Being an expert reflected by structural connectivity: A tractography study on mathematical expertise

Ulrike Kuhl[1], Angela D. Friederici[1] & Hyeon-Ae Jeon[2,3]

[1] Department of Neuropsychology, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany
[2] Daegu Gyeongbuk Institute of Science and Technology (DGIST), Daegu, Korea
[3] Partner Group of the Max Planck Institute for Human Cognitive and Brain Sciences at the Department for Brain and Cognitive Sciences, DGIST, Daegu, Korea

kuhl@cbs.mpg.de

MAX-PLANCK-GESELLSCHAFT

MAX PLANCK INSTITUTE FOR HUMAN COGNITIVE AND BRAIN SCIENCES LEIPZIG

Introduction

Hierarchical processing. The ability to establish embedded representations is a key concept in various domains such as language, music, action, and mathematics. When processing hierarchical structures, elements at superordinate levels persist while elements at subordinate levels are being processed (Jeon, 2014).

Mathematical expertise. Processing mathematical hierarchy is marked by an expertise-dependent functional modulation: Experts recruit a set of core regions, non-experts rely on broader activation around left frontal and parietal areas (Jeon & Friederici, 2016). These differences are related to more controlled, effortful processing in non-experts compared to automated, less demanding processing in experts (Neubauer & Fink, 2009). ***However, little is known about structural correlates of automatic mathematical processing***.

The present study. We explore how varying degrees of automaticity in processing hierarchical arithmetic expressions are reflected in connectivity profiles of relevant areas.

Methods

Participants. Isotropic dMR (1.7mm^3) and T1-weighted MR data were acquired using a 3.0T Siemens TIM TRIO scanner for 22 expert mathematicians and 19 non-expert controls matched for age, sex, handedness, IQ and verbal working memory.

Behavioral assessment. Participants solved algebraic expressions of either hierarchical or linear structure (Fig. 1). Degree of automaticity in mathematics was quantified via the individual's coefficient of variation in reaction times (CV_{RT}), defined as the quotient of standard deviation of reaction time (SD_{RT}) and mean reaction time ($Mean_{RT}$) Segalowitz & Segalowitz, 1993):

$$CV_{RT} = SD_{RT} / Mean_{RT}$$

It has been shown that CV_{RT} decreases for automatized processes and increases for controlled processes (Segalowitz & Segalowitz, 1993).

1

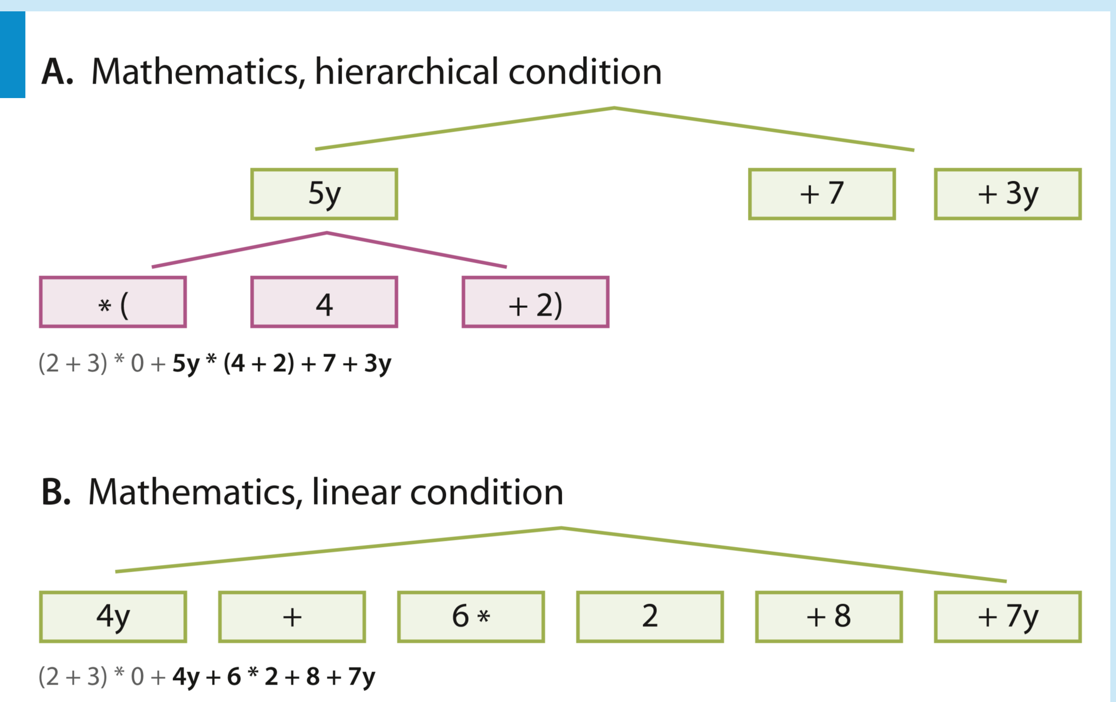

Figure 1: Overview of conditions. Taken from Jeon & Friederici, (2016).

Data pre-processing. Data were processed using FSL 5.0.8 (Smith et al., 2004). bedpostX (Behrens et al., 2007) was used to determine the fibre orientation distribution for each voxel.

Seed definition. Regions commonly activated in non-experts and expert mathematicians when processing hierarchical compared to linear algebraic structures were selected as seed regions for probabilistic tractography: left Insula, left precentral gyrus (lPCG), left superior parietal lobule and bilateral medial pre-motor cortex (rMPC,lMPC; Jeon & Friederici, 2016).

Probabilistic Tractography. Tracking was performed within individual subject space using FSL's probtrackX2 (Behrens et al. 2007). 5000 streamlines were generated per voxel within the seed regions' white matter - grey matter interface Visitation maps were logarithmised and normalised by dividing by the logarithm of maximal possible number of streamlines produced. Spatially normalised visitation maps were averaged and thresholded at the 0.2 level to obtain a mask for statistical analysis. Streamline density was correlated with individual's CV_{RT} scores. Cluster size correction was based on estimated smoothness of the data. Additionally, P-values were Bonferroni corrected for the number of seed regions.

Results

2

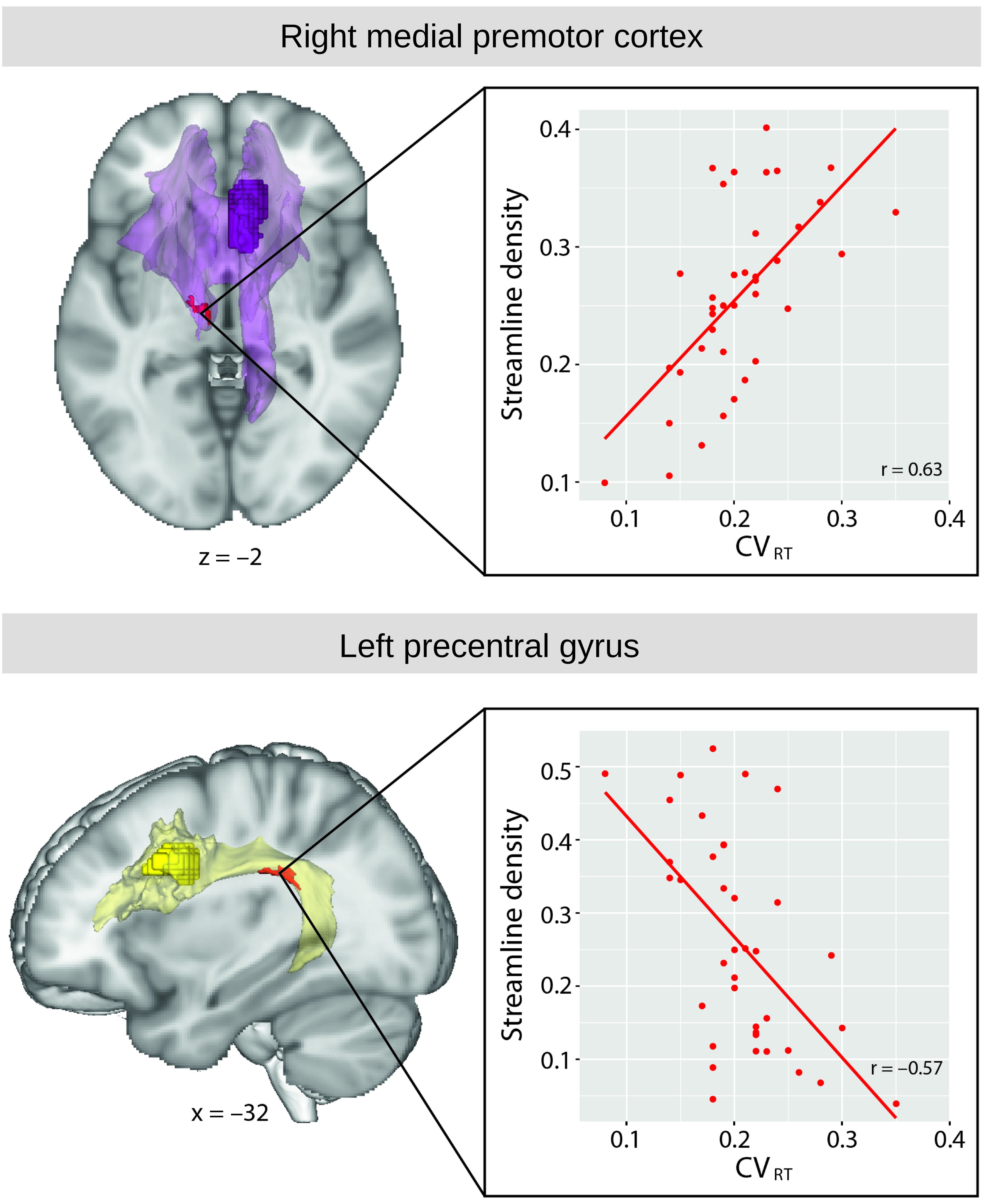

Figure 2: Clusters of significant correlation (red, cluster size corrected at P<0.05 and Bonferroni corrected for the number of seeds) between CV_{RT} scores and streamline density when seeding in right medial pre-motor cortex (top) and left precentral gyrus (bottom). Respective seed regions shown in opaque colors. Transparent regions designate the extend of average tractograms (basis for statistical analysis). Scatterplots highlight correlation within peak voxel of cluster. The positive correlation of CV_{RT} and streamline density within left thalamus when seeding in rMPC (top) reflects involvement of this corticothalamic connection in controlled processing. The negative relationship between CV_{RT} and streamline density within left arcuate fascicle (AF) after seeding in lPCG (bottom) indicates a positive relationship between automaticity of processing and integrity of AF.

Table 1: Clusters and peak coordinates of significant correlations between CV_{RT} score and streamline density (P<0.05, corrected).

Contrasts and seed regions	Size (voxel)	x	y	z	Structure
Positive correlation					
rMPC	94	-7	-18	-3	Left thalamus
Negative correlation					
lPCG	67	-34	-39	25	Left arcuate fascicle

Disussion

Individuals relying on more controlled processing (increased CV_{RT}) show higher connectivity within corticothalamic connections also associated with controlled processing in terms of functional connectivity (Jeon & Friederici, 2016) as well as specificity (Jeon, Anwander & Friederici, 2014).

Individuals relying on more automatic processing (decreased CV_{RT}) showed higher connectivity of lPCG to temporal brain areas via left AF/SLF. These structures are associated with hierarchal processing in language (Friederici, Bahlmann, Heim, Schubotz & Anwander, 2006), a highly automatic process in adult language users (Schneider & Chein, 2003).

Conclusion

Our results suggest

(a) involvement of corticothalamic connections for more demanding processing.

(b) a critical role of the left AF for hierarchical processing - specifically at high degrees of automaticity - be it in language or mathematics.

References

Behrens, T.E. (2007) 'Probabilistic diffusion tractography with multiple fibre orientations: What can we gain?' Neuroimage, 34, 144-155.

Friederici, A. D., Bahlmann, J., Heim, S., Schubotz, R. I., & Anwander, A. (2006). The brain differentiates human and non-human grammars: functional localization and structural connectivity. Proceedings of the National Academy of Sciences of the United States of America, 103(7), 2458-2463.

Jeon, H.-A. (2014). Hierarchical processing in the prefrontal cortex in a variety of cognitive domains. Frontiers in Systems Neuroscience, 8, 223.

Jeon, H.-A., Anwander, A., & Friederici, A.D. (2014). Functional Network Mirrored in the Prefrontal Cortex, Caudate Nucleus, and Thalamus: High-Resolution Functional Imaging and Structural Connectivity. Journal of Neuroscience, 34(28):9202–9212

Jeon, H. A., & Friederici, A. D. (2016). What Does "Being an Expert" Mean to the Brain? Functional Specificity and Connectivity in Expertise. Cerebral Cortex.

Neubauer, A. C., & Fink, A. (2009). Intelligence and neural efficiency. Neuroscience & Biobehavioral Reviews, 33(7), 1004-1023.

Schneider, W., Chein, J.M. (2003). Controlled & automatic processing: behavior, theory, and biological mechanisms. Cogn Sci. 27:525–559.

Smith, S. M., Jenkinson, M., Woolrich, M. W., Beckmann, C. F., Behrens, T. E., Johansen-Berg, H., ... & Niazy, R. K. (2004). Advances in functional and structural MR image analysis and implementation as FSL. Neuroimage, 23, S208-S219.

OHBM, 2017