Cognitive Neuroscience Meets Mathematics Education

Brugge, Hof van Watervliet,
March 25 – 28, 2009
EARLI Advanced Study Colloquium

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Dear participant,

We are pleased to present the program of the EARLI Advanced Study Colloquium on “Cognitive Neuroscience and mathematics education”. The relationship between neuroscience and education has attracted a lot of attention not only within the research community but also among educational policy-makers and practitioners. In all these groups, there is a growing interest to reflect on the position of cognitive neuroscience in research on learning and instruction.

This advanced study colloquium covers a collection of keynote lectures and research papers which all present collaborations between educational researchers and (cognitive) neuroscientists. One of the fields wherein cognitive neuroscience has been most successful in meeting research on learning and instruction is the domain of mathematics, which is the key area of this workshop.

The keynote lectures by Daniel Ansari, Dénes Szücs, and Stanislas Dehaene, who are leading scholars in the field, will address the latest insights and methodological approaches in the neuroscience of mathematical cognition. They will discuss promises and pitfalls of ongoing and future research aimed at bridging neuroscience and mathematics education.

The research papers from various centers that are active in the intersection of neuroscience and mathematics education will report findings of the authors’ latest empirical work on this issue. These presentations will cover various domains of mathematics (number processing, arithmetic, geometry, algebra), a variety of methodological approaches (experimental design, longitudinal studies, training studies, pharmacological intervention, research on learning disorders) and several neuroimaging techniques (fMRI, EEG, NIRS).

Taking the keynote lectures and research papers as input, this advanced study colloquium will offer ample opportunity for an in-depth discussion of the theoretical and methodological challenges of bringing together both fields.
We hope that all participants will enjoy the program and that the colloquium will lay a foundation for further exchange and collaboration between young researchers and experienced scholars from the different participating teams.

Finally, we thank the people who funded this colloquium: the European Association for Research on Learning and Instruction (EARLI) for selecting our proposal as the annual EARLI-sponsored Advanced Study Colloquium; the International Scientific Network on “Stimulating Critical and Flexible Thinking” funded by the Research Foundation Flanders (FWO); the Department of Educational Sciences of the Katholieke Universiteit Leuven.

Special thanks are due to Erik Lenaerts, Karine Dens and Goele Nickmans for their practical support and to all members of the Organising and Programming Committee for their contribution to the composition of this high-quality scientific program.

Bert De Smedt & Lieven Verschaffel
General information

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http://www.hofvanwatervliet.cm.be [Dutch only]

Hotel accommodation [if reserved through the conference secretariat]

Novotel Brugge Centrum
Katelijnestraat 65 B
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Lunches and welcome reception

Orangerie Hof Lanchals
Oude Burg 21
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http://www.hofvanwatervliet.cm.be/start.html [Dutch only]

Conference dinner

Den Dijver
Dijver 5
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http://www.dijver.be/index.cfm?langue=en

Sponsors

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Department of Educational Sciences, Katholieke Universiteit Leuven
Map of Brugge
**Program**

**Wednesday, March 25**

18.00 – 21.00  Registration and welcome reception at Orangerie Hof Lanchals

**Thursday, March 26**

9.15 – 9.30  Introduction  
(Bert De Smedt & Lieven Verschaffel)

*Neuroimaging in children 1* (chair: Bert Reynvoet)

9.30 – 10.15  Neural correlates of Spontaneous Focusing On Numerosity (SFON) in a 9-year-longitudinal study of children’s mathematical skills  
(Minna M. Hannula, Roland Grabner & Erno Lehtinen)

10.15 – 11.00  BrainMath: the influence of age and presentation format on problem solving behaviour and brain activation in school children  
(Kristina Reiss, Andreas Obersteiner, et al.)

11.00 – 11.30  Break

*Higher order mathematical skills 1* (chair: Minna M. Hannula)

11.30 – 12.15  Problem solving in mathematics: insights from reaction time and brain imaging studies  
(Ruth Stavy & Reuven Babai)
12.15 - 13.00 Usage of strategies solving an abstract mathematical task. A combined fMRI and eye-movement analysis (Franziska Preusse, Isabell Wartenburger, et al.)

13.00 – 14.30 Lunch at Orangerie Hof Lanchals

14.30 – 15.45 Keynote lecture: Educational neuroscience: linking neural representations to educational performance (Dénes Szücs)

Theoretical issues (chair: Elsbeth Stern)

15.45 – 16.30 A critique of the thesis that geometrical knowledge is innate (Georgia Griva & Stella Vosniadou)

16.30 – 17.00 Break

Learning disorders (chair: Erno Lehtinen)

17.00 – 17.45 Co-morbidity of mathematical learning disabilities with Attention-Deficit/Hyperactivity Disorder (ADHD) or with reading disabilities (Orly Rubinsten)

17.45 - 18.30 Verbal and spatial routes to math difficulties: comparing number processing in children with 22q11.2 deletion syndrome or Down syndrome (Sophie Brigstocke & Silke Göbel)
**Imaging in children 2 (chair: Daniel Ansari)**

9.30 – 10.15 Numerical and spatial processing in children with and without dyscalculia: preliminary evidence from developmental fMRI study (Liane Kaufmann & Stephan Vogel)

10.15 – 11.00 How can individual differences in task performance and neuroanatomical changes be optimally addressed in developmental fMRI data analyses? (Helga Krinzinger & Klaus Willmes)

11.00 – 11.30 Break

**Higher order mathematical skills 2 (chair: Roland Grabner)**

11.30 – 12.15 The mental representation of integers: a symbolic to analog shift (Sashank Varma & Daniel Schwartz)

12.15 - 13.00 Representations of mathematical functions in graphical and algebraic formats (Mike Thomas & Caroline Yoon)

13.00 – 14.30 Lunch at Orangerie Hof Lanchals

14.30 – 15.45 Keynote lecture: Numeracy and arithmetic in the brain: the roles of development and individual differences Daniel Ansari

**Individual differences in basic numerical abilities (chair: Michael Schneider)**

15.45 – 16.30 Typical and atypical development of basic numerical skills (Karin Landerl & Beate Kajda)
16.30 – 17.00  Break

17.00 – 17.45  Relationships between core number abilities and mathematical outcomes: findings from the Melbourne longitudinal study (Robert Reeve & Judi Humberstone)

17.45 - 18.30  Neuro-mechanism of the mathematical skills: application of cross-modalities hypothesis (Ronit Ram-Tsur, Zemira Mevarech, et al.)

19.30 - …  Conference dinner at Restaurant “Den Dijver”
Saturday, March 28

9.30 – 10.45  Keynote lecture: Cognitive foundations of arithmetical and geometrical intuitions (Stanislas Dehaene)

10.45 – 11.00  Break

Training studies (chair: Bert De Smedt)

11.00 – 11.45  Brain correlates of arithmetic problem solving: the interplay of mathematical competence and training (Roland Grabner, Daniel Ansari, et al.)

11.45 – 12.30  Brain functions and training intervention in children with developmental dyscalculia (Karin Kucian & Stephnie Rotzer)

12.30 – 12.45  Closing session (Bert De Smedt & Lieven Verschaffel)
Educational neuroscience: linking neural representations to educational performance

Dénes Szűcs
Centre for Educational Neuroscience
University of Cambridge, UK

Cognitive psychology and cognitive neuroscience have identified several possible mental representations and their neural markers which may be related to educationally relevant achievements. Our studies focusing on the development of automatic access to semantic information coded by numbers will be reviewed as examples. While acknowledging the importance of cognitive neuroscience studies it will be pointed out that using isolated neuroscience results to draw conclusions for education is still a risky venture because the relationship of neural markers identified by cognitive neuroscience and specific aspects of educationally relevant performance is not yet clear. In order to overcome limitations further research must make a clear distinction between attempts to use neuroscience research results to inform educational practice and between Educational Neuroscience. Educational Neuroscience should first study the relationship between the neural markers of mental representations and normal educational performance in a single context. This would allow Educational Neuroscience to validate the relevance of the neural markers of mental representations identified by cognitive neuroscience research in the educational context.
Numeracy and arithmetic in the brain: the roles of development and individual differences

Daniel Ansari
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University of Western Ontario, Canada

Evidence from adult neuropsychological and functional neuroimaging studies converge to suggest that the inferior parietal lobes play a crucial role in the representation and processing of numerical magnitude and mental arithmetic. While the intraparietal sulcus is thought to subserve numerical magnitude processing, the left temporoparietal cortex has been implicated in adult studies of the neural basis of mental arithmetic. In contrast to the rapidly growing body of behavioral and brain-imaging studies of numerical magnitude and arithmetic processing in adults, little is known about whether and how brain representations of numerical magnitude and the neuronal processing of calculation problems change over developmental time. Furthermore, despite the fact that a large number of children suffer from difficulties with even the most basic aspects of numerical magnitude processing, we currently lack detailed insights into the neurocognitive basis of atypical number development.

To address these outstanding issues I will present data from behavioral and brain imaging investigations into the developmental trajectories of numerical magnitude processing and mental arithmetic. I will discuss data from both typically developing children and those who have mathematical difficulties. Furthermore, I will discuss the merit of studying the effects of individual differences on brain structure and function to understand the neural basis of numerical and mathematical processing and their ontogenesis. These data will illustrate the importance of considering developmental changes and individual differences in the neurocognitive mechanisms underlying numerical magnitude representation and mental arithmetic to gain greater insights into how children develop mathematical skills and how these processes break down in children who have mathematical difficulties. Finally, I will highlight pathways for connecting research on the neurocognitive trajectories of numeracy and arithmetic with educational research and applications.
"Intuition" is a term that we use to refer to knowledge that we deploy spontaneously, often non-consciously, without effort and without a clear awareness of its origins. My proposal is that mathematical intuitions, in the domains of arithmetic and geometry, arise from evolutionarily ancient representations of space, time and number that were inscribed in our primate brains because they were useful to our survival in a spatially and socially organized environment. I will present evidence that even young infants and isolated Amazonian Indians without good access to education possess clear intuitions of number, space, Euclidean and even non-Euclidean geometries. These intuitions, however, are often only approximate. The acquisition of mathematical symbols, through language and education, brings about an increased accuracy of mathematical statements, yet even our advanced mathematical knowledge remains rooted in the foundational intuitive number and spatial senses.
Neural correlates of Spontaneous Focusing On Numerosity (SFON) in a 9-year-longitudinal study of children’s mathematical skills

Hannula, M. M., Grabner, R. & Lehtinen, E.  
University of Turku, Finland

Previous studies on Spontaneous Focusing On Numerosity (SFON) suggest that within a child’s existing mathematical competence, it is possible to distinguish a separate process, which refers to the child’s tendency to spontaneously focus on numerosity. This means that exact number recognition when number is utilized in action, is an intentional cognitive process. It requires specific focusing on the aspect of number and triggering the utilizing process for regarding the numerical knowledge in action (for a review, see Hannula, 2005). The results of the longitudinal studies on preschoolers give support to the existence of developmentally significant individual differences in SFON and stability of SFON, as well as its positive association with the development of mathematical skills (Hannula & Lehtinen, 2005; Hannula, Räsänen & Lehtinen, 2007.

In this study, the neural correlates of SFON were investigated in children by means of electroencephalography (EEG). The main focus of analyses was in the investigation of the dynamics of functional network formation by analyzing task-related changes in oscillatory EEG activity within different frequency bands.

**Aim and research questions**

In particular, the following research questions are investigated:

1. How do EEG responses during encoding of pictures for which the child spontaneously recalls number of something (“SFON trials”) differ from encoding of pictures for which no number is recalled (“non-SFON trials”)?

2. How do EEG responses during encoding of pictures for which the child is instructed to focus on number (FON task) differ from encoding of pictures for which number is either recalled (“SFON trials”) or not recalled (“non-SFON trials”) in the SFON task?
3. Do children with a higher SFON tendency display different EEG patterns during encoding of pictures in these conditions from children with a lower SFON tendency?

4. Are children’s SFON and mathematical skills before school-age and at the age of 12 years related to the behavioral measure of SFON in the EEG task and the EEG responses in the SFON tasks?

Methods
Participants were 29 12-year-old, right-handed, neurologically normally developing children. This study is a part of a 9-year-longitudinal study of these children’s early mathematical skills and SFON from 3 to 12 years of age.

Tasks
Mathematical and SFON tests at the age from 3 to 6 years
SFON, number sequence production and enumeration skills were assessed at the ages of 3, 4, 5, and 6 years (a summary of measures, see Hannula, 2005).

Standardized tests at the age of 12 years
Participants were confronted with two SFON tasks (Imitation and Finding tasks) and the following standardized tests: RMAT mathematics test (Räsänen, 2004), Raven’s colored matrices (Raven, 1976) and MVPT visual perception test, decoding and reading comprehension tests (Lindeman, 1988).

EEG tasks: Photo recall
A set of 108 pictures showing different numbers of people, animals, and/or plants in their natural environment and a scrambled picture as a visual mask were used. Seventy-two pictures were presented in the SFON task, 36 in the FON task.

Two experimental tasks are administered during EEG recording, starting with SFON tasks:

1. **SFON task**: Participants were presented a series of pictures and instructed to look at the picture and memorize it so well that they could later describe the picture to another person, “Pekka”. In particular, Pekka should be able to find the picture from a large pile of pictures based on the description. Each trial started with the presentation of a fixation cross for 3000 ms, followed by the picture, remaining on the screen for 3500 ms, and a visual mask (scrambled picture) for 500 ms. Afterwards the participant was asked to orally describe the picture in detail and participant’s answer is recorded. The next trial was initiated by the experimenter.
2. **FON task**: The protocol of this task corresponded to that of the SFON task with the following exception. The participant was told that “Pekka” is always interested in how many items there are in the picture, so that when the participant describes the picture he or she must remember to mention the numbers of items.

**EEG recording and analysis**
EEG was recorded in 19 scalp positions. The analyses focused on task-related changes in oscillatory activity (event-related desynchronisation and synchronisation; ERD/ERS; Pfurtscheller & Lopes da Silva, 2005) in different frequency bands.

**Results**
Results show that the behavioral measure of SFON in the EEG experiment is related to the SFON tendency from 3 to 6 years of age (r = .46, p < .01), and to the SFON at age 12 (r = .47, p < .01) and marginally (r = .28, p < .10) to mathematical, but not to reading skills, non-verbal IQ or visual perception at the age of 12 years. Preliminary analyses of the EEG data of a small subsample indicate that oscillatory activity (ERD/ERS) for trials, from which children recalled exact number of items in their descriptions of the photos (SFON trials) differs from the ERD/ERS for trials in which children did not mention numbers of items (non-SFON trials). In addition, also differences between spontaneous focusing (SFON trials) and guided focusing (FON trials) emerged. The complete analyses of the EEG data including the brain-behavior correlations will be conducted by the time of the conference.

**Theoretical and educational implications**
The 9-year longitudinal evidence indicates that children’s SFON continues to be an effective component of mathematical development throughout the childhood years all the way until the end of primary school. The distinct nature of spontaneous focusing on numerosity from focusing on non-numerical aspects on one hand, and from guided focusing on numerosity on the other hand seems to be able to be captured by means of EEG. Enhancing children’s SFON tendency even at the school age could be an effective way of increasing children’s spontaneous practice of their number skills leading to better mathematical skills.
Our research aims at identifying the neuronal correlates of number processing and modelling as basic mathematical abilities. Numerical abilities have proven to be fundamental and indispensable for the development of higher mathematical abilities. However, mathematical competency means much more than the ability to solve numerically presented problems. It is important that numerical knowledge can be applied in varying situations (Reiss, 2004). Accordingly, modelling is another key factor of mathematical competency (Kultusministerkonferenz, 2003). In the first years of mathematical education, word problems are used to enhance modelling competency in school children. Nevertheless, studies have shown that word problems are more difficult to solve than numerically presented problems and that various factors have an impact on the difficulty of a specific word problem (Stern, 1997; Verschaffel et al., 1999). Some authors suggest that the age of children might cause important differences with respect to their problem solving strategies (Brown et al., 2003).

In our study we investigated the influence of age and presentation format (numerical problem or word problem) on mathematical problem solving behaviour. To unveil differences in cognitive processing, we applied brain imaging methods. However, neuroscientific approaches have provoked scepticism within the educational community. One barrier between educational science and neuroscience is that they use different research methods. While educational researchers usually conduct questionnaires and paper-pencil tests within classroom settings, neuroscientists ask for high-tech measuring instruments and a laborious setting. However, we doubt that solving mathematical problems using paper and pencil is the same as solving them lying in a scanner and pressing keys. Therefore, in the study presented here we brought neuroscientific measurement into the classroom: The non-invasive method of near-infrared-spectroscopy (NIRS) was used to measure brain activation in school children solving
mathematical problems. As the region of interest we defined the parietal brain area which has been identified as one key region associated with mathematics (e.g. Piazza et al., 2004).

A sample of 46 primary school children (grade 4) and 44 secondary school children (grade 8) were asked to solve two-digit addition tasks. The tasks were presented either in a merely numerical format or as word problems. Reaction time and accuracy were measured. Brain activation was measured by NIRS. To be able to identify brain activation due to calculation processes, the tasks were presented in two conditions, a calculation condition and a reading condition. In the reading condition the tasks had to be read only without calculating; in the calculation condition the result of the tasks had to be calculated.

The results show that older children performed significantly better with respect to reaction time but not with respect to accuracy. Differences in reaction time between word problems and numerical problems were much smaller for 8th-graders than for 4th-graders. The NIRS data show that for both groups brain oxygenation in the bilateral parietal regions was higher in the calculation condition than in the reading condition. However, we found no differences in oxygenation level between the two groups. That means, younger children were slower and therefore showed longer activation times but they did not show a higher level of activation than older children.
Problem solving in mathematics: insights from reaction time and brain imaging studies

Stavy, R. & Babai, R.
Tel Aviv University, Israel

It is well known that students encounter difficulties in solving a wide range of problems in mathematics. This has been shown for example in TIMSS and PISA studies.

For many years we are studying students’ conceptions and thinking processes, focusing on intuitive interference with analytic reasoning. Our research goal is to unveil the reasoning processes associated with overcoming intuitive interference in mathematics problem solving. For this purpose we employ reaction time and brain imaging (fMRI) techniques. We believe that this new research direction will result in better understanding of students' difficulties in this domain and in new ways of teaching.

Here we focused on the nature of intuitive interference in geometry using a comparison-of-perimeters of geometrical shapes task. Accuracy of responses, reaction times and neural correlates were measured while participants compared the perimeters of two geometrical shapes, in two conditions: 1) Congruent - in which correct response is in line with the intuitive reasoning (i.e., larger area - larger perimeter) and, 2) Incongruent – in which the correct answer is counter intuitive (i.e., larger area - same or smaller perimeter).

Our findings show that in the incongruent condition accuracy drops and reaction time for correct responses is longer than in the congruent condition. In addition, distinct patterns of brain activation were found to be associated with congruent and incongruent conditions. Congruent condition led to activation in bilateral parietal brain areas (BA 40), known to be involved in perceptual and spatial processing including that of comparison of continuous quantities. Answering correctly the incongruent condition, activated bilateral orbital aspects of the middle prefrontal gyri (BA 10/11 and BA 11/47), known for their executive inhibitory control over other brain regions. This activation seems to reflect the inhibition of the intuitive interference, suggesting the importance of control mechanisms in overcoming intuitive interference.

The results pointed to the possibility of improving students' problem solving abilities by intervention aimed at
strengthening their executive control mechanisms such as by raising students' awareness to the relevant task variable. To study the effect of such intervention we compared accuracy of responses and reaction times before and after the intervention.

We found that the intervention was instrumental in increasing the accuracy of students' responses in the incongruent condition. Interestingly, while the intervention led to shorter reaction times for the comparison-of-areas task, reaction times for the congruent and incongruent comparison-of-perimeters task were higher in the post-test. These findings suggest that raising students' awareness to the task relevant variable activates effortful and time-consuming control mechanisms. It seems that this activation is general in the sense that it applies to all comparison-of-perimeters conditions: incongruent as well as congruent.

These studies argue that research in mathematics education could benefit from applying cognitive and neuroscience techniques. Using such methodologies could lead to a deeper understanding of students' difficulties and reasoning processes related to overcoming intuitive interference. Further research could also shed light on how task-dependent (e.g., mode of representation, cognitive load) and solver-dependent factors (working memory capacity etc.) affect problem solving in mathematics.
Usage of strategies solving an abstract mathematical task. A combined fMRI and eye-movement analysis

Preusse, F., Ullwer, D., van der Meer, E., Heekeren, H., Kramer, J. & Wartenburger, I.
University of Potsdam, Germany

Research question: What are underlying strategies used by students with high fluid intelligence (hi-IQ) and students with average fluid intelligence (avg-IQ) in solving an abstract mathematical task?

It is well known that persons with high fluid intelligence (hi-IQ) are faster at recognizing relations and in logical reasoning than persons with average fluid intelligence (avg-IQ; Lee et al., 2005 NeuroImage; Prabhakaran et al., 1997, Cognitive Psychology). In our study we compared the performance of a group of hi-IQ high-school students to that of avg-IQ students using an abstract geometric analogy task with multiple levels of task difficulty. This task is prototypical for measuring fluid intelligence.

Functional neuroimaging (fMRI), behavioral and eye-movement data were collected simultaneously while subjects performed the task.

The two groups did not differ in reaction times or reaction accuracy. This may be due to ceiling effects. Yet, hi-IQ and avg-IQ subjects recruited frontal and parietal brain regions differentially as revealed by fMRI. With increasing task difficulty BOLD-signal increased in parietal regions in hi-IQ subjects. Avg-IQ subjects showed increase in BOLD-signal in frontal regions with increasing task difficulty. So there exists no one-to-one relation between intelligence and brain activation. Task complexity modulates activity in frontal and parietal brain regions differently in the two groups. Frontal brain regions are known to be engaged in executive control and working memory processes.

Thus, our data indicate that avg-IQ subjects need more executive control in order to reach the same behavioral performance level.

In the course of the experiment both groups could improve their reaction times. However, on the neural level groups differ in amount of BOLD-signal changes over time. Our preliminary data indicate that short-term learning seems to be associated with distinct ways of becoming neurally
efficient (see also Rypma et al., 2006, NeuroImage). This still is to be analyzed further.

We recorded eye-movements during task performance to detect and characterize differential use of task solving strategies. Hi-IQ subjects showed more effective eye-movement patterns: they fixated more on relevant parts of the analogy stimuli and neglected those areas bearing no additional information. Avg-IQ subjects fixated both, relevant and irrelevant stimuli areas. Only in the course of the experiment they shifted to more fixating on relevant areas and neglecting the irrelevant ones. Thus, the strategies used by hi-IQ subjects seem to be more efficient with respect to task solution. In the course of time avg-IQ subjects shifted their strategies so that they became more similar to those of hi-IQ subjects who were more efficient already in the beginning.

We will present and discuss our data with respect to the educationally relevant question how learning effects in the field of mathematics is modulated by individual differences.
A critique of the thesis that geometrical knowledge is innate

Griva, G. & Vosniadou, S.
University of Athens, Greece

In their article Core Knowledge of Geometry in an Amazonian Indigene Group, Dehaene, Izard, Pica and Spelke (2006) argued that “…core geometrical knowledge is a universal constituent of the human mind” (p.384). In virtue of that, even unschooled people from isolated cultures have the ability to spontaneously understand basic geometrical concepts. This conclusion was derived from the results of experiments with Mundurukú, an Amazonian indigene group whose language has few words dedicated to geometrical and spatial concepts. The Munduruku achieved high success in nonverbal tasks which probed geometrical knowledge. Dehaene et al. (2006) argued that core geometrical knowledge is stable conceptual knowledge, part of our cognitive architecture, which is imposed spontaneously onto variable and imperfect sensory data. They argue that such knowledge is the result of an evolutionary process by means of which our mind has adapted to the geometry most advantageous to our species.

The present paper will examine the above thesis and then submit to a revision of the Dehaene et al (2006) findings. I believe that Dehaene et al. (2006) are probably correct in that our visual system has been adapted to our environment in order to maximize the chances of our successful interaction with it. The question is whether this evolutionary adaptation can be considered to be ‘core knowledge of geometry’.

I argue that the term ‘knowledge’ presupposes a subject who is aware of this knowledge and has access to its conceptual content. I also argue that concepts are mental states which are characterized by permanence and accessibility and which can be invoked in reasoning and problem-solving. Finally I argue that successful performance in the Dehaene et al. (2006) experiments does not require even rudimentary possession of geometric concepts. Rather, it can be explained by recourse to short-lived and inaccessible perceptual representations with non-conceptual contents (e.g., Bermudez, 1995; Tye, 2005).

This argument relies on Pylyshyn (1999, 2001, 2007) and Raftopoulos (2001, 2008 in press) who propose that the early vision system constructs an initial structured but weak,
viewer-centered, representation that encodes spatiotemporal information (position, relative position), as well as featural information (shape, size, orientation). This information is extracted directly from the scene in a bottom-up, computational way, and thus, the content of this weak representation is non-conceptual. The non-conceptual content of such a weak representation suffices for making discriminations with respect to shapes, orientations, and distances, which are exactly the kinds of abilities required for the success in Dehaene et al. (2006) tasks. Having as a starting point the information about shapes, sizes, orientations, and distances that the initial weak representation encodes one can construct the core concepts of Euclidean geometry through a cognitive process that is subserved by selective attention.
Co-morbidity of mathematical learning disabilities with Attention-Deficit / Hyperactivity Disorder (ADHD) or with reading disabilities

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University of Haifa, Israel

A substantial proportion of individuals with Attention-Deficit/Hyperactivity Disorder (ADHD) manifest unexpected problems in mathematics that cause impairment in academic achievement and daily functioning: estimates range from 10% to 60%. However, in contrast to co-occurring reading difficulties, the nature of mathematical difficulty in ADHD has received scant attention from teachers or researchers.

Some researchers attribute the significant mathematical delays in children with ADHD to impairments in attention or working memory. These general cognitive impairments (i.e., not specific to mathematics) are considered to be integral features of the ADHD syndrome and hence, may cause mathematical difficulties in some of these children. An alternative proposition is that subgroups of children with ADHD and mathematical difficulties may exhibit different underlying mechanisms, including specific deficits in basic numerical processing (e.g., quantity processing), as manifest in children with developmental dyscalculia.

Notwithstanding the importance of understanding the nature of underlying mathematical difficulties associated with ADHD, it is also necessary to understand the effects of methylphenidate (MPH) on mathematics, given its widespread use in the treatment of ADHD. MPH is known to enhance frontal lobes activation that are involved with different aspects of semantic processes. By contrast, MPH appears to have little or no influence on parietal lobes activation that are involved with basic cognitive functions such phonological or quantity processes.

Hence, the objective of this study was to investigate effects of stimulant medication on arithmetic performance in children with ADHD who varied in reading and arithmetic abilities.

Data were analyzed from four groups of children with ADHD, who varied in arithmetic and reading abilities, namely: ADHD, ADHD+ Mathematical Disorders (MD; whose arithmetic difficulties stem from deficits in basic numerosity as well as executive dysfunctions), ADHD+ Reading Disorders
(RD; whose arithmetic difficulties arise from deficits in phonological and semantic processes); and ADHD+MD+RD. We developed a novel coding system to analyze existing data derived from school-like math computation work sheets which are used routinely in our controlled trials of stimulant medication (i.e., MPH).

It was found that MPH improved children’s performance of simple addition, but primarily in those with comorbid RD. By contrast, MPH had no effects on simple subtraction. As expected, the stimulant improved behavioral symptoms of ADHD in all four groups of children.

In the discussion I will focus on how stimulant-induced behavioral improvements may not necessarily be accompanied by concurrent improvements in academic functioning. Moreover behavioral manifestations of arithmetic problems in ADHD, MD or RD may have different behavioral underpinnings and show a differential response to stimulant medication, depending on their co-occurrence. Accordingly, clinicians need to understand that children with ADHD+MD will need additional intervention for arithmetic (subtraction), even though they may be showing marked behavioral improvements with stimulant treatment. Likewise, teachers should be advised that addition and subtraction are supported by different neurocognitive processes and that stimulant medication may benefit those aspects of arithmetic that are dependent upon verbal retrieval (e.g., addition) but not those arithmetic skills that are dependent upon basic skills in processing and manipulating quantities (e.g., subtraction).
Verbal and spatial routes to math difficulties: comparing number processing in children with 22q11.2 deletion syndrome or Down syndrome

Brigstocke, S. & Goebel, S.
University of York, UK

Recent research suggests that arithmetical ability in typically developing children can be predicted by symbolic number processing abilities. In addition it might be linked to the acuity of a proposed innate non-symbolic, approximate number sense. Given these potential precursors at least two pathways to developing mathematical difficulties could be proposed: impairment in symbolic number processing (possibly related to verbal skills) and a reduced acuity of the approximate number sense (possibly related to spatial skills).

In order to investigate the relative contribution of low spatial or verbal skills to mathematical difficulties we investigated symbolic and non-symbolic number processing along with cognitive, spatial and verbal skills, reading and working memory in: 1) children with 22q11.2 deletion syndrome (22q) who are impaired in number processing and have weak spatial skills, 2) children with Down syndrome (DS) whose verbal and numerical skills are weaker than their spatial skills.

We tested 28 children with 22q aged between 4 and 18 years on eleven subtests of the British Ability Scales. Despite a low full IQ (mean of 72.4) their mean verbal ability was within the normal range. This was in clear contrast to their non-verbal and spatial skills, which were significantly lower than their verbal skills (F(2,26)=10.32, p < 0.01). While their reading was within the normal range, their number skills were significantly weaker (t(26)=3.16, p <0.01). Using computerized tests we tested the children on symbolic and non-symbolic number processing tasks, a physical number judgement task using a Stroop paradigm, estimation, counting and single digit addition. Overall, a significant distance effect was observed in symbolic number comparison and in non-symbolic comparison. One sample T tests indicated that the gradient of the slope differed significantly from 0 in number comparison (t(24) = 9.6, p<0.001) and non symbolic comparison (t(24) = 6.85, p<0.01). The slope was significantly correlated in both task (r=.49, p<0.01). Furthermore in a physical size comparison task using a
Stroop paradigm, there was a significant difference in reaction times when numerical information was congruent and incongruent with size information (t(56) = 5.2, p<0.001).

We are currently testing children with DS on the same test batteries in order to investigate which of the numerical tasks are impaired (in contrast to the children with 22q) in the context of low verbal but relatively spared spatial skills. Although both groups show weak number skills, given the non-overlapping brain abnormalities reported for the two groups, it seems likely that their mathematical difficulties are the result of two distinct etiologies. Findings from this study might thus identify several possible cognitive and neural pathways involved in the development of mathematical disorders in genetic disorders.

In another project we are currently investigating networks underlying normal number processing in adults with magnetoencephalography (MEG), a child-friendly neuroimaging method. At the workshop we would like to discuss possibilities of using MEG with typical and atypically developing children and how this future research might be able to inform educational issues.
Numerical and spatial processing in children with and without dyscalculia: preliminary evidence from developmental fMRI study

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**Study rationale.** The current study aimed at identifying the neural correlates of nonsymbolic and symbolic number magnitude processing in children with and without dyscalculia. Second, based on previous preschool intervention studies suggesting that spatial training may facilitate the acquisition of mental number representations, we aimed at investigating whether numerical and spatial processing are supported by overlapping brain systems in children. Functional imaging studies with adults have shown that arithmetical processing is supported by (intra)parietal brain regions. However, (intra)parietal activations are less robust in children who show a stronger need to recruit frontal brain regions upon performing numerical tasks (possibly reflecting compensatory efforts). Results of fMRI studies assessing dyscalculic children are inconclusive, some revealing dysfunctional parietal processing, while others did not find any significant group differences in parietal cortex. Because of different methodologies the latter studies are not directly comparable. Thus, there is a clear need to further investigate atypical (and typical) trajectories of numerical development.

Our **research questions** are as follows:
- Is there a functional overlap between numerical and spatial processing in children with and without dyscalculia?
- Do functional activation patterns correspond to behavioural performance patterns?

**Methods.** **Participants.** Dyscalculia diagnosis conformed to DSM-IV criteria; children were matched according to age and IQ. After motion correction, data of 18 children (nonsymbolic paradigm; n=9 dyscalculic) and 12 children (symbolic paradigm; n=6 dyscalculic) remained in the analyses.

**Experimental tasks.** **Nonsymbolic task:** Children were asked to indicate which of two simultaneously presented finger-patterns showed more fingers. **Symbolic task:** Children had to decide whether three one-digit Arabic numerals were in the correct ordinal sequence (i.e., 2 5 6). **Control tasks** differed with regard to instruction only, containing identical perceptual inputs (Nonsymbolic task: Do the palms of the two
hands show in the same direction? Symbolic task: Do the font-sizes of three stimuli [digits being manipulated to be unrecognizable] gradually increase?)

**Design.** Experimental tasks were presented in box-car fashion. Activations were considered significant at a threshold of \( p<0.001 \), uncorrected (\( p<0.05 \), corrected at the cluster level). Group differences were investigated by conducting task-specific contrasts (number>spatial task). In addition, whole-brain regression analyses were performed to investigate which brain regions are significantly correlated to behavioural data.

**Findings.** Our findings on *non-symbolic number magnitude processing* are suggestive of largely overlapping brain circuits in regions in and around the intraparietal sulcus (IPS) in response to numerical and spatial processing (being consistent with the ATOM hypothesis resting on adult data). Relative to controls, dyscalculic children produced stronger inferior parietal activations (IPS, supramarginal gyrus and – at a lower threshold – to the left angular gyrus). Furthermore, results revealed a negative correlation between parietal activation extents and arithmetic competence level in left (intra)parietal regions and a positive correlation in right (intra)parietal regions. Data on *symbolic number magnitude processing* are currently being analyzed.

**Open questions/discussion.**
- Power?
- Event-related paradigms/analyses in pediatric fMRI?
- Thresholds in ROI/VOI analyses?
- Correlation formula (comparing steepness of regression slopes) with small \( n \)?
- BV tool for psychometric single-case approach?
How can individual differences in task performance and neuroanatomical changes be optimally addressed in developmental fMRI data analyses?

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Developmental studies that compare children with adults are characterised by very large individual differences on the behavioural and neuro-anatomical level. Specifically in the domain of calculation, older children and adults complete even small additions in the number range up to 10 about five times faster than preschool children (RTs varying between 2 - 10 sec). These large behavioural differences (even intra-individual during the course of development) require imaging techniques that are optimally suited for measuring brain activation patterns of both fast and slow calculators. In order to find an optimal design for a non-symbolic addition paradigm for a group of 12 children aged 5-9 and the same number of young adults, (including male and female subjects) we will compare three design types: (1) a self-paced event related design (2) an individualized block design (adapted to the individual mean reaction time) (3) a self-paced block design which will be analysed by independent component analysis. All participants will carry out all three designs of the same paradigm in two independent runs on the same day in a randomized order, which will allow us to compare the three designs according to their reliability independently in children, men, and women.

Furthermore, possible individual differences in neuro-anatomy between children and adults call for sophisticated brain alignment techniques. In this study, Talairach transformation techniques that heavily rely on spatial smoothing of functional data are compared with cortex based analysis techniques that do not require spatial smoothing. Advantages and disadvantages of the above described methods will be systematically discussed.
The mental representation of integers: a symbolic to analog shift

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Conceptual question: How does mastering a mathematical symbol system transform existing (analog) representations?

Most research on mathematical reasoning has focused on the natural numbers (0, 1, 2, ...). This is a relatively concrete concept in that it is grounded in physical activities like verbal counting and moving one’s finger across a number line (Case et al., 1997). The seminal finding is that natural numbers are represented as analog magnitudes – as points on a mental number line (Moyer & Landauer, 1967). A neural correlate of this representation (IPS) has recently been identified (Dehaene et al., 2003). By contrast, most mathematical concepts are abstract, defined less by referents in the world and more by abstract symbol systems. How do people come to understand abstract mathematical symbol systems, and how does this transform existing (analog) representations? We consider the more specific question of how people understand the integers, which extend the relatively concrete natural numbers with the relatively abstract negative integers (-1, -2, ...).

We consider three hypotheses, shown in Figure 1a. Rule augmentation claims that the number line representation of the natural numbers is augmented by the rules of the integer symbol system, which are used to reason about negative integers. Magnitude extension claims that the number line is extended “to the left”, to include negative integers. Discontinuous transformation claims that mastering a new symbol system transforms the existing number line representation in a discontinuous manner (by “cutting” the extended number line and “reflecting” the two segments).

We conducted two experiments to evaluate these hypotheses. In the first experiment, adults compared pairs of integers (see Figure 1b). Comparisons of positives showed a conventional distance effect, whereas mixed comparisons (of a positive to a negative) showed a striking inverse distance effect. This is inconsistent with rule augmentation, which predicts no effect of distance (because mixed comparisons are made using a rule). This is also inconsistent with magnitude extension, which predicts a conventional distance effect (because mixed comparisons are made by consulting a
conventional number line). However, it is consistent with a discontinuously transformed integer number line.

Discontinuous transformation predicts that children who have not had the requisite experience should reason using the rules of the integer symbol system, and should behave as predicted by rule augmentation. This prediction was corroborated in a replication of the adult study using 12-year olds (see Figure 1c). They showed no effect of distance for mixed comparisons.

Discontinuous transformation is a promising account of how mastering a mathematical symbol system transforms existing (analog) representations. It is consistent with neuroimaging findings that over development, mathematical reasoning becomes less symbolic (i.e., less dependent on PFC) and more analog (i.e., more dependent on IPS (Ansari et al., 1995). We speculate that angular gyrus and supramarginal gyrus come to represent the rules of mathematical symbol systems in a more “compiled” form than PFC (Ansari, 2008). These compiled symbolic representations combine with the analog representations of IPS to implement, for example, the discontinuously transformed integer number line (Lee, 2000). (For a similar proposal in the olfactory domain see Anderson et al. (2003)).
Representations of mathematical functions in graphical and algebraic formats

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**Background and research question**
Very little is known about the neural representation of higher mathematical knowledge such as algebra and calculus. However, research on this topic has great potential to inform educational practice, since many students struggle while learning algebra and calculus. The current study investigated neural activity associated with matching of linear and quadratic functions in graphical and algebraic formats.

**Methodology**
Nine right-handed university mathematics students (5 male), age 18-23 yrs were scanned at 1.5 Tesla, using a block fMRI design. On each trial, participants viewed two consecutively presented mathematical functions (quadratic or linear), and indicated whether they represented the same function. The two functions were either in the same format (graph to graph, algebra to algebra), or in different formats (graph to algebra, algebra to graph).

**Results**

*Behavioural data:* There were no significant differences in accuracy or reaction time within either the two “same format” conditions or “cross-format” conditions, however there was a difficulty confound between these conditions, with the cross format condition showing longer reaction times and lower accuracy. Participants were also slightly more accurate responding to quadratic functions than linear functions.

*FMRI data:* The extent and amount of neural activation was much greater when participants were required to translate between formats. Activation specific to cross-format conditions was identified in a large cluster in the left inferior frontal gyrus (triangular to opercular), and two small clusters in the right hippocampus and right cingulate. A conjunction analysis of “same format” conditions was performed to identify regions representing functions independent of format. Significant conjunction clusters were found in the left mid frontal cortex, the left intraparietal sulcus, the right superior parietal lobule (extending into the angular gyrus and the IPS), the left superior parietal lobule (extending into the IPS), and the right lingual gyrus.
Conclusions
Our findings suggest that there may be format independent representation of mathematical functions in the intra parietal sulcus (often associated with “number sense”). However alternative explanations of spatial attention shifts or response planning remain to be ruled out.

Issues to be discussed
We wish to discuss methodological and conceptual issues pertaining to our goal of studying the cognitive processing of gradients of lines and curves within a graphical format. We plan to investigate whether there are graphical equivalents of well-established results from numerical cognition research, such as the distance effect, SNARC effect, and interference and facilitation effects when assessing function gradient and value. We also plan to study whether the horizontal segment of the IPS is involved in magnitude processing in a graphical format.
Typical and atypical development of basic numerical skills

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Deficits in basic numerical processing have been identified as a central and probably causal problem in developmental dyscalculia, however, so far not much is known about the typical and atypical development of such skills. Two studies will be presented. Study 1 assessed basic number skills cross-sectionally, in 268 typically developing and 132 dyscalculic children in Grades 2, 3 and 4. Findings indicate that the efficiency of processing of numbers and numerosities improves over time and that dyscalculic children are generally less efficient than children with typical development. Robust effects of numerical distance, size congruity and compatibility of ten and unit digits in two-digit numbers could be identified as early as end of Grade 2. Only the distance effect for comparing symbolic representations of numerosities changed developmentally. Furthermore, dyscalculic children in Grade 2 showed an especially strong effect of compatibility when comparing two-digit numbers. Apart from that, the patterns of numerical processing were stable across grade and arithmetic levels. We did not find strong evidence that dyscalculic children process numbers qualitatively differently from children with typical arithmetic development. These findings seem to indicate that the cognitive representation of number may be intact in dyscalculia and that access and processing these representations may be the problem rather than representation in itself.

The next step in our line of research is to assess development of numerical skills longitudinally in order to further our understanding of developmental trajectories. In Study 2, similar paradigms for assessing basic numerical skills are applied with 40 typically developing children and 40 children with atypically poor arithmetic development. Children are selected at the beginning of Grade 2 and will be followed until the end of Grade 4, with two assessments per year (t1 – t6). Data from the first two assessments can be presented in the EARLI workshop.
The Melbourne Longitudinal Study of Mathematical Development assessed the core numerical abilities and school-based arithmetical attainment of 250 children over a six year period. Children were assessed individually twice a year, beginning in their first year of school (5 years old). On each occasion children completed core number tasks (e.g., symbolic, non-symbolic quantity judgements, approximation, subitizing etc.), school-based mathematical competencies (e.g., single-digit addition etc.), as well as general ability measures (IQ, working memory etc.). The general aim was to determine, over the course of the study, whether (1) core abilities are stable and are related to each other, (2) school-based competencies are stable, (3) core ability profiles can be used to predict school-based competencies once general ability measures are taken into account. Of particular interest was whether ability profiles (e.g., a dyscalculia profile) could be isolated from the overall ability distributions. This interest was motivated by a theoretical need to move beyond cut-off criteria (e.g., those who score below the 10th percentile on a test), often used to identify math disabled individuals. And, also to identify core diagnostic indices that could be used with very young children as well as adults (items on standardised tests typically change with age and rely on calculation knowledge). Specifically, we used classification procedures (e.g., mixture modelling) to identify core profiles, and to determine whether these are stable across time.

Here, we report research on the consistency of, and interrelationships among, (1) dot enumeration (subitizing) (“how many dots on the computer screen”), and (2) number comparison (“which number is bigger”); and how they relate to school-based measures. Analysis of the dot enumeration data yielded four distinct profiles (from non-subitizers to very fast subitizers). Children’s profile membership remained remarkably stable over time, even though profile parameters (subitizing slope, speed and range) changed. Moreover, profile membership predicted performance on school-based measures across the six years of the study. Analysis of the
number comparison data yielded the expected number distance effect (numbers that are closer in magnitude take longer to judge than numbers that are further apart in magnitude); and classification analysis revealed three distinct profiles that differed on speed of responding. Although the number comparison profiles were related to the subitizing profiles, they were not associated with school-based math performances. Further analysis showed that the subitizing profiles were unrelated to general cognitive measures, whereas the number comparison profiles were related.

These findings raise important conceptual questions about the relationship among core number competencies, especially in terms of how they are related to each other (over time), and to school-based math abilities more generally. In addition, the methodological approach adopted suggests one way of moving beyond cut-off criteria by identifying distinct competency profiles. Although the study identified a dyscalculia profile, it also identified an extremely highly competent group. It is equally important to focus on the performances of different ability profiles, not just those individual in the less able profile.
Neuro-mechanism of the mathematical skills: application of cross-modalities hypothesis

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Introduction: Dehaene suggested three different numerical representations (verbal, non-verbal semantic and visual–spatial) utilized depending on the task demands (Dehaene et al., 1999, 2003). In a different study it was concluded that children with arithmetic difficulties have problems specifically in automating basic arithmetic facts which may stem from a general speed-of-processing (SOP) deficit (Bull & Johnston, 1997). Deficits in SOP were also connected to weak automaticity in dyslexia that relates to cerebellum dysfunction (Nicolson & Fawcett, 2005). A new hypothesis suggested that slow SOP within each modality, visual and auditory, produces an excessive asynchrony in the SOP of the two systems which may cause dyslexia. (Breznitz & Meyler, 2003). Lately, Ram-Tsur and her colleagues found connections between naming abilities to synchronization cross-modalities (CM) and reading acquisition skills in preschool children (in prep). The main research question is whether there is a connection between CM synchronization, automaticity and the acquisition of mathematical skills.

Method: 75 children from 1st grade participated in 13 different experiments. 4 of the experiments examined simple reaction time (RT) for each modality (visual and auditory), 2 experiments examined simple RT and 2 experiments examined choice RT and accuracy of CM information processing, 2 experiments examined RT and accuracy of synchronization CM, and the other 3 experiments examined choice RT and accuracy of mathematical CM information processing. In 2 of the mathematical experiments participants were asked to decide whether what they heard (beeps/number) is equal or not to what they saw (dots/numbers/words of numbers). In the third mathematical experiment the participants had to decide which of the two modalities stimulated first: visual or auditory (same stimuli were used).

Results: We split the participants into 2 groups based on their automaticity ability (their naming performance) - the Low Naming Abilities (LNA) group and the High Naming Abilities (HNA) group. Correlations were found between RT-
CM synchronization experiments and mathematical beeps and digits match experiments. In addition, one way ANOVA was conducted on mathematical abilities, with group (LNA/HNA) as a between-subject variable. Results revealed that LNA had prolonged duration than the HNA in problems task where participants had to decide which group has more. Also, we found in a task of meta-mathematical word problems that LNA required longer duration than the HNA. Furthermore, in a task that the participants had to decide $<=$ between 2 dots groups the LNA had more mistakes than the HNA. In addition, we found significant group difference in some of the mathematical CM experiments. On the "mathematical beep match" experiment the LNA had less accurate answers than the HNA group. In the "mathematical digit match" experiment the LNA group had more mistakes than the HNA.

**Conclusions:** We found in each of the two groups (NLA and NHA) correlations between CM synchronization performance and mathematical abilities. We demonstrated that the group with higher ability of automaticity has better mathematical abilities and vice versa. Those new findings have theoretical and practical contribution for understanding the core deficit of dyscalculia and the comorbidity between dyslexia and dyscalculia.
Brain correlates of arithmetic problem solving: the interplay of mathematical competence and training

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The acquisition of arithmetic skills represents an essential step in the development of mathematical competence, and a large number of behavioural studies have provided important insights into the cognitive changes that accompany this long-term learning process. As an example, it has been repeatedly found that younger children primarily use effortful and slow procedural strategies (e.g., counting) in solving arithmetic problems, whereas older children increasingly rely on the fast and efficient retrieval of arithmetic facts stored in long-term memory (Siegler, Adolph, & Lemaire, 1996). How the process of arithmetic skill acquisition is reflected in the brain has only recently moved into the focus of research. Functional neuroimaging studies have revealed that parietal brain circuits support arithmetic problem solving and that their activation dynamically changes as a function of development and training (Ansari, 2008). In particular, these studies suggest an age- and training-related increase in the functional specialisation of parietal cortices for mental arithmetic (Delazer et al., 2003; Rivera, Reiss, Eckert, & Menon, 2005).

Aims
Two functional magnetic resonance imaging (fMRI) studies are presented. The aim of the first study was to investigate how mathematical competence is related to brain activation during arithmetic problem solving. In the second study, participants of lower and higher mathematical competence underwent an extensive training of arithmetic facts to evaluate whether the observed competence-related activation differences can be attenuated by cognitive training.

Methods and results
In Study I, 25 young adult students were selected from a larger pool based on their results in tests of intelligence and arithmetic performance. Half of them displayed higher mathematical competence (mathematical-numerical IQ: $M = 107$, $SD = 6$, $n = 12$), the other half lower mathematical competence ($M = 88$, $SD = 5$, $n = 13$). The groups were matched with respect to non-numerical intelligence and age.
During fMRI acquisition, participants had to solve single-digit (e.g., “6 x 8”) and multi-digit (e.g., “13 x 6”) multiplication problems. As expected, individuals with higher mathematical competence generally outperformed their less competent counterparts, which was accompanied by stronger activation in the left parietal cortex, specifically in the angular gyrus. Additional correlation analyses uncovered that the activation in the left angular gyrus did not only differ between groups but is linearly related to the individual level of mathematical competence, even when variability in experimental task performance was controlled for (see Fig. 1).

![Left Angular Gyrus](image)

**Figure 1.** Significant correlation between activation in the left angular gyrus and mathematical-numerical intelligence.

In Study II similar groups of adult students with higher ($M = 112$, $SD = 8$, $n = 14$) and lower mathematical competence ($M = 88$, $SD = 5$, $n = 14$) participated. They participated in a five-day training on a set of 10 complex multiplication facts (e.g., 14 x 7) and in a subsequent fMRI test session in which the trained as well as untrained multiplication problems had to be solved. Training considerably improved the performance of both groups and resulted in activation increases in the angular gyrus and activation decreases in a wide-spread fronto-parietal network. Competence-related differences only emerged in the untrained problems in which, similar to Study I, the more competent individuals displayed better performance and stronger activation of the left angular gyrus. In the trained problems, however, the group difference diminished at both, the level of performance and brain activation (see Fig. 2).
Figure 2. Region-of-interest (ROI) analysis of the left angular gyrus. Significant group differences ($p < .05$) between participants with higher mathematical competence (higher math) and those with lower mathematical competence (lower math) only emerged in the untrained multiplication problems.

**Discussion**

The results from Study I demonstrate that the involvement of task-specific parietal brain circuits underlies individual differences in mathematical competence independent of other intellectual abilities. Study II extends these findings by showing that the angular gyrus is critically involved in arithmetic fact learning and displays a high functional plasticity for training. The absence of competence-related activation differences after the training suggests that the relation between mathematical competence and angular gyrus activation in novel or untrained problems is due to differences in arithmetic fact retrieval rather than in basic characteristics of numerical information processing. In conclusion, the presented studies provide further insights into the brain correlates of arithmetic skill acquisition and show how functional neuroimaging data can inform about the involvement of cognitive processes underlying individual differences in mathematical competence. Moreover, they show how a high level of expertise in a small set of problems attenuates competence-related differences in brain activation during problem solving.
Brain functions and training intervention in children with developmental dyscalculia

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The goal of the present project was to develop and test an appropriate training intervention for dyscalculic children. Careful prearrangement is needed and accordingly the project consists of three sub-projects – project 1a aimed to find the neural correlates of behavioral characteristics of DD. In project 1b a specific training intervention for dyscalculic children was developed and behaviourally evaluated, which aimed to enhance the internal number line representation. The findings of these two sub-projects provided the substrate of project 2 “neuroplastic changes after training intervention in children with developmental dyscalculia”. In project 2, children with DD will undergo functional magnetic resonance imaging (fMRI) measurements before and after the specific training, as developed in project 1b. The main goal is to assess if performance will improve and if there are alterations in cerebral activation, and therefore, evidence for brain plasticity due to specific training.

By now, sub-projects 1a and 1b are finished. In project 1a, a domain-general and a domainspecific approach was followed. We investigated spatial working memory as well as number representations in children with DD using fMRI. Results of the spatial working memory paradigm demonstrate for the first time an involvement of spatial working memory processes in the neural underpinnings of DD.

In project 1b a computer-based training called “Rescue Calcularis” was developed, programmed and evaluated in typically-achieving children. After five weeks of training, children improved behaviourally in a number-line task specifically related to the training. fMRI results indicate training effects of more automatised access to the internal mental number line.

To date, children with DD are tested. They accomplish the training during five weeks and are tested before and after with the two fMRI-paradigms of project 1a (spatial working memory and mental number line) as well as behaviourally.
Our results provide several interesting aspects for
discussion:
- Domain-general vs. domain specific factors involved in DD
- Correlation of behavioural results with activation of the IPS
- Neuroplastic training effects – decrease or increase in
activation
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