations underpinning educational neuroscience are misguided, and this makes it difficult to design or assess new teaching methods on the basis of neuroscience. Regarding the design of instruction, it is widely assumed that remedial instruction should target the underlying deficits associated with learning disorders, and neuroscience is used to characterize the deficit. However, the most effective forms of instruction may often rely on developing compensatory (nonimpaired) skills. Neuroscience cannot determine whether instruction should target impaired or nonimpaired skills. More importantly, regarding the assessment of instruction, the only relevant issue is whether the child learns, as reflected in behavior. Evidence that the brain changed in response to instruction is irrelevant. At the same time, an important goal for neuroscience is to characterize how the brain changes in response to learning, and this includes learning in the classroom. Neuroscientists cannot help educators, but educators can help neuroscientists.

Keywords: educational neuroscience, education, instruction, neuroscience, mind, brain, and education
COMMENTS

The Promise of Educational Neuroscience: Comment on Bowers (2016)

John D. E. Gabrieli
Massachusetts Institute of Technology

Bowers (2016) argues that there are practical and principled problems with how educational neuroscience may contribute to education, including lack of direct influences on teaching in the classroom. Some of the arguments made are convincing, including the critique of unsubstantiated claims about the impact of educational neuroscience and the reminder that the primary outcomes of education are behavioral, such as skill in reading or mathematics. Bowers’ analysis falls short in 3 major respects. First, educational neuroscience is a basic science that has made unique contributions to basic education research; it is not part of applied classroom instruction. Second, educational neuroscience contributes to ideas about education practices and policies beyond classroom curriculum that are important for helping vulnerable students. Third, educational neuroscience studies using neuroimaging have not only revealed for the first time the brain basis of neurodevelopmental differences that have profound influences on educational outcomes, but have also identified individual brain differences that predict which students learn more or learn less from various curricula. In several cases, the brain measures significantly improved or vastly outperformed conventional behavioral measures in predicting what works for individual children. These findings indicate that educational neuroscience, at a minimum, has provided novel insights into the possibilities of individualized education for students, rather than the current practice of learning through failure that a curriculum did not support a student. In the best approach to improving education, educational neuroscience ought to contribute to basic research addressing the needs of students and teachers.

Keywords: educational neuroscience, education, instruction, neuroscience, mind, brain, and education
Human Cognitive Neuroscience

• *Brain & Psychology*
  perception, learning & memory, thinking, emotion, social cognition

• *Brain & Mental Health*
  psychiatric disorders & neurodevelopmental disorders

• *Brain & Education*
Human Cognitive Neuroscience

• functional and structural neural architecture of the human brain
• variation of that architecture – development, personality, sex, culture, socioeconomic status
• differences of that architecture in neurodevelopmental and neuropsychiatric disorders

*but, whose life is better?*

Gabrieli et al., *Neuron*, 2015
Neuropsychiatric Diseases & Neuroimaging

• MRI studies 1995-2016 (PubMed)
  - about 20,000 publications

  schizophrenia – 5983
  depression – 6254
  anxiety – 3105
  autism – 1849
  ADHD – 1303
  dyslexia – 655
  OCD – 704
Neuropsychiatry & Neuroimaging & Genetics

DSM V – May 2013
Neuroeducation

• Basic neurocognitive research about learning

• Neurocognitive research about educational outcomes

• When brain measures outperform conventional behavioral measures
Biomedicine

Basic Research ↔ Clinical Care

academic medical centers
Education

Basic Research  ≠  Education

learning

psychology & neuroscience

education

schools of education
Education Research

**Inputs**
- Curriculum
- Teachers
- Class Size
- Technology
- Learning Time

**Outcomes**
- Test Scores
- Educational Attainment
Education Research
Inside the Student Mind & Brain

Cognition

Socio-Emotional
Declarative (Explicit) Memory
Neural Systems

- medial temporal lobe
- dorsolateral prefrontal cortex
Location of hippocampus
Hippocampus of Human Brain

a sea horse
THE AMNESIC PATIENT H.M.

1926  Birth
1942  Age 16, First major seizure
1953  Age 27, Bilateral medial temporal-lobe resection
1955  Report of pervasive and profound anterograde amnesia by Dr. Brenda Milner
1962  Neuropsychological examinations characterizing the amnesic syndrome

Figure 14.20 The hippocampus of H.M. The hippocampus (H) and entorhinal cortex (EC) are present in the brain of a normal subject (right), but absent bilaterally in the brain of H.M. (left).

> What were the consequences of bilateral removal of H.M.'s hippocampus? (p. 441)
HM: Global Anterograde Amnesia

- High Average Intelligence
- Intact Short Term Memory (7 digits)
- Normal Conversation, Math Performance
- Good Memory of Distant Past (his name, his school, his parents)
- Personality Maintained
- Unable to Acquire New Memories for Events & Facts (people, places, news)
  - all modalities
  - all materials (verbal & nonverbal)

Retrograde Amnesia → 1953 surgery → Anterograde Amnesia
Declarative (Explicit) Memory

Neural Systems

• dorsolateral prefrontal cortex
  (deficits in source, recency, frequency)
Stages of Memory

- Encoding
- Storage
- Retrieval

Behavior

Functional neuroimaging
Visual Encoding Task

“indoor or outdoor?”

Event

fixation point

15.84 s

Event

fixation point

2.88 s 10.08 s

Event

fixation point

24 events X 4 runs

Event

2.88 s 10.08 s

0 s 380 s
Event-Related Design For Subsequent Memory

Separate response recorded for each stimulus

Later memory test

Compare fMRI responses leading to successful vs unsuccessful memory encoding
Making Memories: Remembered > Forgotten

How do declarative memory systems develop in the brain?
Pediatric Neuroimaging
9.5 year old girl, scanned 3 times over 6 months

You have let me have more fun in 3 days than I could have in any other place. Just think of it! I'm playing a game when at the same time I'm a research ginny pig and who knows I might help someone else my age if they have any brain problems while still earning money. And what do you think beats that? Nothing. Thanks!
Experimental Design

Participants: 14 adults (ages 19-24 years), 35 children (ages 8-17 years)

Memory Task:

Encoding (scanned):
250 scenes

Recognition test: Item | Response | Condition
---|---|---
Old; Remembered | R
Old; Familiar | K
New | F
Development of Remembrance

**Recognition Performance**

![Graph showing the correlation between age and recognition performance. The Pearson's correlation coefficient (r) is 0.29*, p < 0.05.](image)

**Corrected 'hit' score**

![Graph showing the correlation between age and corrected 'hit' score. The Pearson's correlation coefficient (r) is 0.33*, p = 0.02.](image)

"R"  
$r = 0.33^*, p = 0.02$

"K"  
$r = -0.01, n.s.$
Remembered > Forgotten

Ofen et al., *Nature Neuroscience*, 2007
Neuroeducation

- Basic neurocognitive research about learning

- Neurocognitive research about educational outcomes

- When brain measures outperform conventional behavioral measures
Global Income Inequality
Widening Academic Achievement Gap Between the Rich and the Poor

Income Achievement Gap and Black-White Achievement Gap
Reading, 1943-2001 Birth Cohorts

Source: Reardon (2011)
SES & Educational Attainment

High-Stakes Statewide Standardized Tests

Massachusetts Comprehensive Assessment System
MCAS – Math & ELA
Grey Matter = Cell Bodies
White Matter = Myelinated Axons
Cortical Thickness Analysis
Greater Cortical Thickness Correlates with Better Standardized Test Scores

Mackey et al., *Psychological Science*, 2015
Greater Cortical Thickness With Higher SES (Paid Lunch > Free Lunch)

Mackey et al., Psychological Science, 2015
Similar Patterns of Relative Thickness Across the Brain in Lower (LI) and Higher (HI) SES Students

LI  |  Left  |  HI
---  |  ---  |  ---
\[\text{Images of brain sections for LI and HI on the left.}\]

Right

LI  |  Right  |  HI
---  |  ---  |  ---
\[\text{Images of brain sections for LI and HI on the right.}\]

\[\text{Histograms showing the number of vertices at different thicknesses for LI and HI.}\]
No SES Effects on Cortical Surface Area or White-Matter Volume

*** p = .001
Developmental Brain Changes in Cerebral Cortex

Gogtay et al., *PNAS*, 2004
Cortical Brain Growth Thinning
Ages 4-21

Gogtay et al., PNAS, 2004
A Paradox

• higher SES is most often associated with *thicker or greater cortex* (this study; Hanson et al., 2013; Jednoróg et al., 2012; Lawson et al., 2013; Noble et al., 2012, 2015; Hair et al., 2015; Betancourt et al., 2015)

• in other studies in which SES is not considered (higher SES?) *thinner cortex* associated with better neuropsychological functioning (Schnack et al., 2014; Squeglia et al., 2013)

• is accelerated thinning detrimental or adaptive or both?
Executive Functions, Schools, and Academic Achievement

Executive Functions
(cognitive control, supervisory attentional system)
regulation/management of cognitive (& emotional) processes
- working memory
- reasoning
- flexibility
- problem solving
- planning & execution of plan

Academic Achievement
scores on statewide standardized tests
Executive Function as a Mediator Between SES & Academic Achievement Throughout Childhood

parental education and family income and changes in reading and math achievement in a sample of 336 children between the ages of 6 and 15 years from the NIH MRI Study of Normal Brain Development

Path output with standardized estimates and 95% confidence intervals for the Full Model

Gwendolyn M Lawson, and Martha J Farah International Journal of Behavioral Development 2015;0165025415603489
Meta-Analysis of 189 Neuroimaging Studies of Working Memory

Rottschy et al., *NeuroImage*, 2012

activation for fluid reasoning (Prabhakaran et al., *Cognitive Psychology*, 1997)
Working Memory, Brain, & MCAS

- diverse sample of 53 8th graders
- N-Back test of working memory capacity
N-Back Performance

Finn et al., Developmental Science, 2016
Greater Activation in Prefrontal & Parietal Neocortices with Greater Working Memory Demand

Finn et al., *Developmental Science*, 2016
Greater Working Memory Activation Associated With Higher MCAS Math Test Scores

Finn et al., Developmental Science, 2016
Greater Activation in High-Than Low-Income Students in Response to Increasing WM Demands

Finn et al., Developmental Science, 2016
Executive Functions, Schools, and Academic Achievement

• 1,367 8th graders in 32 middle school in Boston Public Schools
  - 47% male, 77% free-lunch eligible
  - 41% African-American, 36% Hispanic, 12% White

• MCAS scores (Math & ELA) from 4th and 8th grades

• three measures of executive function
  - fluid reasoning
  - working memory capacity
  - processing speed

Finn et al., Psychological Science, 2014
Processing Speed
Working Memory
Working Memory
Answer?
Answer?

6 7 4
Fluid Reasoning
Schools Vary In Raising Test Scores

- student growth percentile

### MCAS ELA

- **Charter**
- **Traditional**
- **Exam**

### MCAS Math

- **Charter**
- **Traditional**
- **Exam**
Schools Influence Test Gains, But Not Executive Functions

% Variance explained by school

- Math: 34.4%
- ELA: 23.6%
- PS: 6.7%
- WM: 1.1%
- FR: 1.3%
- Composite: 2.3%

Finn et al., *Psychological Science*, 2014
• Brain differences associated with academic achievement or SES can reflect genetics, environment, and gene x environment interactions
• Brain differences do NOT indicate fixed biological or cognitive differences
• Brain is plastic
Early Language Experience

SES is strongly correlated with children’s language exposure = “30 million word gap” (Hart & Risley 1995)

Great variability in language exposure even within SES groups (LENA Natural Language Study, 2006)
LENA = Language ENvironment Analysis

- Small, child-worn recorder than can hold a whole day’s worth of audio (≥16 hours)
- Software automatically analyzes recordings and determines:
  - How many “adult words” the child heard
  - How many “child vocalizations” the child said
  - How many “conversational turns” occurred between the child and any adult
SES “gaps” in Vocabulary & Words Heard

$n = 60$ children ages 4-6 years

Romeo et al., SfN 2016

**Word Gap**

$r = 0.32$

$p < 0.01$

**Vocabulary Gap**

$r = 0.63$

$p < 0.001$
Language Exposure and the Brain

- fMRI: heard simple stories; forward > backwards speech
- correlation with conversational turns independent of SES

Region of significant correlation (pars triangularis + pars opercularis)

Two girls, same age & SES
Top hears >1000 CTs per day
Bottom hears < 500 CTs per day

Romeo et al., SfN 2016
Neuroeducation

- Basic neurocognitive research about learning
- Neurocognitive research about educational outcomes
- When brain measures outperform conventional behavioral measures
DEVELOPMENTAL DYSLEXIA

- unexplained difficulty in reading
  in 5 to 10% of children
Natural Development of Spoken & Heard Language
Learning to Read: Formal, Explicit Instruction
### UNITS OF WRITTEN & SPOKEN LANGUAGE

<table>
<thead>
<tr>
<th>Item</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pictures</td>
<td><img src="image.png" alt="Picture" /></td>
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<table>
<thead>
<tr>
<th>Words</th>
<th>Book</th>
<th>Scarf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphemes</td>
<td>B</td>
<td>OO</td>
</tr>
<tr>
<td>Phonemes</td>
<td>/b/</td>
<td>/oo/</td>
</tr>
</tbody>
</table>

**Phonemes** - smallest linguistic units of sound  
**Graphemes** - letter or letters  
45 phonemes in English  
Learning to read is learning to map phonemes onto graphemes via **phonological awareness**
DYSLEXIA: CAUSES

• Phonological Hypothesis
deficit in processing of speech sounds
  poor grapheme-phoneme mapping

• Fluency

• Lower-level perceptual processes (?)
### PARTICIPANTS

<table>
<thead>
<tr>
<th></th>
<th>Normal Reading Children</th>
<th>Dyslexic Reading Children</th>
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</thead>
<tbody>
<tr>
<td>Sample</td>
<td>N=23</td>
<td>N=22</td>
</tr>
<tr>
<td>Age</td>
<td>10.5 (1.9)</td>
<td>10.8 (0.9)</td>
</tr>
<tr>
<td>Non-Verbal IQ</td>
<td>13.4</td>
<td>11.3</td>
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<tr>
<td>Word Reading</td>
<td>108.7</td>
<td>78.9</td>
</tr>
<tr>
<td>Decoding</td>
<td>110.3</td>
<td>86.2</td>
</tr>
<tr>
<td>Comprehension</td>
<td>110.8</td>
<td>85.6</td>
</tr>
</tbody>
</table>

Temple et al., *PNAS*, 2003
Phonological Processing Task

- Rhyme Letters: 0 - 18 seconds
- Match Letters: 18 - 36 seconds
- Match Lines: 36 - 54 seconds

- 5 pairs of stimuli / block
- 6 blocks / condition
- Total scan time = 4.5 minutes
PHONOLOGICAL PROCESSING

Typical Children

Dyslexic Children

Temple et al., PNAS, 2003
Reduced Response for Phonological Analysis of Print In Dyslexia
Brain Plasticity Associated With Effective Remediation In Children with Dyslexia

computer-based training for poor readers

Temple at al., PNAS, 2003; PNAS; Gabrieli, Science, 2009
Brain Effects of Training: Phonological Processing

Compensation & Normalization
Prediction vs. Correlation

• Correlations are usually “overly optimistic”
  - weak relation from one sample to another
• Predictions aim to generalize across samples and to yield single-subject values
  (e.g., leave-one-out cross validation in which each subject’s prediction is based on model from other subjects, independent samples)
Neuroprediction

• most group comparisons are based on group *homogeneity*; neuroprediction based on *heterogeneity* (*diversity*)

• brain mechanisms for prediction reflect *brain’s capacity to respond to education*, may or may not reflect pathophysiology or plasticity in response to treatment
Predicting Compensation in Dyslexia

• some children compensate, some children do not compensate
• what is the brain basis of compensation? more like typical development? an alternative brain pathway?
• who compensates? who does not compensate?

Hoeft et al., PNAS, 2011
Phonological Awareness for Print

Do the two words rhyme?

light & bite -> YES, RHYME
roof & soft -> NO, DON’T RHYME
Predicting Compensation in Dyslexia

• 25 children with dyslexia, 20 typically reading children
• Time 1 – fMRI on visual rhyme task of phonological ability, DTI, 17 behavioral measures (language, reading, IQ, others)
• 2.5 years
• Time 2 – reading scores
Compensation in Dyslexia Over 2.5 Years

**Diagram:**

**A**
- Single Word Reading (WRMT-WID[ssl])
- Time 1 vs. Time 2
- **Compensated**
- **Not Compensated**
- Control data

**B**
- Comprehension (WRMT-PC[ssl])
- Time 1 vs. Time 2
- **Compensated**
- **Not Compensated**
- Control data

**Legend:**
- Red: Compensated
- Blue: Not Compensated
- Black: Controls
- Green: Norm (ss=100)
- Green dashed: 1SD below norm (ss=85)
Activation in Right Frontal Cortex Predicts Compensation

Hoeft et al., PNAS, 2011
Predictors of Future Reading Ability: Diffusion Tensor Imaging (DTI) Measure of Superior Longitudinal Fasciculus Organization

![Graphs showing relationships between reading gain, fMRI activation, and SLF White Matter Integrity for Right and Left IFG.](image-url)
Typical Maturation of Reading Network for Phonological Awareness for Print
Typical Maturation of Reading Network for Phonological Awareness for Print
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Typical Maturation of Reading Network for Phonological Awareness for Print
Activation in Right Frontal Cortex Predicts Compensation

Hoeft et al., *PNAS*, 2011
Multivoxel Pattern Analysis (Support Vector Machine)
Predicting Compensation in Dyslexia

• none of 17 behavioral measures predicts reading gains 2.5 years later, alone or in combination

• greater activation in right frontal cortex predicts compensation & greater white matter integrity in right superior longitudinal fasciculus - 72%

• multivoxel pattern analysis - 92%
Neural Predictors of Individual Differences in Response to Math Tutoring in Primary-Grade School Children

24 children in grade 3
progress not correlated with baseline behavioral measurea including IQ, working memory, math ability

Supekar et al., PNAS, 2013
Neuroeducation

• Basic neurocognitive research about learning
• Neurocognitive research about educational outcomes
• When brain measures outperform conventional behavioral measures

Individuated education; prediction (prevention not failure); most relevant for learning difficulties?
Collaborators & Support

• **Income-Achievement Gap**
  
  Amy Finn
  Chris Gabrieli
  Martin West
  Mathew Kraft
  Allyson Mackey
  Julia Leonard
  Rachel Romeo

• **Dyslexia**
  
  Elise Temple
  Russ Poldrack
  Fumiko Hoeft

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