Neuroscience and Early Childhood Math Education:
A Blueprint for Better Bridges

Assessing the efficacy of a new research design for establishing connections between cognitive neuroscience findings and preschool math learning

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"The more the schemata are differentiated, the smaller the gap between the new and the familiar becomes, so that novelty, instead of constituting an annoyance avoided by the subject, becomes a problem and invites searching."

- Jean Piaget

Project Description

A large body of literature describes the rift between neuroscience and education, two theoretically related fields that have struggled to establish common ground. Researchers have pointed to a disconnect between the promise of neuroscience data and actual application to the classroom. This project considers the ways that cognitive neuroscience and education can forge common ground to ameliorate these problems. Building on the claim that a connection between data and the classroom will necessitate bi-directional and collaborative communication between scientists and educators, a clinical interview method has been chosen as the tool for uncovering teachers' experience-based mental models of learning processes in their students' brains. Drawing on the need for common models and language, these interviews are based around video segments of children learning math in the early childhood classroom. The overarching goal of the project is to engender meaningful discussion between educational neuroscience researchers and teachers in order to establish important connections between data on the brain and learning as it truly takes place in the pre-school environment. Interviews were carefully recorded and analyzed in an interpretive fashion to identify important variables and observation categories for future research.

Background and Theoretical Approach

Neuroscience and Education

At first glance, the fields of education and neuroscience might seem intrinsically linked. After all, learning takes place in the brain. Education, perhaps now more than ever, recognizes the need for a clearer understanding of how students learn. Over the past decades, neuroscience research has made significant advances, uncovering new and exciting data on the learning brain.

Yet, the literature tells a different story. Neuroscience and education are theoretically related fields that have struggled to forge common ground. Since the 90's, declared by the US Congress to be the "Decade of the Brain," much of the initial zeal for direct application of neuroscience data has faded. Early attempts to use neuroscience theories in the classroom resulted in misunderstandings and questionable educational policies based on hyped ideas such as synaptogenesis, critical periods and enrichment (Bruer, 1997; Mayer, 1998).

This has led the research community to react with appropriate caution and skepticism about further attempts to merge neuroscience and education. Bruer has been at the forefront of this position since his 1997 paper "Neuroscience and Education: A Bridge Too Far" (Bruer, 1997; Bruer, 2006). He makes the claim that the theoretical distance between neuroscience and education may simply be too great. The core concepts used by neuroscientists are different from those used by psychologists and classroom teachers, leading to inevitable misunderstandings. Bruer also questions how a superficial fascination with synapses and brain images causes teachers to overlook a substantial body of largely untapped cognitive psychology research (Bruer, 2006). He poses that researchers should instead devote efforts to shorter bridges between education and cognitive psychology, cognitive psychology and neuroscience (Bruer, 1997).

Mayer (1998) points out that there is an inherent problem in the goal of tailoring neuroscience findings for educators in order to base educational practices on neuroscience. Instead, he poses that the bridge between cognitive neuroscience and educational psychology needs to be a "two-way street," where educational theory guides and informs neuroscience research.

Yet, neuroscience has continued to advance, and every day new findings about how students' brains learn to read, write, do math – and handle the stress of too much homework – are showing up on bestseller tables at the bookstore, covers of popular magazines and television screens. The larger field of neuroscience has branched and merged with other disciplines, leading to subfields of cognitive, social and developmental neuroscience. In 1999 NRC declared "Neuroscience has advanced to the point where it is time to think critically about the form in which research information is made available to educators so that is it interpreted appropriately for practice."

Over the last decade the "neuroscience and education argument" (Bruer, 1997) has continued to reverberate among researchers in education, psychology and neuroscience as they regard the promise of new data on the brain for advancing the science of education and learning. Researchers have posed new solutions for building stronger bridges that can "span the chasm" between neuroscience and education (Ansari and Coch, 2006; Goswami, 2006, Bruer, 2006).

A sober consensus remains in the current literature that describing *how* data on structural and functional changes in the brain can actually be used to inform educational policy and practice is a difficult task (Ansari and Coch, 2006; Goswami, 2006, Bruer, 2006). For one, researchers identify a lack of ability on the part of teachers to acquire and recognize relevant data, leading to acceptance of "neuro-myths" and "Brain-Based" learning packages that are not supported by science. Ansari and Coch (2006) refer to questionable media reports and oversimplified claims about left/right brain learners, "exercising" the whole brain, and "brain-buttons" that inundated schools over the last decade.

Another problem is teachers' lack of knowledge and skills necessary to interpret neuroscience data. Goswami (2006) notes that the progress in neuroscience labs is largely theoretical, and without a firm understanding of *hypothesis*, *theory* and *established model*, teachers are not able to establish how data fits into the "big picture." Furthermore, Goswami states that teachers often view scientific research as too concerned with establishing rigor in precise experimental manipulations and complain that science researchers simply provide too much data.

Educational Neuroscience

Taken together these obstacles stack up to a difficult project, yet hints of promise are emerging in recent literature. Researchers have begun to collaborate across the disciplines of neuroscience and education and a new interdisciplinary field has emerged. This is evidenced by the growth of new research centers and educational programs such as the Centre of Educational Neuroscience at Cambridge, the MBE Society (http://www.imbes.org) and graduate program in Mind, Brain and Education at Harvard University, the undergraduate program in Neuroscience and Education within the Education Department at Dartmouth College, and the graduate program in Neuroscience and Education within the Biobehavioral Science

Department at Teacher's College, Columbia University where the present project was developed.

The field of educational neuroscience has become an exciting new area of educational research. A central position within this field is the acknowledgment that attempts at direct application of neuroscience data to the classroom is indeed a "bridge too far" (Bruer, 1997; Goswami, 2006). Instead the aim of new investigation is finding possible ways to "build strong bridges" (DeSmedt, Ansari, Grabner, Hannula, Scheider and Verschaffel, 2010) through multiple bi-directional and reciprocal interactions between researchers in education and *cognitive neuroscience.*

This model can be seen as incorporating Bruer's (1997, 2006) emphasis on the importance of cognitive psychology to both education and neuroscience, as well as Mayer's "two-way street" (Mayer, 1997). The emergence of cognitive neuroscience as a subfield of neuroscience was driven by the linking of connectionist models of thought and behavior developed by cognitive psychologists (see Anderson, 2005 for a full review) with new neuroscience techniques for creating images of the active brain. Through various techniques involving electromagnetic (MEG, EEG, ERP) and hemodynamic (PET, MRI, fMRI) measurement, data is collected and used to build models or pictures of brain structures, connections and pathways (Campbell, 2006).

Educational neuroscience researchers hold that cognitive psychology informed by, and informing, cognitive neuroscience should make up the core of educational neuroscience (Berninger & Corina, 1998; Bruer, 1997; Campbell, 2006; Geake & Cooper, 2003). Cognitive neuroscience research focuses on the neural mechanisms underlying human behavior and cognition, which matches closely with educational research on learning and instruction. Bruer (1997) pointed out, as one note of optimism in "A Bridge too Far," cognitive models can be seen as a locus of similarity between research in neuroscience and education. After all, cognitive neuroscience is built on models of brain processes provided by cognitive psychology, and these models are as fundamental to cognitive neuroscience as they are to the applied science of learning.

Furthermore, in identifying solutions for building bridges between neuroscience and education, bi-directional collaboration is a vital element. Ansari and Coch (2006) describe a need for "practical mechanisms" to support and foster meaningful integration between the brain-lab and the classroom so that teachers will be more informed consumers. This must be accomplished through awareness and understanding of similarities and differences between research in neuroscience and education, and by establishing points of contact between scientists and educators including bidirectional dialogue and collaborative experiment design.

Goswami (2006) urges that a new generation of multi-disciplinary researchers must dedicate their combined expertise in both neuroscience and education to presenting high quality knowledge on the brain in digestible form and interpreting neuroscience *from the perspective of* and *in the language of* educators. This requires that such researchers spend time with educators in order to establish ways that meaningful communication can be established. Common models of students' thinking need to be established between researchers and teachers in order to support and sustain true and equal collaboration, and to foster successful exchange of relevant data between disciplines. An active project must also be underway to develop a common language between neuroscientists and educators so that each understands one another clearly, and so that neither side is put off by misinterpreted theories or jargon. As Mayer (1998) recognized, drawing on teachers' experience and intuitions about students' learning presents new hope for collaborative design of cognitive neuroscience research that will be truly meaningful to educators.

Cognitive Neuroscience and Mathematics

Amid the growing field of cognitive neuroscience, mathematics learning has presented an area of particular promise. In *Proceedings for the 30th Conference of the International Group for the Psychology of Mathematics Education* held in Prague in 2006, Campbell describes a building frustration on the part of math educators with purely theoretical models of student' learning. He discusses his own desire as a math educator to see inside his student's brain in order to understand how it is changing in response to instruction, and what is happening when breakdowns in understanding inevitably occur. Campbell outlines how advances in cognitive neuroscience hold new possibilities for filling in these gaps in educators' understanding of students' learning.

In a recent position paper based on issues presented at the EARLI Advanced Study Colloquium on Cognitive Neuroscience and Math Education, held in Belgium in 2009, De Smedt et al (2010) state that bringing cognitive neuroscience to bear on mathematics learning has led to very productive research in recent years (Ansari, 2009; Dehaene, 2009; Lipton & Spelke, 2005; Lemer, Dehaene, Spelke, & Cohen, 2003). The authors point out however, that neuroimaging studies aimed at describing relationships between brain activity and instructional practice are still scarce.

In order to explore such connections, neuroscience must be guided by educational and psychological theories. Referencing research by de Jong et al (2009), De Smedt et al outline specific questions prominent in educational research that could drive future cognitive neuroscience research, such as learning from multiple representations, cognitive load and the role of affective processes in learning. The authors conclude that educational researchers can play a pivotal role by identifying important variables which need to be incorporated into educational neuroscience investigations.

Educational Neuroscience and Early Childhood Math

Math education in the preschool years has been a source of question and controversy for decades. In 2002, the National Council of Teachers of Mathematics and the National Association for the Education of Young Children collaborated to produce a joint position statement recognizing the failure of US students to achieve mathematical prowess consistent with peers in other countries and advocating an increased attention to early childhood math education (National Association for the Education of Young Children & National Council of Teachers of Mathematics, 2002). While many educators now agree that math education should begin early, there is a lack of understanding of how children's mathematical thinking develops, and how best to support it in the classroom (Ginsburg, Jang, Preston, VanEsselstyn, & Appel, 2004).

A growing body of research in education and developmental psychology has investigated the development of mathematical thinking and best practice for teaching math to young children (Piaget, 1970; Clements, 1999; Ginsburg, Jang, Preston, VanEsselstyn & Appel, 2004; Seo & Ginsburg, 2004). Ginsburg (1988, 1989, 1997, 1998, 2007) has contributed much to this burgeoning field by building on Piaget's method of cognitive clinical interviews as a research tool to assess children's mathematical knowledge, problem-solving strategies and overall understanding of math concepts at various stages of development. This has provided researchers and educators with new ways to "enter the child's mind (Ginsburg, 1997)" and observe mathematical thinking in order to improve math teaching and assessment.

In recent years there has been a call for preschool math curricula that are research based (Clements, 2007; Clements & Samara, 2007). Questions have arisen regarding the appropriateness of teaching mathematics to very young children, the best mode of instruction, and the role of concrete manipulatives in math learning (Ginsburg, Boyd and Sun Lee, 2008). Finally, despite misinterpretation of early discoveries about neurons and synapses, cognitive neuroscience confirms that the early years of life are very important in a child's mathematical development, serving as a foundation on which she will build subsequent knowledge (Baroody, 2007, Spelke & Dehaene, 1999, Xu, Spelke, & Goddard, 2005). Clearly, math educators and educational neuroscience researchers want to achieve a fuller and more accurate understanding of how the young brain develops mathematically in order to know how to best support both typical and atypical math learning.

Even so, there is a lack of cognitive neuroscience research leading to insightful explanatory models of children's learning processes that have proven relevant for application in the early childhood math classroom. Part of the reason for this is that these models do not result from the carefully controlled experiments favored by cognitive psychology and neuroscience. As any preschool math teacher will tell you, 3 and 4-year olds are spontaneous, unpredictable, and fickle learners.

Higher-level cognitive processes, even in the adult brain, are by nature non-linear, full of feedback loops and processes that compete and coordinate. Models of these processes that can be understood and used by teachers must be true explanatory models that are iconic and analog in nature being built up from "more primitive and familiar notions (Clement, 2000). "

In conclusion, while educational neuroscience research does not as yet provide a full or applicable model of children's math learning, the field is much closer to this possibility than ever. Within the current literature is a blueprint for new research methods that can begin constructing this model. It is clear that such research must involve (1) bi-directional collaboration between early childhood math teachers and educational neuroscience researchers (2) involve opportunities for open discussion, reflection and exchange of ideas and (3) create common ground for meaningful communication about research questions, including a shared language and theoretical framework.

Project Aim

The aim of this project was to develop and assess the initial efficacy of a research model for determining how and in what ways cognitive neuroscience research can be made meaningful to early childhood math educators. The specific goals of the project were:

(1) To design a research model that would incorporate recommendations in the current literature for *bi-directional collaboration*, *common models* and *common language* in order to foster meaningful communication between educational neuroscience researchers and teachers
(2) To gather pilot data on the efficacy of the research model for engaging or changing teacher's current mental models of student's learning
(3) To identify important variables and observation categories for use of the research model in future investigation

Research Model Design

The primary goal of this project was the careful construction of a research design that could explore how cognitive neuroscience on children's math learning could effectively engage teachers.

Bi-directional Collaboration

The first task was to choose a research technique that would allow collection of data on teachers' authentic thoughts and ideas through bi-directional communication between researcher and teacher.

A cognitive clinical interview method was chosen as the research technique that would best accomplish this goal. Since it was developed by Piaget (1955, 1975) to describe internal thought structures in children, the clinical interview method has branched into a variety of techniques for research in psychology and education (Strauss, 1993), including math education (Clement, 2000; Ginsburg, 1989, 1997; Ginsburg & Opper, 1988; Ginsburg, Jacobs & Lobez, 1998; Ginsburg, Jang, Preston, VanEsselstyn & Appel, 2004; Ginsburg, Boyd, & Sun Lee, 2008). The strength of the clinical interview method, as opposed to non-clinical data gathering techniques, is that it can be used to collect and analyze data on mental processes at the level of a subject's authentic ideas and meanings, and to expose hidden structures and processes in the subject's thinking that could not be detected by less open-ended techniques (Clement, 2000).

As the clinical interview method is by nature an open-ended technique several issues regarding reliability of data will be addressed. Clement (2000) outlines important considerations for researchers using the technique in order to foster reliability. First, he suggests preparing set protocols for interviews that can be used with repeated subjects. Second, videotaping interviews creates a rich record of verbal and behavioral data that can be reexamined and shared. Finally, a combination of generative and convergent interview methods allows interviews to be first analyzed in an exploratory fashion so that observation categories can be developed for later coding of data.

In his own research constructing models of problem solving in algebra students, Clement urges the need to begin with generative, interview-based case studies. These are analyzed and theoretical hypotheses take the form of models that are grounded in naturalistic observation of behaviors. As data is collected and analyzed, these initial models are revised in a bi-directional research technique incorporating both bottom up (inductive) and top-down (deductive) methods. Through this process, investigators become sensitized regarding what to look for, and observation categories can be developed for future data, providing the foundation for the design of convergent studies.

Based on these recommendations, the following elements were incorporated into the research design:

Three set protocols were developed for each clinical interview. The choice of questions for the protocols drew on the seminal work of Piaget (1975), as well adaptations of these methods developed by Clement (2000), Strauss, (1993) and Ginsburg, (1989, 1997). The first protocol, (Interview 1) was designed to collect teachers' unique path to teaching, educational background, and personal philosophy or approach. The second protocol (Interview 2) includes six questions that relate to discussion of a specific teaching moment. The final protocol (Interview 3) asks a series of four questions that invite teachers to relate findings of cognitive neuroscience to the teaching moment, their own classrooms and personal philosophies, as well as to describe ways that the neuroscience information impacted or changed their opinions/beliefs about early math learning. It is important to note that, while questions for these protocols were pre-set, the interviewer was able to react responsively to answers as they were collected by asking follow-up questions to clarify and extend the investigation (Clement, 2000). These protocols and questions will be discussed in further detail in the Materials and Methods section of his paper. A script for each protocol is also included in the Appendix.

Each clinical interview was video recorded. Repeated review of recorded interviews would allow data to be initially analyzed in an open-ended exploratory fashion in order to develop observation categories for future analysis and coding.

Common Models

The second task in the goal of assembling the research design was to identify common models of student learning in order to allow meaningful discussion between researcher and teachers, and guide the incorporation of neuroscience data into this discussion.

It is noteworthy that even with all the new data coming from research, there is a marked lack of insightful explanatory models of students' learning processes. Part of the reason for this is that children's cognitive processes are complex, highly influenced by environment and experience, and full of interactions between development, instruction and social and emotional factors. Furthermore, teachers' experiences with these processes are not derived from study of development and cognition, but on their time spent in the classroom, teaching, observing and assessing their students.

Clement asserts that subjects, in this case teachers, do have pre-existing knowledge structures and reasoning processes that guide their thoughts and beliefs about students' learning. These mental models have strong effects on teachers' ideas and approaches. Strauss (1993) claims that without determining the nature of teachers' mental models about children's minds and learning, new information will not be able to engage or change these models. Using a semi-structured clinical interview technique he collected and analyzed teachers' answers to questions about what they would do in specific teaching situations, uncovering mental models that he could then connect to information processing models presented by cognitive psychology (i.e. working memory, elaborative processing).

In a similar way, this project aimed to use clinical interview to first access these pre-existing models so that they could be utilized in discussion of student learning, and later connected to models presented by cognitive neuroscience. In order to guide meaningful discussion of students' learning, a problem space needed to be established within which both researcher and educator could observe, reflect on and analyze student instruction, behavior, strategy, and performance. By incorporating the elements that teachers naturally chose to describe learning processes, new information could be introduced on the level of a teachers' unique model.

A case-based research approach was chosen as the technique that would best accomplish this goal. Widely used in teacher education and educational research, case-based instruction is a practice-anchored learning pedagogy that can be used to provide teacher candidates and researchers with multiple opportunities to consider complexities of teaching and learning (Andrews, 2002; Kilbane, 2008; Rosen, 2008; Steinkuehler et al, 2002). Kilbane (2008) emphasizes that cases illustrate life in the classroom as it actually is, not as it should be. Recent research on the case-based method has revealed that computer cases which offer video vignettes of learning moments combined with interactive discussion questions have the greatest impact on the quality of teacher's reflective narratives (Rosen, 2008). Teachers are asked to watch and reflect on video-recorded teaching moments as they happen in real time, thus allowing them to describe learning processes on the level of their own personal models of these processes.

Video vignettes of early childhood math teaching moments were chosen from the VITAL (video interactions for teaching and learning) archives of Teacher's College, Columbia University. Lee, Ginsburg and Preston (2009), in their description of the project, state that improving early childhood teacher preparation is the most pressing need for early childhood mathematics education in the United States. VITAL provides prospective teachers with "engaging and intellectually stimulating hands-on and minds-on learning experiences that supplement the traditional textbook and readings." The present design extends the use of VITAL as a tool for collecting data on teachers' knowledge.

The questions for the second protocol (Interview 2) were based on these learning vignettes, and imbedded at points throughout the video so that teachers were able to draw on specific teaching moments they had just watched when reflecting on answers to the questions. Finally, the neuroscience-based models of learning presented to teachers were constructed based on these video cases in order to relate to the specific elements and variables central to each. These video vignettes and the corresponding neuroscience supplements will be discussed in further detail in the Materials and Methods section of this paper.

Common Language

The final task in assembling the research design was to establish a common language to allow for meaningful discussion between researcher and teachers, and guide the incorporation of neuroscience data into this discussion.

A basic familiarity with behavioral and educational terms was assumed for subjects during construction of interview protocols and presentation of neuroscience information. Care was taken to strip away any psychological jargon, mathematical terminology, and neuroscience language that may not be already part of subjects' vocabulary. Throughout interviews, close attention was paid to the language and terms used by an individual subject. Any follow-up questions or discussion remained consistent with this vocabulary and terminology, and did not introduce new language.

It was established that neuroscience information would be presented to teachers in two ways. First, a one-page summary of recent cognitive neuroscience findings relevant to the specific teaching moment they watched was given to teachers to read. This written summary was accompanied by a simple iconic drawing of the brain, with key areas discussed in the written summary clearly labeled. Additional pictures and symbolic elements served to illustrate the neuroscience information in a way consistent with the figures and diagrams one might find in pre-service teacher education materials. In both of these supplementary materials, vocabulary did not exceed that which a teacher might come into contact with in coursework materials. For example brain areas were discussed as being in the "front," "back" or "side" of the brain rather than "frontal" "pre-frontal" "occipital" or "temporal." Neuroscience supplements will be discussed in further detail in the materials and methods section of this paper.

Collection of Pilot Data

The second goal of this project was to test the efficacy of the research model by collecting pilot data. Interviews were planned over the course of the 2010 – 2011 academic year with early childhood math educators from various educational and philosophical backgrounds that had been teaching between two and five years in a variety of pre-school programs. It was established that each interview would be video recorded using a Macintosh MacBook Pro. Recordings of interviews would be edited and organized using the iMovie program. Finally, videos would be exported to Quicktime and stored on an external hard drive for later review and analysis.

Materials and Methods

Project Design

Subjects were randomly assigned to one of three research vignettes: Number Sense, Arithmetic, or Pattern. Each vignette was composed of three clinical interviews including (1) a short, structured interview asking teachers to provide information on their background, path to teaching, and philosophical approach (2) a semi-structured interview built around video cases of early math teaching moments (3) a more open-ended reflective interview following presentation of neuroscience supplements. Research vignettes were presented as a PowerPoint Presentation on a Macintosh MacBook computer. All clinical interviews were video recorded using the iMovie program on the same computer.

Research Vignettes

The three math topics chosen for the vignettes share a solid foundation of relevant literature from the fields of education, developmental psychology, cognitive psychology and most recently, cognitive neuroscience. These topics are also central to questions guiding current investigation into the development of mathematical thinking in the brain.

Each vignette included unique video cases and neuroscience supplements.

Video Cases

All videos were chosen from the VITAL (Video Interactions for Teaching and Learning) vault at Teacher's College, Columbia University. Each is less than three minutes in length, and was divided into three segments shorter than one minute.

Each video was chosen to present a teaching moment that aimed at building or assessing a child's/children's understanding of either number sense, arithmetic or pattern. Below are brief descriptions of each video case:

Number Sense

- Case showed teacher at a private Manhattan preschool in her own classroom with a group of preschool students
- Teacher agreed to be video recorded while teaching lessons adapted from the Big Math For Little Kids curriculum, which is based on current research about how number sense is built
- Activity involved asking a group of children to find "fours" of among representations of different numbers and quantities on multi-colored cards spread on the floor: numerals with and without number words, lines, dots, and pictures of objects.
    - CLIP 1: teacher introduces task to children
    - CLIP 2: very young child is called up to find a four, uses a trial-and-error approach until guided to pick up correct card by color
    - CLIP 3: older child comes forward and quickly finds a correct card

Arithmetic

- Case showed graduate student at Teachers College conducting a teaching interview with a preschool student in a Manhattan preschool classroom
- Graduate student recorded interview as training in using the clinical interview method to assess and support children's learning of arithmetic
- Activity involved asking child to count using small green blocks. Using a game of "adding apples," child was presented with two addition problems
    - CLIP 1: Child counts the blocks she has (six) arranged in two rows of three
    - CLIP 2: Interview gives child seven more blocks, she incorporates them into rows and counts thirteen correctly

    - CLIP 3: Interviewer gives child one more block, she incorporates it, and incorrectly counts thirteen again

Pattern

- Case showed graduate student at Teachers College and teacher (Principal Investigator) conducting a teaching interview with a preschool student in teacher's own classroom in Montessori-based private progressive preschool
- Graduate student recorded interview as training in using the clinical interview method to assess and support children's learning of pattern/early algebra
- Activity involved (1) asking child to watch teacher construct an ABAB pattern involving alternating groups of objects which she first describes with language and (2) asking child to build a similar pattern by herself which the teacher describes with language
    - CLIP 1: Child watches teacher as she "thinks of pattern in her mind," describes pattern verbally ("Three cameos, two blue stones…") and then constructs it, placing cameos horizontally and stones vertically
    - CLIP 2: Teacher describes new pattern for child to "hold in her mind:" ("Two cameos, three blue stones…)
    - CLIP 3: Child assembles pattern, preserving correct number in groups and ABAB structure, but beginning with blue stones and placing all groups horizontally

Clinical Interviews

Protocols for Interviews 1 and 3 were identical for all research vignettes. (See Appendix A and C).

The second clinical interview protocol (Interview 2) sought to probe teachers' in-the-moment reactions to early math teaching moments. For each of the three vignettes, number sense, arithmetic and pattern, video clips were edited into three segments which were embedded into PowerPoint slides. Segments were based on natural divisions in the teaching moment, i.e. task-set up, task presentation by the teacher, and task performance by the student.

After each clip, teachers were asked two questions, for a total of six (See Appendix B). Though there is slight variation in the ordering of the questions based on differences in each video, the questions follow a basic continuum: The first set of questions invites reflection on student *behavior*, such as engagement and interaction with materials. The second set asks subjects to evaluate the *conceptual teaching method*, i.e. the concept the teacher was attempting to teach, and the approach used to teach it. The last set of questions aimed at teachers' intuitions regarding *cognition*, including the child's developing mathematical abilities and strategies in solving the tasks.

In this way, Interview 2 was consistent with the cognitive clinical interview method of probing knowledge structure in a careful, step-up fashion. Questions were scaffolded to describe teachers' relative place on a continuum of knowledge spanning behavioral, educational, psychological, developmental, and cognitive levels of analysis regarding teaching and learning.

For each vignette, Interview 2 included a different consideration noted after the last set of questions on the student's cognitive process:

For *number sense*, the interviewer remained particularly open to exploration of why the second child was able to perform the task of finding four so much more quickly and easily than the first child.

For *arithmetic*, the interviewer remained particularly open to exploration of the use of blocks in solving the problem, including why the child arranged the blocks the way she did, and how this affected her performance/success.

For *pattern*, the interviewer remained particularly open to exploration of why the child preserved the overall structure of the pattern, but did not preserve the order described with language and neglected spatial details.

Neuroscience Supplements

The information presented in the neuroscience supplements provided teachers with a simplified summary of current and sound cognitive neuroscience findings related to the topics of number sense, arithmetic and pattern. Rather than giving teachers a complete model or a prescription for teaching, these supplements instead aimed to establish a problem space within which both teacher and researcher could meet to ask and answer questions about the specific teaching moment they watched.

Neuroscience information was presented in two ways: (1) as a one-page printed summary of research findings and (2) as an iconic diagram of the brain with relevant labels, pictures and symbols.

The printed supplements first summarize what has come to be generally agreed upon within the field of imaging research regarding the brain areas active in the type of math task presented in the video case. Next the supplements briefly outline how brain pathways and connections might support performance of these mathematical tasks during the preschool years. Finally, the supplements present teachers with a suggestion or thrust of the research to guide speculation and open the way for further questions and debate. These descriptions are simple and stripped of any neuroscientific language that may be unfamiliar to teachers. For example, "taking pictures of adults and children's brains" is used instead of "PET" or "fMRI." Additionally, by using language such as "researchers want to know," "researchers pose that," "some studies suggest," and "children's brains…seem to have," the supplements aimed at creating space for the collaborative construction, through active bi-directional dialogue, of models incorporating cognitive neuroscience findings into a teacher's own experience-based intuitive model of math learning.

The picture supplements supported printed information in a visual format. These diagrams were similar to figures explaining learning processes that teachers might encounter in a pre-service or graduate teacher education textbook. The picture supplements showed a simple picture/pictures of the brain that were biologically accurate with well-defined gyri but without colored regions or superimposed outlines. Brain areas described in the printed supplement were labeled clearly with words, i.e. *vision, general reasoning, language, working memory*. Simple and colorful images were gathered online and laid out in general proximity to corresponding brain regions. For instance, a card with the word "Five" was placed beside labeled language areas in the left hemisphere, while a line of rubber ducks was placed beside visuo-spatial areas in the right hemisphere.

It is important to note that these neuroscience supplements were carefully constructed by the principal investigator, based on nearly two years of studying peer-reviewed literature and graduate coursework in cognitive psychology, developmental psychology, cognitive neuroscience and education. Information was drawn from numerous, wide-spread and qualified sources, and presented in a way that the Principal Investigator felt would be meaningful and easily understood by teachers, based on five years of experience teaching and developing math curricula in an early childhood classroom.

Care was put into presenting "high quality knowledge on the brain in digestible form and interpreting neuroscience *from the perspective of* and *in the language of* educators (Goswami, 2006)." Thus, the information in the neuroscience supplements does not involve direct connections between piecemeal findings and recommendations for teaching. Rather, the statements in the neuroscience supplements represent the current thrust of the literature on math learning and the brain, built in turn on a foundation of educational, developmental and cognitive psychology.

Furthermore, the models are presented in their current - and incomplete - theoretical state, with corresponding questions, ambiguities and gaps in knowledge. This was done in hopes that current models could be analyzed and extended collaboratively by both teacher and researcher. A complete theoretical background of the developing theories on math learning presented in the neuroscience supplements is beyond the scope of this paper. Even so, a full reference section, including many solid reviews, has been provided after neuroscience supplements in Appendix D.

Pilot Data Acquisition

Subjects

Six teachers were recruited from a range of New York City preschools, including public Pre-K, private, and progressive programs. All teachers were female, and had been teaching in early childhood between two and seven years. Subjects were either currently enrolled in or had completed an Early Childhood Education degree program. No teachers had completed coursework in neuroscience.

Subjects were assigned randomly to on of the three research vignettes, so that two interviews were collected for Number Sense, two for Arithmetic, and two for Pattern. Partly due to the desire to keep interview sessions natural and not overly "scientific," verbal consent was obtained prior to interview. Teachers were informed that pilot data was being gathered, and that written consent would be obtained before any recorded material was shown publicly or online, and before any personal quotes were published.

Methods

Interviews were conducted at quiet, familiar, yet neutral locations, including empty school classrooms, or rooms in residences other than the subjects' home. Teachers were comfortably seated with interviewer before the computer and briefly told that they would be watching some videos of preschool children learning math, and reflecting on what they saw. Noise-blocking headphones were provided while watching video clips.

Interview 1 was conducted. Subjects then were shown the PowerPoint Presentation. Slide 1 informed the subject that they would be watching a pre-school aged child/pre-school children in a Manhattan preschool. Slides 2 – 4 showed video clips 1 – 3. Between each clip, subjects were recorded answering two questions to complete Interview 2. Powerpoint presentations as well as the iMovie program were kept in separate windows on the desktop to allow for easy transition between presentation and recording.

Subjects were presented with neuroscience supplements upon completion of Interview 2. Printed material was in paper form, and the picture was shown as the last PowerPoint slide. Subjects were given as much time as needed to get a general sense of the material, and were assured that they did not need to memorize or repeat information. Once subjects confirmed that they felt sufficiently familiarized with the neuroscience supplements, Interview 3 was conducted.

As previously mentioned, Interview 3 was a more open-ended and reflective clinical interview that attempted to find matches between teachers' intuitions and neuroscience information, evidence of misconceptions about neuroscience, and any teacher perspectives or knowledge regarding questions or holes in current theories of math learning in the young brain.

In order to explore these connections, follow-up questions were asked to further expose teachers' thoughts and beliefs. Specific considerations for each research vignette are outlined below.

Number Sense

- How do teacher's intuitions about the importance of building a strong number sense in preschool children match educational research?
- What intuitions does teacher have regarding different kinds of mathematical information represented different ways in the brain?
- What evidence does teacher's reflection reveal of brain myths about different kinds of learners (i.e. visual or verbal) or "exercising the whole brain?"
- Particular openness was given to any intuitions about how to best support the building of number sense as a concept
- Consideration was given to the fact that teachers had watched implementation of a research-based curriculum: Big Math For Little Kids (Greenes, Ginsburg & Balfanz, 2004).

Arithmetic

- How do teacher's intuitions about how and when to support arithmetic skills match educational research?
- What intuitions does teacher have regarding the development of arithmetic, and how this interacts with the need for concrete objects and the use of symbols?
- What evidence does teacher's reflection reveal of brain myths about purely constructivist enrichment models or a built in "math center" in the brain?
- Particular openness was given to any intuitions about how and when the shift to language-based math facts happens or should happen to best support mathematical development.
- Consideration was given to the fact that teachers had watched a teaching moment built on the clinical interview method, which allowed free use of concrete materials for problem solving, but was also teacher directed.

Pattern

- How do teacher's intuitions about the teaching pattern support current finding in educational research about children's use of visuo-spatial skills in math tasks?
- What intuitions does teacher have regarding how such tasks draw on language, math facts and visuo-spatial reasoning?
- What evidence does teacher's reflection reveal of brain myths about right/left brain learners?
- Particular openness was given to any intuitions about the role of visuo-spatial abilities in building the deep mathematical understanding needed for higher-level math skills such as algebraic thinking.
- Consideration was given to the fact that teachers had watched a teaching moment that was based on a progressive visuo-spatial method of math instruction (the Montessori method).

After completion of Interview 3, teachers were thanked for their participation and dismissed.

Pilot Data Analysis

The research design yielded a small and cohesive set of pilot data, while still allowing for at least one degree of comparison both across and within vignettes. The six interview subjects were currently teaching in a variety of pre-school classrooms, including public Pre-K, private and progressive programs. They had varied background experiences, ranging from daycare centers to private and lab preschools. They also had varied education, spanning partially completed coursework for a BA in Early Childhood with pending certification, to an MA in Early Childhood with certification. Subjects were randomly assigned to one of three research vignettes. Thus, six interviews were analyzed, two for each research vignette: Number Sense, Arithmetic and Pattern.

The goal of preliminary data analysis was to (1) determine the efficacy of the research design in engaging/changing teacher's models of students' thinking (2) identify important variables and observation categories for further research. Interviews were considered as individual cases. Recorded interviews were watched repeatedly in order to organize answers to interview questions.

In order to address the overall efficacy of the research design in engaging teacher's mental models, answers to Interview 2 were transcribed and compared across all subjects. As previously discussed in Materials and Methods, Interview 2 questions proceeded on a continuum, calling on teachers' independent abilities to utilize behavioral observation, educational and mathematics language, developmental psychology, and finally cognitive psychology in their answers. Three observation categories were set up, based on the overarching level of analysis that questions invited teachers to use in their reflection on the video case segments.

(1) Are teachers able to comfortably answer questions based on observations of children's *behavior* in a given teaching moment?
(2) Are teachers able to easily identify the *concept being taught* and discuss why they would use a similar/different approach?
(3) Will teacher's discussion of students' developing math abilities and strategies reveal an explanatory model of children's cognitive processes during the teaching moment?

For the final question, answers were reviewed to determine if a teacher's intuitive model was able to provide an adequate explanation regarding specific considerations for each math topic. For Number Sense, why was the second child was able to perform the task so much more quickly and easily? For Arithmetic, what was the significance of the child's use of blocks? For Pattern, why did the child preserve the structure of the pattern, but not the order prescribed in language, or the spatial orientation of the materials?

In order to assess how the neuroscience information presented in the supplements engaged teachers' current models, answers 1 - 3 of Interview 3 were transcribed and compared across all subjects, including answers to follow-up questions. Answers were organized according to the level at which the developing models of mathematical thinking in preschool students, presented in educational neuroscience, matched teachers' own intuitive models as described in Interview 2. Three observation categories were set up, based on the specific considerations guiding the interview, which are outlined in Materials and Methods. These considerations aimed to identify:

(1) How teachers' intuitive models match the foundational developmental or educational psychology theories on the math topic.
(2) How teachers' intuitive models match the models of mathematical thinking presented by cognitive psychology, on which cognitive neuroscience models are based.
(3) Evidence of brain myths specifically relevant to the math topic.

In order to identify how neuroscience information might impact or change a teacher's current model of mathematical thinking, answers to Interview 3, including question 4, were reviewed in order to gather case descriptives on how the neuroscience information (1) resolved questions or ambiguities regarding a student's thought process, (2) changed a teachers' opinions or beliefs about children's mathematical thinking, or (3) gave a teacher new insight into students' thinking.

To assess the ability of the research design in establishing a common language between researchers and teachers, interviews were thoroughly combed for (1) terms that were not easily understood by teachers, (2) instances where teachers were able to substitute their own definitions of forgotten or unfarmiliar terms, (3) phrases that exemplify meaningful communication, including teachers' descriptions of experience-based intuitions and active sense-making of neuroscience information.

Finally, all interviews were searched for any instances where teacher's intuitions could be seen as guiding current questions in educational neuroscience research.

Preliminary Results and Discussion

For the purpose of discussion, subjects are labeled Teacher 1 – Teacher 6. Teachers 1 and 2 participated in the Number Sense vignette. Teachers 3 and 4 participated in the Arithmetic vignette. Teachers 5 and 6 participated in the Pattern Vignette.

Interview 2: Teacher Mental Models

Behavior

Based on the six interviews conducted for this project, most teachers were comfortable reflecting on student's behavior, and all but one were able to assess student engagement and the significance of specific behaviors to the math task being taught. Teacher 1 explained that she did not know if students watching the lesson were engaged from their behavior. All other teachers described students' being "*quiet,"* or "*fixated*," "*orienting,"* "*listening*," and answering questions "*right away*." All teachers were able to explain why a student picked up a "*red"/"orange*" card, identify the skill a student was demonstrating by counting blocks, and relate the significance in a child's assembly of a pattern.

Conceptual Teaching Approach

All teachers were able to discuss the math concept being taught, as well as their alignment with the teaching method. Differences did emerge between vignettes on teachers' ability to name the math concept and use educational or mathematical language. For instance, both teachers struggled to name the concept of Number Sense. Teacher 1 said, "*What four looks like…a conceptual understanding that numbers are represented in different ways*." She admitted that their was a term for this concept, and was embarrassed that she could not remember it. Teacher 2 answered, "*Different numbers, different ways they are represented...ways you can show four*." Teachers had no problem in the Arithmetic vignette, both replying "*addition*," right away. There was some uncertainty in the Pattern vignette, due in both cases to the different elements incorporated in the pattern task (counting, ordering, spatial layout), though both teachers identified that the task involved "*patterns*." Teacher 5 described "*units of number, patterns, grouping, visual patterning*," while Teacher 6 described a "*numerical repeating pattern – groups of numbers*."

Both subjects in the Number Sense vignette claimed that they would teach this concept differently. Teacher 1 stated that the lesson could better be taught in smaller groups, with a longer and more flexible time course for each student to answer questions. This would allow the teacher to better assess student understanding. She also claimed that more sensory/tactile support was needed. Teacher 2 claimed that rather than leading children to the answer with clues (the teacher guided the child to pick up an orange card), the teacher should have let her pick up a wrong card, and then discuss why it did not show four. Both teachers in the Arithmetic vignette claimed that they would teach this concept in a similar way, using manipulatives, though Teacher 2 stated she would start with a smaller number of blocks first to see where counting abilities broke down. Both teachers in the Pattern vignette claimed they would use the same teaching method of modeling the pattern with language before asking the child to lay it out. Teacher 5 added that she would need to first assess what individual pattern abilities the student had before presenting all the elements together in one task.

Cognition

Teachers answers to the final questions in Interview 2 revealed mixed abilities in discussing students' cognitive processes, including the math abilities and mental strategies used to solve math tasks. For Number Sense, the questions probed teachers' intuitions about why the second child was able to solve the task more quickly and easily than the first. Teacher 1 claimed that the task drew on "*rote counting*" and "*one to one correspondence*," and posed that the second child had had previous exposure to symbols and more exposure to similar activities, and thus was able to pick up the card with less scaffolding. Teacher 2 claimed that the child needed to know "*what the number four is*," have a "*literacy of how to show four*," and needed to be able to count to four. She posed that the second child was paying closer attention to the activity and had already scanned the card. She outlined his strategy as looking, counting, matching dots to numbers...."*seeing four, counting four and recognizing the symbol*."

For Arithmetic, the questions probed teachers' intuitions regarding the child's use of blocks in solving the task. Teacher 3 claimed that the addition task required the child to use counting skills, and "*remember*" the amount 13, though she admitted she did not know the correct terminology for this skill. Teacher 3 claimed that the child's strategy involved adding the blocks into her own group to "*make them hers*" and then counting. She claimed that the child simply messed up in her counting, but that her strategy was sound. Teacher 4 claimed that the child drew on one to one correspondence, as well as visuo-spatial skills in arranging the blocks in rows. She concluded that the child's strategy led her to solve the task incorrectly, guessing that perhaps she "*got stuck*" on the number 13.

For Pattern, the questions probed teachers' intuitions regarding why the child preserved the overall structure of the pattern, but did not follow the order as prescribed in the teacher's language, nor the spatial orientation of the materials. Teacher 5 claimed that the child needed to be able to count to three, understand what two and three mean, and have some familiarity with pattern. She posed that the child listened and remembered the pattern in her head and then started from the beginning in assembling the pattern. Teacher 5 admitted that she did not know why the child did not reproduce the exact order and spatial layout, guessing that she "*focused more*" on the pattern. Teacher 6 also claimed that the child needed to understand numbers, have a concept of pattern, and be able to count. She guessed that the child simply "*associated two with cameos and three with stones*," and "*let that be what was floating in her mind…She wasn't thinking about order*."

Interview 3: Impact of Neuroscience Information

Answers to Interview 3 revealed differences between subjects regarding how individuals' intuitions matched educational, developmental and cognitive psychology theories regarding specific math concepts. While examination of each interview is beyond the scope of this discussion, the interviews conducted in the Number Sense vignette serve as an example of these differences.

Teacher 1 felt that the neuroscience information presented was about initial development of math concepts, and demonstrated the importance of making connections between different kinds of math information. She went on to describe how different parts of the brain are "*active*," and math information needs to be "*dispersed*" and "*connected*" throughout the brain. Teacher 1 stated that the idea that *"math concepts are stored in different areas of the brain would suggest to me that you want to expose or connect those math concepts to as many areas as you can."* Ultimately, she felt that this supported her intuition that more sensory and tactile information should be incorporated into the teaching of this concept. In light of this, she felt that the lesson she had relied mostly on language, but lacked in both adequate time, and sensory interaction with concrete materials.

In contrast, Teacher 2 felt that the neuroscience information supported her intuition that throughout mathematical development, "*all children are developing in brain functions differently*." Therefore some areas are stronger than others. Teacher 2 felt this supported her intuition that children learn in different ways and "*if one way isn't working*" a teacher can "*go with the other*." Rather than seeing an importance in teachers guiding students to build connections, she felt that math learning should be less teacher-directed. As long as information is provided as both "*numbers and tallies*" the children will "*figure out the connection from there*."

Research on the topic of number sense confirms that the concept underlies later mathematical abilities (Baroody, 2010; Dehaene, 1997; Dehaene, Piazza, Pinel & Cohen, 2003). Cognitive psychology and neuroscience literature shows that mathematical information is represented in different areas of the brain (Delazer & Benke, 1997; Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Lemer, Dehaene, Spelke & Cohen, 2003) and that symbolic information is mapped onto more abstract numerical knowledge through experiences, instruction and practice (Gilmore, Indefrey, Steinmetz & Kleinshmidt, 2001; Lipton & Spelke, 2005; Piazza, Pinel, LeBihan & Dehaene, 2007; Strauss, 2003).

Studies such as that of Baroody, Eiland and Thompson (2009) have investigated the success of various methods of instruction (structured or semi-structured discovery, direct instruction and unstructured practice) for fostering preschooler's number sense. In line with the intuitions of Teacher 1, recent research is showing that the brain learns complex concepts best when they are taught and experienced through various sensory stimuli (Rains, Kelly, & Durham, 2008; Tokuhama-Espinosa, 2008b; Tokuhama Espinosa, 2010).

The intuitions of Teacher 2 showed some possible interference from misconceptions about the significance of mathematical information being represented in different areas of the brain. Her answers seem to show some evidence of brain myths regarding visual versus verbal learners, and isolated parts of the brain being "stronger" than others like muscles. Working from her own model, which likely was impacted by her background in Special Education, she interprets the findings to mean that "stronger" parts of the brain can be used if others aren't "working."

Educational research does lend some support to the idea that differentiated instruction (allowing students to learn at their own level and pace) makes sense given students' different intelligences and cognitive preferences (Tomlinson, 1999, Tomlinson & McTighe, 2006). However, the educational neuroscience literature cautions that despite its success in classrooms, more research needs to be conducted in order to establish why differentiated instruction appears to work based on brain research. Differentiation based on different intelligences and cognitive preferences remains intelligent speculation (Tokuhama-Espinosa, 2010).

Furthermore, thinking about the *ways* different children might take in and learn new information is a separate consideration from *how* conceptual understanding is fostered and achieved. In other words, though children might show strengths or weaknesses for various kinds of mathematical information, this does not mean that building strong knowledge of and connections between all of these types of information is not still vital for conceptual development.

Reviewing answers for Interview 3 yielded substantial evidence of neuroscience information having impacted or changed teachers' current models. The reflections of Teacher 6 provide an example of how the neuroscience information resolved ambiguities inherent in the video case. At first, the subject could not figure out how the video demonstrated the student favoring or relying on visuo-spatial abilities over math facts and language in solving the pattern task; rather the two seemed to be working in tandem.

Through consideration of what she has seen in her own classroom, Teacher 6 was able to construct a new model of how visuo-spatial abilities interact with math facts and language to yield a deeper understanding of numerical patterns. She describes how a change occurred in her student's understanding of one hundred as they counted the days of school and hung numbers in rows of ten on the wall. As soon as they were able to *"see"* the remaining numbers to one hundred on their hands, their guesses about how many days were left became much more accurate. It was as if the physical and visual connection to the idea helped them internalize it. She concluded that about ninety percent of the math work in her Montessori-based classroom is indeed built on the idea that mathematical understanding must involve visual representations of mathematical patterns, such as a triangle of colored bars of beads that represent numbers one through ten. As these beads are manipulated, arranged, and physically matched to numbered tiles, solid mathematical understanding is built.

The reflections of Teacher 3 provide an example of how the neuroscience information changed teachers' opinions or beliefs regarding the math topic. She related how, in her own classroom, she had always used both symbols and concrete objects for children of any age when teaching beginning addition, as long as they know numbers and amounts. After considering the developmental shift that occurs from reasoning and working memory to symbols and mathematical language, the subject mused, *"Now that we're talking about it, I never thought of the reason of why we were using them…that's just what you do when you're teaching. I didn't think about the way children's minds work to that extent…Wow, children maybe three and under are working on just what they can hold in their minds."*

The reflections of Teacher 2 provide an example of how the neuroscience information gave teachers new insight into student's thinking. At first, she claimed that number sense as a concept was not something that was explicitly taught in her emergent, child-centered classroom. After considering how mathematical information is represented in the brain and connected into the concept of number sense, she realized that her students' discoveries during block play demonstrated how *"different areas process different representations of numbers."* They see and handle quantities, use language to count, compare more or less, and use math to *"figure things out."* In this way there is "*number sense all over the place."* Teacher 2 said the neuroscience information reminded her that *"sometimes you are not understanding what kids are understanding…*," that " *[neuroscience] is another way of observing the child."*

Common Language

In the six interviews conducted there were few instances where teachers were not able to understand terms. The flexibility of the clinical interview allowed the researcher to repeat and re-word phrases slightly so that teachers were able to succeed in understanding and answering all questions. One curious finding was that all six teachers paused for some length while answering question 5 of Interview 2, which asked them to list the math abilities that the child needed to have to solve the task. At some point during their answer, all six teachers also repeated the term "math abilities" to themselves, which aided them in thinking of a few more.

There were several instances of teachers not being able to remember or access the correct educational or mathematical term for an ability or concept, but this did not deter them in substituting adequate definitions in their own words. As examples, Teacher 2 used "what number four is…a literacy of how to show four," in the place of number sense. Teacher 1 used "what four looks like," when she cannot recall the proper term, likely in place of the term *subitize.* Teacher 3 admitted she was not sure of "terminology" for math abilities involved in addition, but was able to identify "counting skills" and "remembering the amount of 13," which serves as a fair definition for *cardinality*.

Most importantly, review of the interviews yielded many phrases that exemplify meaningful communication between educator and researcher regarding students' mathematical thinking as it relates to cognitive neuroscience findings. As Teacher 1 stated, knowing that math concepts can be stored in different areas of the brain *"[suggests] to me that you want to expose – or connect – those math concepts to* *as many areas as you can."* As teacher 3 articulated, the neuroscience perspective is "*very exciting, even though it's scientific…teaching is such an intuitive science…younger children respond more to objects because they use their working memory, reasoning, what they know…It just confirms that they way that I approach teaching math is a way that works for children of this age."* As Teacher 5 stated, *"I'm interested to know more…it's not enough to help me be a better teacher. Some of it is what I already know…so, you know these things are in different parts of the brain, and…so I should do what better?"*

For each of the three math topics explored in these interviews, important questions emerged during teacher interviews that can be seen as particularly relevant in that they touch upon areas at the forefront of the body of research on which the neuroscience supplements drew (Full References in Appendix D). For Number Sense, these questions concern the teacher's role in building strong number sense in students. What is the importance of adequate time for students to explore materials and solve tasks? How important is sensory or tactile information in building this concept? What aspects of number sense do children build on their own, and which require direct instruction for connections to be made between different kinds of mathematical information as it is stored in the brain?

For Arithmetic, these questions concern when and how the shift from reliance on concrete objects to visual and language abilities occurs or should occur. At what age in development (somewhere between three and five according to teachers interviewed) do children naturally make this shift? How does language learning interact with this shift, ie (as Teacher 4 observed in her own multi-lingual classroom), why do English language learners seem to have an advanced ability to solve addition problems using language?

For Pattern, these questions concern the role of visuo-spatial abilities in understanding of pattern. How should teaching of pattern incorporate and build different elements of pattern (language, counting, number sense, sensory, visuo-spatial) into instruction? What evidence is there that students need the visuo-spatial element in order to recognize and understand mathematical patterns, a valuable component of algebraic and abstract mathematical thinking, in a meaningful way?

Discussion

According to the preliminary data, this research design achieved the aim of establishing common models and language in order to engender meaningful discussion between researcher and teachers. Video cases served as a functional problem space within which interviewer and interviewee could meet to explore various topics in early childhood mathematics. The clinical interview technique served it's purpose in gathering teacher's intuitive mental models at the level of their own thoughts and beliefs, and provided a rich source of descriptive data on how neuroscience information engaged/impacted teachers' current models. Finally, analysis of this data revealed observation categories that can be used for use of the research model in further study. Interesting interactions between teachers' intuitions and gaps in neuroscientific knowledge point the way back to the brain lab.

While this study was designed as a generative method, the results open the way for application of more convergent methods. The use the observation categories and variables discussed above can continue to refine ongoing generative research, via both inductive and deductive methods (Clement, 2000).

In further studies, answers to Interview 2 may be assigned values according to Teacher Efficacy and Teacher Beliefs coding schemes similar to those employed in current educational research using video cases to assess teacher knowledge (see Rosenfeld, 2010 for a review).

A rubric could also be designed to rate the impact of neuroscience information on teacher's current beliefs. Common elements, elements that appear in more than fifty percent of interviews, could be collected for teachers' models and language. In this way, a larger set of data could be analyzed with increased reliability.

Ultimately, this project demonstrated that the teachers interviewed have strong instincts that match, question, and challenge current educational neuroscience findings, and they can be valuable contributors in identifying important avenues for further research. As Tokuhama-Espinosa (2010) states: "Great teachers have always sense what methods worked; thanks to brain-imaging technology and better research techniques, it is now possible to substantiate many of these beliefs with empirical scientific research."

Project Significance

This project approaches the rift between neuroscience and education from a truly neuroeducational perspective. According to Kurt Fischer, head of the Mind Brain and Education initiative at Harvard, what education needs is not a "quick fix" from neuroscience, but rather the creation of a new field that integrates neuroscience and other cognitive sciences with education. (Fischer and Immordino-Yang, 2008). In terms of its research goals, mechanisms and methodology, this project can be seen as a true collaboration between developmental and cognitive psychology, education and neuroscience.

The project design represents a new research method, assembled from time-honored methods that share the conviction that close and careful observation of the child or student is what allows us to enter his mind. (Piaget, 1975, Ginsburg, 1997, Kilbane, 2008). These methods cannot be conducted in controlled laboratories where subjects spend a few hours signing forms and being measured with machines. While such studies certainly have their place in scientific study, the successful educational neuroscience researcher must spend time with teachers, in natural settings, having honest, respectful and meaningful discourse (Goswami, 2006). True and equal collaboration needs a shared language and ways of thinking, and these take time.

The Principal Investigator of the current project has completed both undergraduate and graduate degrees in cognitive and educational neuroscience, and has over two years of training using the cognitive clinical interview method to assess both children's mathematical thinking, and teacher's knowledge of student thinking. She has also co-developed the program and curricula at a progressive preschool, and has been teaching in this program for five years. In this sense, the design of this project can be seen as an example of innovative work by a new generation of multi-disciplinary researcher who is dedicating combined expertise in both neuroscience and education “to presenting high quality knowledge on the brain in digestible form and interpreting neuroscience *from the perspective of* and *in the language of* educators,” in order to “foster successful exchange of relevant data between disciplines (Goswami, 2006).”

The overarching goal of the proposed research is to begin building a foundation for collaborative experiment design between educators and neuroscientists in order to answer “big picture” questions that matter to teachers. Mayer (1998) claims that drawing on teachers’ experience and intuitions about students’ learning presents new hope for collaborative design of cognitive neuroscience research that will be truly meaningful to educators. Within his general skepticism for building a bridge between neuroscience and education, Bruer (2006) holds out tentative hope for the rare imaging study that goes beyond simply establishing localization claims and instead exemplifies both a sufficient appreciation for the complexity and subtlety of competing cognitive models and an ability on the part of researchers to interpret imaging data in light of all the relevant behavioral and neuropsychological data available.

Implications for future research

This project offers important considerations and questions for the developing field of educational neuroscience. First, finding a way to establish a common language between educators and neuroscience researchers may allow access to a wealth of intuitive knowledge about the learning brain that can resolve ambiguities, answer questions, and fine-tune investigations for researchers. *What matches will be revealed between teachers’ intuitions about students’ brains and neuroscience findings once the barrier of different language is removed*?

On the other hand, misconceptions and gaps in teacher’s knowledge will be exposed, allowing for insight into why certain teaching strategies and approaches may not be optimal for student learning, understanding and achievement, and offering ideas for better teaching. As teacher 5 expressed, the neuroscience information presented in this project was "*not enough to help me be a better teacher…* " She felt that the information showed her that she needed to know more about math learning in the brain order to guide application to the classroom. *What holes in teachers' knowledge about the brain will be revealed (independent from unfamiliar/unknown neuroscience vocabulary or terminology)?*

As Teacher 3 remarked, "Teaching is an intuitive science." In successful classrooms, teachers are constantly at work, applying approaches and assessing their students' behavior, memory for new information and subsequent understanding. All along teacher's models must be flexible enough to adapt and change based on "what works" in the classroom. The issues that arose in these interviews, including appropriate degree of time, scaffolding and sensory support for activities, the interplay of concrete and abstract in supporting conceptual understanding, and the roles of language, working memory and spatial skills in mathematical problem solving, are issues with which teachers are *experientially* familiar, even when they may not be able to remember the terminology.

Many teachers spend their careers trying and assessing various strategies in their own classrooms, as well as communicating and debating with other teachers about these issues. Since the "Decade of the Brain," neuroscience has been humbled by the realization, even as knowledge has advanced more rapidly than ever, of how very little we actually know about the thinking brain. There is adequate reason to suppose that teacher's choices to redesign or reject prior strategies throughout their teaching careers may reflect experienced-based intuitions about how children's brains at various ages can be engaged, supported to process and remember new information, and to build conceptual understanding. *How do teacher's choices to redesign or reject prior strategies based on "what works" in their classroom reflect an intuitive understanding of neuroscience-based recommendations?*

Teachers' intuitions can also be seen as a means of establishing another level of validity beyond replicated findings in the brain lab. Brain research is time-consuming, expensive and tedious. The obstacles preventing US students from the achieving deep mathematical understanding needed for academic success need to be remedied now.

This ethic of care and respect for teachers' intuitions is in its own right a significant aspect of the project. Ultimately, the work of the educational psychology researcher and the teacher, the cognitive neuroscientist and the neuroeducator all merge within the child's brain. If neuroscience hopes to cross the bridge into the classroom, it needs to consider that teachers have, in essence, been peering into children's brains long before the first brain imaging techniques emerged.

Overarching teaching approaches such as standards-based public Pre-K curricula, research-based math curricula, the Montessori method, and various aspects of progressive curricula such as constructivist and emergent approaches preserve and pass on teaching methods that share, to varying degrees, the conviction they "work." The Early Childhood Education research community has come to realize that building an understanding of why certain approaches work where others fail is a complex but necessary endeavor if education is going to institute successful and long lasting changes in the quality – and equality – that we provide our youngest students (Clements, 2007).

Math education is a somber example of the crisis that occurs when many of the accepted teaching methods used in classrooms *aren't* working to build sufficient understanding in students. There are big questions left unanswered in both the educational and educational neuroscience research. Drawing on the analysis and comparison of two teacher's reflections on number sense (in Preliminary Results and Discussion above) revealed how teachers' intuitions can be brought to bear on these questions. For instance: *How is developing number sense best supported in the pre-primary years, and what implications are there for the classroom environment? What neuroscientific support is there for the importance of adequate time spent exploring materials in a sensory way and asking questions? What support is there for the importance of overt instruction versus active construction of knowledge for the development of this concept?*

From the other side of the classroom wall, educational neuroscience offers a set of scientifically sound recommendations for teaching that have been carefully teased apart from intelligent speculation, misinterpreted findings, and neuromyths. For example, Mind Brain and Education Science literature advocates active construction of knowledge, situated learning experiences, and a key role of motor and sensory experiences in learning (Hardiman & Denkla, 2009; Tokuhama-Espinosa, 2010). *In what way are teachers' various philosophies/approaches regarding best practice supported by current neuroscience recommendations such as those provided by Mind Brain and Education Science? How do these philosophies/approaches correlate with a teacher's having intuitive models of learning that align with neuroscience?*

In the face of these questions, this project represents a promising start. The design offers a valuable tool for continued investigation through bi-directional collaboration. The model is infinitely portable, is not restricted by time or location, and is inexpensive. The collection and coding of further data can begin right away to address the questions above as they pertain to all teachers as well as specific sub-groups of teachers. For example, as this project is being submitted, upcoming interviews have been scheduled with groups of early childhood teachers using a standard universal Pre-K math curriculum at a public school in a low-income area of Brooklyn, as well as at a successful charter school, also in a low-income neighborhood in Harlem, where teachers are trained in implementing research-based math curricula. New questions, variables and observation categories will continue to further improve and refine the research method as they naturally arise.

In conclusion, we are left with a sense of one shared research project between teachers and researchers. The lines dividing knowledge into the separate spheres of education, developmental and cognitive psychology, cognitive and educational neuroscience have crossed enough that they have blurred. Or, as Piaget puts it, the schemata, or building blocks of knowledge, have been sufficiently diversified so that new information, rather than producing annoyance and causing avoidance, "becomes a problem and invites searching (Piaget, 1955). " In this picture, the goal lies not in what can be accomplished once the bridge between neuroscience and education has been constructed, but rather in the deep connections that are naturally formed through the shared project of creative problem solving.

Principle Investigator

Julia Niego

Julia Niego received a BA in Behavioral Neuroscience from Colgate University, where she designed and implemented ERP studies examining changes in brain activity associated with an anti-stereotype training task, and co-authored an article for *Developmental Neuropsychology* (Kelly et al, 2002*)* hypothesizing a role for gesture in co-defining speech during development. Beginning in 2004 she has collaboratively developed a progressive Montessori-based program at a private preschool in Brooklyn, NY, where she is currently teaching, researching and supporting staff understanding of learning and development through regular meetings and workshops. She recently accepted a position for Fall 2011 to co-develop an early childhood component curriculum for a neuropsychology-based tutoring program run by Dr. Anna Warren-Levy. Julia is currently a MS student in Neuroscience and Education at Teacher's College, Columbia University, where she has spent two years learning the clinical interview method in addition to completing extensive coursework in cognitive neuroscience and education. She is graduating in May 2011 with a Masters of Science in Neuroscience and Education.

Project Advisors

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Appendix A

Clinical Interview Protocol 1: Teacher background

Pre-Video

Teacher Information

Can you tell your name?

How many years have you been teaching in early childhood?

Can you describe your general path to teaching?

Can you briefly describe your general philosophy or approach, something that possibly sets you apart from other teachers?

Appendix B

Clinical Interview 2 Protocols: Teacher mental models

(Scaffolded Interview)

Number sense

Can you reflect on the teaching example you just saw:

1) Did the children seem engaged during lesson? How could you tell?

2) What math concept do you think the teacher was attempting to teach to the group?

3) Would you have taught this concept differently? Why/why not?

4) Did this child perform the task correctly/incorrectly? Why/why not?

5) What math abilities would you say children had to have in order to perform this task?

6) What was this child's strategy in performing the task so quickly?

Walk subject through child's mental process.

(Explore any mention of different representations of math information/ *connections* between mathematical information)

Arithmetic

Can you reflect on the teaching example you just saw:

1) Does the child seem engaged in the task? How can you tell?

2) Why does the teacher choose to begin the lesson this way?

3) What math concept do you think the teacher is attempting to teach?

Would you have taught this concept differently? Why/why not?

4) What math abilities would you say the child had to have in order to solve this task?

5) Did the child solve the first task correctly/incorrectly? Why/why not?

The second? Why/why not?

6)) What do you think was the child's strategy in solving the problem?

Walk subject through child's mental process.

(Explore any mention of handling blocks)

Pattern

Can you reflect on the teaching example you just saw:

1) Did the child seem engaged during lesson? How could you tell?

2) What math concept do you think the teacher was attempting to teach?

3) Would you have taught this concept differently? Why/why not?

4) Did she solve the task correctly/incorrectly? Why/why not?

5) What math abilities would you say the child had to have in order to solve this task?

6) What do you think was the child's strategy in solving the problem?

Walk subject through child's mental process.

(Explore any mention of child's actual construction of the pattern, i.e. not following the exact language)

Appendix C

Clinical interview protocol 3: Neuroscience follow-up

Protocol 2: Follow-up

(More open-ended interview)

Does this information relate to the teaching moment you just saw? How?/In what ways?

Does this information relate in any way to what you observe in your own classroom/students?

Does this information match in any ways with your personal philosophy/approach as an early childhood teacher?

Can you think of any ways that this information might impact your ideas/thoughts/beliefs about teaching math, specifically number sense/arithmetic/pattern, to young children?

Appendix D

Neuroscience Supplements

Printed Supplements

Supplement 1: Number Sense

Cognitive neuroscience researchers want to know how a child's brain develops to achieve understanding of a mathematical concept such as "number sense."

Taking pictures of students' brains while performing math tasks has revealed that:

The areas in the brain where different kinds of mathematical information are represented are largely in place by age 3.

Language areas at the front left side of the brain are involved with processing verbal math information such as number words ("five") and algorithms ("plus")

Vision areas at the very back of the brain are involved with processing written/drawn math information such as written numerals (5) or symbols (+).

Association areas at the top back of the brain are involved with processing quantitative information ("How much"/"How many?").

Visuo-spatial areas at the top back and front of the brain on the right side are involved with processing visual and spatial information (shape, structure and space).

These areas can be active or not depending on the math task a person is doing.

A person's brain looks different when listening to number words, or recognizing a written numeral, or counting dots, or estimating the number of objects in a group.

A specific concept that a child develops about math, such as number sense, involves connections between these different areas

These connections happen through mathematical experiences where more than one kind of math information is called upon at the same time.

Studies suggest that the way math information is learned directly influences how and where it is represented in the brain. Furthermore, the way students are guided to use this mathematical information influences the way it is integrated and built into mathematical concepts.

Supplement 2: Addition

Cognitive neuroscience researchers want to know how a child's brain develops to be able to complete a task such as the addition task presented in this lesson.

Research on math learning has shown that children become much faster at solving arithmetic tasks as they get older. Taking pictures of students' brains while performing math tasks has revealed that:

The areas in the brain that handle arithmetic tasks are largely in place by age 3

Areas on either side of the front of the brain handle general reasoning

Areas just behind the front of the brain serve as a mental workspace for temporarily holding and manipulating facts and information that a child needs to solve a given math problem

Areas at the front left side of the brain (behind the left ear) handle math language (number words)

Areas at the back of the brain handle visual information (written numerals)

Younger brains look different than older brains when solving arithmetic tasks

Younger children show most activity in general reasoning and working memory areas, while older children show more activity in language and visual areas

This shift corresponds with a change in children's strategies for solving arithmetic problems

Young children rely on manipulation of concrete objects to solve addition and subtraction problems, whereas later on they are able to perform math "in their heads," using abstract representations of numbers via language and visual symbols

Studies suggest that the way a child's brain processes math information at a certain stage in development directly influences the strategy they use when solving an arithmetic task. On the other hand, recent research suggests that teaching children new strategies may actually influence language and visual areas to "take over" during arithmetic tasks so that general reasoning and working memory are freed up to handle more complex information, set goals, and monitor progress.

Supplement 3: Pattern

Cognitive neuroscience researchers want to know how a child's brain develops to be able to complete a task such as the pattern task that this child just did. By taking pictures of child and adult brains in the process of solving math problems, researches pose that:

The areas in the brain that handle various mathematical jobs are largely in place by age 3

Areas at the upper back of the brain store concepts of "how much"

Areas at the front left side of the brain handle language (number words)

Areas at the front of the brain hold facts and information that a child needs to solve a given math problem

On the right side this area holds needed visual and spatial information like a "sketchpad"

Children's brains, like adult brains, seem to have two main "pathways" or connections between these areas

The left side handles quantitative math information learned through language, like numbers and counting

The right side handles visuospatial math information learned through sensory experience, like shape, structure and pattern

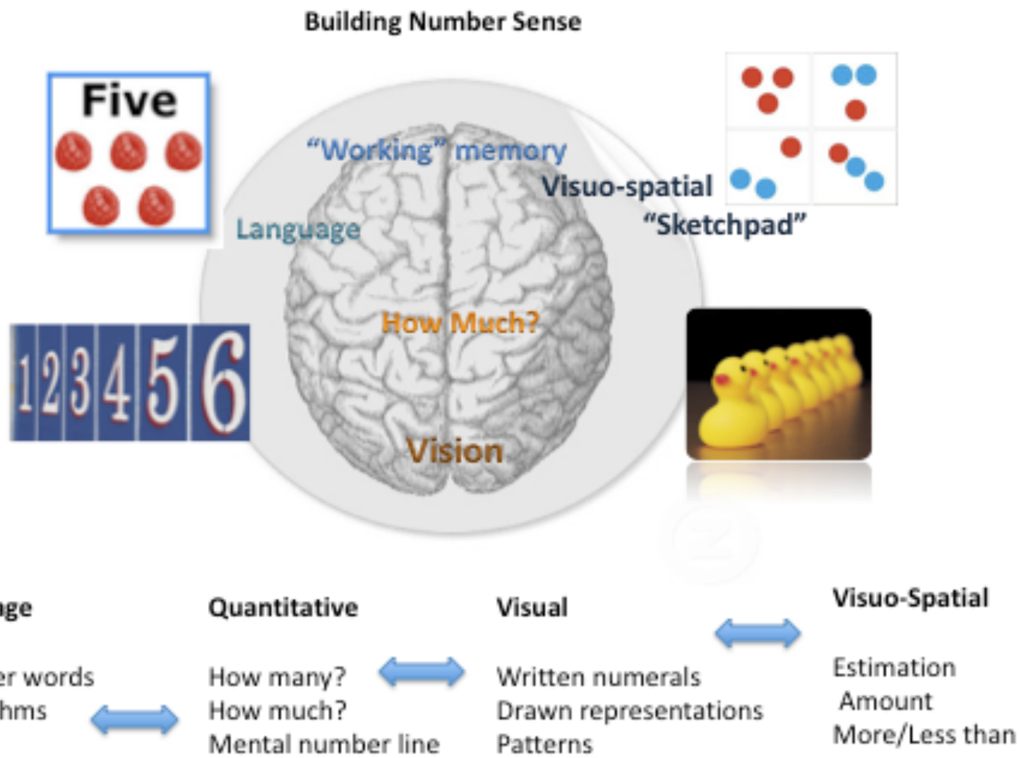
BUT children's brains do not handle a math problem the same way that adults' brains do

By looking at pictures of brains doing math, researchers can see that these math areas and the connections between them look different in adults and children when they are solving the same kinds of problems

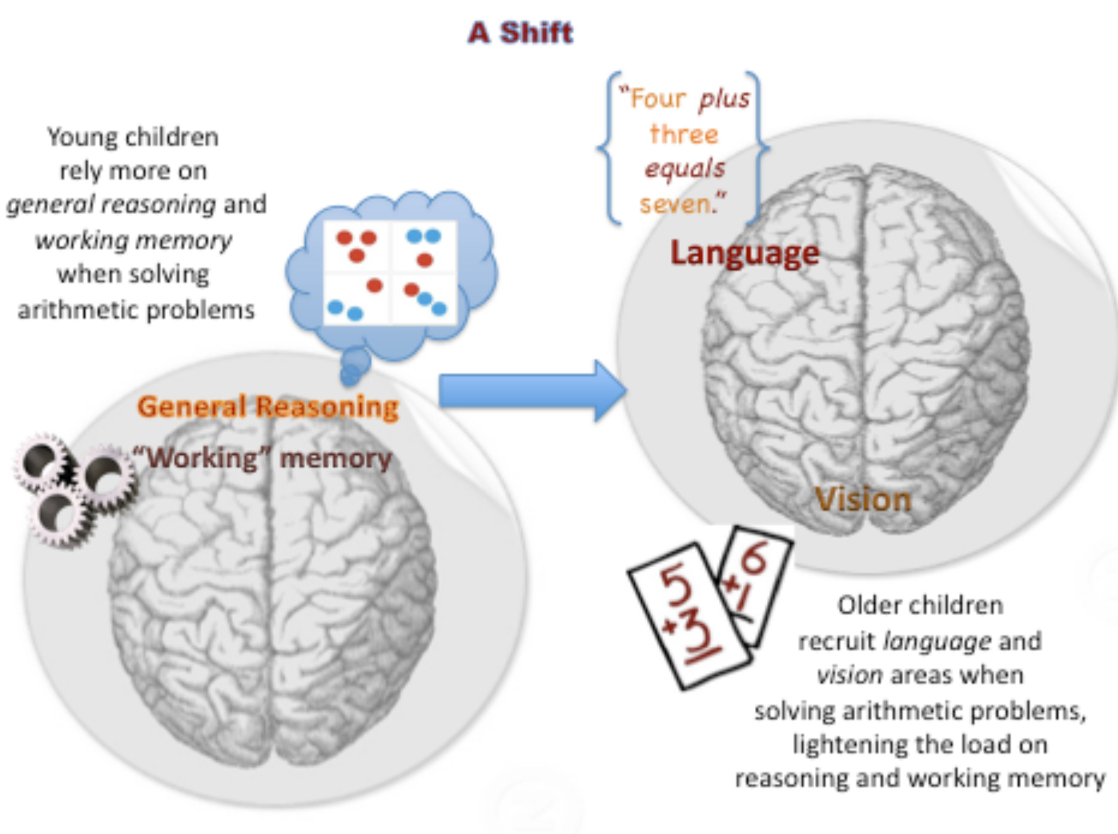
Some studies suggest that preschool and kindergarten aged children may rely more on visuo-spatial knowledge to grasp math concepts, and then gradually shift to incorporate more quantitative knowledge as their brains develop mathematically.

Picture Supplements

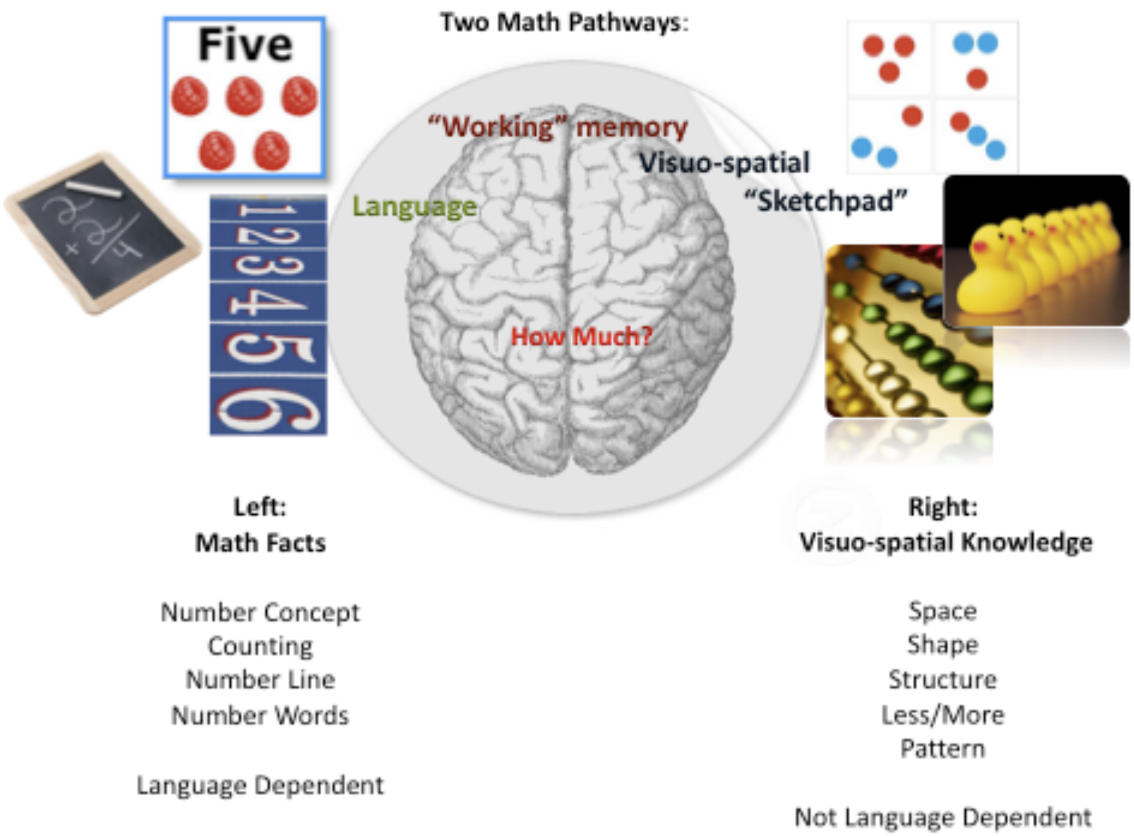
Supplement A: Number sense



Supplement B: Arithmetic



Supplement C: Pattern



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