Supporting Information

Tsang et al. 10.1073/pnas.0906094106

SI Text

Lateralization Analyses. ***Larger tract volume in left aSLF compared with right.*** Tract volume was quantified as the number of voxels encompassed in the left and right aSLF ROI (e.g., the number of voxels the tracts pass through within the 7-mm-long segment of tract). The mean volume of the right aSLF was 405 mm^3, whereas that of the left was 509 mm^3; this difference was statistically reliable [t (25) = 2.7, $P < 0.02$]. However, no difference was found between the left and right tracts in FA, axial diffusivity, or radial diffusivity. Tract volume did not correlate significantly with FA in the left [r (25) = 0.15, n.s.] or right [r (26) = 0.21, n.s.] aSLF.

Larger correlation in left aSLF compared with right. We found a significant correlation between FA and mental approximation on the left but not on the right aSLF; however, the difference between these two correlation values was not significant [t (25) = 0.69, n.s.]. The data do not provide conclusive evidence on the lateralization of FA–math relationships in frontoparietal white matter pathways, but it is notable that (*i*) the left aSLF showed significant or nonsignificant trends toward correlations with both approximate and exact arithmetic, whereas (*ii*) the right aSLF showed only a trend with approximate arithmetic and zero correlation with exact arithmetic. Left lateralization of the math–FA relationship in the aSLF is consistent with Dehaene's triple-code model (1), which emphasizes left but not right inferior frontal cortex for its role in language processes involved in arithmetic.

Whole-brain analyses. To compare our data set with prior whole-brain analyses, we used the Statistical Parametric Mapping (SPM) voxel-based morphometry (VBM) (2) and the FMRIB Software Library (FSL) tract-based spatial statistics (TBSS) (3) and tested for age-corrected correlations between mental math performance and FA. These whole-brain methods are useful in discovering other white matter regions relevant for mental arithmetic, although they may not distinguish reliably between parallel branches of the SLF, for example. Using VBM, at $P < 0.05$ corrected for multiple comparisons, no white matter regions correlated with math scores. At a more lenient $P < 0.01$ uncorrected for multiple comparisons, FA positively correlated with approximation scores in several regions, including the left corona radiata, left superior frontooccipital fasciculus/internal capsule, left SLF, and brainstem. TBSS produced more widespread positive correlations, even at $P < 0.05$ (corrected for multiple comparisons), including bilateral SLF, inferior longitudinal fasciculus/inferior frontooccipital fasciculus, corona radiata, internal and external capsule, and the splenium of the corpus callosum. The differences between these methods are likely to arise from differences in brain alignment and methods for pooling FA values. The correlation in the corona radiata generalizes previous findings (4) using different math measures and suggests that there may be other brain circuits for math processing beyond the specialized frontoparietal network.

Behavioral Results: Accuracy on Exact Arithmetic, but Not Simple Facts, Improves with Age. Subjects' accuracy increased with age at different rates for each test type (Fig. S1). Whereas exact calculation scores increased sharply with age, accuracy on simple math facts was consistently high among all age groups, and estimation scores only trended toward an age increase. As such, the variance in scores on the exact calculation task was twice that of the simple facts and approximate arithmetic tests, both before and after partialling out the variance due to age. The small variance in simple facts scores limits our power in detecting a correlation with FA in the aSLF.

The analysis excluded items for which subjects were visibly distracted from the task or failed to answer. Within-subject reliability for accuracy (Cronbach's α) (5) ranged from 0.73 to 0.90. Subjects were sorted into three age quantiles and measured using three tests. A 3 × 3 repeated-measures ANOVA on accuracy with test type as the within-subjects factor and age quantile as the between-subjects factor revealed significant main effects of age [F (2, 31) = 3.76, $P < 0.05$] and test type [F (2, 30) = 30.03, $P < 0.01$]. The oldest group of children was more accurate than the youngest (oldest–youngest = 0.08, $P < 0.05$); the middle group of children did not differ from either (middle–youngest = 0.06, n.s.; oldest–middle = 0.02, n.s.). Accuracy was greater on simple facts than approximate [F (1, 31) = 8.65, $P < 0.01$] or exact addition [F (1, 31) = 61.19, $P < 0.01$]; approximation was in turn more accurate than exact addition [F (1, 31) = 43.07, $P < 0.01$]. There was a significant interaction between age and test type [F (4, 62) = 2.56, $P < 0.05$]. Post hoc comparisons, using Tukey-Kramer honestly significant difference (6) to take into account unequal cell sizes on the age factor, showed that accuracy on the approximation and simple facts tasks was not significantly different at any age level. However, the youngest and middle children were less accurate on exact addition than simple facts (difference in young group, 24%; middle group, 17%) and approximate arithmetic (difference in young group, 16%; middle group, 15%). In the oldest children, the three tests did not differ.

1. Dehaene S, Cohen L (1995) Towards an anatomical and functional model of number processing. *Mathematical Cogn* 1:83–120.
2. Ashburner J, Friston KJ (2000) Voxel-based morphometry—the methods. *Neuroimage* 11:805–821.
3. Smith SM, et al. (2006) Tract-based spatial statistics: Voxelwise analysis of multi-subject diffusion data. *Neuroimage* 31:1487–1505.
4. van Eimeren L, Niogi SN, McCandliss BD, Holloway ID, Ansari D (2008) White matter microstructures underlying mathematical abilities in children. *Neuroreport* 19:1117–1121.
5. Cronbach LJ (1951) Coefficient alpha and the internal structure of tests. *Psychometrika* 16:297–333.
6. Kramer CY (1956) Extension of multiple range tests to group means with unequal numbers of replications. *Biometrics* 12:307–310.

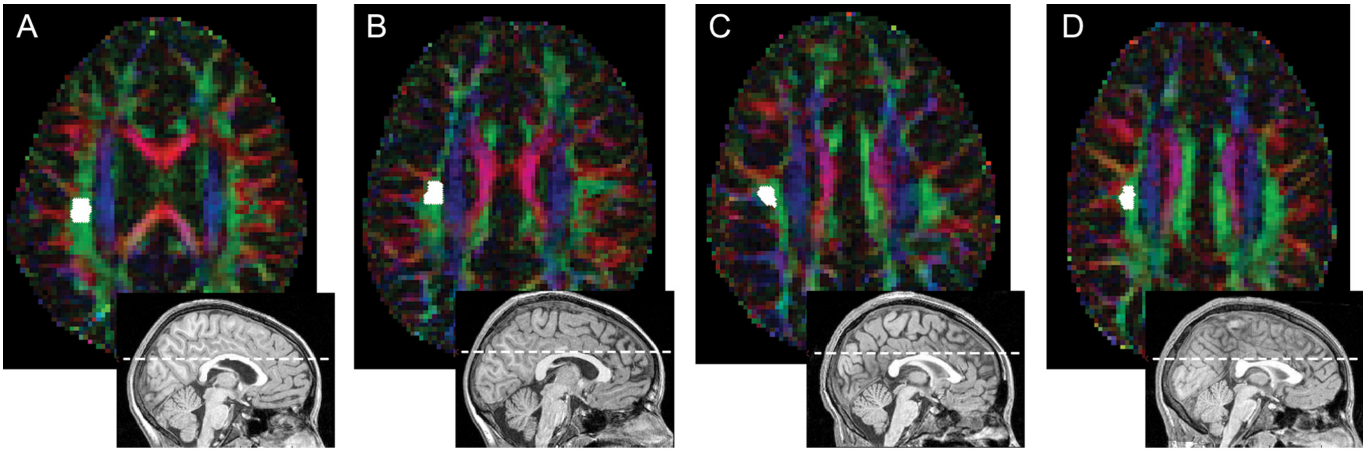

Fig. S1. Typical aSLF ROIs, left hemisphere. Axial maps show FA, diffusion direction information, and left aSLF ROI slices (white) in 4 typical subjects: (*A*) 10-year-old girl (acpc slice coordinate z = 26); (*B*) 12-year-old boy (z = 32); (*C*) 13-year-old girl (z = 30); and (*D*) 14-year-old boy (z = 26). Dotted lines in coronal images indicate axial slice position.

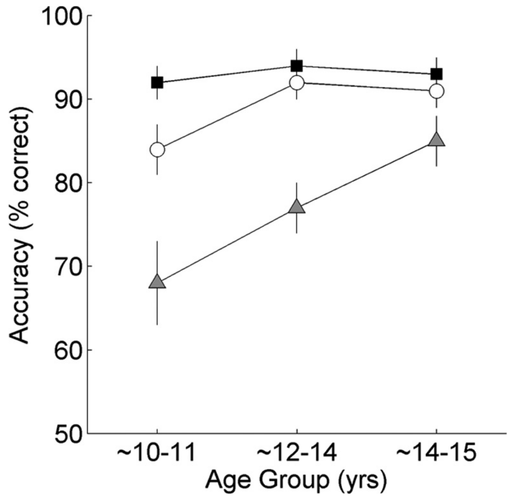

Fig. S2. Mental arithmetic skills in different age groups. For behavioral analysis, subjects were split into three age groups: 10–11 years (n = 12), 12–14 years (n = 11), and 14–15 years (n = 11). Subjects in all age groups scored close to ceiling on simple math facts (black squares; mean = 93%, SD = 7%, range, 74–100%). Approximation skill (white circles; mean = 89%, SD = 8%, range, 65–100%) improved rapidly with age and converged with simple facts by the middle age group. Accuracy on the exact calculation task (gray triangles; mean = 76%, SD = 15%, range, 44–98%) was lowest and increased linearly with age. Error bars ± 1 SEM. Note that the effects of age on subjects' math ability (and FA) were removed before the correlation analyses described in the main text.

Table S1. Control measures: Descriptive statistics and age-corrected correlations with FA in the aSLF

Control tests	n	Mean (SD)	Range	Age-corrected correlations with FA			
				Left aSLF*		Right aSLF	
				r	P	r	P
FSIQ	28	110 (13)	90–145	0.18	0.37	−0.05	0.82
Written calculation	27	118 (15)	89–140	0.002	0.99	−0.09	0.63
Rapid digit naming	28	10 (3)	4–16	0.23	0.24	−0.24	0.23
Basic reading	28	106 (12)	84–125	0.19	0.35	0.02	0.90

FSIQ, Wechsler Intelligence Scale for Children-4, Full-Scale IQ; Written Calculation, Wide Range Achievement Test-4; Rapid Digit Naming, Comprehensive Test of Phonological Processing; Basic Reading, Woodcock-Johnson-III.

*Number of subjects = $n - 1$, because one subject did not have an identifiable aSLF in the left hemisphere.