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Neuroanatomical Correlates of the Income Achievement Gap

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Abstract

In the United States, the difference in academic achievement between higher- and lower-income students (i.e., the income achievement gap) is substantial and growing. Here, we investigated neuroanatomical correlates of this gap in adolescents ($n = 58$) in whom academic achievement was measured by statewide standardized testing. Cortical gray matter volume was significantly greater in students from higher-income backgrounds ($n = 35$) compared to students from lower-income backgrounds ($n = 23$), but cortical white matter volume and total cortical surface area did not differ between groups. Cortical thickness in all lobes of the brain was greater in students from higher-income than lower-income backgrounds. Thicker cortex, particularly in temporal and occipital lobes, was associated with better test performance. These results represent the first evidence that cortical thickness differs across broad swaths of the brain between higher- and lower-income students, and that cortical thickness is related to academic achievement test scores.

Introduction

Educational achievement is highly correlated with socioeconomic status (SES) (Bradley & Corwyn, 2002). In the United States, the “income achievement gap”, the difference in academic achievement between students from higher- and lower-income backgrounds, is substantial and growing (Reardon, 2011). The income achievement gap is evident from the beginning of school, and culminates in wide disparities in high school and college completion (Duncan & Magnuson, 2011). Reasons for this gap may include differences in school quality, social expectations, chronic stress, and language exposure (Ackerman & Brown, 2010; Duncan & Brooks-Gunn, 1997). Approximately 50% of U.S. public school

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Author Contributions

A.P. Mackey conducted the analyses. A.S. Finn designed the study and collected data. J.A. Leonard assisted with data collection and data analysis. C.F.O. Gabrieli assisted with study design and cultivating relationships with local schools. D.S. Jacoby-Senghor guided the analyses of race and ethnicity. M.R. West contributed to statistical analyses. J.D.E. Gabrieli designed and supervised the study. A.P. Mackey and J.D.E. Gabrieli drafted the manuscript, and A.S. Finn, J.A. Leonard, D.S. Jacoby-Senghor, C.F.O. Gabrieli, and M.R. West provided critical revisions. All authors approved the final version of the manuscript for submission.

students (24 million children) qualify for free or reduced-price lunch, a widely used proxy for being from a lower-income household (U.S. Department of Education, 2011–2012). Here, we investigated the neuroanatomical correlates of the income achievement gap by comparing the structure of the cerebral cortex, which supports perception, language, and thought, between public school students who do (lower-income) or do not (higher-income) receive free or reduced price lunch, and by relating this neuroanatomy to performance on standardized tests of academic skills.

Prior studies of the impact of SES on brain development have reported less cortical gray matter or thinner cortex in lower SES groups. These studies have had limited statistical power (Jednoróg et al., 2012), averaged across large brain regions in an undifferentiated way (Luby et al., 2012; Hanson et al., 2013), or focused exclusively on a few regions of interest (Lawson, Duda, Avants, Wu, & Farah, 2013; Noble, Houston, Kan, & Sowell, 2012), e.g. only prefrontal cortex (Lawson et al., 2013). Prefrontal cortex (PFC) has been a focus of studies of SES because it is sensitive to stress and important for language (Hackman & Farah, 2009). Moreover, because PFC, like association cortex more broadly, is slower to develop than primary cortices (Giedd & Rapoport, 2010), it may be susceptible to environmental influence into adulthood. Thus, it is unknown whether SES selectively influences late-maturing association cortices. Importantly, no study has related SES differences in brain structure to cognitive measures or educational outcomes, such as standardized tests of academic achievement.

Here, we related cortical structure to family income and performance on standardized tests of academic skills. We focused on a narrow age range to have sufficient statistical power for whole-brain analyses, because in broad age ranges, it is difficult to detect individual differences over and above effects of age. We compared cortical gray matter volume (neuron cell bodies, axons, dendrites, glia, and capillaries), cortical white matter volume (axons and glia), and cortical surface area between students from lower-income and higher-income backgrounds. We investigated between-group differences in cortical thickness, a neuroanatomical measure that increases early in development and then decreases through adolescence (Giedd & Rapoport, 2010). We examined whether the relative patterns of cortical thickness were similar in lower- and higher-income groups. Finally, we related, for the first time, cortical thickness to a statewide measure of academic achievement so as to explore the links between SES, brain structure, and academic achievement.

Methods

The Committee on the Use of Humans as Experimental Subjects at the Massachusetts Institute of Technology approved this research. Participants provided informed, written assent for participation, and parents provided written consent.

Participants

As part of a larger study on adolescent neurocognitive development, students were recruited from a variety of local public schools, summer camps, outreach programs, and teen centers. Advertisements were also placed in local papers and on websites. Our initial goal was to recruit 100 students, but our recruitment was limited by the funding period, and challenges

faced in recruiting students from lower-income backgrounds for brain imaging research. Three participants were excluded for the following reasons: no income information or standardized test scores available ($n = 1$), abnormal brain structure ($n = 1$, Higher-Income), and excessive motion artifacts ($n = 1$, Higher-Income). In total, data are presented for 58 students (27 males).

Income groups

With family consent, free/reduced price lunch status was obtained from a database maintained by the Massachusetts Department of Elementary and Secondary Education (MassDESE) in collaboration with the Center for Education Policy Research at Harvard University. Students were eligible for free or reduced price lunch if their family incomes were below 185% of the poverty line, which approximately translates into less than \$42,000 per year for a family of two adults and two children. 23 students (7 boys) received free or reduced price lunch within three years of study participation (Lower-Income group, LI), and 35 students (20 boys) did not (Higher-Income group, HI). For a subset of participants, a parent-report measure of family income was available (LI: $n = 17$; HI: $n = 29$). Family income was coded as the median of the income bin selected (Less than \$5,000; \$5,000–\$11,999; \$12,000–\$15,999; \$16,000–\$24,999; \$25,000–\$34,999; \$35,000–\$49,999; \$50,000–\$74,999; \$75,000–\$99,999; \$100,000–\$199,999; or \$200,000 or greater) except for the lowest and highest bins, which were coded as \$5,000 and \$200,000 respectively. The groups differed significantly on family income (LI: $M = \$46,353$, $SD = \$46,072$, 95% CI = \$22,665 – \$70,041; HI: $M = \$145,465$, $SD = \$60,478$, 95% CI = \$122,461 – \$168,470; $t(44) = 5.8$, $p < .0001$). We focused our neuroimaging analyses on the difference between the income groups based on lunch status, because we had complete data for this measure, but the results of analyses with the continuous parent-report measure of income were substantively similar (see Table S1 and Figure S1 in the Supplemental Materials available online).

The groups differed in their distribution of boys and girls ($X^2(1, n = 58) = 3.98$, $p = .05$), so we controlled for sex in all analyses. The groups did not differ by age (LI: $M = 14.47$, $SD = .38$; HI: $M = 14.35$, $SD = .47$; $t(56) = 1.05$, $p = .3$). Participants completed a form that asked which ethnic category they identified with (Hispanic or Latino, Not Hispanic or Latino, Do not report) and which racial category they identified with (American Indian/Alaskan Native, Asian, Native Hawaiian or other Pacific Islander, Black or African American, White, More than one race, Other, Do not report). The HI group reported the following racial and ethnic identities: 6% African-American, 14% Asian, 54% White, 3% Native Hawaiian or Pacific Islander, 17% multiple races, 6% did not report race; 91% not Hispanic, 3% Hispanic, 6% did not report ethnicity. The LI group reported the following racial and ethnic identities: 22% African-American, 4% Asian, 54% White, 4% Native Hawaiian or Pacific Islander, 26% multiple races, 35% did not report race; 35% not Hispanic, 65% Hispanic. Mirroring demographic distributions in the United States, the LI group contained a larger proportion of ethnic and racial minorities than the HI group. Analyses about the relationship between income and cortical thickness that control for race and ethnicity are reported in Tables S2 and S3 in the Supplemental Material available online. Briefly, in all regions that differed in cortical thickness between income groups, income remained a significant predictor of

cortical thickness after controlling for race or ethnicity. Neither race nor ethnicity explained significant variance in cortical thickness in these regions.

Standardized test scores

Scaled scores on the Massachusetts Comprehensive Assessment System (MCAS) tests were also retrieved from the MassDESE database. At the time the 2012 MCAS tests were administered, three students in the LI group were in 7th grade. All other students were in 8th grade. MCAS tests were administered in March (English/Language Arts, ELA) and May (Math) of 2012. Neuroimaging data were acquired between February 2012 and January 2013. Scaled scores were obtained for Math and ELA. Scaled scores reflect student performance relative to grade level expectations, and allow for comparison across Math and ELA, and across 7th and 8th grade. Scores ranged from 200 to 280, with scores above 240 classified as proficient.

Special education and limited English proficiency information was also obtained through this database. None of the participants was enrolled in special education or limited English proficiency programs during the three years for which data was available.

Example questions from the MCAS exams are available from the Massachusetts Department of Education website (<http://www.doe.mass.edu/mcas/2012/release/>). Proficiency rates for students with and without free/reduced price lunch are also available online (<http://www.doe.mass.edu/mcas/>).

Neuroimaging data acquisition

Data were acquired at the Athinoula A. Martinos Imaging Center at the McGovern Institute for Brain Research at the Massachusetts Institute of Technology. Data were acquired using a 32-Channel Tim Trio 3 Tesla, high-speed magnetic resonance imaging (MRI) scanner (Siemens, Erlangen, Germany). An automated scout image was acquired, and shimming procedures were performed to optimize field homogeneity. A multi-echo high-resolution structural image was acquired using a special protocol optimized for pediatric populations (TR/TEs/flip angle/resolution = 2530ms/1.64ms; 3.44ms; 5.24ms; 7.04ms/7°/1mm isotropic) (Tisdall et al., 2012).

Structural imaging analyses

Data were visually inspected for image quality. Two observers who were blind to income group and MCAS scores rated each image on a scale of 1 (perfect) to 4 (unusable) based on a visual guide of artifacts associated with motion. If ratings differed by 1 point or more, a third blind observer made a final decision. As noted above, one participant was excluded for poor image quality. Ratings did not differ between the Lower-Income and the Higher-Income groups (LI: $M = 2.04$, $SD = .45$; HI: $M = 2.04$, $SD = .43$; Difference: $t(56) = -.05$, $p = .96$), nor were they correlated with MCAS scores ($r(56) = -.01$, $p = .92$).

Structural analyses were conducted with Free Surfer 5.3. In all analyses, we controlled for sex because the two groups differed in sex distribution, and brain anatomy has been shown to differ between boys and girls (e.g., Lenroot et al., 2007). The volume-based stream was

used to calculate total cortical gray matter and white matter volume, as well as estimated intracranial volume (ICV) (methods fully described in Fischl et al., 2002, 2004). In analyses of cortical gray and white matter volume, and total cortical surface area, we controlled for estimated ICV, because these measures are highly correlated with head size but cortical thickness is not (Panizzon et al., 2009). We report the parameter estimates of income group in regression models that include sex and ICV.

Surface-based analysis tools were used to construct models of the boundary between white matter and cortical gray matter, as well as the pial surface. The distance between the white and pial surface is defined as the cortical thickness at each location of cortex (Fischl & Dale, 2000). The details of these methods are described in Dale, Fischl, & Sereno, 1999. Surfaces were edited as needed. An observer who was blind to income group and MCAS scores checked final surfaces. Surfaces of individual participants were resampled to a standard brain (fsaverage) and smoothed with a kernel of 15 mm full-width half max (FWHM). General Linear Models (GLMs) were constructed to test for the following effects: 1) cortical thickness difference between the Lower- and Higher-Income groups, 2) correlation between cortical thickness and average MCAS score across groups (with and without controlling for income group). All whole-brain analyses were cluster-corrected for multiple comparisons using Monte-Carlo simulation (cluster-forming $p < .05$, cluster-wise $p < .05$, adjusted for both hemispheres) (Hagler, Saygin, & Sereno, 2006).

Results

Performance on the Massachusetts Comprehensive Assessment System (MCAS) differed significantly between the Lower Income (LI) group and the Higher Income (HI) group for both Math (LI: $M = 239.0$, $SD = 14.4$, 95% CI = 232.7 – 245.2; HI: $M = 258.7$, $SD = 18.4$, 95% CI = 252.4 – 265.1; Difference: $t(56) = 4.4$, $p = .0001$, $d = 1.01$) and English/Language Arts (LI: $M = 245.4$, $SD = 7.8$, 95% CI = 242.0 – 248.8; HI: $M = 257.0$, $SD = 10.2$, 95% CI = 253.5 – 260.5; Difference: $t(56) = 4.7$, $p < .0001$, $d = 1.07$). Scores on Math and English/Language Arts were highly correlated in this sample ($r(56) = .73$, $p < .0001$), so we averaged the scores to create the variable of interest for neuroimaging analyses.

In our sample, 57% of students in the LI group scored above proficient (greater than 240) on the average of Math and English/Language Arts, compared to 91% of students in the HI group. Comparatively, statewide, 47% of 8th grade students who received free or reduced price lunch scored proficient or above, compared to 77% of students who did not receive free lunch. As with many cognitive neuroscience studies, the students and families who participated in this study seemed to be higher-performing than would be expected from a random sample. However, the difference in the percentage of students reaching proficiency between the LI and HI groups (34%) was consistent with what is observed across the state (30%).

Cortical gray matter volume was significantly greater in the HI group compared to the LI group (Figure 1; LI: $M = 480,375 \text{ mm}^3$, $SD = 51,874 \text{ mm}^3$, 95% CI = 457,943 mm^3 – 502,807 mm^3 ; HI: $M = 551,447 \text{ mm}^3$, $SD = 56,943 \text{ mm}^3$, 95% CI = 531,887 mm^3 – 571,007 mm^3 ; Difference: $t = 3.49$, $p = .001$, partial $\eta^2 = .18$). In contrast, there were no significant

differences between groups in either surface area along the white matter surface (LI: $M = 166,868 \text{ mm}^2$, $SD = 17,487 \text{ mm}^2$, 95% CI = $159,306 \text{ mm}^2 - 174,430 \text{ mm}^2$; HI: $M = 181,301 \text{ mm}^2$, $SD = 16,116 \text{ mm}^2$, 95% CI = $175,765 \text{ mm}^2 - 186,837 \text{ mm}^2$; Difference: $t = 1.24$, $p = .22$), or cortical white matter volume (LI: $M = 427,169 \text{ mm}^3$, $SD = 60,453 \text{ mm}^3$, 95% CI = $401,027 \text{ mm}^3 - 453,311 \text{ mm}^3$; HI: $M = 452,865 \text{ mm}^3$, $SD = 60,454 \text{ mm}^3$, 95% CI = $436,369 \text{ mm}^3 - 469,360 \text{ mm}^3$; Difference: $t = -.56$, $p = .58$).

Cortex was thicker in the HI group than in the LI group across broad swaths of the brain (Figure 2A, Table 1), including bilateral temporal and occipital lobes. The HI group also exhibited significantly greater cortical thickness in lateral PFC in the right hemisphere, but not in the left. Across both hemispheres, the distribution of cortical thickness values for the HI group was shifted towards greater thickness values, relative to the LI group (Figure 2B). Despite between-group differences in cortical thickness, the patterns of thickness were similar within each group. Consistent with histological studies, primary sensory cortices were thinner than motor and association cortices (Economo, 2009), and sulci were thinner than gyri (Hilgetag & Barbas, 2005).

Cortical thickness correlations with MCAS scores largely resembled cortical thickness differences between groups. Across all students, higher average MCAS scores correlated significantly with greater cortical thickness from primary visual cortices dorsally to parietal cortex, and ventrally through the extent of the temporal lobe (Figure 3, Table 1). Prefrontal cortical thickness and MCAS performance were not significantly correlated. When income group was included as a covariate, no correlations remained significant at the whole brain level. Within the clusters defined from the whole brain analysis, relationships between test scores and thickness were significant after controlling for income group or the continuous measure of family income (Table S4 in the Supplemental Material available online). Thus, controlling for family income reduced but did not eliminate positive relationships between cortical thickness and test scores.

Family income remained a significant predictor of average MCAS scores when controlling for cortical thickness within the five clusters defined from the whole brain analysis (Figure 3, Table 1), but the strength of this relationship was greatly reduced. Across all students, the gap in average MCAS scores between the HI and LI groups controlling for sex was 16.07 points ($t(55) = 4.8$, $p < .0001$, $d = 1.13$). Controlling for cortical thickness within the five clusters that correlated significantly with MCAS reduced this gap to 8.99 points ($t(50)$, $p = 0.023$, $d = 0.63$). This reduction in the gap in average MCAS scores between the HI and LI groups could reflect either a direct influence of cortical thickness on achievement or the influence of unmeasured differences between HI and LI students that are correlated with both MCAS scores and cortical thickness. However, this result implies that cortical thickness in clusters correlated with MCAS performance could account for as much as 44 percent of the income achievement gap in this sample.

Discussion

Neuroanatomical correlates of the income achievement gap were observed. Adolescents from higher-income backgrounds, who had higher standardized test scores, exhibited greater

cortical thickness in all lobes of the brain. Although the income groups differed in cortical thickness, they did not differ in cortical surface area, cortical white matter volume, or patterns of cortical thickness. Better performance on academic achievement tests was associated with thicker cortex throughout posterior cortices. Differences in cortical thickness could account for almost half of the income achievement gap in this sample. Relationships between cortical thickness and test scores were driven in part by family income differences. The lower-income group had a larger proportion of racial and ethnic minorities, as characterizes lower SES groups in the United States, but neither race nor ethnicity explained significant variance in cortical thickness in the regions that differed significantly between income groups when included as a predictor in analyses.

Our results were consistent with other developmental studies of SES in that we observed less gray matter in the lower-SES group (Hanson et al., 2013; Jednoróg et al., 2012; Lawson et al., 2013; Noble et al., 2012) and no differences in cortical white matter volume (Jednoróg et al., 2012; Hanson et al., 2013; but see Luby et al., 2012). However, our findings from whole-brain analyses were inconsistent with the hypothesis that SES disproportionately influences association cortices in general, or PFC in particular. Instead, SES differences were evident in both early-developing primary cortices and late-developing association cortices.

Thinner cortex in the lower SES group could reflect less gray matter formation early in development (Hanson et al., 2013) or accelerated thinning. Thicker cortex is not inherently better: the optimal relationship between cognitive development and cortical thickness is complex. In adolescents in whom SES was not considered, thinner cortex was associated with better neuropsychological functioning (Schnack et al., 2014; Squeglia, Jacobus, Sorg, Jernigan, & Tapert, 2013). A slower developmental trajectory of thickening and thinning has been linked with better cognitive skills (Shaw et al., 2006).

We know neither the causes nor the cellular bases of differences in cortical thickness. Low SES is associated with many factors that influence brain development, including enhanced exposure to stress and reduced environmental enrichment (Hackman & Farah, 2009). In humans, the cellular characteristics that underlie SES-related differences in brain structure are unknown. However, in animal models, stress has been associated with reduced cortical dendritic volume (McEwen & Morrison, 2013), and environmental enrichment with greater cortical dendritic volume, synaptogenesis, and glial proliferation (Markham & Greenough, 2004).

Critically, neuroanatomy is modifiable through experience. Neuroimaging studies have shown changes in brain structure after a few weeks of learning (Zatorre, Fields, & Johansen-Berg, 2012). Therefore, educational programs may positively influence neuroanatomical circuits that support cognitive abilities. For example, a combination of child and parental support enhanced electrophysiological brain measures and cognitive functions in younger children from lower-SES backgrounds (Neville et al., 2013). Future studies will show how effective educational practices support academic gains, and whether these practices alter cortical anatomy.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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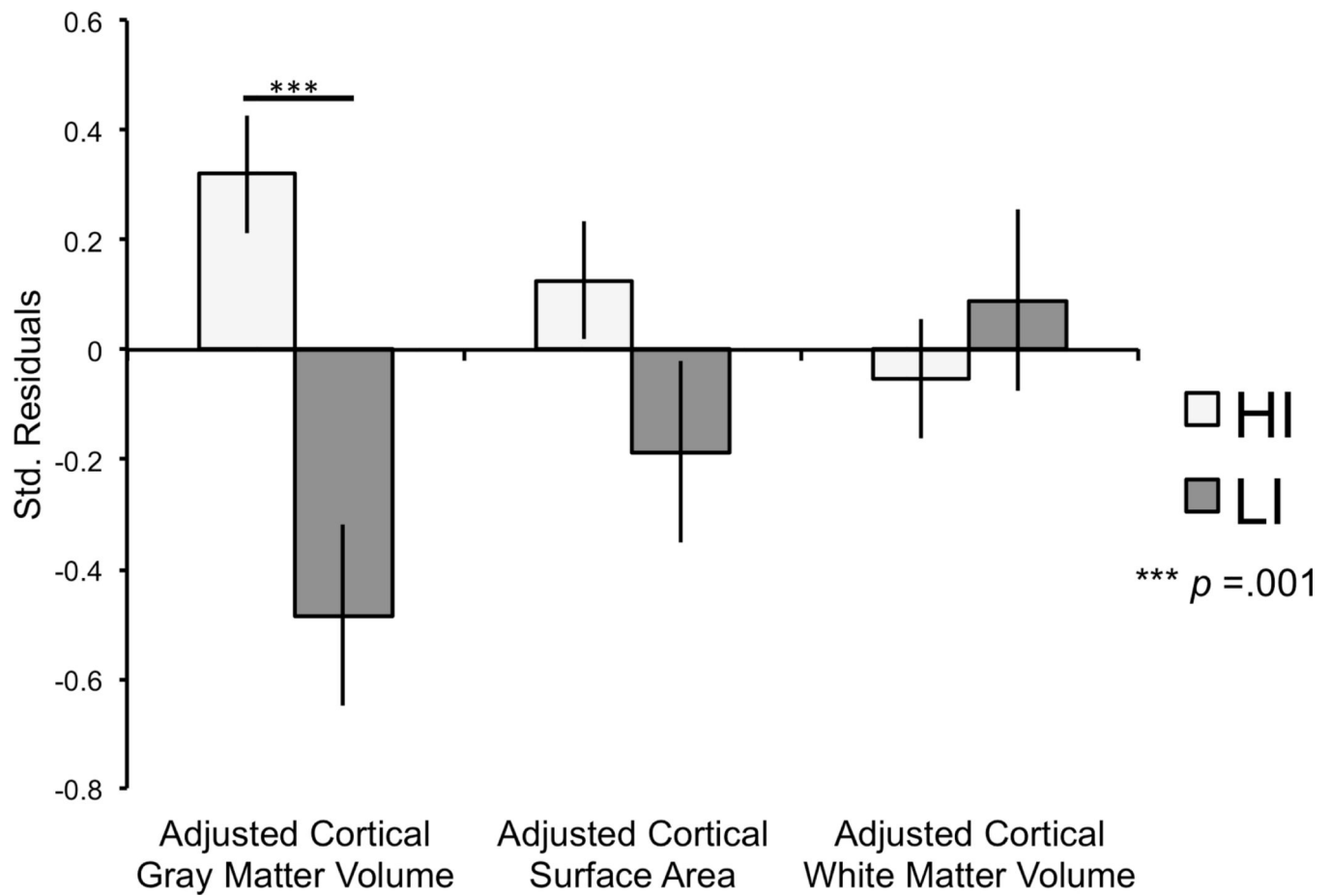


Figure 1.

Volume and surface area differences between income groups. HI: Higher Income, LI: Lower Income. Volume and surface area measurements are adjusted for sex and estimated intracranial volume.

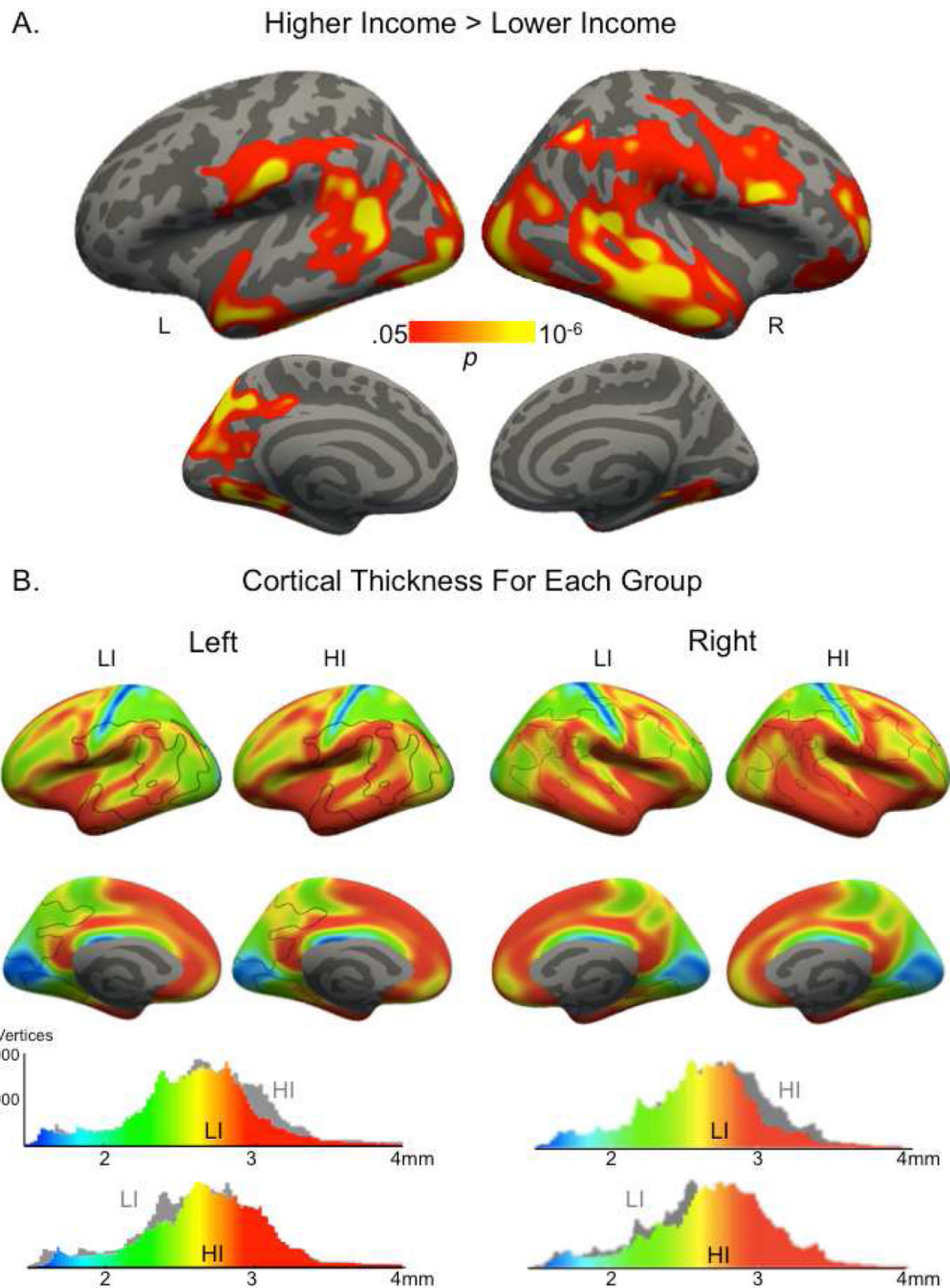


Figure 2. Cortical thickness differences between income groups. A: Higher-Income > Lower-Income. Sex is included as a nuisance regressor. Results are cluster-corrected for multiple comparisons (cluster-forming $p < .05$, cluster-wise $p < .05$, adjusted for both hemispheres). Cluster statistics are shown in Table 1. Results are displayed on inflated surfaces, with darker gray indicating sulci, and lighter gray indicating gyri. B: Cortical thickness for each group. Cortical thickness in millimeters is displayed for each group separately, overlaid with the significant results from part A. Histograms represent the number of vertices for each

thickness value, and show the color scale plotted on the cortical surfaces. The top row of histograms shows the LI group in color, and the HI group in gray, and the bottom row shows the HI group in color and the LI group in gray.

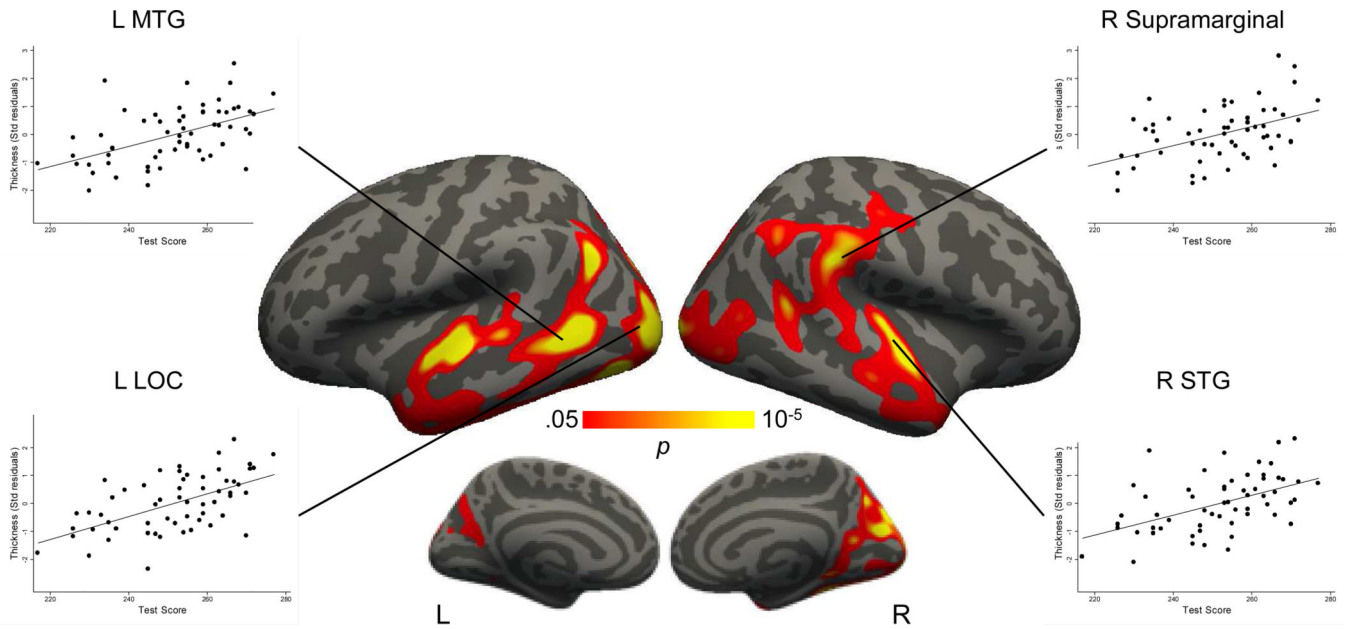


Figure 3. Cortical thickness is positively correlated with test scores. Sex is included as a nuisance regressor. Results are cluster-corrected for multiple comparisons (cluster-forming $p < .05$, cluster-wise $p < .05$, adjusted for both hemispheres). Results are displayed on inflated surfaces, with darker gray indicating sulci, and lighter gray indicating gyri. Scatter plots show cortical thickness values extracted from significant clusters, adjusted for sex (cluster statistics are shown in Table 1).

Cluster statistics for the Higher Income (HI) > Lower Income (LI) contrast (Figure 2A), and correlation with standardized academic test scores (Figure 3).

Table 1

	Peak significance ($-\log_{10} p$)	Peak MNI coordinate			Area of cluster (mm ²)	Cluster-wise p
		x	y	z		
HI > LI						
L Postcentral	5.52	-59	-19	26	5398	.0002
L Inferior Temporal	5.50	-46	-31	-22	5630	.0002
L Lateral Occipital	4.74	-43	-75	-10	9065	.0002
R Middle Temporal	5.51	49	-22	-14	18455	.0002
R Rostral Middle Frontal	4.35	27	49	2	3096	.0002
R Inferior Frontal <i>pars opercularis</i>	3.90	49	8	18	2797	.0004
Correlation with Test Scores						
L Middle Temporal	4.94	-53	-61	5	2863	.0004
L Lateral Occipital	4.77	-41	-76	-11	15314	.0004
R Cuneus	4.61	6	-74	22	9602	.0004
R Superior Temporal	3.92	56	-7	-2	3065	.0008
R Supramarginal	3.14	54	-37	31	3984	.0004