Journal Club

Editor's Note: These short, critical reviews of recent papers in the *Journal*, written exclusively by graduate students or postdoctoral fellows, are intended to summarize the important findings of the paper and provide additional insight and commentary. For more information on the format and purpose of the Journal Club, please see http://www.jneurosci.org/misc/ifa_features.shtml.

Forecasting Longitudinal Growth in Children's Numerical Abilities

Charlotte E. Hartwright and Francesco Sella
Department of Experimental Psychology, University of Oxford, Oxford, OX1 3UD, United Kingdom

Review of Evans et al.

Modern society requires individuals to possess solid numerical skills to succeed in everyday life (Gerardi et al., 2013). Understanding the cognitive and neural markers of early numerical skills could provide much needed information about the development of long-term mathematical capabilities, and inform early intervention for those at risk of mathematical learning disability. In this regard, a longitudinal approach can disentangle whether specific brain networks and cognitive processes are predictive, rather than the consequential effect, of mathematical achievement.

In a recent study published in *The Journal of Neuroscience*, Evans et al. (2015) investigated whether morphometric and functional brain indices acquired from children aged 8 years could predict their respective longitudinal gains in numerical skills. After assessing participants' mathematical skills, IQ, and reading comprehension, the authors acquired structural and resting-state functional MRI data. Assessments were repeated two or more subsequent times during the children's development, acquiring data up to age 14 years in some instances. Rather than using children's scores in mathematical ability, the authors calculated a measure of performance change as the main outcome variable in their study. To compute this change measure, for each child, the authors fit a linear regression to the standardized scores of the Numerical Operations subscale of the Wechsler Individual Achievement Test-II (WIAT-II; Wechsler, 2001) as a function of age. This approach provided a measure that captured each child's change in performance between testing sessions, which was used as an explanatory variable within the neuroimaging analyses. This enabled the authors to identify the neural correlates of a change in performance, rather than those responsible for an absolute level of achievement.

Evans et al. (2015) sought specificity to identify brain regions involved in longitudinal growth for numerical operation skills, rather than other academic skills or cognitive processes. This was achieved by using two different scales to evaluate specific aspects of mathematical ability. One scale featured mathematical problems that were embedded in short stories. In this instance, additional reasoning skills, beyond pure calculation, are required to solve each mathematical problem (Lucangeli et al., 1998). Conversely, the second scale evaluated knowledge of calculation algorithms and numerical symbols (e.g., x^9/x^3) and can be considered a purer measure of numerical skill. By controlling for the first scale, the authors obtained a neurocognitive measure of performance change on the basis of numerical skill acquisition, rather than improvements in fluency with the language of mathematics per se.

Informed by the results of a whole-brain analysis, structural and functional connectivity measures extracted from the left ventrotemporal occipital (VTOC; particularly the fusiform gyrus), posterior parietal (PPC) and prefrontal (PFC) cortices were shown to be correlated with longitudinal gains in numerical abilities. Gray matter volume in these regions was associated with longitudinal growth of numerical skills and not with mathematical achievement, reading, working memory, or IQ measures acquired at baseline. Importantly, the association between gray matter in this network and the growth in numerical skills remained significant even when measures of mathematical reasoning, word reading, and working memory were statistically controlled. Similarly, functional connectivity among these regions was correlated with longitudinal gains in numerical abilities, but not with mathematical reasoning or reading. These results were validated using machine learning, wherein it was possible to define functions that were predictive of the change measure, based on gray matter volume in the VTOC, PPC, PFC, and, separately, connectivity metrics.

The left lateralised network described by Evans et al. (2015) is consistent with previous reports of typical cortical development, where left PFC and PPC mature earlier than the corresponding regions in the contralateral hemisphere (Gogtay et al., 2004). Moreover, the involvement of a

Received Oct. 17, 2015; revised Nov. 24, 2015; accepted Dec. 2, 2015.

This research was funded by the European Research Council, award 338065 "Learning and Achievement."

Correspondence should be addressed to Dr. Charlotte Hartwright, Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford, OX1 3UD, UK. E-mail: charlotte.hartwright@psy.ox.ac.uk.

DOI:10.1523/JNEUROSCI.3803-15.2016

0270-6474/16/360646-03$15.00/0

predominantly left lateralized fronto-parietal network in number cognition is relatively well established (Moeller et al., 2015; for review, see Matejko and Ansari, 2015). The balance of frontal to parietal recruitment shifts as greater mathematical proficiency is achieved during childhood or, analogously, in adults following mathematical training. Reduced activation in the frontal cortices is accompanied by increased recruitment of parietal regions, which may reflect less reliance on resource-heavy computations requiring, for example, working memory and attention, toward specialized numerical processes computed within PPC (Matejko and Ansari, 2015). Relatedly, fractional anisotropy (FA) in the superior longitudinal fasciculus (SLF), an association tract that connects temporal and lateral PFC through PPC, is correlated with greater arithmetic skill in children (Tsang et al., 2009), and changes in FA in the left SLF following math tutoring parallel performance gains in mathematical learning (Jolles et al., 2015). FA in the inferior longitudinal fasciculus (ILF), an occipito-temporal tract that is thought to support consolidation of visual memories (Catani et al., 2003), correlates with performance in calculation, but not in mathematical problem solving (van Eimeren et al., 2008). Together, these data highlight that brain indices consistent with the network outlined by Evans et al. (2015) relate to current mathematical ability and changes in mathematical performance. Evans et al. (2015) add to this literature by highlighting that features of this network might also be prognostic in this domain.

There is growing evidence for the utility of baseline brain metrics to predict learning outcomes. For example, Gryga et al. (2012) demonstrated that initial cerebellar gray matter volume could predict relevant motor performance outcomes, as well as the amount of gray matter change in other cortical regions, including M1, after motor skill learning. Initial hippocampal gray matter volume was correlated with behavioral improvements after short-term math tutoring (Supekar et al., 2013). Likewise, midline occipito-parietal gray matter volume was predictive of learning rate when learning to juggle (Sampaio-Baptista et al., 2014). While these studies reflect relatively short-term learning interventions, Qin et al. (2014) demonstrated that fine-tuning of hippocampal-neocortical circuits around adolescence accompanies the transition to mature strategies in arithmetic problem solving. Such circuits were relatively unstable in participants aged 7–9 years, during which time counting strategies, rather than arithmetic facts, tended to be used. The absence of any predictive role for the hippocampi in Evans et al. (2015) may be explained by heterogeneity in problem-solving strategies adopted for the Numerical Operations subtest, and related variability in hippocampal–neocortical architecture at the initial time point. It could also be that the protracted analyses within their work preclude the relevance of the hippocampi, where hippocampal indices would be relevant for a more transient period.

Evans et al. (2015) demonstrate an enduring role for neural features in future learning outcomes, indicating that numerical ability may reflect considerable genetic predisposition. Indeed, in adolescence, genetic factors explain over two-thirds of the variance in FA in the parietal and frontal lobes (Chiang et al., 2009). Over half of the phenotypic variability in children's mathematical ability can be explained by genetic effects, where the degree to which structural and functional connectivity can be modified is likely to be largely determined by genetics (de Zeeuw et al., 2015). Nevertheless, recent data suggest that brain stimulation, teamed with mathematical training, may facilitate plasticity over and above training alone, allowing the possibility to enhance each individual's capacity to learn (Snowball et al., 2013; Grabner et al., 2015). In addition to acting as early biomarkers for learning disability as Evans et al. (2015) suggest, the potential for their approach to inform neuroenhancement-based interventions, and to measure the efficacy of such interventions (for example, by highlighting achievement beyond an individual's neural predicted level) is also worthy of note.

Evans et al. (2015) present a fronto-parietal network comprising VTOC, PFC, and PPC where brain indices extracted at around 8 years of age were predictive of longitudinal change in numerical skills. Recent evidence suggests that this network is likely to be supported by the SLF, connecting PPC and PFC to support domain-general and specialized numerical processes, and the ILF, an occipito-temporal pathway responsible for visual memory consolidation, which will be accomplished in part by the fusiform gyrus. These data suggest what may be a somewhat unexpected fixedness in mathematical ability, which is supported by behavioral genetics. However, in addition to directing early detection of learning disabilities, their work is informative to future research examining plasticity following cognitive training, neuroenhancement, and educational interventions.

References

Catani M, Jones DK, Donato R, ffytche DH (2003) Occipito-temporal connections in the human brain. Brain 126:2093–2107. CrossRef Medline

Chiang MC, Barysheva M, Shattuck DW, Lee AD, Madsen SK, Avedissian C, Klunder AD, Toga AW, McMahon KL, de Zubicaray GI, Wright MJ, Srivastava A, Balov N, Thompson PM (2009) Genetics of brain fiber architecture and intellectual performance. J Neurosci 29:2212–2224. CrossRef Medline

de Zeeuw EL, de Geus EJC, Boomsma DI (2015) Meta-analysis of twin studies highlights the importance of genetic variation in primary school educational achievement. Trends Neurosci Educ 4:69–76. CrossRef

Evans TM, Kochalka J, Ngoon TJ, Wu SS, Qin S, Battista C, Menon V (2015) Brain structural integrity and intrinsic functional connectivity forecast 6 year longitudinal growth in children's numerical abilities. J Neurosci 35:11743–11750. CrossRef Medline

Gerardi K, Goette L, Meier S (2013) Numerical ability predicts mortgage default. Proc Natl Acad Sci U S A 110:11267–11271. CrossRef Medline

Gogtay N, Giedd JN, Lusk L, Hayashi KM, Greenstein D, Vaituzis AC, Nugent TF 3rd, Herman DH, Clasen LS, Toga AW, Rapoport JL, Thompson PM (2004) Dynamic mapping of human cortical development during childhood through early adulthood. Proc Natl Acad Sci U S A 101:8174–8179. CrossRef Medline

Grabner RH, Rutsche B, Ruff C, Hauser T (2015) Transcranial direct current stimulation of the posterior parietal cortex modulates arithmetic learning. Eur J Neurosci 42:1667–1674. CrossRef Medline

Gryga M, Taubert M, Dukart J, Vollmann H, Conde V, Sehm B, Villringer A, Ragert P (2012) Bidirectional gray matter changes after complex motor skill learning. Front Syst Neurosci 6:37. CrossRef Medline

Jolles D, Wassermann D, Chokhani R, Richardson J, Tenison C, Bammer R, Fuchs L, Supekar K, Menon V (2015) Plasticity of left perisylvian white-matter tracts is associated with individual differences in math learning. Brain Struct Funct. Advance online publication. doi: 10.1007/s00429-014-0975-6. CrossRef Medline

Lucangeli D, Tressoldi PE, Cendron M (1998) Cognitive and metacognitive abilities involved in the solution of mathematical word problems: validation of a comprehensive model. Contemp Educ Psychol 23:257–275. CrossRef Medline

Matejko AA, Ansari D (2015) Drawing connections between white matter and numerical and mathematical cognition: a literature review. Neurosci Biobehav Rev 48:35–52. CrossRef Medline

Moeller K, Willmes - von Hinckeldey KF, Klein E (2015) A review on functional and structural brain connectivity in numerical cognition. Front Hum Neurosci 9:227. CrossRef Medline

Qin S, Cho S, Chen T, Rosenberg-Lee M, Geary

DC, Menon V (2014) Hippocampal-neocortical functional reorganization underlies children's cognitive development. Nat Neurosci 17:1263–1269. CrossRef Medline

Sampaio-Baptista C, Scholz J, Jenkinson M, Thomas AG, Filippini N, Smit G, Douaud G, Johansen-Berg H (2014) Gray matter volume is associated with rate of subsequent skill learning after a long term training intervention. Neuroimage 96:158 –166. CrossRef Medline

Snowball A, Tachtsidis I, Popescu T, Thompson J, Delazer M, Zamarian L, Zhu T, Cohen Kadosh R (2013) Long-term enhancement of brain function and cognition using cognitive training and brain stimulation. Curr Biol 23:987–992. CrossRef Medline

Supekar K, Swigart AG, Tenison C, Jolles DD, Rosenberg-Lee M, Fuchs L, Menon V (2013) Neural predictors of individual differences in response to math tutoring in primary-grade school children. Proc Natl Acad Sci U S A 110:8230 – 8235. CrossRef Medline

Tsang JM, Dougherty RF, Deutsch GK, Wandell BA, Ben-Shachar M (2009) Frontoparietal white matter diffusion properties predict mental arithmetic skills in children. Proc Natl Acad Sci U S A 106:22546 –22551. CrossRef Medline

van Eimeren L, Niogi SN, McCandliss BD, Holloway ID, Ansari D (2008) White matter microstructures underlying mathematical abilities in children. Neuroreport 19:1117–1121. CrossRef Medline

Wechsler D (2001) Wechsler Individual Achievement Test, 2nd Ed. San Antonio, TX: The Psychological Corporation.