What scaffolds the early development of numerical and mathematical competencies?

Dr. Daniel Ansari
Department of Psychology & Brain and Mind Institute
Western University
London, ON
E-mail: daniel.ansari@uwo.ca
www.numericalcognition.org

1. What have you learned about teaching/learning in your research?

a.) The role of numerical magnitude processing in early math learning

A particular focus of my research has been on uncovering the basic, early-developing, building blocks of numerical and mathematical abilities. In research on the development reading the core competencies that scaffold the acquisition of literacy, such as phonological awareness, are well understood (Gabrieli, 2009). In contrast, what scaffolds the early development of mathematical competencies is, to-date, comparatively less clear.

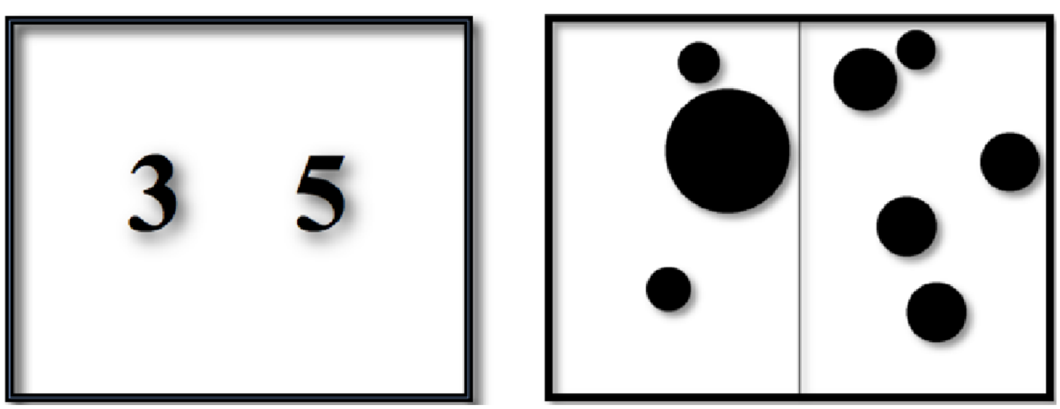
Understanding the basic foundations upon which higher-level competencies are built is important for several reasons. First of all, by understanding what skills represent the foundations of math, we can better understand how higher-level competencies are learnt on the basis of simpler skills and abilities. This has direct implications for the design of curriculum and especially how math is taught not only in the early grades but also in kindergarten and even earlier on. Furthermore, since math learning is a highly cumulative process, gaining more refined insights into the early scaffolds of higher-level skills can help us to identify children who might go onto experience difficulties with math learning early on and provide structured, evidence-based educational intervention for such children. Too often learning difficulties are detected long after the onset of formal schooling.

So what are some of the early foundational competencies in math learning? The research in my laboratory and that of others has focused on the ability of children to processing of numerical magnitudes as a key, early developing, competency.

First of all it is necessary to clarify what a numerical magnitude is? A numerical magnitude is the total number of items in a set (also referred to as numerical quantity). Numerical magnitudes can be presented either in a *non-symbolic* or in a *symbolic* form. A non-symbolic numerical magnitude could be a group of 5 apples used to represent the quantity 5. Any set of physical objects can be used to non-symbolically represent numerical magnitude. Beyond the visual modality, numerical magnitude can also be represented auditorily. For example the number of beeps in a countdown is a non-symbolic representation of numerical magnitude. Symbolic representations of numerical magnitude such as numerals (e.g. Arabic numerals) and number words are so-called non-iconic representations of numerical quantity. This means that the relationship between the symbol and the numerical magnitude it represents is arbitrary and needs to be learnt over the course of learning and development (e.g. there is nothing about the shape of the symbol '7' that directly connects it with 7 objects).

So does children's understanding of symbolic and non-symbolic numerical magnitude represent a foundational skill? The answer to this question from our research and that of others is yes. In a large body studies we have asked children to demonstrate their understanding of symbolic and non-symbolic numerical magnitudes by engaging in comparison tasks. In these tasks children are asked to judge which of two symbolic or non-symbolic numerical quantities is numerically larger (see Figure 1 for an example of such a test). What we and others have found is that children who are relatively fast and accurate at making such comparisons are also those children who do comparatively better on standardized test of arithmetic abilities and for whom their teacher report higher levels of achievement in math (e.g. Bugden & Ansari, 2011; De Smedt, Verschaffel, & Ghesquiere, 2009; Holloway & Ansari, 2009; Nosworthy, Bugden, Archibald, Evans, & Ansari, 2013).

FIGURE 1



SYMBOLIC COMPARISON **NON-SYMBOLIC COMPARISON**

Not only have we and others been able to show that numerical comparison performance is correlated with individual differences in children's mathematical competencies, but also that such skills measured in kindergarten predict math skills in the early primary school grades (e.g. Bartelet, Vaessen, Blomert, & Ansari, 2013; Geary, Hoard, Nugent, & Bailey, 2013).

Moreover, in many of the above-cited studies, the investigators examined whether numerical magnitude comparison abilities predicted individual differences in math achievement over and above other important variables such as reading ability, working memory and IQ. What these studies have revealed is that numerical magnitude comparison ability to account for unique variance in children's math ability. This is not to say that other factors are not important (indeed many of them, such as working memory, are critical) but that the basic ability to represent and compare numerical magnitudes appears to be an important competency to have early on in math learning.

Taken together, our data show that an important building block of math learning is numerical magnitude processing. Children need to have a good understanding of numerical magnitudes. It is clear from research with human infants and non-human animals that non-symbolic numerical magnitude processing skills have a long evolutionary history and can be measured already very early in development.(e.g. Libertus & Brannon, 2009). Over the course of learning and development, children need to connect these pre-existing, non-symbolic representations of numerical quantity with the cultural, symbolic representations of numerical magnitude, such as number words and digits (symbolic-non-symbolic mapping).

Our research findings suggest that the connection/mapping between symbolic and non-symbolic representations of numerical magnitude is particularly important. Specifically we find that children's symbolic number processing abilities (more so than their ability to process non-symbolic numerical magnitude processing) are particularly strong predictors of individual difference in math achievement. In other words, children who have particularly strong symbolic representation of numerical magnitude (presumably built on the connections between symbolic and non-symbolic representations) also perform comparatively better on test of early mathematical skills (such as arithmetic).

b.) *<u>A disorder of math learning: Developmental Dyscalculia</u>*

Another, related area of our research program focuses on better understanding why some children experience significant and persistent difficulties in learning even the most basic numerical and mathematical skills, while at the same time performing perfectly well in other domains of learning such as literacy. *Children with such a specific difficulty in learning math are said to suffer from a learning disorder known as 'Developmental Dyscalculia'*. Research on and awareness of Developmental Dyscalculia is severely lagging behind our understanding of Developmental Dyslexia. *It has been estimated that for every 14 studies published in Dyslexia there is only 1 study on Developmental Dyscalculia* (Berch & Mazzocco, 2007). This is striking given the evident importance of basic math skills.

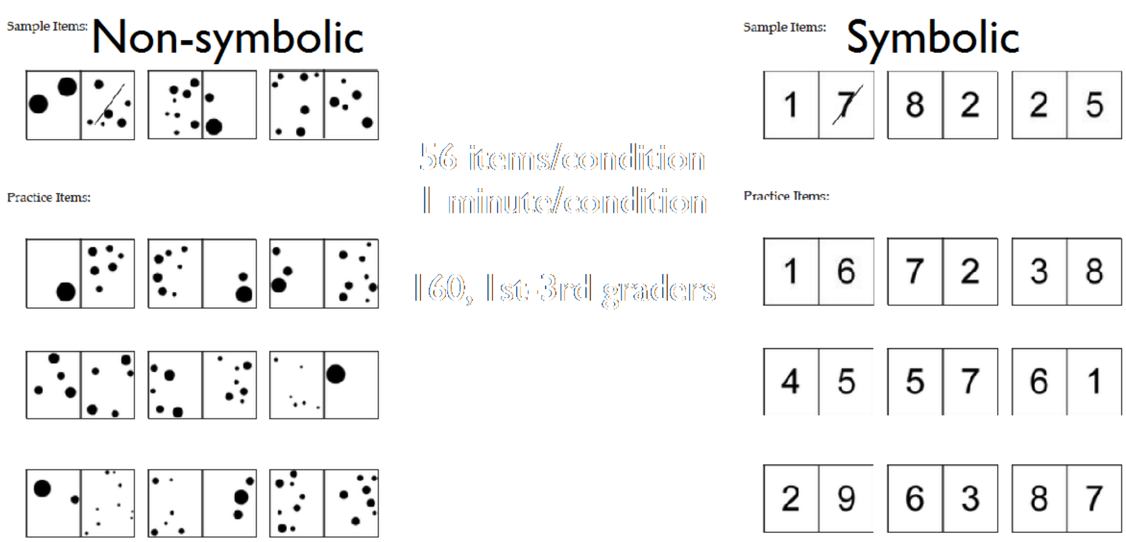
Our research aims to contribute to efforts to fill this current knowledge gap, by conducting research aimed at gaining a better understanding of what kinds of mental representation and processes are impaired in children with Developmental Dyscalculia (DD). We have used both behavioural as well as brain-imaging methods to gain a better understanding of DD. Our brain imaging data have revealed that the brains of children with DD functional atypically (compared to children without DD) during numerical magnitude processing (Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007). Furthermore, we have found that specific deficits in DD can exist in isolation or be shared with developmental difficulties in language, working memory and reading (Archibald, Oram Cardy, Joanisse, & Ansari, 2013). Moreover our ongoing studies are revealing that children with DD are particularly impaired in the processing of symbolic numerical magnitudes, such as Arabic numerals, which supports the hypothesis that at the heart of DD lies impairment in processing numerical magnitudes, particularly in the symbolic form. It should be noted, however, that DD is a complex specific learning disorder and other factors, such as visuo-spatial working memory have also been found to be strongly impaired in individuals with DD (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013). *In other words, there are multiple factors that play a role in DD, numerical magnitude processing being one of them.*

2. ***Based on your research on cognition, what promising practices would you identify to support student learning in mathematics?***

As discussed above, our research has identified some low-level processing abilities, such as numerical magnitude processing, that develop early. In view of these findings, more attention might be paid to strengthening children's understanding of numerical magnitudes, particularly number symbols. This should happen before instructing arithmetic. *Children need a fluent understanding of the meaning of number symbols before they can use them to perform mental operations with symbols, such as calculation.* Activities that help children understand the relationship between symbols and the quantities they represent may be particularly fruitful to strengthening the mental mapping between symbolic and non-symbolic representations of numerical magnitude. In concert with this, activities that help children understand the ordinal relationships between numbers (that numbers are embedded in a sequence with other numbers) may help children not only to understand symbol-quantity relationships but also symbol-symbol relationships. The use of number lines has proven to be particularly effective tool to strengthen such representations (e.g. Siegler & Ramani, 2008)

To facilitate the screening of students who may lack a fluent understanding of symbolic and non-symbolic numerical magnitudes, we have recently developed and published a 2-minute paper and pencil test of symbolic & non-symbolic numerical magnitude comparison (see Figure 2 for example pages from this test). In this test students are instructed to cross out the large of two magnitudes as quickly as they can (they get 1 minute for symbolic and non-symbolic, respectively). We have now administered this measure to over 500 children from senior kindergarten to grade 3 in Ontario schools. Our results show that individual difference of this test correlate with and predict (over time) variability in math achievement (Nosworthy et al., 2013; Nosworthy, 2013). We are currently developing a website where we will publish norms for this test. This website (to be published online in the Spring of 2014) will allow interested educators to download the test free of charge (along with the instructions) and subsequent to administration get standardized tests (standard scores and percentile rank) for any child who has taken the test.

FIGURE 2: Example pages from the 2-minute paper-and-pencil numerical magnitude processing test

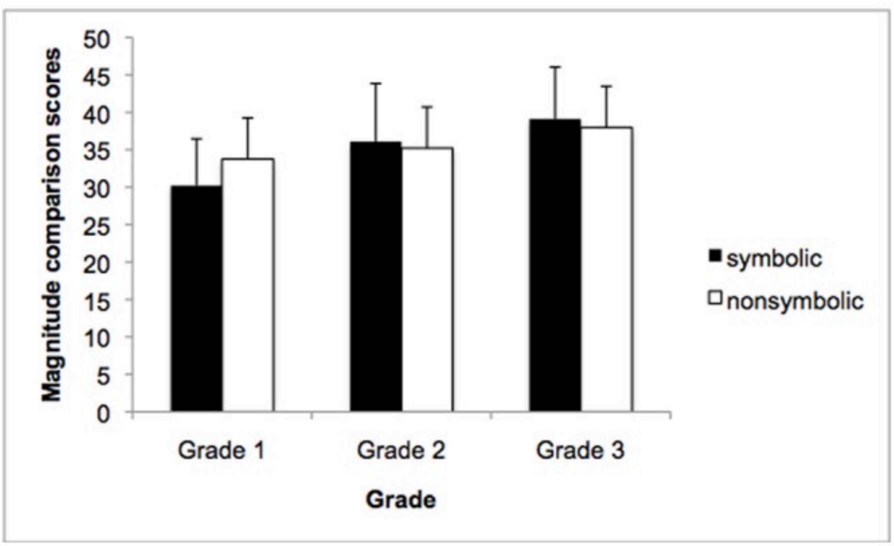


3. ***What further questions about mathematics teaching and learning are you now beginning to examine?***

In our ongoing research we are broadly pursuing the following avenues of investigations:

A.) *How does the processing of number symbols change between the beginning and end of 1st grade?* Against the background of recently collected data we have reason to believe that the representation and processing of Arabic numerals changes dramatically over the course of first grade. Specifically, as can be seen from Figure 3, our data have revealed in SK (not shown) and grade 1 children are significantly better at processing non-symbolic compared to symbolic (Arabic numerals) representations of numerical magnitude. However, from grade 2 onwards, symbolic processing ability is greater than non-symbolic. We think that therefore the time between SK and Grade 2 represents somewhat of a *sensitive period* for the development of fluent symbolic number processing. We are now investigating specifically what happens to the representation and processing of number symbols during this developmental period using both behavioral and brain imaging methods. We are also investigating what drives individual differences in these developmental changes.

FIGURE 3: Symbolic and non-symbolic number processing across grades 1-3



B.) *Gaining a deeper understanding of children with persistent Developmental Dyscalculia.* In ongoing research we are carrying out an in-depth longitudinal study of a group of children with DD who we have been following for 4 years. These children have had a consistent profile of very low math achievement for 4 years. We are now looking at their neurocognitive profile using in-depth behavioral and brain-imaging methods. This study will provide novel insights into the symptoms of DD and give us clues about the potential causes of this specific learning disorder. We then hope to use this information to inform the design of better methods for the diagnosis and remediation of DD.

C.) *Design and evaluation of evidence-based tools to strengthen children's understanding of numerical magnitude.* We have run a small pilot study to test the efficacy of a tablet-based intervention tool to strengthen the kindergartner's understanding of numerical magnitude, specifically the relationship between symbolic and non-symbolic representations of numerical magnitude. We are exploring avenues to continue such research in an effort to find better tools to help children at risk early on in development.

References:

Archibald, L. M. D., Oram Cardy, J., Joanisse, M. F., & Ansari, D. (2013). Language, reading, and math learning profiles in an epidemiological sample of school age children. *PloS one*, *8*(10), e77463. doi:10.1371/journal.pone.0077463

Bartelet, D., Vaessen, A., Blomert, L., & Ansari, D. (2013). What basic number processing measures in kindergarten explain unique variability in first-grade arithmetic proficiency? *Journal of experimental child psychology*, *117C*, 12–28. doi:10.1016/j.jecp.2013.08.010

Berch, D. B., & Mazzocco, M. M. M. (2007). *Why is math so hard for some children?* . Baltimore: Paul Brookes Publishing.

Bugden, S., & Ansari, D. (2011). Individual differences in children's mathematical competence are related to the intentional but not automatic processing of Arabic numerals. *Cognition*, *118*(1), 32–44. doi:S0010-0277(10)00218-0 [pii]10.1016/j.cognition.2010.09.005

De Smedt, B., Verschaffel, L., & Ghesquiere, P. (2009). The predictive value of numerical magnitude comparison for individual differences in mathematics achievement. *J Exp Child Psychol*, *103*(4), 469–479. doi:S0022-0965(09)00026-5 [pii] 10.1016/j.jecp.2009.01.010

Dehaene, S. (1997). *The Number Sense*. New York, NY: Oxford University Press.

Gabrieli, J. D. (2009). Dyslexia: a new synergy between education and cognitive neuroscience. *Science*, *325*(5938), 280–283. doi:325/5938/280 [pii] 10.1126/science.1171999

Geary, D. C., Hoard, M. K., Nugent, L., & Bailey, D. H. (2013). Adolescents' functional numeracy is predicted by their school entry number system knowledge. *PloS one*, *8*(1), e54651. doi:10.1371/journal.pone.0054651

Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: the numerical distance effect and individual differences in children's mathematics achievement. *J Exp Child Psychol*, *103*(1), 17–29. doi:S0022-0965(08)00052-0 [pii] 10.1016/j.jecp.2008.04.001

Libertus, M. E., & Brannon, E. M. (2009). Behavioral and Neural Basis of Number Sense in Infancy. *Curr Dir Psychol Sci*, *18*(6), 346–351. doi:10.1111/j.1467-8721.2009.01665.x

Nosworthy, N. An Investigation of the Association Between Arithmetic Achievement and Symbolic and Nonsymbolic Magnitude Processing in 5-9 Year-old Children: Evidence from a Paper-and-pencil Test. , University of Western Ontario - Electronic Thesis and Dissertation Repository (2013). Retrieved from http://ir.lib.uwo.ca/etd/1387

Nosworthy, N., Bugden, S., Archibald, L., Evans, B., & Ansari, D. (2013). A Two-Minute Paper-and-Pencil Test of Symbolic and Nonsymbolic Numerical Magnitude Processing Explains Variability in Primary School Children's Arithmetic Competence. *PloS one*, *8*(7), e67918. doi:10.1371/journal.pone.0067918

Price, G., Holloway, I., Räsänen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in Developmental Dsycalculia. *Current Biology*, *17*(24).

Siegler, R. S., & Ramani, G. B. (2008). Playing linear numerical board games promotes low-income children's numerical development. *Developmental science*, *11*(5), 655–61. doi:10.1111/j.1467-7687.2008.00714.x

Szucs, D., Devine, A., Soltesz, F., Nobes, A., & Gabriel, F. (2013). Developmental dyscalculia is related to visuo-spatial memory and inhibition impairment. *Cortex; a journal devoted to the study of the nervous system and behavior*. doi:10.1016/j.cortex.2013.06.007