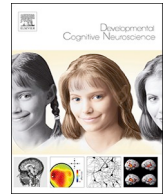




Contents lists available at ScienceDirect

Developmental Cognitive Neuroscience

journal homepage: www.elsevier.com/locate/dcn

Advances in Understanding the Development of the Mathematical Brain



Mathematical thinking has served as a central test case for theories of cognition and cognitive development for decades (e.g., Gelman and Gallistel, 1986; Piaget, 1952; Wynn, 1990) and philosophical debates on human nature and the mind for much longer. The theoretical implications of understanding the development of mathematics, however, should not overshadow its translational importance. Many children struggle to learn mathematical concepts (see Butterworth et al., 2011). This is problematic, as mathematics is ubiquitous and extremely important to success in modern life. By some estimates, for example, mathematics achievement is a better predictor of life success than literacy (e.g., Duncan et al., 2007). Thus, a better understanding of mathematical thinking has the potential to inform our understanding of human symbolic learning as well as suggest ways in which we can optimize it through education.

The last few decades of research on mathematical thinking have built a rich foundation on which to investigate the relationships between mathematical thinking, development, and the brain. From past research, we see that a reliable network of brain regions appears to be critical for mathematical thought in educated human adults (e.g., Arsalidou & Taylor, 2011; Dehaene et al., 2003; Menon, 2015). Some portions of the network, including intraparietal regions, appear to be specialized for numerical and mathematical thinking (e.g., Amalric & Dehaene, 2016), abnormalities or damage to which impair mathematics (Price et al., 2007; Menon, 2016). Co-activation of other nodes of the network suggests the conditions under which mathematics interfaces with more general symbolic, language abilities, and executive abilities (e.g., Menon, 2015; Vanbinst & De Smedt, 2016). From behavioral research, we also see that early mathematics learning follows a reliable trajectory (e.g., Libertus & Brannon, 2010; Wynn, 1990) and early individual differences predict later achievement (Duncan et al., 2007; LeFevre et al., 2009; Starr et al., 2013). This trajectory coincides with tremendous gains in linguistic and general executive abilities, undoubtedly contributing to the capacity to learn more complex mathematics (see Blair & Razza, 2007; Chu & Geary, 2015; Fuhs & McNeil, 2013; LeFevre et al., 2010). Formal education and informal experience (e.g., such as parental input) have a critical impact on mathematics proficiency and fluency over development (e.g., Berkowitz et al., 2015; LeFevre et al., 2009). Finally, behavior of human infants and children is guided by basic, non-verbal numerical and mathematical intuitions, evidence that some aspects of mathematical thinking might be present before education or instruction (e.g., Feigenson et al., 2004; Gilmore et al., 2007). Together, this work has led to a number of prominent and competing contemporary theories of mathematics development (Carey, 2009; Danker & Anderson, 2007; Siegler, 2016; Spelke, 2003; McClelland et al., 2016).

This foundation, as well as technological advances in applying brain measures to developmental populations, provides the opportunity to gain new insights. This special issue highlights some impressive examples of how developmental cognitive neuroscience is currently being applied to further our understanding of the development of the mathematical brain. We see a few prominent themes are emerging from this latest work.

First, there is starting to be enough accumulated evidence to move beyond single studies and allow meta-science of the literature. Several papers in this special issue provide novel insights into the current literature on the development of the mathematical brain through meta-analytic approaches. Arsalidou, Pawilw-Levac, Sadeghi, and Pascual-Leone present a meta-analysis of the regions of the brain associated with calculation in children, providing evidence for both the commonly known frontal and parietal regions near the cortical surface, as well as lesser recognized regions like the insula, claustrum, and cingulate deeper within the brain. They argue based on their meta-analysis that more attention should be given to these deeper regions, which may be implicated in the motivational aspects of mathematics.

Pollack and Ashby used meta-analytic techniques to investigate the overlap between retrieval-based arithmetic and phonological processing in adults and children. They find that children engage widespread frontal regions and the left fusiform gyrus for both types of processing, whereas activity in adults is more restricted to left lateralized inferior frontal regions as well as inferior parietal regions. These results suggest substantial overlap in the regions of the brain involved in phonological and arithmetic fact processing, with a broader engagement of domain general and symbolic processing resources in children to a more focused processing of symbols and their linguistic referents in adults.

Peters and De Smedt provide a comprehensive narrative review of literature to date on the anatomical and function brain correlates of arithmetic, as well as expert commentary on the way forward. They highlight consistent findings in the literature of interconnected frontal, parietal, temporal regions that engage for children during arithmetic, as well as various changes in structure, function, and connectivity over as arithmetic develops. They note that these changes broadly correspond to changes in strategy (from calculation to fact retrieval) and competence over development, but that the actual causes of these changes and their relationship to disability are not yet understood. They note that age as a developmental variable needs to be used more carefully, additionally taking into account the particular tasks, assessments, strategies, and instructional environments of the children studied. Based on their review, they also admonish those in the field to take advantage of emerging technologies to further study the entire arithmetic network

<https://doi.org/10.1016/j.dcn.2018.04.006>

and its' interconnections rather than particular nodes, to better understand these issues.

Second, current work is moving beyond the role of particular brain regions and attempting to better understand the mathematical brain as a network and dependencies between brain regions in this network. Two papers in this special issue examine the relationship between functional connectivity and mathematics. **Price, Yeo, Wilkey, and Cutting** examine the relationship between resting state functional connectivity of subareas of the intraparietal sulcus (IPS) in 1st grade children and arithmetic performance a year later. They find higher interconnectivity between sub-regions of the IPS during rest is related to better arithmetic in children. In contrast, they found higher functional connectivity between parietal and frontal and parietal and temporal regions at rest to be negatively associated with arithmetic development. These relationships were robust and appear to be specific to arithmetic, as they held, even after controlling for a variety of other general cognitive and achievement factors. As the authors conclude, there are a number of possible interpretations of these findings and more work is needed to determine which interpretation is correct. However, given the relative ease of collecting resting-state connectivity data compared to active task brain imaging data with young children, this paper provides a promising methodological approach for future work.

Michels, O'Gorman, and Kucian used an experimental training paradigm to compare functional connectivity of IPS between older children with developmental dyscalculia and typical developing peers before and after a number line training intervention. As has been seen before, they found more connectivity, or hyper-connectivity, in those with developmental dyscalculia. Remarkably, however, both groups were responsive to the 5-week intervention, with group hyper-connectivity disappearing at post-test. These results suggest differences in functional connectivity may be important to explaining dysfunction, but plasticity in functional connectivity may allow for remediation with proper experience.

Third, researchers are seeking out deeper causal explanations by testing the necessity and role of experience in formation and development of the brain systems for mathematics through varied and innovative research designs and populations. Two papers in the special issue focus on the role of early life experience in mathematical development. **Glenn, Demir-Lira, Gibson, Congdon, and Levine** study the effects of early brain injury on preschool numerical development. They show that children with early brain injury are slightly delayed relative to neurotypical peers in both learning of early number concepts and preschool mathematics achievement. Longitudinal data also suggest that children with early brain injury are slower to move through common developmental stages of numerical development. Despite these findings, however, the authors provide evidence that the delays are relatively minor and that numerical experience through parental number talk equally influenced children with and without brain injury. Together, the findings of **Glenn and colleagues** suggest that mathematical development is fairly resilient to early injury and, with proper experience, may be able to somewhat remediated.

Amalric, Denghien, and Dehaene investigate the role of visual experience in the formation of the brain networks supporting high-level mathematics concepts. They show the engagement of a similar network common to mathematics in sighted mathematicians and a small group of mathematicians who have been blind from childhood. Furthermore, the engaged network is also similar to that widely found when non-mathematicians perform more basic mathematics, supporting the idea that visual experience is not necessary for the formation of mathematics-specific networks in the brain.

Two papers in this special issue report findings from experimental research across different age groups. **Mathieu, Epinat-Duclos, Leone, Fayol, Thevenot, and Prado** investigate the emergence of spatial meaning for arithmetic operators and its neural correlates. They find that around 12–13 years of age, children start to a relationship between

spatially relevant activity in the hippocampus and the perception of the plus sign (+). Furthermore, this activity increases with age and is related to the degree to which operator priming, or presentation of the plus sign prior to a mathematical problem, facilitated addition. They speculate that these finding may reflect the building of associations between the spatial system and the operation of addition in late childhood.

Park studied the emergence of the direct perception of numerosity in children using visual evoked potentials. He shows that numerosity-specific activity arising from right occipital sites emerges steadily after 3 years of age. In contrast, direct perceptual sensitivity to other non-numerical magnitudes is not present (and/or does not increase) in childhood. These findings contrast with other work with younger populations showing behavioral and neural sensitivity to numerosity and other non-numerical parameters, albeit with less strict and systemic controls and contrasts. Park suggests that these new findings may suggest either earlier numerical competencies may not be as specific to number as previous thought or simply computed by other mechanisms (e.g., parietal regions) with direct numerical perception developing only later. Further work is needed, especially at younger ages to reconcile these findings with the rest of the literature.

Together, the articles of this special issue provide a selection of exciting new work expanding the boundaries of our knowledge of the development of the mathematical brain.

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