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Original Paper

Stronger Association between Nucleus Accumbens Density and Body Mass Index in Low-Income and African American Children

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Abstract

Background: *The nucleus accumbens' (NAc) size, function, and density influence individuals' body mass index (BMI). However, little is known about racial and socioeconomic status (SES) differences in the role of NAc density as a predictor of childhood BMI.* ***Objectives:*** *We used the Adolescent Brain Cognitive Development (ABCD) data to investigate racial and SES differences in the effect of NAc density on childhood BMI.* ***Methods:*** *This cross-sectional study included 9497 children between ages 9 and 10. Mixed-effects regression models were used to analyze the data. The predictor variable was NAc density measured using diffusion MRI (dMRI). The outcome variable was BMI, operationalized as a continuous variable. Covariates included sex, age, ethnicity, family structure, and parental education. Race (White, African American, Asian, and Other/mixed) and household income (< 50k, 50-100 k, and 100+ k) were the moderators.* ***Results:*** *High NAc diffusion tension (density) was predictive of higher BMI, net of covariates. However, the positive association between NAc density and BMI was stronger in African Americans than in White, and in low-income than in high-income children.* ***Conclusions:*** *Our findings suggest that although high NAc has implications for children's BMI, this effect varies across racial and SES groups. More research should be performed on the role of obesogenic environments in altering the effect of NAc on childhood BMI.*

Keywords

children, obesity, cortical thickness, body mass index

1. Background

High body mass index (BMI) is not randomly distributed throughout our society. High BMI is more common in African American and low socioeconomic status (SES) individuals than White and high SES people (Jones, 2018). African American children, particularly African American girls, have the highest BMI across all racial and ethnic groups (Jones, 2018). As high childhood, BMI is a predictor of poor health outcomes across domains, and as childhood BMI predicts the future health of adults, there is a need to understand the social and biological mechanisms that contribute to BMI inequalities across race and SES groups. Such research may help us eliminate racial and SES inequalities in childhood BMI, which itself is a contributing factor to health disparities later in life (Igel, Saunders, & Fins, 2018).

As SES and race predict the social and environmental contexts in which people live, it is important to explore racial and SES variations in the contributions of various risk and protective factors that shape BMI and obesity in children (Assari, Thomas, Caldwell, & Mincy, 2018). This is because the effects of race and SES are not limited to their direct and main effects but also their indirect effects through changing vulnerability to various risk and protective factors (Assari et al., 2018).

The development of high BMI and obesity also have neurological predictors that reflect susceptibility to binge eating and food-seeking behaviors (Aitken, Greenfield, & Wassum, 2016). That means brain structures and functions that distinguish obesity-prone individuals from other individuals may predict future obesity (Azzout-Marniche et al., 2016; Durst, Konczol, Balazsa, Eyre, & Toth, 2019). This is partly because brain structures such as the Nucleus accumbens (NAc) can reflect who would regulate urges for food-seeking behaviors, which is a known cause of obesity (Aitken et al., 2016). However, less is known about racial and SES differences in the implications of such brain structures (e.g., NAc) for children's BMI (Lowe, Reichelt, & Hall, 2019; Marqués-Iturria et al., 2013; Ronan, Alexander-Bloch, & Fletcher, 2020; Sharkey, Karama, & Dagher, 2015; Vainik et al., 2018).

Theoretically speaking, the salience of the NAc on childhood BMI may vary across populations (Lowe et al., 2019; Marqués-Iturria et al., 2013; Ronan et al., 2020; Sharkey et al., 2015; Vainik et al., 2018), because individuals live in neighborhoods and contexts that differ in their obesogenic conditions. While a large body of research has connected brain structures and their shape and function, such as cortical thickness (CT) (Lowe et al., 2019; Marqués-Iturria et al., 2013; Ronan et al., 2020; Sharkey et al., 2015; Vainik et al., 2018) and NAc density (Silvah et al., 2020; van de Giessen, de Bruin, la Fleur, van den Brink, & Booij, 2012; van de Giessen et al., 2013), to high BMI in children and adults, very little is known about the heterogeneity of these effects.

2. Objectives

This epidemiological study compares racial and income groups of 9-10 years old American children for the predictive role of NAc density on BMI. Our first hypothesis was that NAc density is associated with BMI (Lowe et al., 2019; Marqués-Iturria et al., 2013; Ronan et al., 2020; Sharkey et al., 2015; Vainik et al., 2018). Our second hypothesis was that the effect of NAc density on children's BMI is stronger in

disadvantaged (African American and low-income) than socially privileged (White and high-income) families.

3. Methods

A secondary analysis was performed with a cross-sectional design. We used data from the Adolescent Brain Cognitive Development (ABCD) study (Alcohol Research: Current Reviews Editorial, 2018; B. J. Casey et al., 2018). The ABCD only included children who were between the ages of 9 and 10 years. The ABCD children were enrolled from multiple cities across multiple states. Children were recruited into the ABCD study from 21 sites. The primary strategy for sampling in the ABCD study was sampling through school systems (Garavan et al., 2018).

The children's BMI at baseline was calculated based on participants' measured height and weight. BMI was treated as a continuous measure. Using resting-state fMRI, NAc density was defined as diffusion tensor imaging measures (dMRI) in our subcortical (ASEG) regions of interest (ROIs). To be more specific, our outcome was average fractional anisotropy within ASEG ROI left-accumbens-area. This is treated as a continuous measure (Figure 1). A full description of diffusion MFR in the ABCD study is available here (B. Casey et al., 2018). Race was a categorical variable: African American, Asian, Other/mixed race, and White. Ethnicity was 1 for Hispanics and 0 for non-Hispanics. Parents reported their schooling: less than high school, high school, some college, college graduate, and graduate studies. Family income was a three-level categorical variable: 1 for less than $50,000, 2 for $50,000- $100,000, and 3 for $100,000 or more.

The Data Analysis and Exploration Portal (DEAP), which operates based on the R statistical package, was applied for data analysis. The DEAP is available at the NIH NDA. Mean (standard deviation; SD) and frequency (relative frequency; %) of all variables were described overall and by race and family income. We also used the ANOVA and chi-square tests for bivariate analysis to compare the study variables across racial and income groups.

Appendix 1 shows our models. For multivariable modeling, we ran mixed-effects regression models. In our model, the NAc density was the predictor, BMI was the outcome, and demographic, ethnicity, family structure, and parental education were the covariates. Race and income levels were the moderators. All models were performed in the pooled sample (n = 9497). Our 1st model was performed in the absence of any interaction terms; our 2nd model was performed with the presence of interaction terms between race and NAc density. Our 3rd model was performed with the presence of interaction terms between household income and NAc density. Before we perform our models, we ruled out multi-collinearity between study variables. We also explored the distribution of our predictor, outcome, residuals, and quantiles (Appendix 2). Unstandardized coefficient (b), SE, and p-value were reported for our model. A p-value of equal or less 0.05 was significant.

The ABCD study protocol received Institutional Review Board (IRB) approval from several institutions, including but not limited to the University of California, San Diego (UCSD). All participating children

provided assent. All participating parents signed informed consent (Auchter et al., 2018). Our study was exempt from a full IRB review.

4. Results

4.1 Descriptives

A total number of 9497, 9-10 years old children entered our analysis. In this study, 6411 children (67.5%) were White, 1321 children (13.9%) were African American, 200 individuals (2.1%) were Asian and the remaining 1565 children (16.5%) were other/mixed race. Table 1 summarizes the descriptive statistics for the children overall and by race. African American and mixed/other race children had the highest BMI and Asian and White children had the lowest BMI.

Table 1. Descriptive Statistics

Characteristics	Level	All	White	African American	Asian	Other/Mixed	p
	n	9497	6411	1321	200	1565	
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	
Age (Month)		119.06 (7.47)	119.13 (7.49)	119.04 (7.23)	119.90 (7.82)	118.67 (7.54)	0.060
BMI		18.62 (3.88)	18.17 (3.51)	20.38 (4.80)	17.57 (3.18)	19.12 (4.05)	< 0.001
Left NAc Density		0.23 (0.04)	0.23 (0.04)	0.23 (0.04)	0.24 (0.05)	0.24 (0.05)	< 0.001
Sex	Female	4574 (48.2)	3029 (47.2)	668 (50.6)	103 (51.5)	774 (49.5)	0.067
	Male	4923 (51.8)	3382 (52.8)	653 (49.4)	97 (48.5)	791 (50.5)	
Parental Education	< HS Diploma	334 (3.5)	127 (2.0)	103 (7.8)	4 (2.0)	100 (6.4)	< 0.001
	HS Diploma/GED	749 (7.9)	287 (4.5)	294 (22.3)	2 (1.0)	166 (10.6)	
	Some College	2399 (25.3)	1338 (20.9)	524 (39.7)	15 (7.5)	522 (33.4)	
	Bachelor	2533 (26.7)	1921 (30.0)	198 (15.0)	52 (26.0)	362 (23.1)	
	Post Graduate Degree	3482 (36.7)	2738 (42.7)	202 (15.3)	127 (63.5)	415 (26.5)	
Married Family	No	2817 (29.7)	1281 (20.0)	929 (70.3)	31 (15.5)	576 (36.8)	< 0.001
	Yes	6680 (70.3)	5130 (80.0)	392 (29.7)	169 (84.5)	989 (63.2)	
Household income	< 50K	2638 (27.8)	1141 (17.8)	865 (65.5)	30 (15.0)	602 (38.5)	< 0.001
	> =50K& < 100K	2727 (28.7)	1943 (30.3)	296 (22.4)	47 (23.5)	441 (28.2)	
	> =100K	4132 (43.5)	3327 (51.9)	160 (12.1)	123 (61.5)	522 (33.4)	
Hispanic	No	7709 (81.2)	5335 (83.2)	1254 (94.9)	181 (90.5)	939 (60.0)	< 0.001
	Yes	1788 (18.8)	1076 (16.8)	67 (5.1)	19 (9.5)	626 (40.0)	

Nucleus accumbens (NAc)

Body mass index (BMI)

Table 2 summarizes the descriptive statistics for the children by household income. From all the participants, 2638 (27.8%) had household income less than 50K, 2727 (28.7%) participants had a household income between 50K and 100K, and 4132 (43.5%) participants had household income 100K+. Children from low-income families had the highest and children from high-income families had the lowest BMI.

Table 2. Descriptive Statistics by Family Income

	level	All	< 50K	> =50K& < 100K	> =100K	p
N		9497	2638	2727	4132	
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	
Age (months)		119.06 (7.47)	118.78 (7.44)	118.83 (7.50)	119.39 (7.46)	0.001
BMI		18.62 (3.88)	19.93 (4.47)	18.63 (3.87)	17.78 (3.19)	< 0.001
Left NAc Density		0.23 (0.04)	0.23 (0.04)	0.23 (0.04)	0.23 (0.04)	0.040
		n(%)	n(%)	n(%)	n(%)	
Race	White	6411 (67.5)	1141 (43.3)	1943 (71.3)	3327 (80.5)	< 0.001
	African American	1321 (13.9)	865 (32.8)	296 (10.9)	160 (3.9)	
	Asian	200 (2.1)	30 (1.1)	47 (1.7)	123 (3.0)	
	Other/Mixed	1565 (16.5)	602 (22.8)	441 (16.2)	522 (12.6)	
Sex	Female	4574 (48.2)	1300 (49.3)	1311 (48.1)	1963 (47.5)	0.361
	Male	4923 (51.8)	1338 (50.7)	1416 (51.9)	2169 (52.5)	
Parental Education	< HS Diploma	334 (3.5)	314 (11.9)	18 (0.7)	2 (0.0)	< 0.001
	HS Diploma/GED	749 (7.9)	587 (22.3)	134 (4.9)	28 (0.7)	
	Some College	2399 (25.3)	1214 (46.0)	836 (30.7)	349 (8.4)	
	Bachelor	2533 (26.7)	344 (13.0)	933 (34.2)	1256 (30.4)	
	Post Graduate Degree	3482 (36.7)	179 (6.8)	806 (29.6)	2497 (60.4)	
Married Household	No	2817 (29.7)	1750 (66.3)	721 (26.4)	346 (8.4)	< 0.001
	Yes	6680 (70.3)	888 (33.7)	2006 (73.6)	3786 (91.6)	
Hispanic	No	7709 (81.2)	1774 (67.2)	2199 (80.6)	3736 (90.4)	< 0.001
	Yes	1788 (18.8)	864 (32.8)	528 (19.4)	396 (9.6)	

Nucleus accumbens (NAc)

Body mass index (BMI)

4.2 Overall Effect of NAc Density on BMI.

In the pooled sample, NAc density was predictive of BMI. However, the associations between NAc density and BMI was more robust in African American than White and low-income than high-income children (Table 3).

Table 3. Additive and Multiplicative Effects of Nucleus Accumbens (NAc) Density Overall and by Race and Socioeconomic Status

	Estimate	SE	P
Model 1			
Left NAc Density	4.81***	1.04	<0.001
Model 2			
Left NAc Density	4.25***	1.24	0.001
Race (African American)	0.12	0.60	0.837
Race (Asian)	0.97	1.44	0.501
Race (Other/Mixed)	0.32	0.53	0.543
Race (African American) x Left NAc Density	5.29*	2.58	0.040
Race (Asian) x Left NAc Density	-5.98	5.92	0.313
Race (Other/Mixed) x Left NAc Density	-0.25	2.20	0.911
Model 3			
Left NAc Density	9.33***	1.76	< 0.001
Household income (> =50K& < 100K)	1.16*	0.54	0.033
Household income (> =100K)	1.09*	0.51	0.032
Household income (> =50K& < 100K) x Left NAc Density	-5.51*	2.31	0.017
Household income (> =100K) x Left NAc Density	-6.58**	2.13	0.002

Nucleus accumbens (NAc)

*p<0.05 **p<0.01 ***p<0.001

4.3 Overall Effect of NAc Density on BMI

Figure 1 shows the positive association between NAc density and BMI in the pooled sample.

Figure 2 shows the positive association between NAc density and BMI in the pooled sample based on family income. As this figure shows, the associations between NAc density and BMI was stronger in African American than White children.

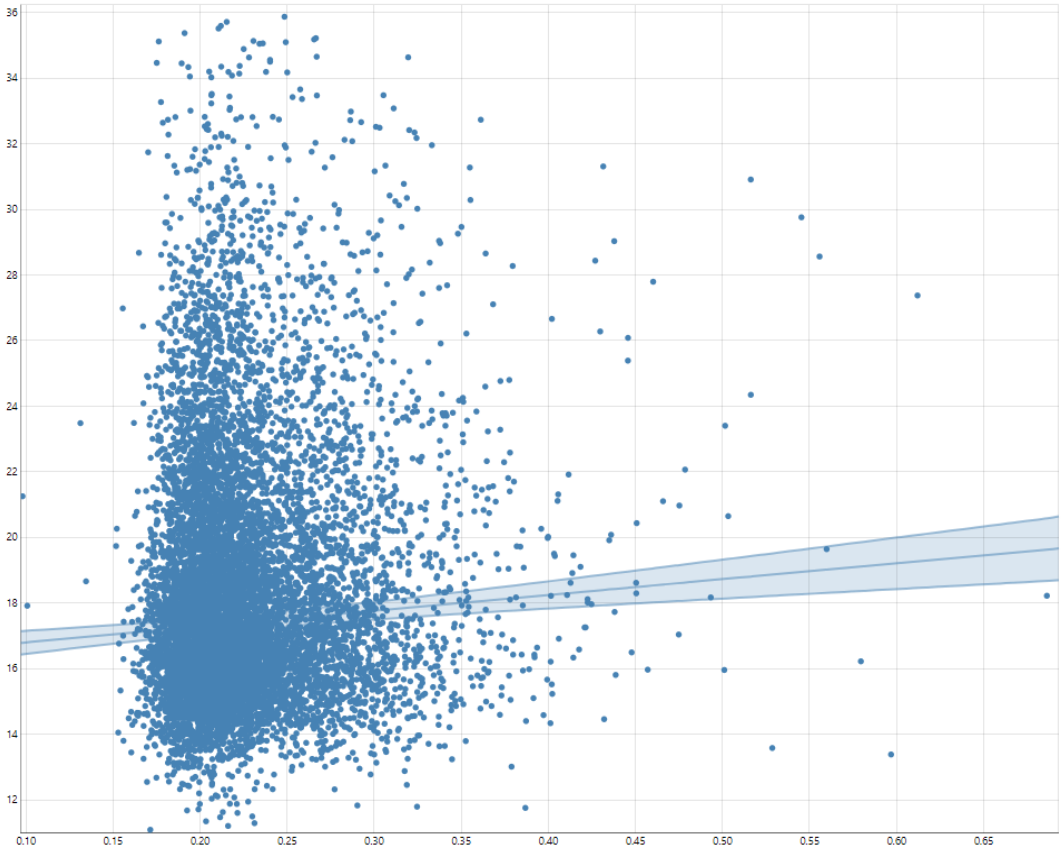

Figure 1. Association between NAc Density and Body Mass Index (BMI) Overall

Figure 2. Association between Nucleus Accumbens (NAc) Density and Body Mass Index (BMI) by Race

Figure 3 shows the positive association between NAc density and BMI in the pooled sample based on family income. As this figure shows, the associations between NAc density and BMI were stronger in low-income than high-income children.

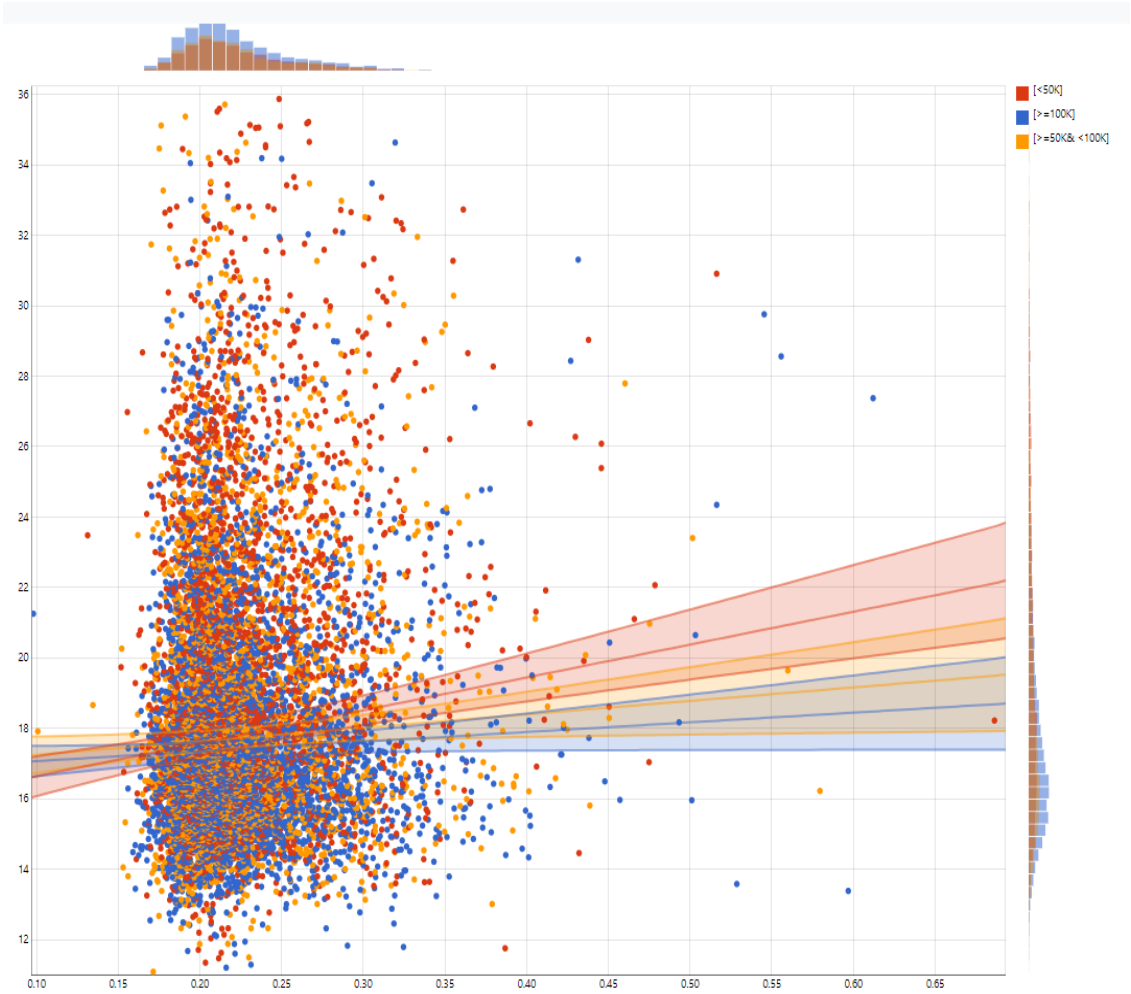

Figure 3. Association between Nucleus Accumbens (NAc) Density and Body Mass Index (BMI) by Household Income

5. Discussion

As our finding showed, NAc density was associated with BMI in 9-10 years old American children. According to our study, this effect was stronger for African Americans and low-income than White and high-income children.

Various brain structures such as the cerebral cortex (Durst et al., 2019; Oterdoom et al., 2018) and NAc (Cho, Yoon, & Kim, 2015; Haberny & Carr, 2005; Lin & Pivorun, 1989; Pan, Siregar, & Carr, 2006; Silvah et al., 2020) impact obesity risk through a wide range of mechanisms such as emotion regulation and control of the response to food cues. The brain's influence on obesity risk is in part through the dopaminergic inputs' activity following exposure to food cues. The NAc, a component of the striatum,

jointly works with the cerebral cortex to regulate feeding and eating (Oterdoom et al., 2018; Salamone, Mahan, & Rogers, 1993). In the NAc, GABA (a hormone released by the brain **to regulate dopamine levels in its reward pathways**) predicts hyperphagia, overeating, and associated weight gain (Meena, Nakhate, Kokare, & Subhedar, 2009). The NAc and thalamus may also shape appetite (Kalyanasundar et al., 2015) and food-seeking behaviors (Cho et al., 2015; Haberny & Carr, 2005; Lin & Pivorun, 1989; Pan et al., 2006; Silvah et al., 2020). The NAc regulates various motivational behaviors as a part of the reward system (Oginsky, Goforth, Nobile, Lopez-Santiago, & Ferrario, 2016).

The effect of neural circuits (e.g., cue-triggered motivation) on obesity may depend on the degree by which one's environment promotes obesity (e.g., access to "junk-food") (Oginsky, Goforth, et al., 2016). Chronic and repeated exposure to fast food may interact with the brain mechanisms that regulate food cues (e.g., striatum) (Waeiss, Knight, Engleman, Hauser, & Rodd, 2020). That is, the NAc may show an interaction with one's environment (which may predispose an individual to obesity risk). The very same neural risk factors may show a larger effect on BMI in obesogenic environments. In contrast, when a family has access to healthy food and other buffers, food options and diet may stay healthy even when the individual seeks to eat, in response to food-related cues. Thus, to what degree an individual becomes susceptible to high BMI and obesity is not merely a function of the brain but also the intersection of brain, behaviors, and environment (Oginsky, Maust, Corthell, & Ferrario, 2016).

Many brain structures such as the NAc, striatum, and cerebral cortex regulate food-seeking behaviors and respond to food cues (Waeiss et al., 2020). The family's and neighborhood's food environment as well as available food and dietary habits may modulate the influence of the NAc on BMI because food cue-induced behaviors would be associated with different caloric intakes. Future research should investigate the interaction between food environment, food habits, and brain structures and functions such as those of the NAc, prefrontal cortex, and thalamus in shaping obesity risk through regulating food-seeking behaviors (D'Cunha et al., 2017; Sadeghzadeh, Babapour, & Haghparast, 2015; Shalev, Finnie, Quinn, Tobin, & Wahi, 2006; Shalev, Robarts, Shaham, & Morales, 2003; Tobin, Sedki, Abbas, & Shalev, 2013).

6. Conclusion

In this study, NAc density was associated with BMI among 9-10-year-old American children. However, this association was not the same across racial and SES groups of children. The stronger gradient effect of NAc density on childhood BMI may be due to the variation in the obesogenic environments where low and high SES African American and White families live.

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supporters is available at https://abcdstudy.org/federal-partners.html. A listing of participating sites and a complete listing of the study investigators can be found at https://abcdstudy.org/Consortium_Members.pdf. ABCD consortium investigators designed and implemented the study or provided data, but did not necessarily participate in the analysis or writing of this report. This manuscript reflects the views of the authors and may not reflect the opinions or views of the NIH or ABCD consortium investigators. The ABCD data repository grows and changes over time. The current paper used Curated Annual Release 2.0, also defined in NDA Study 634 (doi:10.15154/1503209). DEAP is software provided by the Data Analysis and Informatics Center of ABCD located at UC San Diego, with generous support from the National Institutes of Health and the Centers for Disease Control and Prevention under award number U24DA041123. Shervin Assari was supported by the National Institutes of Health (NIH) grants 5S21MD000103, D084526−03, CA201415 02, DA035811-05, U54MD008149, U54MD007598, and U54CA229974.

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Appendix 1. Formula Used for Model Estimation in the DEAP

Model 1

anthro_bmi_calc ~ dmri_dti.fa_subcort.aseg_accumbens.area.lh + race.4level + sex + high.educ.bl + married.bl + age + household.income.bl + hisp

Random: ~(1|abcd_site/rel_family_id)

Model 2

anthro_bmi_calc ~ dmri_dti.fa_subcort.aseg_accumbens.area.lh + race.4level + sex + high.educ.bl + married.bl + age + household.income.bl + hisp + dmri_dti.fa_subcort.aseg_accumbens.area.lh * race.4level

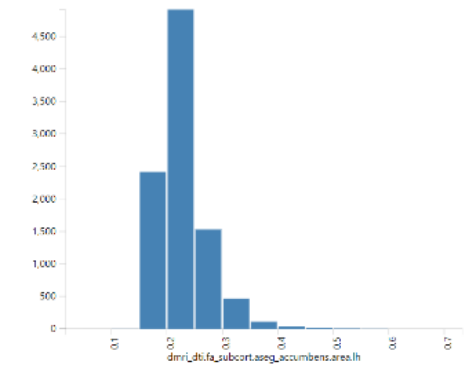
Random: ~(1|abcd_site/rel_family_id)

Model 3

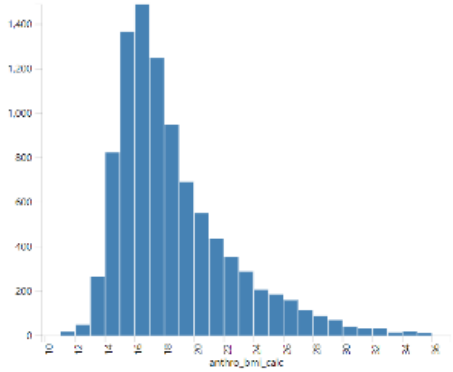
anthro_bmi_calc ~ dmri_dti.fa_subcort.aseg_accumbens.area.lh + race.4level + sex + high.educ.bl + married.bl + age + household.income.bl + hisp + dmri_dti.fa_subcort.aseg_accumbens.area.lh * household.income.bl

Random: ~(1|abcd_site/rel_family_id)

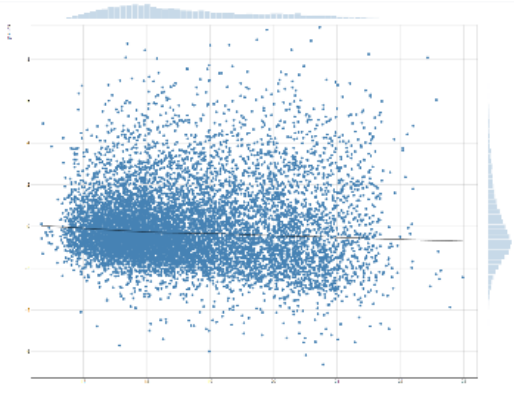
Appendix 2. Distribution of Our Predictor (a), Outcome (b), Residuals (c), and Quantiles (d)



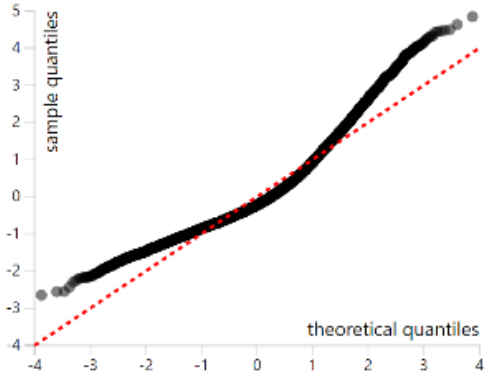
(a)



(b)



(c)



(d)