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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. In the research reported 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 ($n = 35$) than in students from lower-income backgrounds ($n = 23$), but cortical white-matter volume and total cortical surface area did not differ significantly between groups. Cortical thickness in all lobes of the brain was greater in students from higher-income than lower-income backgrounds. Greater cortical thickness, particularly in temporal and occipital lobes, was associated with better test performance. These results represent the first evidence that cortical thickness in higher- and lower-income students differs across broad swaths of the brain and that cortical thickness is related to scores on academic-achievement tests.

Keywords

academic achievement, brain, adolescent development, cognitive neuroscience

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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 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). In the research reported 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, in public-school students who do (lower income) and 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 lesser cortical thickness in lower-income groups. However, these studies have had limited statistical power (Jednoróg et al., 2012), averaged across large brain regions in an undifferentiated way (Hanson et al., 2013; Luby et al., 2012), or focused exclusively on a few regions of interest

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(e.g., only prefrontal cortex, or PFC; Lawson, Duda, Avants, Wu, & Farah, 2013; see also Noble, Houston, Kan, & Sowell, 2012). 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. Notably, 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 in 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 we could explore the links between SES, brain structure, and academic achievement.

Method

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

Students were recruited from a variety of local public schools, summer camps, outreach programs, and teen centers as part of a larger study on adolescent neurocognitive development. Advertisements were also placed in local papers and on Web sites. Our initial goal was to recruit 100 students, but our recruitment was limited by the funding period and by the 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 from the higher-income group), and excessive motion artifacts (n = 1 from the higher-income group). In total, data from 58 students (27 males, 31 females) were analyzed.

Income groups

With family consent, free or 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 are eligible for free or reduced-price lunch if their family income is 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. Twenty-three students (7 boys, 16 girls) received free or reduced-price lunch within 3 years of study participation (lower-income group), and 35 students (20 boys, 15 girls) did not (higher-income group).

For a subset of participants, a parent-report measure of family income was available (lower-income group: n = 17; higher-income group: 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 more) except for the lowest and highest bins, which were coded as $5,000 and $200,000, respectively. The groups differed significantly on family income (lower-income group: M = \$46,353, SD = \$46,072, 95% confidence interval, or CI = [$22,665, $70,041]; higher-income group: 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 in lunch status between the income groups 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 Fig. S1 in the Supplemental Material available online).

The groups differed in their distribution of boys and girls, $\chi^2(1, N = 58) = 3.98$, $p = .05$, so we controlled for sex in all analyses. The groups did not differ by age (lower-income group: M = 14.47 years, SD = 0.38; higher-income group: M = 14.35 years, SD = 0.47), $t(56) = 1.05$, $p = .30$. 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 higher-income 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 lower-income 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, these data showed that the lower-income group contained a larger percentage of ethnic and racial minorities than the higher-income group. (Analyses about the relationship between income and cortical thickness when controlling for race and ethnicity are reported in Tables S2 and S3 in the Supplemental Material.) 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 lower-income group were in 7th grade. All other students were in 8th grade. MCAS tests were administered in March (English/Language Arts) and May (Math) of 2012. Scaled scores were obtained for Math and English/Language Arts. Scaled scores reflect student performance relative to grade-level expectations and allow comparison across Math and English/Language Arts and across 7th and 8th grade. Scores ranged from 200 to 280, with students scoring above 240 classified as proficient.

Information regarding special education and limited English proficiency were also obtained through this database. None of the participants was enrolled in special-education or limited-English-proficiency programs during the 3 years for which data were available. Example questions from the MCAS exams are available from the Massachusetts Department of Education Web site (http://www.doe.mass.edu/mcas/2012/release/), as are proficiency rates for students eligible and not eligible for free or reduced-price lunch (http://www.doe.mass.edu/mcas/).

Neuroimaging-data acquisition

Data were acquired between February 2012 and January 2013 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 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 (repetition time = 2,530 ms; echo times = 1.64 ms, 3.44 ms, 5.24 ms, 7.04 ms; flip angle = 7°; resolution = 1-mm 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, 1 participant was excluded because of poor image quality. Ratings did not differ between the lower-income group (M = 2.04, SD = 0.45) and the higher-income group (M = 2.04, SD = 0.43), $t(56) = -0.05$, $p = .96$, nor were they correlated with MCAS scores, $r(56) = -.01$, $p = .92$.

Structural analyses were conducted with FreeSurfer Version 5.3 (Fischl et al., 2002; Fischl et al., 2004). 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; Fischl et al., 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 cortex location (Fischl & Dale, 2000). The details of these methods are described in Dale, Fischl, and 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 15-mm full-width half-maximum kernel. General linear models were constructed to test for cortical-thickness difference between the lower- and higher-income groups and for correlations between cortical thickness and average MCAS score across groups (with and without controlling for income group). All whole-brain analyses were cluster-corrected

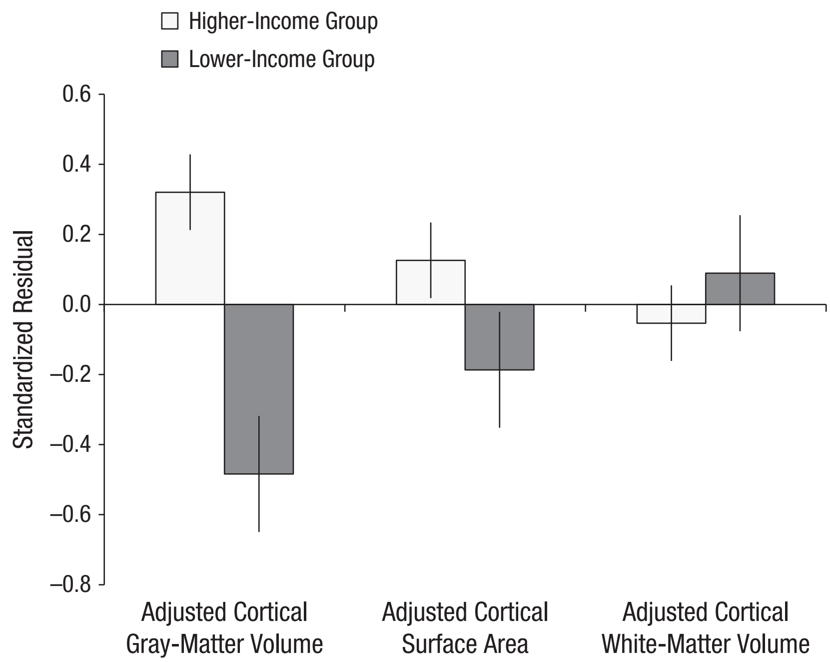

Fig. 1. Volume and surface-area differences between income groups. The graph presents residuals after adjusting for sex and estimated intracranial volume. Error bars show ±1 *SE*.

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 MCAS differed significantly between the lower-income group and the higher-income group for both Math (lower income: $M = 239.0$, $SD = 14.4$, 95% CI = [232.7, 245.2]; higher income: $M = 258.7$, $SD = 18.4$, 95% CI = [252.4, 265.1]), $t(56) = 4.4$, $p = .0001$, $d = 1.01$, and English/Language Arts (lower income: $M = 245.4$, $SD = 7.8$, 95% CI = [242.0, 248.8]; higher income: $M = 257.0$, $SD = 10.2$, 95% CI = [253.5, 260.5]), $t(56) = 4.7$, $p < .0001$, $d = 1.07$. 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 lower-income group scored above proficient (greater than 240) on the average of Math and English/Language Arts, compared with 91% of students in the higher-income group. Comparatively, statewide, 47% of 8th grade students who received free or reduced-price lunch scored proficient or above, compared with 77% of students who did not receive free or reduced-price lunch. As with many cognitive neuroscience studies, the students and families who participated in this study seemed to perform better than would be expected from a random sample. However, the difference in the percentage of students reaching proficiency between the lower-income and higher-income groups (34%) was consistent with what is observed across the state (30%).

Cortical gray-matter volume was significantly greater in the higher-income group than in the lower-income group (Fig. 1; lower income: $M = 480{,}375$ mm^3, $SD = 51{,}874$, 95% CI = [457,943, 502,807]; higher income: $M = 551{,}447$ mm^3, $SD = 56{,}943$, 95% CI = [531,887, 571,007]), $t(56) = 3.49$, $p = .001$, $\eta_p^2 = .18$. In contrast, there were no significant differences between groups in area along the white-matter surface (lower income: $M = 166{,}868$ mm^2, $SD = 17{,}487$, 95% CI = [159,306, 174,430]; higher income: $M = 181{,}301$ mm^2, $SD = 16{,}116$, 95% CI = [175,765, 186,837]), $t(56) = 1.24$, $p = .22$, or in cortical white-matter volume (lower income: $M = 427{,}169$ mm^3, $SD = 60{,}453$, 95% CI = [401,027, 453,311]; higher income: $M = 452{,}865$ mm^3, $SD = 60{,}454$, 95% CI = [436,369, 469,360]), $t(56) = -0.56$, $p = .58$.

Cortex thickness was greater in the higher-income group than in the lower-income group across broad swaths of the brain (Fig. 2a, Table 1), including bilateral temporal and occipital lobes. Compared with the lower-income group, the higher-income group also exhibited significantly greater cortical thickness in lateral PFC in the right hemisphere, but not in the left. Across both hemispheres, the higher-income group had greater cortical-thickness values, relative to the lower-income group (Fig. 2b). Despite between-group differences in cortical

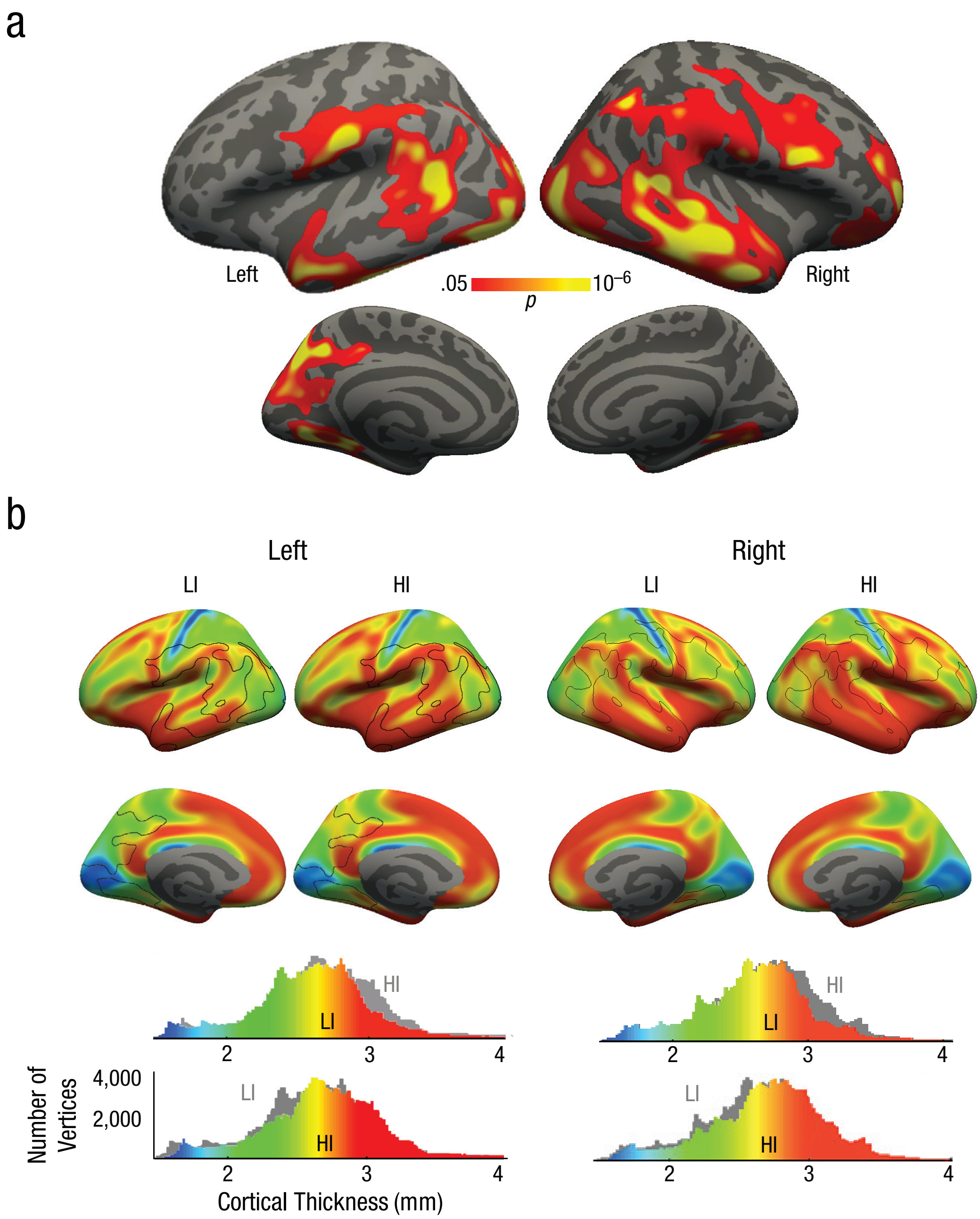

Fig. 2. Cortical-thickness differences between income groups. The brain images in (a) show regions where cortical thickness was significantly greater in the higher-income (HI) group than in the lower-income (LI) group. In all analyses, sex was included as a nuisance regressor. Results were cluster-corrected 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. In (b), cortical thickness in millimeters is displayed for each group separately. The gray outlines show the areas in which results were significant in the HI > LI contrast. The histograms show the number of vertices as a function of thickness value and the color scale plotted on the cortical surfaces. The top row of histograms shows results for the lower-income group in color and the higher-income group in gray, and the bottom row shows results for the higher-income group in color and the lower-income group in gray.

thickness, the patterns of thickness were similar within each group. Consistent with histological studies, our results showed that primary sensory cortices were thinner than motor and association cortices (von Economo, 2009), and sulci were thinner than gyri (Hilgetag & Barbas, 2005).

Table 1. Regions Where Cortical Thickness Was Significantly Greater in the Higher-Income Group Than in the Lower-Income Group, and Regions Where Cortical Thickness Was Significantly Correlated With Academic Test Scores

Region	Peak significance ($-\log_{10} p$)	Peak MNI coordinates *x*	*y*	*z*	Area of cluster (mm^2)	Cluster-wise *p*
Higher income > lower income contrast						
Left postcentral gyrus	5.52	–59	–19	26	5,398	.0002
Left inferior temporal cortex	5.50	–46	–31	–22	5,630	.0002
Left lateral occipital cortex	4.74	–43	–75	–10	9,065	.0002
Right middle temporal gyrus	5.51	49	–22	–14	18,455	.0002
Right rostral middle frontal gyrus	4.35	27	49	2	3,096	.0002
Right inferior frontal gyrus pars opercularis	3.90	49	8	18	2,797	.0004
Correlation with test scores						
Left middle temporal gyrus	4.94	–53	–61	5	2,863	.0004
Left lateral occipital cortex	4.77	–41	–76	–11	15,314	.0004
Right cuneus	4.61	6	–74	22	9,602	.0004
Right superior temporal gyrus	3.92	56	–7	–2	3,065	.0008
Right supramarginal gyrus	3.14	54	–37	31	3,984	.0004

Note: MNI = Montreal Neurological Institute. Test scores were standardized scores on the Massachusetts Comprehensive Assessment System (MCAS).

Correlations between cortical thickness and MCAS scores largely resembled the pattern of cortical-thickness differences observed 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 (Fig. 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 cortical thickness were significant after controlling for income group or the continuous measure of family income (see Table S4 in the Supplemental Material). 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 (Fig. 3, Table 1), but the strength of this relationship was greatly reduced. Across all students, the gap in average MCAS scores between the higher-income and lower-income groups after 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 scores reduced this gap to 8.99 points, $t(50) = 2.35$, $p = .023$, $d = 0.63$. This reduction could reflect either a direct influence of cortical thickness on achievement or the influence of unmeasured differences between higher-income and lower-income 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% of the income-achievement gap in this sample.

Discussion

The present study demonstrated neuroanatomical correlates of the income-achievement gap. Adolescents from higher-income backgrounds, who had higher standardized test scores than adolescents from lower-income backgrounds, 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 greater thickness 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 differences in family income. 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.

Our results were consistent with other developmental studies of SES in that we observed less gray matter in the lower-income group than in the higher-income group (Hanson et al., 2013; Jednoróg et al., 2012; Lawson et al.,

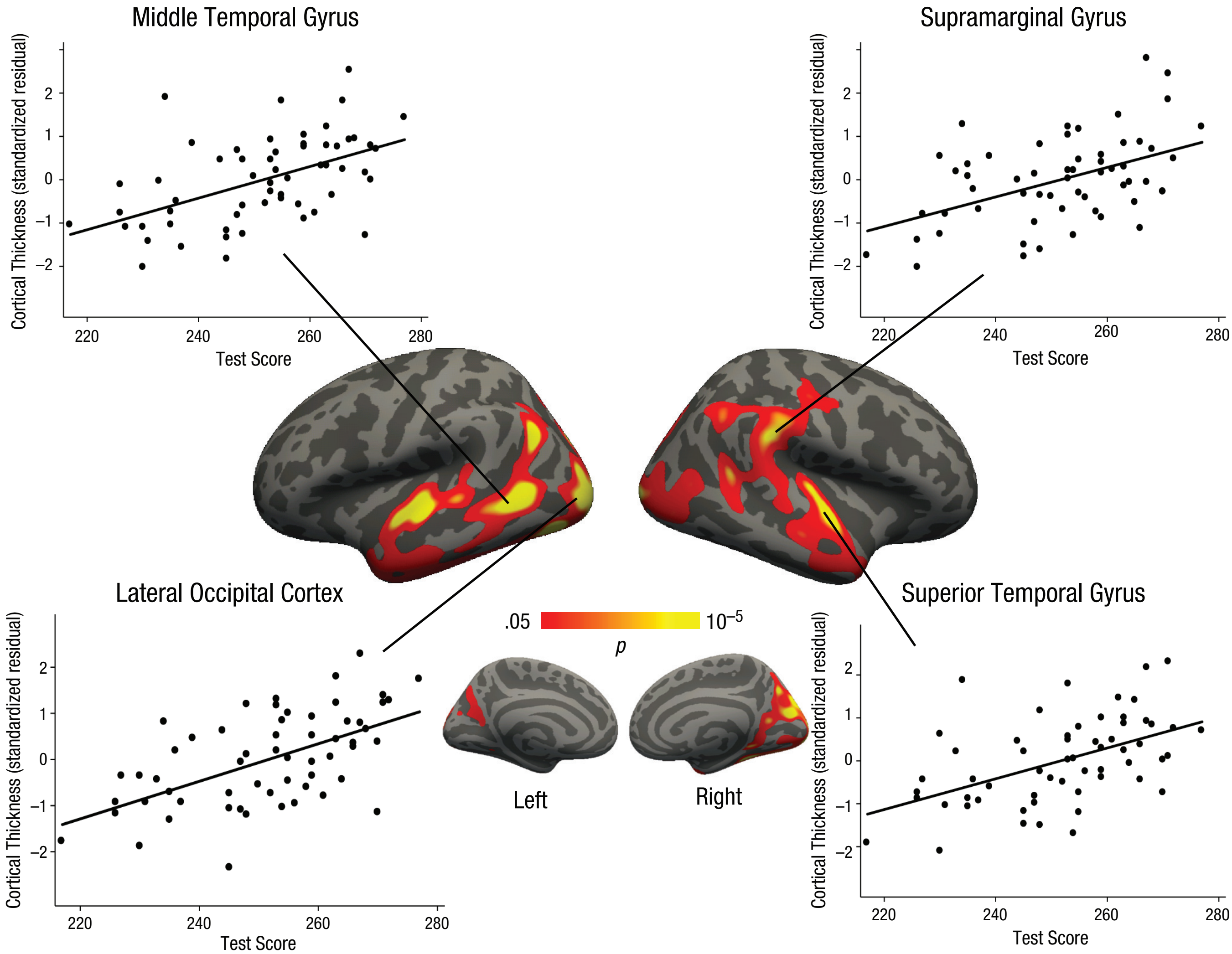

Fig. 3. Correlations between cortical thickness and test scores. Sex was included in the analysis as a nuisance regressor. Results were cluster-corrected for multiple comparisons (cluster-forming $p < .05$, cluster-wise $p < .05$, adjusted for both hemispheres). Results are displayed on inflated surfaces, with darker gray indicating sulci and lighter gray indicating gyri. The scatter plots (with best-fitting regression lines) show results for four of the five regions with significant correlations (cluster statistics are shown in Table 1).

2013; Noble et al., 2012) and no differences in cortical white-matter volume (Hanson et al., 2013; Jednoróg et al., 2012; 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.

Less cortical thickness in the lower-income than in the higher-income group could reflect less gray-matter formation early in development (Hanson et al., 2013) or accelerated thinning. A 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, a 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).

Neither the causes nor the cellular bases of differences in cortical thickness are known. 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 has been linked 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, an intervention that involved both children and parents was shown to enhance electrophysiological brain measures and cognitive functions in younger children from lower-income backgrounds (Neville et al., 2013). Future studies will show how effective educational practices support academic gains and whether these practices alter cortical anatomy.

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 analysis. C. F. O. Gabrieli helped design the study and cultivate 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.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information can be found at http://pss.sagepub.com/content/by/supplemental-data

References

Ackerman, B. P., & Brown, E. D. (2010). Physical and psychosocial turmoil in the home and cognitive development. In G. W. Evans & T. D. Wachs (Eds.), *Chaos and its influence on children's development: An ecological perspective* (pp. 35–47). Washington, DC: American Psychological Association.

Bradley, R. H., & Corwyn, R. F. (2002). Socioeconomic status and child development. *Annual Review of Psychology*, *53*, 371–399. doi:10.1146/annurev.psych.53.100901.135233

Dale, A. M., Fischl, B., & Sereno, M. I. (1999). Cortical surface-based analysis: I. Segmentation and surface reconstruction. *NeuroImage*, *9*, 179–194. doi:10.1006/nimg.1998.0395

Duncan, G. J., & Brooks-Gunn, J. (1997). *Growing up poor*. New York, NY: Russell Sage Foundation.

Duncan, G. J., & Magnuson, K. (2011). The nature and impact of early achievement skills, attention skills, and behavior problems. In G. J. Duncan & R. Murnane (Eds.), *Whither opportunity? Rising inequality, schools, and children's life chances* (pp. 47–70). New York, NY: Russell Sage Foundation.

Fischl, B., & Dale, A. M. (2000). Measuring the thickness of the human cerebral cortex from magnetic resonance images. *Proceedings of the National Academy of Sciences, USA*, *97*, 11050–11055. doi:10.1073/pnas.200033797

Fischl, B., Salat, D. H., Busa, E., Albert, M., Dieterich, M., Haselgrove, C., . . . Dale, A. M. (2002). Whole brain segmentation: Automated labeling of neuroanatomical structures in the human brain. *Neuron*, *33*, 341–355. doi:10.1016/S0896-6273(02)00569-X

Fischl, B., Van Der Kouwe, A., Destrieux, C., Halgren, E., Segonne, F., Salat, D. H., . . . Dale, A. M. (2004). Automatically parcellating the human cerebral cortex. *Cerebral Cortex*, *14*, 11–22. doi:10.1093/cercor/bhg087

Giedd, J. N., & Rapoport, J. L. (2010). Structural MRI of pediatric brain development: What have we learned and where are we going? *Neuron*, *67*, 728–734. doi:10.1016/j.neuron.2010.08.040

Hackman, D. A., & Farah, M. J. (2009). Socioeconomic status and the developing brain. *Trends in Cognitive Sciences*, *13*, 65–73. doi:10.1016/j.tics.2008.11.003

Hagler, D. J., Saygin, A. P., & Sereno, M. I. (2006). Smoothing and cluster thresholding for cortical surface-based group analysis of fMRI data. *NeuroImage*, *33*, 1093–1103. doi:10.1016/j.neuroimage.2006.07.036

Hanson, J. L., Hair, N., Shen, D. G., Shi, F., Gilmore, J. H., Wolfe, B. L., & Pollak, S. D. (2013). Family poverty affects the rate of human infant brain growth. *PLoS ONE*, *8*(12), Article e80954. Retrieved from http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0080954

Hilgetag, C. C., & Barbas, H. (2005). Developmental mechanics of the primate cerebral cortex. *Anatomy and Embryology*, *210*, 411–417. doi:10.1007/s00429-005-0041-5

Jednoróg, K., Altarelli, I., Monzalvo, K., Fluss, J., Dubois, J., Billard, C., . . . Ramus, F. (2012). The influence of socioeconomic status on children's brain structure. *PLoS ONE*, *7*(8), Article e42486. Retrieved from http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0042486

Lawson, G. M., Duda, J. T., Avants, B. B., Wu, J., & Farah, M. J. (2013). Associations between children's socioeconomic status and prefrontal cortical thickness. *Developmental Science*, *16*, 641–652. doi:10.1111/desc.12096

Lenroot, R. K., Gogtay, N., Greenstein, D. K., Wells, E. M., Wallace, G. L., Clasen, L. S., . . . Giedd, J. N. (2007). Sexual dimorphism of brain developmental trajectories during childhood and adolescence. *NeuroImage*, *36*, 1065–1073. doi:10.1016/j.neuroimage.2007.03.053

Luby, J. L., Barch, D. M., Belden, A., Gaffrey, M. S., Tillman, R., Babb, C., . . . Botteron, K. N. (2012). Maternal support in early childhood predicts larger hippocampal volumes at school age. *Proceedings of the National Academy of Sciences, USA*, *109*, 2854–2859. doi:10.1073/pnas.1118003109

Markham, J. A., & Greenough, W. T. (2004). Experience-driven brain plasticity: Beyond the synapse. *Neuron Glia Biology*, *1*, 351–363. doi:10.1017/s1740925x05000219

McEwen, B. S., & Morrison, J. H. (2013). The brain on stress: Vulnerability and plasticity of the prefrontal cortex over the life course. *Neuron*, *79*, 16–29. doi:10.1016/j.neuron.2013.06.028

Neville, H. J., Stevens, C., Pakulak, E., Bell, T. A., Fanning, J., Klein, S., & Isbell, E. (2013). Family-based training program improves brain function, cognition, and behavior in lower socioeconomic status preschoolers. *Proceedings of the National Academy of Sciences, USA*, *110*, 12138–12143. doi:10.1073/pnas.1304437110

Noble, K. G., Houston, S. M., Kan, E., & Sowell, E. R. (2012). Neural correlates of socioeconomic status in the developing human brain. *Developmental Science*, *15*, 516–527. doi:10.1111/j.1467-7687.2012.01147.x

Panizzon, M. S., Fennema-Notestine, C., Eyler, L. T., Jernigan, T. L., Prom-Wormley, E., Neale, M., . . . Kremen, W. S. (2009). Distinct genetic influences on cortical surface area and cortical thickness. *Cerebral Cortex*, *19*, 2728–2735. doi:10.1093/cercor/bhp026

Reardon, S. F. (2011). The widening socioeconomic status achievement gap: New evidence and possible explanations. In G. J. Duncan & R. Murnane (Eds.), *Whither opportunity? Rising inequality, schools, and children's life chances* (pp. 91–115). New York, NY: Russell Sage Foundation.

Schnack, H. G., van Haren, N. E. M., Brouwer, R. M., Evans, A., Durston, S., Boomsma, D. I., . . . Hulshoff Pol, H. E. (2014). Changes in thickness and surface area of the human cortex and their relationship with intelligence. *Cerebral Cortex*. Advance online publication. doi:10.1093/cercor/bht357

Shaw, P., Greenstein, D., Lerch, J., Clasen, L., Lenroot, R., Gogtay, N., . . . Giedd, J. (2006). Intellectual ability and cortical development in children and adolescents. *Nature*, *440*, 676–679. doi:10.1038/nature04513

Squeglia, L. M., Jacobus, J., Sorg, S. F., Jernigan, T. L., & Tapert, S. F. (2013). Early adolescent cortical thinning is related to better neuropsychological performance. *Journal of the International Neuropsychological Society*, *19*, 962–970. doi:10.1017/S1355617713000878

Tisdall, M. D., Hess, A. T., Reuter, M., Meintjes, E. M., Fischl, B., & van der Kouwe, A. J. W. (2012). Volumetric navigators for prospective motion correction and selective reacquisition in neuroanatomical MRI. *Magnetic Resonance in Medicine*, *68*, 389–399. doi:10.1002/mrm.23228

U.S. Department of Education, National Center for Education Statistics, Common Core of Data (CCD). (2011–2012). *Public Elementary/Secondary School Universe Survey*. Washington, DC: U.S. Department of Education.

von Economo, C. (2009). *Cellular structure of the human cerebral cortex* (L. C. Triarhou, Ed.). Basel, Switzerland: Karger.

Zatorre, R. J., Fields, R. D., & Johansen-Berg, H. (2012). Plasticity in gray and white: Neuroimaging changes in brain structure during learning. *Nature Neuroscience*, *15*, 528–536. doi:10.1038/nn.3045