Educational Neuroscience: A field between false hopes and realistic expectations

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Research on Learning and Instruction
Evolutionary perspective on humans: Brain of stoneage people but can nonetheless construct and use computers
The miracle of condensed learning through schooling

Years ago some fundamental steps were made in Human intellectual development

- 40.000: Last fundamental changes in genes that guide brain development
- 5.000: Use of script
- 3000: Use of number symbols
- 2200: Concept of density (Archimedes)
- 800: Arabic number system common in Europe
- 400: Analytic geometry (Descartes)
- 300: Laws of mechanics (Newton)
What enables most humans to acquire script and mathematics within few years?

- We do not enter the world with a brain that resembles an empty vessel
- Our brain is prepared for an (almost) effortless learning of the basic principles of the physical and social world: **Core knowledge** (instinct)
- And we do NOT know this from brain research but from infancy research starting in the late 1980th using the violation of expectation paradigm (Baillargeon, Spelke, Carey, Wynn...).
What enables most humans to acquire script and mathematics within few years?

- Language and unique working memory functions make us competent
- As a consequence, we are better than any other species in connecting originally independent core knowledge for constructing complex competencies
- Literacy: Core knowledge for object recognition and sound differentiation are combined (Neural Recycling hypothesis)
- Mathematics: combining the approximate number system, which allows the rough representation of larger sets of discrete objects with the core system of exact small-number representation exact representations of small sets
Cultural tools needed for recycling ancient functions

morpho syllabic
CIV : XXVI =

104 : 26 =

Challenges that require teacher-guided conceptual restructuring:

\[ \frac{2}{4} + \frac{1}{3} \neq \frac{3}{7} \]

\[ \frac{6}{7} > \frac{6}{8} \]
Proportional Reasoning  $a/b = c/d$
Proportional Reasoning  \( \frac{a}{b} = \frac{c}{d} \)

More is not always more.
It is the ratio, not the difference.

Which of both mixtures will have a stronger taste of orange?
Or do both taste the same?
Imagine the following study:

- 40 students, around 12 years old, end of 5th grade, same school in a middle class neighborhood
- All children had the same math teachers during their entire school career
- The children get a test on proportional which contains 6 items, with 3 of them requiring the understanding of multiplicative relationships (full proportional reasoning)
Results

- 20 of the 40 children have an understanding of multiplicative relationships, 15 of them a robust one
- Half of the children do not have an understanding of multiplicative relationships
- All differences have to be traced back to individual characteristics
Why do students differ in proportional reasoning (PR)

- **Piagetian view:** PR requires the transition from the concrete operational to the formal operational stage
- **Neo-Piagetian view:** Limits on working memory functions hamper complex mental operations required for PR
- **Psychometric View:** The more intelligent a student is, the earlier s/he acquires PR
- **Cognitive Constructivist view:** PR emerges by extending and restructuring prior conceptual and procedural mathematical knowledge
- **Neuroscientific view:** PR requires particular structural and functional characteristics of the brain
Evidence for the Piagetian view

- Developmental coincidence with other formal reasoning abilities, e.g., Control of Variables Strategy or Deductive Reasoning
- Formal reasoning strategies do emerge spontaneously at age 10-13 without direct instruction
- Weakness of the view:
  - Stage theories do not model the dynamics of development
  - Formal reasoning is highly content-specific
Evidence for the Neo-Piagetian view

- Developmental coincidence of working memory functions and PR (both competencies boost simultaneously)
- Correlations of .30-.40 between PR and WM-batteries around age 12
Evidence for the Psychometric view

- Correlations of .40-.50 between IQ and PR at age 12-15
Evidence for the cognitive constructivist view

- Prior knowledge is the best predictor of future learning
- Longitudinal studies show strong relationships between early mathematical competencies and (kindergarten, elementary school) on proportional reasoning and understanding fractions
- Condensed knowledge (chunks, facts, procedures) relieves working memory resources
- Relational number concept that goes beyond the counting function of numbers is the precondition for understanding proportions and fractions
- Number line concept, arithmetic word problems that deal with the quantitative comparison
Quantitative comparison, seriation, number line

Sally’s house is 12 meters tall. Her school is 30 meters tall. She says that her school is about twice as tall as her house.

Do you agree or disagree with Sally? Explain.
Performance in relational quantitative reasoning at age 5 can better account for mathematical performance in grade three than simultaneously measured IQ.

**Domain-specific knowledge matters**

Explaining variance in PR at the age of 12: Best guess of the results of a regression analysis

<table>
<thead>
<tr>
<th>Test</th>
<th>% explained incremental Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tests on relational number understanding at age 7-9</td>
<td>50</td>
</tr>
<tr>
<td>Intelligence test age 12</td>
<td>10</td>
</tr>
<tr>
<td>Working memory battery age 12</td>
<td>-</td>
</tr>
<tr>
<td>Formal reasoning problems age 12</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>60</td>
</tr>
</tbody>
</table>
Advice for teachers when dealing with PR

- **Piagetian view**: Don’t teach PR before students reach the formal operational stage. Forget it.

- **Neo-Piagetian view**: Consider cognitive load when teaching proportions, promote chunking and automation to better exploit working memory.

- **Psychometric View**: Be aware of individual differences within each age group (some 8 year old understand it, while other 15 year olds still have difficulties).

- **Cognitive Constructivist view**: Promote conceptual change for numbers and mathematical operations by presenting problems that go beyond the counting function of numbers. Once students have understood principles, foster deliberate practice in order to condense knowledge.
Behavioral psychological and educational research is ready for supporting a worldwide implementation of improved math curricula

To be expected effects on proportional reasoning at age 12

Conventional curriculum

Improved curriculum
Evidence for the Neuroscience view: Brain Imaging while solving mathematical problems

- Electroencephalography (EEG)
- Near Infrared Spectroscopy (NIRS)
- Functional magnetic resonance imaging (fMRI)
The Mathematical Brain

- Number problems are ideal for Brain Imaging Research
- Parts in the brain are specialized on number processing
When children suffering from dyscalculia are presented with arithmetic problems

- They show less activation in the «numerical brain areas»

- They show more activation in the frontal lobe because they have not constructed a Numerical network that allows fact retrieval and quick inference
The Left Angular Gyrus

- Fact retrieval vs computation in 2-digit multiplication problems (a training study)
- Neural underpinnings of fact retrieval: Activation in the Roland Grabner, now University of Graz
What will neuroscientists do with our PR sample?

- fMRI during problem solving
- Split PR-score by median
- Present the sample with multiplication problems and with conflicting PR-problems
Results to be expected

- **Multiplication problems:** High PR-achievers will show less frontal lobe activation and more Left Angular Gyrus activation than low achievers do.

- **Difficult PR-problems:** High PR-achievers will show more frontal lobe activation than low achievers because they recognize the conflict between difference and ratio.
Expensive but interesting confirmation of what we already know from behavioral results

- The statistical power of the brain-data is much lower than the power of the behavioral data (IQ, Math test), therefore median split rather than correlational analysis was conducted. This is a usual procedure in high impact journals in neuroscience, although not accepted by journals dealing with learning and education.

- Behavioral learning research helped neuroscientists to make progress in understanding the human brain.
Unfortunately that is not enough for many Neuroscientists  
(some with poor, others with good reputation in their field)

- They feel called to advise teachers on how to improve schooling
- Teachers, educational decision makers, and journalists hang on their lips
- Many of them are not even aware of behavioral educational research
- Concerns from educational scientists are more than wounded vanity
What many neuroscientists would advise to improve PR can be very different from what cognitive constructivists recommend:

- When faced with conflicting PR-problems, high achievers will show more frontal lobe activation than low achievers.
- Frontal-lobe = executive functions (EF).
- Insufficient EF is the real problem of low achievers, so let’s train them.
Numerous studies on training working-memory (summarized in several meta analyses) failed to demonstrate transfer effects of training working memory.

These trainings only produces task-specific effects, or at the most near transfer.

To date this does not prevent Neuroscientists (and unfortunately also some experimental Psychologists) from recommending trainings of working memory functions.

They should know it better: The brain is not a muscle.
When Neuroscientists deal with fractions


- The authors found: When adults faced with fractions in the scanner, «the anterior intraparietal sulcus is activated, a key region for the processing of whole numbers. These findings demonstrate that the human brain uses the same analog magnitude code to represent both absolute and relative quantity»

- “These experiments change the way we should think about fractions. We have shown that our highly-trained brains represent fractions intuitively, a result that could influence the teaching of arithmetic and mathematics in schools”

- Message: Knowledge about fractions is already in the brain, but mathematics teachers are unable to activate it
Why at Educational Neuroscience makes dangerous

- Domain specific knowledge is either ignored or marginalized
- Brain activation is considered a cause rather than a correlate of learning
- Fallacy: Whatever stimulates brain activation improves learning
Transcranial electrical stimulation

Electric current to the brain ‘boosts maths ability’

Image courtesy of the BBC

Roi Cohen Kadosh
Educational neuroscience as a field

- It emerged around 1995 and the focus was on early education and on aging
- Web of Science: (neuroscience OR brain) AND education 1995-october 2015: 32,544 articles
- In 2015: 1,471
- < 5000 behavioral articles
Problems

- Methodological standards of high-impact journals with «neuroscience» in the title are different from behavioral journals
- Small n, not enough power for appropriate statistical analyses
- Samples are neither described in detail nor justified (convenience research)
- Problems to be presented during brain imaging have to be simple and they have to be presented repeatedly
- Neural correlates of condensing knowledge (chunking, automating) can be identified, while meaningful learning cannot
Different explanations of identical observations

- Neuroscience
- Synapses
- Brain plasticity

- Cognitive science
- Knowledge
- Experience
There are detrimental age effects on storing and retrieving information from the memory.

- loss of neural plasticity
- interference in an increasingly complex knowledge base
Societies should take care of early education, but why?

- otherwise critical periods of brain plasticity will be missed
- time should be used for acquiring basic knowledge that can be used for later learning
The younger one is, the easier it is to acquire a second language

- decrease of brain plasticity in the language area
- Negative transfer because of dominant first language knowledge
What makes synapses more attractive than knowledge?

Seduced by the brain: The brain is a wonderful projection surface for art, analogies and metaphors - for experts as well as for novices.
The garden analogy (agricultural view)
The agriculture view of the brain: Preparing the soil for a better harvest by plowing and fertilizing

Improve synaptic plasticity, Brain enhancement
The garden analogy: Pruning

Competitive Elimination of synapses in adolescence
Respectable Neuroscientists admit that we are far away from understanding the brain

- In the last years, brain imaging techniques have improved considerably, which means we can observe structural and functional neural correlates of learning and behavior in greater detail
- However, we are FAR away even from explaining the neurophysiological basis of pathological brain stages like schizophrenia or dementia
- When Neuroscientists explain the neural basis of learning they cite Hebb (1949): “What fires together wires together”
Demonstrating importance of prior knowledge for learning
- Daniel built a boat.
- Jack flew a kite.
- Bob ate an apple.
- David went over the roof.
- Ralph hid an egg.
- Victor set the sail.
- Peter wrote a drama.
- John pressed the button.
- Who ate the apple?
- Who hid the egg?
- Who flew the kite?
- Who went over the roof?
- Who pressed the button?
- Who set the sail?
- Who built the boat?
- Who wrote a drama?
What happened to your synapses?

Why did your hippocampus fail?

What about your amygdala?
• Noah built a boat.
• Benjamin Franklin flew a kite.
• Adam ate an apple.
• Father Christmas went over the roof.
• The Easter Bunny hid an egg.
• Christoph Columbus set the sail.
• William Shakespeare wrote a drama.
• Thomas Edison pressed the button.
- Who ate the apple?
- Who hid the egg?
- Who flew the kite?
- Who went over the roof?
- Who pressed the button?
- Who set the sail?
- Who built the boat?
- Who wrote a drama?
Explaining learning difficulties with the brain is like…

- explaining an air-crash with gravitation
Some principle remarks

Analyse & Kritik 29 / 2007 (Heft 1)

*Ralph Schumacher*

The Brain Is Not Enough
Potentials and Limits in Integrating Neuroscience and Pedagogy

Head of the MINT learning center and expert in philosophy of science
Different Levels of Description / Explanation

- physical
Different Levels of Description / Explanation

- functional
- physical
Different Levels of Description / Explanation

- economical
- functional
- physical
Different Levels of Description / Explanation

- esthetical
- economical
- functional
- physical
Different Levels of Description / Explanation Refer to Different Kinds of Entities, Facts and Frameworks

- psychological description of the human mind (mental states, behavioural criteria, intentional explanations)
- neuroscientific description of the human brain (brain states, physiological / functional criteria, causal explanations)
The Significance of Neuroscientific Studies for Psychology (top down)

- Neuroscientific Explanations of Cognitive and Learning Deficits
- Dyslexia: Children suffer from impaired phonological awareness.
- Dyslexia may be explained by diminished brain activity in the temperoparietal areas (Simos et al, 2002).
The Significance of Neuroscientific Studies for Psychology (top down)

- Neuroscientific Explanations of Cognitive and Learning Deficits
- Dyslexia: Children suffer from impaired phonological awareness.
- Dyslexia may be explained by diminished brain activity in the temperoparietal areas (Simos et al, 2002).
- However, neuroscientific research does not give us information about the contents of treatments and trainings to remediate a specific cognitive and learning deficit.
What do we have to know to improve learning conditions at school?

What does the force meter display if 1 kilogram weights are hanged on both sides?

\[ F_K = 10N \]
The Underdetermination of Neuroscience with Regard to Learning at School (bottom up)

- In order to design learning opportunities at school, educators have to know students’ knowledge preconditions.
- But it is not possible to reduce the description of knowledge preconditions to descriptions of brain states.
- Why?
The Underdetermination of Neuroscience with Regard to Learning at School (bottom up)

- In order to design learning opportunities at school, educators have to know students’ knowledge preconditions.
- But it is not possible to reduce the description of knowledge preconditions to descriptions of brain states.
- Why?
- Because descriptions of cognitive states refer to frameworks and facts outside the brain, e.g. to mathematical and physical symbol systems, and to Newton’s third axiom.
The Underdetermination of Neuroscience with Regard to Learning at School (bottom up)

- Thus, cognitive concepts are indispensable to describe knowledge preconditions.
- Therefore, neuroscientific knowledge about the brain cannot be sufficient to provide specific instructions for improving learning opportunities at school.
- **The Regatta Analogy:** What do I have to know to participate successfully in a regatta?
The Underdetermination of Neuroscience with Regard to Learning at School (bottom up)

- Therefore, no matter how far neuroscience advances, it cannot – in principle - provide the specific knowledge required for planning educational environments.
2003/2005: In search for a fruitful collaboration

Elsbeth Stern
Roland Grabner
Ralph Schumacher
Worthwhile Questions

1) Deviant brain functions in children who suffer from dyslexia or dyscalculia: To what extent have insights from neuroscience already informed the development of therapeutic treatments?

2) Neural underpinnings of errors: As learning almost inevitably goes with making errors, brain activities during feedback processing and error correction may shed light on more or less successful learning trajectories.
2016: Topical Issue

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Ralph Schumacher

Neuroscience and Education

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Worthwhile Questions and answers after 13 years of research

Deviant brain functions in children who suffer from dyslexia or dyscalculia: To what extent have insights from neuroscience already informed the development of therapeutic treatments?

Experts admit: Neural correlates have been identified but there was no impact on treatment programs
Worthwhile Questions and answers after 13 years of research

Neural underpinnings of errors: The EEG-component «error related negativity» has been further confirmed – by using the flanker task.
Jeffrey Bowers, Cognitive Neuroscience, *Psychological Review*, 2015: Educational neuroscience only tells us what we know already or gives us information that is irrelevant. The problems faced by classroom teachers dealing with learning difficulties can only be diagnosed and addressed through behavioral methods.
Consequences for teacher education

- Mathematics teachers who falsely believe that hydrochloric acid is a brain transmitter can nonetheless provide effective classroom practice.
- Teachers who are not aware of the difference between procedural and conceptual knowledge cannot. They will present practice problems to students who did not undergo conceptual change.
- Nonetheless, learning about the brain in the evolutionary context will teachers help to better understand difficulties with academic learning.
Educational Neuroscience will have a future if neuroscientists…

- are willing to really understand the concepts developed in cognitive and learning psychology rather than trivializing them
- understand the importance of content knowledge and the limits of transfer
- consider results of brain imaging techniques as correlates and not as causes of cognitive activities
- don’t generalize findings about information processing of simple tasks presented in the scanner to the complex competencies to be learned at school
Educational Neuroscience will contribute to a unified scientific model of academic learning if neuroscientist

- stop deriving pseudo-scientific educational consequences from each single experiment
- follow the methodological standards that have been established in behavioral journals (only report findings that survive appropriate statistical analyses, describe and justify the sample used)
- are aware that learning is an interaction between an individual, his or her brain, and the demands of the environment
Thank you for your neural activation!
Thank you for your neural activation!
Thank you for activating your prior knowledge!
Literature