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Original Paper

Diminished Association between Parental Education and Parahippocampal Cortical Thickness in Pre-Adolescents in the US

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Abstract

Introduction: *Socioeconomic status (SES) indicators, such as parental education and household income, are associated with the thickness of various cortical areas. However, less is known about the parahippocampal region. Additionally, more research is required regarding how the correlation between SES indicators and cortical thickness differs among diverse racial groups.* ***Purpose:*** *This study uses a national sample of pre-adolescents ages 9 to 10 years old in the US and was performed with two aims in mind. First, to investigate the correlations between two SES indicators, namely parental education and household income, and parahippocampal cortical thickness. Second, to explore racial differences in these associations.* ***Methods:*** *In this cross-sectional study, we used data from the Adolescent Brain Cognitive Development (ABCD) study to analyze the Structural Magnetic Resonance Imaging (sMRI) data of 9,849 US pre-adolescents between the ages of 9 and 10 years old. The main outcomes were parahippocampal cortical thickness separately calculated for the right and the left hemispheres using sMRI. The independent variables were parental education and household income, which were both treated as nominal variables. Age, sex, ethnicity, and family structure were the covariates, and race was the moderator. Mixed-effects regression models were used for data analysis with and without interaction terms.* ***Results:*** *High income positively associated with right and left parahippocampal cortical thickness in the fully adjusted models. Race showed a statistically significant interaction with parental education on children's parahippocampal cortical thickness, suggesting that* *the correlations between parental education with the right and left parahippocampal cortical thickness were significantly larger for White than Black and other/mixed race pre-adolescents. No interaction was found for household income and race.* ***Conclusions:*** *The association between parental education and pre-adolescents parahippocampal cortical thickness may be weaker in Black than in White American children.* ***Consistent*** *with the findings of Marginalization-related Diminished Returns (MDRs), parental education shows weaker links for some brain indicators, such as parahippocampal cortical thickness, in Black and other racial and minority children when compared to White children.*

Keywords

socioeconomic status, parental education, household income, brain development, pre-adolescents, sMRI, parahippocampus

1. Introduction

Promising non-invasive neuroimaging technologies, including structural magnetic resonance imaging (sMRI), have led to considerable knowledge on the structural development of the brain across the lifespan (Ehrler, Latal, Kretschmar, von Rhein, & Tuura, 2020; Lei et al., 2015; Mueller, Lim, Hemmy, & Camchong, 2015). These technologies have also shown that differences in brain development are correlated with early life experiences, such as childhood socioeconomic status (SES) (Agorastos, Pervanidou, Chrousos, & Kolaitis, 2018; Basmacı Kandemir et al., 2016; Butler, Yang, Laube, Kühn, & Immordino-Yang, 2018; Di Segni, Andolina, & Ventura, 2018). In humans, brain maturation, responsible for higher-level cognitive function, continues through childhood and adolescence. Therefore, the window for experience-dependent change is long (Sowell et al., 2003). Structural MRI can measure the structure and volume of white and gray matter (Lei et al., 2015). Altered cortical thickness in brain structures can be seen in some diseases and a wide variety of disorders, including depression (S. Assari, 2020), anxiety disorders (Tromp et al., 2019), dissociative disorder (Basmacı Kandemir et al., 2016), attention deficit hyperactivity disorder (ADHD) (Albaugh et al., 2019; Ameis et al., 2016), and autism spectrum disorder (ASD) (Ameis et al., 2016; Di, Azeez, Li, Haque, & Biswal, 2018; Gibbard, Ren, Skuse, Clayden, & Clark, 2018). Cortical thickness is also associated with altered cognitive and emotional domains, such as working memory (Rosen, Sheridan, Sambrook, Meltzoff, & McLaughlin, 2018; Urger et al., 2015), executive function (Urger et al., 2015; Ursache, Noble, Pediatric Imaging, & Study, 2016), language development (Novén et al., 2021; Urger et al., 2015), and emotion regulation (Versace et al., 2015).

Among various SES indicators, parental education and income are linked to structural brain differences (Chan et al., 2018; Hunt et al., 2020; Palacios-Barrios & Hanson, 2019; Rosen et al., 2018; Taylor, Cooper, Jackson, & Barch, 2020) that have implications for cognitive development across numerous domains, including language (Romeo et al., 2018), self-regulation (Farley & Kim-Spoon, 2017; Palacios-Barrios & Hanson, 2019), memory (Hackman, Gallop, Evans, & Farah, 2015), socio-emotional processing (Stevens, Lauinger, & Neville, 2009), and behaviors (Farah, 2017). High SES reduce the risk of early adversity, poverty, economic insecurity, and lack of resources, which are all factors that interfere with normal brain development (Yaple & Yu, 2020). High household income and parental education are proxies of growing up in low-stress environments, food security, environmental safety, and parental protection, which are all factors that promote children's brain development (Shervin Assari & Bazargan, 2019a, 2019b). Parental education is a major SES indicator that is not covered by financial resources availability (Shervin Assari & Boyce, 2021), which means that income and parental education tend to be associated with differential effects for children (Shervin Assari & Caldwell, 2018). However, few studies have included both income and parental education as social determinants of brain development (Shervin Assari, 2020b; Shervin Assari, Shanika Boyce, Mohsen Bazargan, & Cleopatra H Caldwell, 2020b; Shervin Assari, Caldwell, & Bazargan, 2019). High parental education is indicative of effective and involved parenting, (Shervin Assari, Shanika Boyce, Mohsen Bazargan, & Cleopatra H. Caldwell, 2020a), cognitively stimulating environments, and protective against poor economic environment (Shervin Assari & Boyce, 2021; Jenkins et al., 2020). Parental education is protective against children's alcohol problems (Andrabi, Khoddam, & Leventhal, 2017; Barr, Silberg, Dick, & Maes, 2018), antisocial behavior (Tuvblad, Grann, & Lichtenstein, 2006), smoking (Shervin Assari, Mistry, Caldwell, & Bazargan, 2020; Purnaningrum, Joebagio, & Murti, 2017), aggressive behavior (Cabello, Gutiérrez-Cobo, & Fernández-Berrocal, 2017), substance use (Shervin Assari, Caldwell, & Bazargan, 2020; Gerra et al., 2020), behavioral problems (Hosokawa & Katsura, 2018), mental disorders (Holstein et al., 2021; Reiss, 2013), and problems in vocabulary and language skills (Richels, Johnson, Walden, & Conture, 2013). One cross-sectional study of 1,099 participants between 3 and 20 years old showed the effects of parents' years of education on many brain regions with implications for reading, language, executive functions, social cognition, and spatial skills (Noble et al., 2015).

Various SES indicators, particularly parental education, may have fewer effects for minorities, while family income may cause more equal outcomes across racial groups (Shervin Assari et al., 2019). People of color with high education are much more likely to be discriminated against in the workspace and job market (S. Assari, 2018). As a result, they make less money, and have lower incomes than non-White families (Shervin Assari, 2020a). When income reaches the family's pocket, a great number of environmental and structural obstacles have already been overcome. Thus, income may generate equal outcomes across different racial and ethnic groups (Shervin Assari & Boyce, 2021).

Neuroanatomical changes bear the hallmarks of experience-based events (Hagadorn, Johnson, Smith, Seid, & Kapheim, 2021). To the best of our knowledge, many studies to date have established a link between SES indicators and brain structures, including cortical volume (Kim et al., 2019; Lawson et al., 2017). Volumetric indicators of the cerebral cortex are implicated in the development of some problems, such as pediatric anxiety (Gold et al., 2017), obstructive sleep apnea (Philby et al., 2017), obesity (Esteban-Cornejo et al., 2017), chronic stress (Merz et al., 2019), ADHD (Boedhoe et al., 2020), and major depressive disorder (Murphy et al., 2020). However, surprisingly little is known about whether SES indicators, such as parental education and household income, influence the volumetric aspects of the right and left parahippocampus. Cortical volume represents a composite score of cortical thickness and cortical surface area. These two brain properties are evolutionarily and developmentally distinct (Raznahan et al., 2011). Thus, there is a need to investigate determinants of cortical thickness separately from cortical volume and area. **Additionally**, there is a need to examine racial differences in the associations between parental education and household income on the parahippocampal cortical thickness. To respond to the existing gap in the literature, we have decided to examine the links between parental education and household income with right and left parahippocampal cortical thickness in children.

Most existing studies on the link between SES and structural and functional development of the brain have assumed that one-size-fits-all. These studies only report the overall effects of SES on the population as a whole (Dubois & Adolphs, 2016; Kim et al., 2019; Lawson et al., 2017; Noble, Houston, Kan, & Sowell, 2012). They do not report whether racial groups are different or similar in the effects of parental education and household income on children's parahippocampal cortical thickness. In addition, the majority of sMRI studies have focused on the additive influences of race/ethnicity and SES, rather than their multiplicative effects. This is important because SES indicators and race/ethnicity are thought to overlap as they are both proxies of stress, trauma, and adversities (Evans et al., 2016; Javanbakht et al., 2016; Javanbakht et al., 2015). Despite knowing about the additive effects of SES and race on brain structure and function (Javanbakht et al., 2016; Javanbakht et al., 2015), some research suggests that SES indicators tend to show diminished effects on the brain development of Black compared to White children (Shervin Assari, Boyce, & Bazargan, 2020b; Dotson, Kitner-Triolo, Evans, & Zonderman, 2009).

According to the Marginalization-related Diminished Returns (MDRs) framework (Shervin Assari, 2018, 2020b), SES indicators, especially parental education, may produce fewer beneficial influences on developmental, behavioral, and health outcomes for racial minority families because of discrimination, racism, stratification, and marginalization (Shervin Assari & Boyce, 2021). Such MDRs may be more relevant to parental education than family income, as multiple studies have shown that parental education effects on depression (Shervin Assari & Caldwell, 2018), attention (Shervin Assari, Boyce, & Bazargan, 2020a), impulse control (S. Assari, C. H. Caldwell, & M. A. Zimmerman, 2018), social and behavioral problems (Shervin Assari, Boyce, Caldwell, & Bazargan, 2020; Boyce, Bazargan, Caldwell, Zimmerman, & Assari, 2020), inhibitory control (Shervin Assari & Islam, 2020), suicidality (Shervin Assari, Boyce, Bazargan, et al., 2020a), anxiety (S. Assari & Jeremiah, 2018), and attention deficit hyperactivity disorder (ADHD) (Shervin Assari & Cleopatra Howard Caldwell, 2019) are weaker for Black than White children. As a result of these MDRs, there are residual risks and sustained disparities in behavior and development in Black families with high SES, partly because Black families are treated differently across SES levels (Noble et al., 2015). However, to our knowledge, there are no previous studies examining the effects of parental education and household income on parahippocampal cortical thickness using the MDRs framework.

1.1 Aims

This study accessed data from the Adolescent Brain Cognitive Development research (ABCD) (Casey et al., 2018; Karcher, O'Brien, Kandala, & Barch, 2019; Lisdahl et al., 2018; Luciana et al., 2018; Research

& Staff, 2018) to explore racial variations for the effects of parental education and household income on both the right and the left side of parahippocampal cortical thickness in 9 to 10-year-old pre-adolescents. We tested additive and multiplicative effects of race, parental education, and household income on parahippocampal thickness. Also, in agreement with the MDRs literature (Shervin Assari, Boyce, Bazargan, et al., 2020b; Boyce et al., 2020), we hypothesized that parental education would have a weaker effect on parahippocampal thickness for Black and other racial minority pre-adolescents compared to White pre-adolescents. This means that we expect pre-adolescents' parahippocampal cortical thickness to remain similar in Black pre-adolescents with low and high parental education, whereas the difference in parahippocampal cortical thickness is expected to be large between low and high parental education for White pre-adolescents. However, for family income, we expect similar effects for White and Black pre-youth (no MDRs are expected for family income).

2. Methods

2.1 Design and Settings

This secondary cross-sectional data analysis was based on the Adolescent Brain Cognitive Development (ABCD) study (Casey et al., 2018; Karcher et al., 2019; Lisdahl et al., 2020; Luciana et al., 2018; Research & Staff, 2018), which is a study examining children's brain development. The ABCD study collected a wealth of data on SES, sex, and racial and ethnic diversity in the US (Auchter et al., 2018; Research & Staff, 2018). We will briefly review some critical aspects of the study (Auchter et al., 2018).

2.2 Participants and Sampling

The ABCD study participants were 9 to 10-year-old pre-adolescents selected from 21 cities across different states, encompassing over 20% of the total US population of 9 and10-year-old children (Auchter et al., 2018; Garavan et al., 2018). The study participants were selected from schools that met specific sex, race, ethnicity, SES, and urbanicity criteria. These recruitment processes were precisely designed, implemented, and evaluated across the 21 study sites (Ewing, Bjork, & Luciana, 2018). Despite the fact that the ABCD sample is not representative or random, the careful sampling employed makes the sample a near estimation of the population of U.S. children over sociodemographic and demographic factors. The results, therefore, are reliable regarding age, SES, ethnicity, sex, and urbanicity. A more detailed description of the sampling procedure can be found in Garavan et al. (2018)'s paper.

Analytical sample:

The participants consisted of 9849 children aged 9 to 10-years-old, and could be included regardless of race, ethnicity, and the presence or absence of psychopathology (Garavan et al., 2018). Participant eligibility was determined by having complete data and meeting imaging quality for T1 images.

2.3 Process

Brain Imaging:

Structural MRI (sMRI) modality was used to estimate right and left parahippocampal cortical thickness. Brain imaging in the ABCD study was based on three 3 tesla (T) scanner platforms: Philips Healthcare, GE Healthcare, and Siemens Healthcare (Hagler Jr et al., 2019). T1-weighted and T2-weighted brain images, carefully harmonized, were drawn from the MRI devices (Casey et al., 2018). In order to reduce bias due to variation in imaging sites, the weighted brain images were corrected for gradient non-linearity distortions (Jovicich et al., 2006). These available pre-processed structural data are calculated based on T1- and T2-weighted images that maximize mutual information's relative position and orientation across images (Wells III, Viola, Atsumi, Nakajima, & Kikinis, 1996). By using tissue segmentation and sparse spatial smoothing, the ABCD study performed intensity non-uniformity correction.

Moreover, images have been resampled with 1-mm isotropic voxels into rigid alignment within the brain atlas.Using FreeSurfer software, version 5.3.0 (Harvard University), these volumetric measures were constructed. Images have also undergone surface optimization (Fischl & Dale, 2000; Fischl, Sereno, & Dale, 1999) and nonlinear registration to a spherical surface-based atlas (Fischl et al., 1999).

2.4 Study Variables

The study included parental education and household income as independent variables, race as the moderator, ethnicity, age, sex, family structure as cofounders, and right and left parahippocampal cortical thickness as the dependent variables.

Independent Variables:

Parental Educational Attainment: Parental education was defined as a five-level nominal variable: less than high school diploma, high school diploma/GED, some college, bachelors' degree, and graduate studies. Less than a high school diploma was the reference group.

Household Income: Parents reported their total highest annual income (before taxes and deductions), including income from all sources, such as social security, wages, rent from properties, disability, veteran's benefits, and unemployment benefits. Furthermore, household income was defined as a 3-level nominal variable: less than 50 thousand dollars, 50-100 thousand dollars, and more than 100 thousand dollars. Thus, less than 50 thousand was the reference group.

Dependent variables:

Right and Left Parahippocampal Cortical Thickness: The outcomes were the right and left children's parahippocampal cortical thickness (mm), measured by sMRI at rest (T1). Our outcome had a normal distribution (**Appendix Figure**).

Moderators:

Race. Race was reported by the parent and was treated as a nominal variable: Black, Asian, Other/Mixed, and White (reference group).

Confounders:

Age. Age was a continuous variable. Parents reported their child's age in months.

Sex. A categorical variable with 1 for boys and 0 for girls.

Ethnicity. A dichotomous variable coded as Latino = 1 and non-Latino = 0

Parental Marital Status. Another dichotomous variable, self-reported by the parent interviewed, and coded 1 vs. 0 for married and unmarried (any other condition).

2.5 Data Analysis

Using Data Exploration and Analysis Portal (DEAP), which uses R and is a user-friendly online platform for multivariable analysis of the ABCD data, we reported the mean (standard deviation (S.D.)) and frequency (%) depending on the variable type. We also performed ANOVA and Chi-square to explore bivariate relations between racial groups. Linear regression in DEAP is based on mixed-effect models; given participants are nested to families and families are nested to sites. The primary outcome was the children's parahippocampal cortical thickness. The independent variables were parental education and household income. Race was the moderator. Age, sex, family marital status, and ethnicity were the covariates. To run multivariable analyses, three mixed-effects regression models were run for each outcome (**Appendix**). *Model 1* tested the additive effects of household income, parental education, and race, with all the covariates, without interaction terms. *Model 2* included the interaction terms between parental education and race on the right and left parahippocampal cortical thickness. *Finally, model 3* included the interaction terms between household income and race on the right and left parahippocampal cortical thickness. Also, coefficients (b), SEs, and p-values were reported from our regressions. Moreover, we checked the normal distribution of our outcomes, lack of collinearity between predictors, and the distribution of errors for our model (**Appendix**). **Figure appendix** shows the distribution of our variables and mixed-effects regression assumptions. **Box appendix** shows our models.

2.6 Ethical Aspect

While the original ABCD research protocol went through an Institutional Review Board (IRB) in several institutions, including the University of California, San Diego (UCSD), our analysis was found to be exempt from further IRB review by the Charles R Drew University of Medicine and Science (CDU). The study protocol was also approved by the IRB in several institutions. Furthermore, all children were asked for their assent, and parents signed the consent form (Auchter et al., 2018).

3. Results

3.1 Sample Descriptive Data

This study included 9,849 children aged 9 to 10 years old. Of those children, 5,124 (52.0%) were male and 4,725 (48.0%) were female. 6,604 (67.1%) of these children were White, 1,403 (14.2%) Black, 213 (2.2%) Asian American, and 1,629 (16.5%) other/mixed race. The right and the left parahippocampal cortical thickness were significantly different across racial groups. Black and other/mixed race participants showed the lowest parental education, respectively, compared to White children. Income was also notably lower in Black and other/mixed race families in comparison to White and Asian American families (**Table 1**).

Table 1. Descriptive Characteristics Overall and by Race (n = 9849)

Level	Overall	All	White	Black	Asian	Other/Mixed	p
N		9849	6604	1403	213	1629	
		Mean(SD)	**Mean(SD)**	**Mean(SD)**	**Mean(SD)**	**Mean(SD)**	
Age (Months)		119.07 (7.50)	119.14 (7.52)	119.00 (7.26)	119.53 (7.96)	118.82 (7.56)	0.349
Right Parahippocampus(mm)		2.95 (0.24)	2.98 (0.24)	2.86 (0.23)	2.85 (0.25)	2.93 (0.24)	< 0.001
Left Parahippocampus(mm)		3.00 (0.28)	3.03 (0.28)	2.89 (0.26)	2.91 (0.29)	2.98 (0.28)	<0.001
		n(%)	**n(%)**	**n(%)**	**n(%)**	**n(%)**	
Parental Education	< HS Diploma	358 (3.6)	137 (2.1)	111 (7.9)	5 (2.3)	105 (6.4)	< 0.001
	HS Diploma/GED	809 (8.2)	312 (4.7)	319 (22.7)	3 (1.4)	175 (10.7)	
	Some College	2519 (25.6)	1399 (21.2)	553 (39.4)	18 (8.5)	549 (33.7)	
	Bachelor	2615 (26.6)	1972 (29.9)	209 (14.9)	54 (25.4)	380 (23.3)	
	Post Graduate Degree	3548 (36.0)	2784 (42.2)	211 (15.0)	133 (62.4)	420 (25.8)	
Hispanic Ethnicity	No	7984 (81.1)	5481 (83.0)	1333 (95.0)	193 (90.6)	977 (60.0)	< 0.001
	Yes	1865 (18.9)	1123 (17.0)	70 (5.0)	20 (9.4)	652 (40.0)	
Sex	Female	4725 (48.0)	3126 (47.3)	698 (49.8)	107 (50.2)	794 (48.7)	0.299
	Male	5124 (52.0)	3478 (52.7)	705 (50.2)	106 (49.8)	835 (51.3)	
Household Income	< 50K	2799 (28.4)	1205 (18.2)	923 (65.8)	31 (14.6)	640 (39.3)	< 0.001
	> =50K & < 100K	2828 (28.7)	2009 (30.4)	313 (22.3)	52 (24.4)	454 (27.9)	
	> =100K	4222 (42.9)	3390 (51.3)	167 (11.9)	130 (61.0)	535 (32.8)	
Married Family	No	2956 (30.0)	1338 (20.3)	982 (70.0)	32 (15.0)	604 (37.1)	< 0.001
	Yes	6893 (70.0)	5266 (79.7)	421 (30.0)	181 (85.0)	1025 (62.9)	

Notes: Source: Adolescent Brain Cognitive Development (ABCD) Study; * Chi-square test; ** Analysis of Variance (ANOVA)

Table 2 summarizes the mixed-effects regression models' fit statistics performed in the total sample. Our models showed a better fit when we included interactions between parental education and race on the parahippocampus, compared to main effects models or models that included the interactions between income and race.

Table 2. Effect Sizes and % Variance Explained

	Right			Left		
		Education	Income		Education	Income
	Main Effect	Interaction Effect	Interaction Effect	Main Effect	Interaction Effect	Interaction Effect
N	9849	9849	9849	9849	9849	9849
R-squared	0.051	0.053	0.048	0.046	0.052	0.047
ΔR-squared	9e-04	0.025	0.021	0.001	0.024	0.020
ΔR-squared (%)	0.09%	2.52%	2.18%	0.13%	2.42%	2.09%

3.2 Main Effects

As shown by **Table 3** and **Figure 2**, when all confounders were controlled, household income showed protective effects on the right parahippocampal cortical thickness. These effects were significant for household income of between 50K and 100K (*b = 0.0175; p = 0.0209*), as well as income above 100K (*b = 0.0189; p = 0.0271*). However, there was no association between parental education and the right parahippocampal cortical thickness when household income was controlled. For the left parahippocampal cortical thickness, parental education had a stepwise (dosage-dependent) interaction for high school diploma/ GED (*b = 0.0312; p = 0.0779*), some collage (*b = 0.0498; p = 0.0021*), bachelor (*b = 0.0434; p = 0.0118*) and graduate degree (*b = 0.0548; p = 0.0016*). Moreover, household income over 100 K had a significant association on the right parahippocampal cortical thickness (*b = 0.0264; p = 0.0076*).

Table 3. Mixed-effects Regressions in the Overall Sample with Right and Left Parahippocampal Cortical Thickness as the Outcomes

	Right			Left		
	b	SE	p	B	SE	p
Parental Education (HS Diploma/GED)	-0.001	0.015	0.933	0.031#	0.018	0.078
Parental Education (Some College)	0.009	0.014	0.500	0.050**	0.016	0.002
Parental education (Bachelor)	0.005	0.015	0.762	0.043*	0.017	0.012
Parental education (Graduate Degree)	0.021	0.015	0.156	0.055**	0.017	0.002
Race (Black)	-0.104***	0.008	< 1e-6	-0.109***	0.010	< 1e-6
Race (Asian)	-0.136***	0.017	< 1e-6	-0.143***	0.020	< 1e-6
Race (Other/Mixed)	-0.038***	0.007	< 1e-6	-0.047***	0.008	< 1e-6
Hispanic	-0.018*	0.008	0.019	-0.021*	0.009	0.017
Sex	-0.064***	0.005	< 1e-6	-0.063***	0.005	< 1e-6
Age	-0.001*	0.000	0.020	-0.002***	0.000	3.23e-05
Household Income (> =100K)	0.019*	0.009	0.027	0.026**	0.010	0.008

Household Income (> =50K& < 100K)	0.018*	0.008	0.021	0.013	0.009	0.156
Married Family	0.007	0.006	0.294	0.011	0.007	0.129

Outcomes: right and left parahippocampal cortical thickness. #p < 0.1, *p < 0.05, **p < 0.01, ***p < 0.001

3.3 Interactive Effects

As **Table 4** and **Figure 1** show, *Model 2* found interactions between parental education and race on right and left parahippocampal cortical thickness. For the right parahippocampal cortical thickness side, we observed significant interaction when we considered the effects of bachelor and Black (*b = -0.07068, p = 0.0462*), high school diploma/GED and Asian (*b = -0.32999, p = 0.0532*), some college and Asian (*b = -0.22133, p = 0.0620*), and post graduate degree and Asian (*b = -0.18036, p = 0.0921*). Furthermore, we found significant interaction of bachelor and Black *(b = -0.08125, p = 0.0483*), some collage and other race (*b = -0.07337, p = 0.0533*), bachelor and other race (*b = -0.06880, p = 0.0750*), and post graduate degree and other race (*b = -0.07921, p = 0.0382*) on the left parahippocampal cortical thickness side. These suggest that the association between parental education and parahippocampal cortical thickness was diminished for Black, Asian and other race, as compared to White children (**Figure 1**).

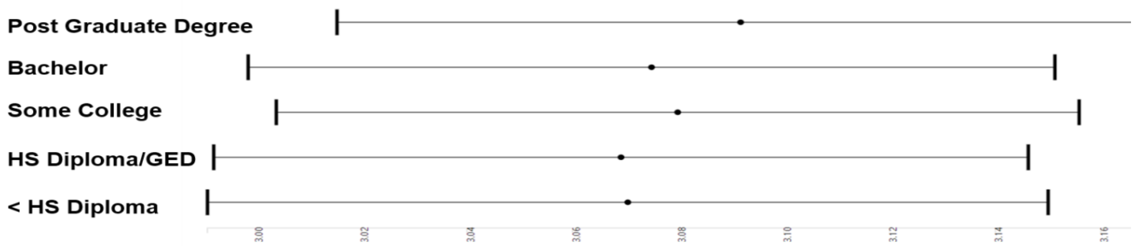
Table 4. Mixed-effects Regressions on the Effects of Parental Education and Race on the Right and Left Parahippocampus

	Right			**Left**		
	b	**SE**	**p**	**b**	**SE**	**p**
Parental Education (High school Diploma/GED)	0.005	0.024	0.853	0.052#	0.028	0.069
Parental Education (Some College)	0.033	0.022	0.129	0.091***	0.025	0.000
Parental education (Bachelor)	0.034	0.022	0.130	0.084**	0.026	0.001
Parental education (Graduate Degree)	0.044*	0.022	0.049	0.091***	0.026	0.000
Race (Black)	-0.073*	0.031	0.019	-0.062#	0.036	0.084
Race (Asian)	0.044	0.105	0.679	0.012	0.122	0.923
Race (Other/Mixed)	-0.001	0.030	0.961	0.019	0.035	0.596
Hispanic	-0.017*	0.008	0.025	-0.020*	0.009	0.022
Sex	-0.064***	0.005	< 1e-6	-0.063***	0.005	<1e-6
Age	-0.001*	0.000	0.022	-0.002***	0.000	3.66e-05
Household Income (> =100K)	0.018*	0.009	0.034	0.025*	0.010	0.012
Household Income (> =50K& < 100K)	0.017*	0.008	0.022	0.011	0.009	0.220
Married Family	0.007	0.006	0.277	0.012	0.007	0.117
Parental Education (HS Diploma/GED) × Race (Black)	-0.020	0.036	0.581	-0.029	0.042	0.485
Parental Education (Some College) × Race (Black)	-0.025	0.033	0.443	-0.060	0.038	0.115
Parental Education (Bachelor) × Race (Black)	-0.071*	0.035	0.046	-0.081*	0.041	0.048

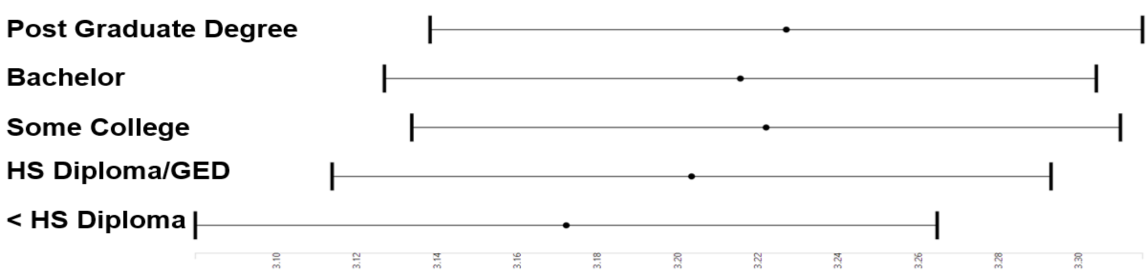
Parental Education (Post Graduate Degree) × Race (Black)	-0.009	0.035	0.792	-0.002	0.041	0.967
Parental Education (HS Diploma/GED) × Race (Asian)	-0.330#	0.171	0.053	-0.160	0.198	0.419
Parental Education (Some College) × Race (Asian)	-0.221#	0.119	0.062	-0.121	0.137	0.378
Parental Education (Bachelor) × Race (Asian)	-0.172	0.110	0.117	-0.148	0.127	0.245
Parental Education (Post Graduate Degree) × Race (Asian)	-0.180#	0.107	0.092	-0.168	0.124	0.175
Parental Education (HS Diploma/GED) × Race (Other/Mixed)	0.025	0.038	0.511	-0.025	0.044	0.567
Parental Education (Some College) × Race (Other/Mixed)	-0.043	0.033	0.184	-0.073#	0.038	0.053
Parental Education (Bachelor) × Race (Other/Mixed)	-0.054	0.033	0.104	-0.069#	0.039	0.075
Parental Education (Post Graduate Degree) × Race (Other/Mixed)	-0.037	0.033	0.257	-0.079*	0.038	0.038

Notes: Source: ABCD Study; Mixed-effects regression model is used; All covariates such as race, ethnicity, age, sex, income, family, and site were controlled

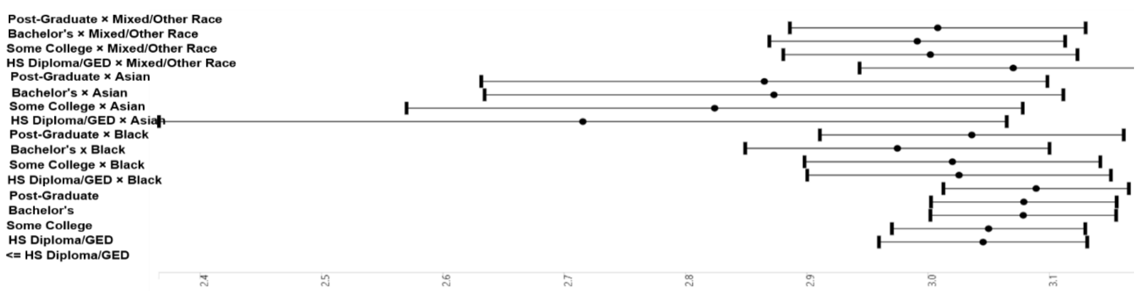
#$p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$



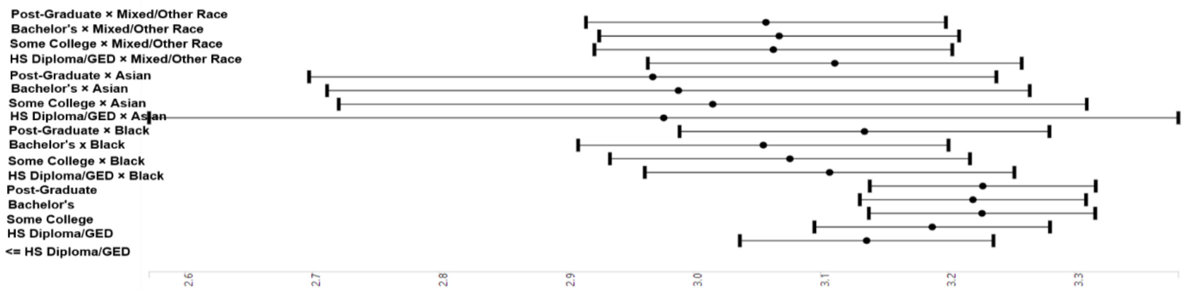
(a) right, overall



(b) left, overall



(c) right, by race



(d) left, by race

Figure 1. Effects of Parental Education on the Right and Left Parahippocampal Cortical Thickness Overall and by Race

As shown in **Table 5** and **Figure 2**, being Black did not change the effects of household income on the left and right parahippocampal cortical thickness, although being Asian American interacted with household income (*b = -0.12438, p = 0.0245*).

Table 5. Mixed-effects Regressions on the Effects of Household Income and Race on the Right and the Left Parahippocampus

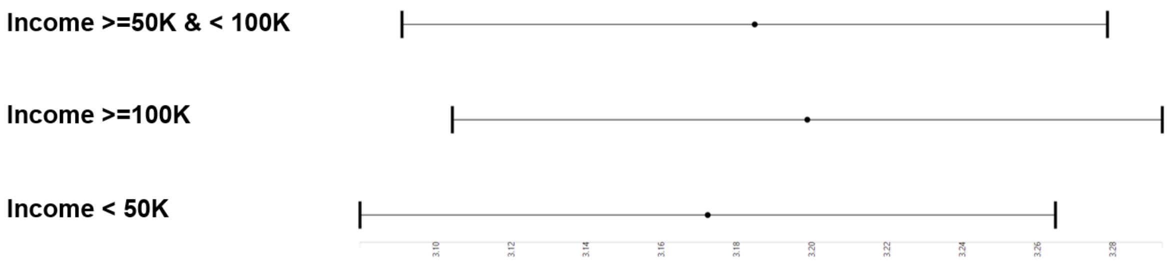
	Right			Left		
	b	**SE**	**p**	**b**	**SE**	**p**
Household Income [> =100K]	0.026**	0.010	0.009	0.028*	0.011	0.015
Household Income [> =50K& < 100K]	0.024*	0.009	0.010	0.012	0.011	0.289
Race (Black)	-0.095***	0.011	< 1e-6	-0.112***	0.013	< 1e-6
Race (Asian)	-0.085*	0.043	0.049	-0.045	0.050	0.372
Race (Other/Mixed)	-0.030*	0.012	0.012	-0.048***	0.014	0.000
Hispanic	-0.017*	0.008	0.022	-0.022*	0.009	0.014
Sex	-0.064***	0.005	< 1e-6	-0.063***	0.005	< 1e-6
Age	-0.001*	0.000	0.021	-0.002***	0.000	3.53e-05
Parental Education (HS Diploma/GED)	-0.001	0.015	0.937	0.032#	0.018	0.074
Parental Education (Some College)	0.010	0.014	0.470	0.049**	0.016	0.002
Parental Education (Bachelor)	0.005	0.015	0.745	0.042*	0.017	0.014
Parental Education (Post Graduate Degree)	0.022	0.015	0.149	0.054**	0.017	0.002
Married Family	0.007	0.006	0.310	0.011	0.007	0.154
Household Income (> =100K) × Race (Black)	0.002	0.022	0.931	0.020	0.025	0.433
Household Income (> =50K& < 100K) × Race (Black)	-0.028	0.018	0.126	0.001	0.021	0.954
Household Income (> =100K) × Race (Asian)	-0.067	0.048	0.159	-0.124*	0.055	0.025
Household Income (> =50K& < 100K) × Race (Asian)	-0.045	0.054	0.406	-0.094	0.063	0.132

Household Income (> =100K) × Race (Other/Mixed)	-0.017	0.016	0.292	-0.003	0.019	0.879
Household Income (> =50K& < 100K) × Race (Other/Mixed)	-0.004	0.017	0.833	0.010	0.020	0.625

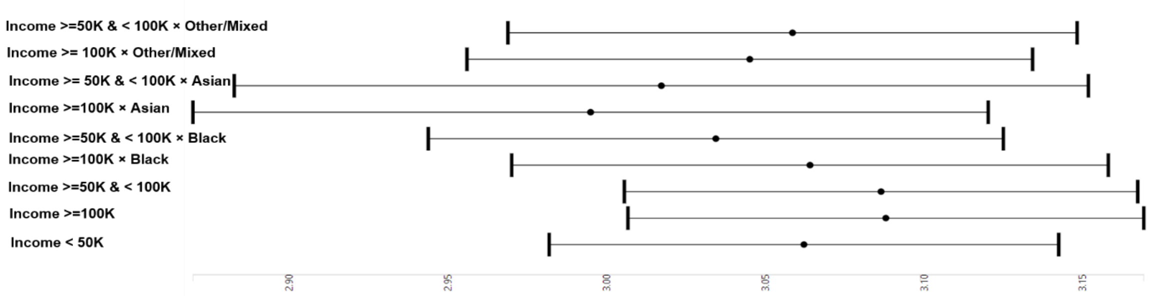
Notes: Source: ABCD Study; Mixed-effects regression model is used; All covariates such as race, ethnicity, age, sex, income, family, and site were controlled

#$p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

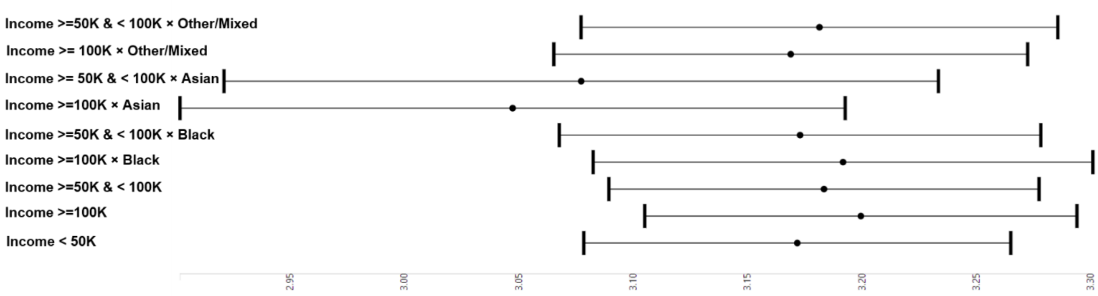
(a) right parahippocampal cortical thickness, overall



(b) left parahippocampal cortical thickness, overall



(c) right parahippocampal cortical thickness, by race



(d) left parahippocampal cortical thickness, by race

Figure 2. Effects of Household Income on the Right and Left Parahippocampal Cortical Thickness Overall and by Race

4. Discussion

In line with the MDRs, there were racial differences in the associations between high parental education and right and left parahippocampal cortical thickness. The correlation between higher parental education with right and left parahippocampal cortical thickness was larger for White children than Black children. The same pattern was not found for household income.

As mentioned, the majority of neuroimaging studies have shown that SES indicators, such as parental education and household income, have a link with brain structure and function in adolescents and young people, such as the hippocampus, cerebral cortex, thalamus, and amygdala (Hanson, Chandra, Wolfe, & Pollak, 2011; Jednoróg et al., 2012; Lawson, Duda, Avants, Wu, & Farah, 2013; Noble et al., 2012). For example, one study with participants aged 5 to18 years old indicated an association between SES and gray matter volume in the hippocampus and amygdala (Noble et al., 2012). In a cross-sectional study, 1,099 individuals aged 3 to20 years old showed the steepest correlation between parental education and the children's left hippocampal volume when parental education was at lower levels, indicating that socioeconomic disparities may be most apparent in children of less educated parents (Noble et al., 2015). Moreover, Noble and colleagues also found a strong relationship between the number of years of parental education and larger cortical surface area in many brain regions involved in language, reading, social cognition, executive functions, and spatial skills (Noble et al., 2015). Conversely, no associations were found between parental education and right hippocampal volume, and none between income and either right or left hippocampal volumes (Noble et al., 2015). In contrast, Hanson et al. have found correlations between parental education and right hippocampal size (Hanson et al., 2011). Another study of pre-adolescents aged 12 and 13 years old, undergoing fMRI while passively looking at emotional faces, revealed a negative interaction between SES (measured by household income and parental education) and activity in both the amygdala and the dorsomedial PFC whilst viewing angry faces (Muscatell et al., 2012). However, very few studies to date have been conducted on the relations between parental education and household income with parahippocampal cortical thickness.

It is necessary to characterize the mechanisms through which parental education affects brain development. Parental education is, in fact, correlated with brain structure due to being proxies of lower levels of risk-taking behavior in parents (Spann et al., 2014), high-quality parenting (Anton, Jones, & Youngstrom, 2015; Woods-Jaeger, Cho, Sexton, Slagel, & Goggin, 2018), and lower stress across numerous domains (Parkes, Sweeting, & Wight, 2015). As such, parenting and parental behaviors can have an important effect on the brain development of children and adolescents (Shervin Assari & Bazargan, 2019a). Indeed, both parental education and household income are considered as a social environment that leads to a child's development. Consequently, both parenting and SES are particularly important to take into account when considering pre-adolescent brain development; several studies have consistently demonstrated that both parenting and SES have long-term protective benefits against problem behaviors (Choi, Wang, & Jackson, 2019), psychopathologies (Padilla-Moledo, Ruiz, & Castro-Piñero, 2016), and poor cognitive performance (Shervin Assari, Boyce, Bazargan, et al., 2020b;

Shervin Assari & Cleopatra H Caldwell, 2019). Moreover, resource scarcity may have resulted in lower SES in the families, which continue to restrict their healthy brain development.

In line with the MDRs, our findings confirmed that parental education is more likely to have a weaker effect on numerous health outcomes in racial minorities compared to White individuals. Some studies also provide evidence for mechanisms described in the MDRs framework, such as social and behavioral problems (Shervin Assari & Boyce, 2020), attention (Shervin Assari, Boyce, & Bazargan, 2020a), impulsivity and inhibitory control (Shervin Assari, Caldwell, & Mincy, 2018), ADHD (Shervin Assari & Cleopatra Howard Caldwell, 2019), anxiety (Shervin Assari, Cleopatra Howard Caldwell, & Marc A Zimmerman, 2018), depression (Shervin Assari, Gibbons, & Simons, 2018), and suicidality (Shervin Assari, Boyce, Bazargan, et al., 2020a) in Black adolescents.

As previously noted, parental education and race have multiplicative effects on parahippocampal cortical thickness. It was found that Black pre-adolescents, regardless of their SES, are more likely to remain at high risk. Conversely, high parental education reduces the risk in White pre-adolescents. Several MRI and behavioral studies, for example, provide evidence that the parahippocampus is commonly linked to attention deficit hyperactivity disorder (ADHD) (Puiu et al., 2018), intermittent explosive disorder (Puiu et al., 2018), emotional disorder (Schmahmann, 2021), bipolar disorder, depression (Poletti et al., 2019), autism (Pereira et al., 2018), schizotypal disorder (Takayanagi et al., 2020), motor neuron disease (Machts et al., 2021), functional neurological disorders (Williams et al., 2018), memory (Brehmer, Nilsson, Berggren, Schmiedek, & Lövdén, 2020; Kumar, Singh, & Paddakanya, 2021), and executive function (Weise, Bachmann, Schroeter, & Saur, 2019).

Evidently, several questions should be further addressed in future studies, particularly regarding the specific brain structures and functions affected by SES and race, to draw together the currently disparate findings involving a number of brain regions. First, it is crucial for future research to explore societal conditions where parental education is strongly associated with pre-adolescent parahippocampal cortical thickness in Black families. This may provide useful insights into the roles that policymakers, administrators, providers, and authority may play in strengthening infrastructure to reduce racial discrimination. To equalize SES and the marginal returns of SES, appropriate social and economic policies should be developed to address the racial inequalities in brain development. This investigation may help policymakers in equitably promoting brain health for all people. The elaboration of effective strategies requires an understanding and consideration of some underlying mechanisms. First, equity will be achieved by closing the SES-based issues gaps across racial groups. Second, social justice promoting activities can aid policymakers in equalizing the returns of SES in different racial minorities.

Our work documented a significant risk for Black pre-adolescents with both high and low SES background. Consequently, low SES and high SES seemed to play more salient roles as risk and protective factors, respectively, for White pre-adolescents. Yet, Black pre-adolescents from both low and high SES families are more likely to remain at high risk, as documented here in terms of parahippocampal cortical thickness. Environmental aspects, not biological aspects, of race might lead

Black families to barely get even the smallest protective effects of SES – a result of race-related stressors, such as segregation, racism, discrimination, and blocked opportunities. This is consistent with previous studies that have demonstrated that racial discrimination, stress, trauma, and adversities are all strongly associated with brain regions, and functions of Black individuals across all SES levels (Clark, Miller, & Hegde, 2018; Moadab, Bliss-Moreau, Bauman, & Amaral, 2017; Thames et al., 2018).

Our findings showed MDRs for household income but not family income. Income may best represent the material resources available to children, while parental education may be more important in shaping parent-child interactions. Income may be more robust to MDRs, while parental education may be sensitive to it.

Evidently, social determinants, race, and parental education may have multiplicative effects on children's brain development. Thus, we should not overestimate the effects of our policies that exclusively focus on SES. Our findings also reveal the necessity for policy interventions beyond equalizing SES for Black families. Hence, prevention and intervention programs should focus on issues aiming to alleviate the risk and promote the brain development of middle-class Black pre-adolescents. Furthermore, if we can implement interventions like early childhood programs and after-school programs, we will be able to more effectively promote the brain development of underserved communities (Gershoff, Ansari, Purtell, & Sexton, 2016; Neville et al., 2013). In principle, multi-level economic and social policies are needed to reduce the structural and environmental adversities in Black families' lives across all SES levels.

Race as a social determinant, but not a biological factor, has also been conceptualized in all the MDRs literature on pre-adolescents' brain development. Subsequently, racial differences reported here have resulted from the differential treatment of society, but not genes. Here, we consider race as a consequence of racism, including labor market discrimination, low school quality, segregation, and differential policing, all of which lead to a decrease in the effects of parental education, even for people with access to economic and human resources. In other words, this outlook did not consider race as an innate, unchangeable biological marker of brain structure and function (Herrnstein & Murray, 2010).

5. Limitations

Some limitations of our study should be taken into consideration before our findings are interpreted. First, strong causal conclusions concerning brain development are limited in cross-sectional studies. Longitudinal studies will be necessary to fully understand how parental education, household income, and race are linked with changes in, and trajectories of, the parahippocampal cortex. Second, many SES indicators that may play a critical role in changing brain structures, such as the wealth and occupational status of parents, were not included here. Neighborhood-level SES indicators, such as home value, residential-area income, and area-level education level, were also not included; all of our SES indicators were assessed at the family level. In principle, the results may be different if we had included other variables. Third, our sample was not random. Thus, the results may not be representative and generalizable. Fourth, a wide range of relevant functional and structural features of brain structure, including surface area, regional subcortical volumes, size, diffusivity, and density, were not assessed here. These are all key, open questions concerning the extent to which SES factors are associated with brain development across racial groups. Fifth, the sample size was imbalanced, and a large percentage of the sample was White, with less than 20% being Black.

6. Conclusions

Parental education shows a stronger link with parahippocampal cortical thickness for White than for Black American pre-adolescents. This variation may be, in part, due to differences in the living experiences of Black and White middle-class families – a finding that is in line with the Marginalization-related Diminished Returns (MDRs). It is crucial for future research to examine how racism, social stratification, and segregation reduce the effects of parental education on the brain development of children in Black communities, as compared to their White counterparts. Lastly, it is unknown which social processes reduce the benefits of SES indicators in Black communities.

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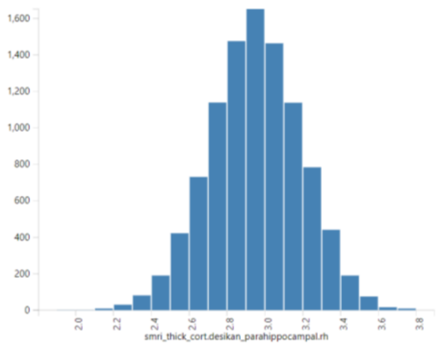
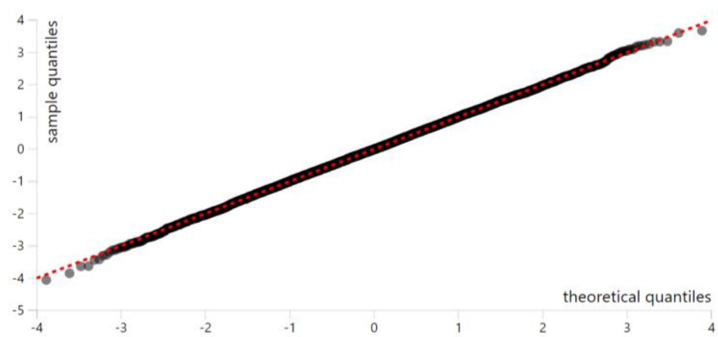


(a) outcome, right



(b) quantiles, right

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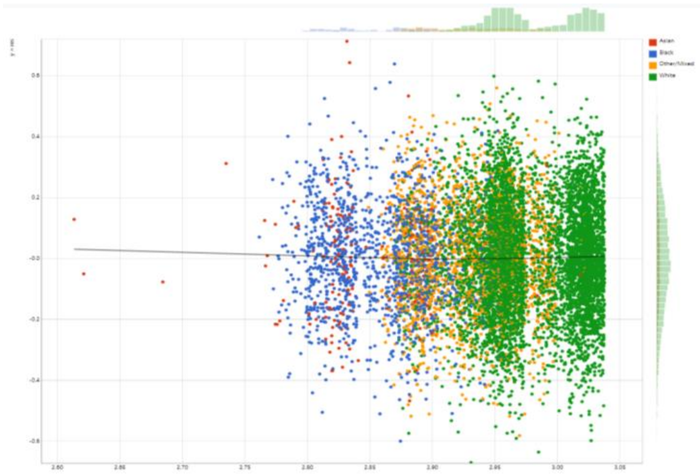
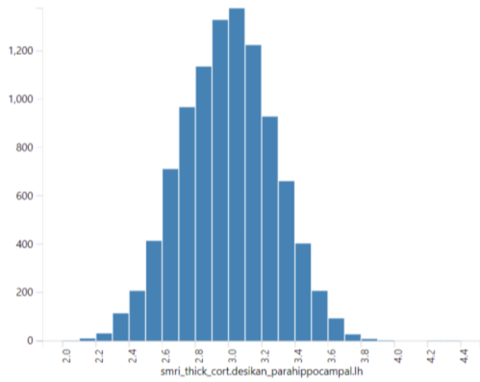


(c) error terms, right



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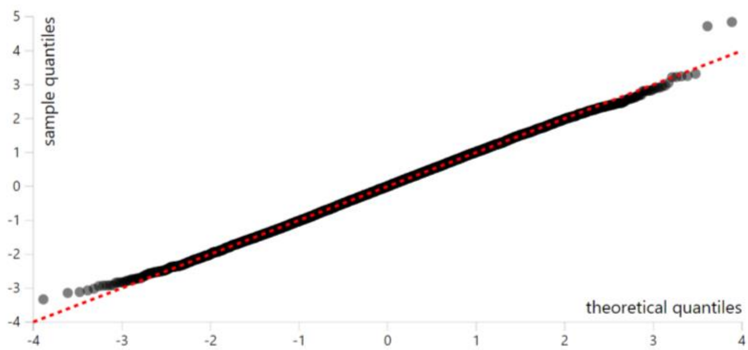

+

(b) quantiles, left

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(c) error terms, left

Supplementary Figure 1. Description of distributions and model error terms for right and left hemispheres

Supplementary Table 1. Model formula in DEAP

Right	Left
Model 1 smri_thick_cort.desikan_parahippocampal.rh ~ high.educ.bl + race.4level + hisp + sex + age + household.income.bl + married.bl	**Model 1** smri_thick_cort.desikan_parahippocampal.lh ~ high.educ.bl + race.4level + hisp + sex + age + household.income.bl + married.bl
Model 2 smri_thick_cort.desikan_parahippocampal.rh ~ high.educ.bl + race.4level + hisp + sex + age + household.income.bl + married.bl + high.educ.bl * race.4level	**Model 2** smri_thick_cort.desikan_parahippocampal.lh ~ high.educ.bl + race.4level + hisp + sex + age + household.income.bl + married.bl + high.educ.bl * race.4level
Model 3 smri_thick_cort.desikan_parahippocampal.rh ~ high.educ.bl + race.4level + hisp + sex + age + household.income.bl + married.bl + household.income.bl * race.4level	**Model 3** smri_thick_cort.desikan_parahippocampal.lh ~ high.educ.bl + race.4level + hisp + sex + age + household.income.bl + married.bl + household.income.bl * race.4level