The Neural Bases of Mathematics: Findings Relevant to Education

Sashank Varma
University of Minnesota
1997-1998

1997-2003

1997-2006


Brain Food
Brain Food
What is your best rhythm and timing for learning?

Find your PACE

energetic
Water
Brain Buttons

active
The Cross Crawl
Hook-ups

clear
positive
“The Love Area”
“The Cola Area”
Outline

• fMRI

• Number
• Arithmetic
• Development
• Learning and transfer
• SES and math games
• Dyscalculia
• Cultural differences

• Conclusion
Outline

• fMRI

• Number
• Arithmetic
• Development
• Learning and transfer
• SES and math games
• Dyscalculia
• Cultural differences

• Conclusion
Magnetic Resonance Imaging (MRI)
Vasculature
functional MRI (fMRI)

We sort of understand this (neurophysiology)

(1) Neuronal activity

↑ neural activity
We sort of understand this (neurophysiology) \rightarrow \text{(1) Neuronal activity}

We’re only starting to understand this \rightarrow \text{(3) Haemodynamic response}

Stimulus or modulation in background \rightarrow \text{(2) Neurovascular coupling}

↑ neural activity \rightarrow \uparrow \text{ blood oxygen}
We sort of understand this (neurophysiology)

We’re only starting to understand this

We sort of understand this (MR Physics)

↑ neural activity ➔ ↑ blood oxygen ➔ ↑ fMRI signal
MRI vs. fMRI
MRI vs. fMRI
Outline

- fMRI
- Number
  - Arithmetic
  - Development
  - Learning and transfer
  - SES and math games
  - Dyscalculia
  - Cultural differences
- Conclusion
Symbolic Numbers as Magnitudes

Moyer & Landauer (1967)
Symbolic Numbers as Magnitudes

Moyer & Landauer (1967)
Symbolic Numbers as Magnitudes

Moyer & Landauer (1967)
Symbolic Numbers as Magnitudes

Moyer & Landauer (1967)
Development of Symbolic Number Magnitudes

Sekuler & Mierkiewicz (1977)
Development of Symbolic Number Magnitudes

Sekuler & Mierkiewicz (1977)
Neural Bases (of Development) of Symbolic Number

Adults

10 Year Olds

neural distance effect

Ansari et al. (2005)
Neural Bases (of Development) of Symbolic Number

Adults

10 Year Olds

neural distance effect; adults R. IPS, L. MFG

Ansari et al. (2005)
Neural Bases (of Development) of Symbolic Number

Adults

10 Year Olds

neural distance effect; adults R. IPS, L. MFG; children R. IFG. R. precentral gyrus

Ansari et al. (2005)
Non-Symbolic Number (Numerosity)

Ansari & Dhital (2006)
Non-Symbolic Number (Numerosity)

Large (3 vs. 8)

Small (5 vs. 7)

non-symbolic distance effect

Ansari & Dhital (2006)
Non-Symbolic Number (Numerosity)

- Large (3 vs. 8)
  - Non-symbolic distance effect; adults: bilateral IPS

- Small (5 vs. 7)

Adults

Ansari & Dhital (2006)
Non-Symbolic Number (Numerosity)

Adults

Large (3 vs. 8)

Small (5 vs. 7)

10 Year Olds

non-symbolic distance effect; adults: bilateral IPS; children: L. IPS (but less than adults)

Ansari & Dhital (2006)
Outline

• fMRI

• Number
• Arithmetic
• Development
• Learning and transfer
• SES and math games
• Dyscalculia
• Cultural differences

• Conclusion
Subtraction and Multiplication Areas

Subtraction (4-2=?)

Multiplication (4×2=?)
Subtraction and Multiplication Areas

Subtraction (4-2=?)

Dehaene et al. (2003)
Subtraction and Multiplication Areas

Subtraction (4-2=?)

Multiplication (4×2=?)

Dehaene et al. (2003)
Subtraction and Multiplication Areas

Subtraction (4-2=?)

Multiplication (4×2=?)

1D; IPS; AG

Dehaene et al. (2003)
Subtraction and Multiplication Areas

Subtraction (4-2=?)

Multiplication (4×2=?)

1x1=1 1x2=2 1x3=3
2x1=2 2x2=4 2x3=6
3x1=3 3x2=6 3x3=9
4x1=4 \textbf{4x2=8} 4x3=12
5x1=5 5x2=10 5x3=15

1D; IPS; AG

Dehaene et al. (2003)
Retrieval and Procedural Areas

Retrieval > Procedural

Procedural > Retrieval

1D arithmetic (all 4 operations)  
Grabner et al. (2009)
Retrieval and Procedural Areas

Retrieval > Procedural

Procedural > Retrieval

1D arithmetic (all 4 operations); L. AG

Grabner et al. (2009)
Retrieval and Procedural Areas

Retrieval > Procedural

Procedural > Retrieval

1D arithmetic (all 4 operations); L. AG; L. IPS

Grabner et al. (2009)
“The Retrieval Area” and Individual Differences

1D x 1D and 2D x 1D problems; high vs low mathematical competence; L. AG

Grabner et al. (2007)
“The Retrieval Area” and Individual Differences

1D x 1D and 2D x 1D problems; high vs low mathematical competence; L. AG

Grabner et al. (2007)
“The Retrieval Area” and Individual Differences

1D x 1D and 2D x 1D problems; high vs low mathematical competence; L. AG

Grabner et al. (2007)
Outline

- fMRI
- Number
- Arithmetic
- Development
- Learning and transfer
- SES and math games
- Dyscalculia
- Cultural differences
- Conclusion
<table>
<thead>
<tr>
<th>Accuracy</th>
<th>Speed</th>
</tr>
</thead>
</table>

age 8-19; addition and subtraction

Rivera et al. (2005)
Shifting Networks with Development

age 8-19; addition and subtraction; $r=ns$
Shifting Networks with Development

Accuracy

Speed

age 8-19; addition and subtraction; $r=ns$; $r=-0.68$

Rivera et al. (2005)
Shifting Networks with Development

Decreasing
with Development

Increasing
with Development

Rivera et al. (2005)
Shifting Networks with Development

Decreasing w/ Development

Increasing w/ Development
Shifting Networks with Development

Decreasing w/ Development

Increasing w/ Development

MFG, ACC, MTL; SMG, FG

Rivera et al. (2005)
Outline

• fMRI
• Number
• Arithmetic
• Development
• Learning and transfer
• SES and math games
• Dyscalculia
• Cultural differences
• Conclusion
Practice Effects

Decreasing with Practice

Increasing with Practice
practice 2D x 1D problems; imaged on practiced and unpracticed problems; IPS

Delazer et al. (2003)
Practice Effects

Decreasing with Practice

Increasing with Practice

1x1=1 1x2=2 1x3=3
2x1=2 2x2=4 2x3=6
3x1=3 3x2=6 3x3=9
4x1=4 4x2=8 4x3=12
5x1=5 5x2=10 5x3=15

practiced 2D x 1D problems; imaged on practiced and unpracticed problems; IPS; AG

Delazer et al. (2003)
Practice and Transfer Effects

practiced 2D x 1D problems; imaged on practiced and unpracticed multiplication, related and unrelated division

Ischebeck et al. (2009)
Practice and Transfer Effects

practiced>unpracticed multiplication: L. AG, precuneus

Ischebeck et al. (2009)
Practice and Transfer Effects

practiced > unpracticed multiplication: L. AG ROI (peak voxel -39, -69, 51)
Practice and Transfer Effects

practiced>unpracticed multiplication, related>unrelated division: L. AG ROI

Ischebeck et al. (2009)
Outline

• fMRI

• Number
• Arithmetic
• Development
• Learning and transfer
• SES and math games
• Dyscalculia
• Cultural differences

• Conclusion
middle- and low-income kindergarteners same on non-verbal problems, differ on verbal/symbolic problems  

Jordan et al. (1992)
Training Number Sense in Low SES Children

The Number Board Game:

Spin spinner and move piece either counting on the numbers (top)...

Ramani & Siegler (2008)
Training Number Sense in Low SES Children

The Number Board Game:

Spin spinner and move piece either counting on the numbers (top) or the colors (bottom)  

Ramani & Siegler (2008)
Training Number Sense in Low SES Children

4 and 5 year olds in Head Start; 1 hour practice over 4 sessions; follow-up 9 weeks later

Ramani & Siegler (2008)
Training Number Sense in Low SES Children

4 and 5 year olds in Head Start; 1 hour practice over 4 sessions; follow-up 9 weeks later

Ramani & Siegler (2008)
Training Number Sense in Low SES Children

Ramani & Siegler (2008)

4 and 5 year olds in Head Start; 1 hour practice over 4 sessions; follow-up 9 weeks later
Outline

• fMRI
• Number
• Arithmetic
• Development
• Learning and transfer
• SES and math games
• Dyscalculia
• Cultural differences

• Conclusion
Dyscalculia

- Defined by low mathematical ability in the context of otherwise normal intelligence, academic achievement, and access to educational resources
- Prevalence: 3-6%
- Neuroscientists are only beginning to identify the neural bases of dyscalculia
Dyscalculia and Arithmetic

approximate arithmetic task

Kucian et al. (2006)
Dyscalculia and Arithmetic

Kucian et al. (2006)

approximate arithmetic task
Dyscalculia: Number Symbols → Numerosities

Large (3 vs. 8)

Small (5 vs. 7)

non-symbolic distance effect

Price et al. (2007)
Dyscalculia: Number Symbols $\rightarrow$ Numerosities

non-symbolic distance effect: normal $>$ dyscalculic

Price et al. (2007)
Dyscalculia: Number Symbols → Numerosities

non-symbolic distance effect: normal > dyscalculic

Price et al. (2007)
Outline

• fMRI

• Number
• Arithmetic
• Development
• Learning and transfer
• SES and math games
• Dyscalculia
• Cultural differences

• Conclusion
<table>
<thead>
<tr>
<th>Cultural Differences in Mathematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>English Speakers</td>
</tr>
</tbody>
</table>

Tang et al. (2006)

comparison, addition
Cultural Differences in Mathematics

English Speakers

Chinese Speakers

comparison, addition; English: Broca, Wernicke

Tang et al. (2006)
Cultural Differences in Mathematics

English Speakers

Chinese Speakers

comparison, addition; English: Broca, Wernicke; Chinese: PMA, SMA

Tang et al. (2006)
Outline

• fMRI

• Number
• Arithmetic
• Development
• Learning and transfer
• SES and math games
• Dyscalculia
• Cultural differences

• Conclusion
Conclusion

• Neuroscience is informing many other areas of mathematical thinking:
  – Infant and pre-school mathematics: numerosity, counting
  – Intermediate mathematics: integers, fractions, place value
  – Advanced mathematics: algebra, geometry, calculus
  – Patient mathematics: acalculia, Gerstmann’s syndrome
  – Prodigies and mathematicians
  – Primate mathematics
  – etc. etc. etc.
Education and the Brain: A Bridge Too Far

Pedagogy Meets Neuroscience

Scientific and Pragmatic Challenges for Bridging Education and Neuroscience

Sashank Varma, Bruce D. McCandliss, and Daniel L. Schacter

Educational neuroscience is an emerging effort to integrate neuroscience methods, particularly functional neuroimaging, with behavioral methods to address issues of learning and instruction. This article summarizes common concerns about converging education and neuroscience. One set of concerns is scientific and epistemological, in which the results of neuroscience are seen as providing evidence and methods that are not relevant to education. The goal is to foster education neuroscience as a conversation between contemporary neuroscience and pedagogy to identify and develop specific strategies to bridge the gap between education and neuroscience.

KEYWORDS: brain development, education, education neuroscience, neuroscience, teaching

Neuroscience has experienced rapid growth in recent years, encouraged in part by the U.S. government's designation of the 1990s as the "Decade of the Brain." (Maclean, 1999). The rapid development of functional neuroimaging techniques has granted neuroscience unprecedented access to the functionality of healthy children and adults. The result has been a wave of new insights into thinking, emotion, motivation, learning, and development. As these insights affect the social sciences, they sometimes inspire misunderstanding of existing methodologies. This is more true in pedagogy, as noted by the Flavors of cognitive neuroscience, Elliott, Boykin, & McGonigle, 2002, developmental neuroscience (Johnson, Mandera, & Gibson, 2003), and social neuroscience (Cacioppo, Yee, & Stolorow, 2002). It is increasingly true in economics, where the rapid rise of neuroscience (Curtain, Lerner, & Stolarow, 2003) has caught the attention of the private press (Faulk, 2006). Other social sciences, including communication (Baldwin et al., 2002), public science (McDonnell, 2006), and sociology (Walter, 2006), are just beginning to confront the question of whether their research can be informed by neuroscience.

Education is somewhat between the two poles of early adopters and innovative researchers. A discussion in the journal Brain (1997) briefly considered the relevance of neuroscience to education. The conclusion: "That neuroscience is "a bridge too far" was universally because Brain was then director of the McArthur Foundation, which was actively funding research in both disciplines. Although it is in its best interest to find some connections between the disciplines, its funding policy (Youlton & Cook, 2006; Byros & Fox, 1998; Gage & Gage, 2003; Gage, 2003; Patton & Stanfield, 2003) is a book and in the book itself never appeared (Halpern & Firth, 2003).

In this article, we suggest that it is quite general between the various paradigms of brain and the opinions of those who followed. Table 1 (summary of research done about converging education and neuroscience) is drawn from Brain (1997) and the following neuroscience. Others come from neuroscience with collaborators in both disciplines, and still others from our own experience. These concerns do not seem to suggest a unified framework but rather a greater diversity (perhaps a healthy skepticism) about the implications of neuroscience for education. We begin by introducing the concerns along with some new evidence about neuroscience that makes the concerns more concrete. We then offer some general framework in which we have heard them expressed. We then offer some general framework in which we have heard them expressed. We then offer some general framework in which we have heard them expressed. We then offer some general framework in which we have heard them expressed. We then offer some general framework in which we have heard them expressed. We then offer some general framework in which we have heard them expressed.
Education and the Brain: A Bridge Too Far

Neuroscience in Middle Schools: A Professional Development and Resource Program That Models Inquiry-Based Science Classrooms

Carrie M. Chinn
David C. Berliner

*Department of Teaching and Learning*

University of Washington

**Pedagogy Meets Neuroscience**

Sushank Varma, Bruce D. McCandliss, and Daniel L. Schwartz

Educational neuroscience is an emerging effort to integrate neuroscience methods, particularly functional magnetic resonance imaging, with behavioral methods to address issues of learning and instruction. This interdisciplinary approach recognizes that both brain and behavior are essential to understanding how people learn and how instruction can be improved. This chapter reviews the current research in educational neuroscience and discusses the implications for education. It also provides a framework for future research in educational neuroscience.

**Scientific and Pragmatic Challenges for Bridging Education and Neuroscience**

Educational neuroscience is a rapidly growing field that is increasingly being applied in educational settings. This chapter identifies some of the key challenges and opportunities for bridging education and neuroscience, including the need for more rigorous research, the importance of interdisciplinary collaboration, and the need for more effective dissemination of research findings. It also highlights some of the successful applications of educational neuroscience in the classroom and discusses the potential for future developments.

**The Learning Brain: Lessons for Education**

Sarah-Jayne Blakemore and Uta Frith

The Learning Brain

Understanding the Brain: The Birth of a Learning Science

COGNITIVE DEVELOPMENT

The Human Brain

Educating the Human Brain

Michael J. Posner and Mary K. Rothbart