The Relationship between Obesity and Cognitive Performance in Children: A Longitudinal Study

Amna Sadaf Afzal, MD, MS¹ and Steven Gortmaker, PhD²

Abstract

Background: The relationship between obesity and academic outcomes remains unclear. We evaluated the association between obesity and cognitive performance in US children.

Methods: We analyzed two nationally representative prospective cohorts of children in the 1979 National Longitudinal Survey of Youth, ages 2 through 8 at baseline and followed for 6 years, from 1988 to 1994 (cohort 1, $n=2672$) and 1994 to 2000 (cohort 2, $n=1991$). The main exposure variable was obesity (defined as never obese, became obese, always obese, and became nonobese). The main outcomes were standardized scores on four cognitive assessments. Univariate regression analyses of test scores on obesity were performed. Fixed-effects regression models, controlling for measured and unmeasured time-invariant confounders, were additionally adjusted for time-variant confounders to analyze the impact of change in obesity status on change in test scores.

Results: Unadjusted analyses revealed a significant association between obesity and Peabody Individual Achievement Test (PIAT) scores. In cohort 1, always obese children had lower PIAT math scores than never obese children ($\beta=-7.48$; $p<0.05$). Always obese boys had lower PIAT math scores than those who were never obese ($\beta=-16.45$; $p<0.01$). In cohort 2, PIAT math scores were lower in the became obese category than the never obese category ($\beta=-4.10$; $p<0.05$). Always obese girls had lower PIAT reading scores than those who were never obese ($\beta=-11.28$; $p<0.01$). Fixed-effects models additionally adjusted for Home Observation Measurement of the Environment, Short Form score and height percentile showed no significant relationship between obesity and test scores in either cohort.

Conclusion: Childhood obesity is unlikely to be causally related to cognitive performance.

Introduction

The prevalence of childhood obesity in the United States has tripled in the past 30 years, and currently over 35% of children are overweight or obese.¹ Childhood obesity is likely to persist into adulthood² and carries several well-described metabolic and cardiovascular consequences.³ Of equal concern are adverse psychosocial consequences,⁴ including lower health-related quality of life⁴ and lower educational attainment and marriage rates, with evidence that these associations may be related to discrimination.⁵ However, the relationship between childhood obesity and earlier cognitive outcomes, such as school performance and standardized test scores, is less well established. The potential impact of obesity on cognitive outcomes is particularly important to define because educational attainment is an important predictor of lifelong health outcomes,⁶ and lower academic perfor-

mance could further predispose obese children to a lower quality of life. Additionally, establishing an association between pediatric obesity and academic outcomes may be important in cost-effectiveness analyses of obesity interventions for children, who do not have other readily quantifiable markers of productivity (such as earned income), given that school performance is a substantial predictor of adult educational attainment and earnings.

Possible mechanisms for an association between obesity and academic performance include psychosocial factors (such as altered peer relationships,⁷ poor self-esteem⁸, and weight-based teasing⁹), physiological factors (such as sleep apnea¹⁰), and school absenteeism stemming from any of these factors.⁴ There also may be a role for teacher perceptions of obese children, with one study showing that weight is more negatively associated with teacher assessments of student performance than actual test scores.¹¹ Alternatively, obesity may act as a surrogate for socioeconomic

¹Children's Hospital at Montefiore, Albert Einstein College of Medicine, Division of Pediatric Gastroenterology and Nutrition, Bronx, NY.

²Department of Society, Human Development, and Health, Harvard School of Public Health, Boston, MA.

factors,^{12,13} such as family education and income level, and any observed relationship may reflect other confounding or mediating factors.¹⁴

There is conflicting existing evidence directly linking childhood obesity and cognitive outcomes, and some studies have been methodologically limited by cross-sectional designs, self-reports of obesity status, or nonvalidated measures of academic outcomes. Cross-sectional studies have found an inverse relationship between BMI and visuospatial organization and general cognitive ability, after controlling for a number of parental and familial covariates,^{15,16} but there may be residual confounding. A few studies focusing mainly on adolescents have found small, but statistically significant, associations with language and math grades,¹⁷ gender-specific (limited to girls) associations with grade progression,¹⁸ and grade point average,^{19,20} whereas others have found no evidence of an independent association.^{14,21,22} At least two longitudinal studies have found an inverse association between BMI and academic performance in elementary school children^{23,24}; Datar and colleagues²³ examined the association between changes in overweight status and changes in school outcomes over time; however, it is difficult to disentangle the effects of change from the effects of residual cross-sectional confounding, because their analysis did not exclude those whose weight status remained stable, as would a fixed-effects analysis.²⁵ Other studies have found no association between obesity and academic performance.^{26,27}

It is worth noting that even studies using similar or overlapping populations within the same data set have found inconsistent results, likely reflecting differences in model specification.^{21,24,26} The timing of obesity development relative to proposed effects on cognitive testing is unclear, and investigators have used a variety of approaches, including using lagged measures of obesity, concurrent measures of obesity, or variables reflecting changes in obesity status.²¹ Given the endogeneity of obesity and the multitude of potential child and family characteristics confounding the relationship between obesity and cognitive performance, investigators have also used instrumental variables (including maternal BMI and genetic markers) and developed complex ordinary least squares models adjusting for multiple covariates.²¹

A simpler, more valid approach may be the use of a fixed-effects model. By creating difference scores for all variables of interest with repeated measurements, fixed-effects models, as proposed by Allison,²⁵ are able to remove potential confounding arising from all time-invariant characteristics of individuals in a longitudinal study. In the case of the association between obesity and cognitive test scores, a fixed-effects approach creates within-subject difference scores for the exposure (obesity) and outcome (test scores) over the study period, and all time-invariant child, family, and household characteristics that impact both obesity status and cognitive test scores effectively drop out of the regression equation.²⁵ The advantage is that even unobserved or immeasurable individual-level char-

acteristics, such as genetics, and fetal exposures that may impact both obesity and cognitive performance are controlled.²⁰

Given the inconsistent evidence, it is unclear whether there is a direct and independent relationship between obesity and academic performance. Therefore, the aim of this study is to prospectively determine the association between obesity and cognitive performance in two consecutive cohorts of young children using a fixed-effects model.

Methods

Population

We utilized prospectively collected data from the National Longitudinal Survey of Labor Market Experience, Youth Cohort (NLSY²⁸; www.bls.gov/nls/nlsy79.htm) to analyze nationally representative cohorts of children. The NLSY79 is an ongoing survey of over 12,000 men and women who were 14–22 years of age when the first round of interviews began in 1979. The NLSY data collection has mainly focused on labor-related topics, but also includes a broad set of additional topics, including education, health, and household and family characteristics.²⁹ Since 1986, a series of cognitive, physiological, and social assessments has been administered biennially to the children of female participants as part of the NLSY79 Child and Young Adult Survey.³⁰ These surveys have included questions around demographic and family characteristics, prenatal and postnatal medical history, current health issues, and educational experiences. Trained field staff obtained consent from mothers and performed the assessments in subjects' homes.

We focused on two cohorts of children born to NLSY mothers. These cohorts were previously defined and studied as part of an analysis of changes in prevalence of obesity and other chronic conditions.³¹ Cohort 1 consists of children ages 2–8 in 1988 and followed for 6 years until 1994. Cohort 2 consists of children ages 2–8 in 1994 and followed for up to 6 years until 2000.

Measures

Obesity status. In-home interviewers directly collected anthropometric data with a scale and tape measure for most of the children (e.g., in cohort 1, >90% of heights and weights were directly measured in 1988 and >76% were directly measured in 1994), but some were self-reported. BMI was calculated as weight in kilograms divided by height in meters squared. Obesity was defined as a BMI greater than or equal to the age- and sex-specific 95th percentile as defined by CDC growth charts.³²

Given the uncertain temporal relationship between obesity development and cognitive effects, we created categorical variables to capture children who had been obese at any point in the study period relative to those who were never obese. Children were defined as never obese,

always obese (obese at the beginning and end of the study period), became obese (obese at the end of the study period) and became nonobese (obese at the beginning of the study period but not the end).

Child Cognitive Development

A number of well-validated cognitive assessments were administered biennially, with eligibility based on the specific test and, in some cases, whether the child had a valid score from previous years. The NLSY testing timeline and a full description of each of the cognitive tests are available elsewhere.³³ We analyzed four cognitive tests: the Peabody Picture Vocabulary Test-Revised (PPVT-R)³⁴; Wechsler Intelligence Scale for Children-Revised (WISC-R) Digit Span Subscale³⁵; and Peabody Individual Achievement Test (PIAT) in Math and Reading Comprehension.³⁶ The PPVT-R, administered to children 2 years of age or older, measures a child's receptive vocabulary and provides an estimate of overall verbal ability. The WISC-R, administered to children age 7 and older during the 1986–1994 assessments and to children ages 7–11 from 1996 onward, measures short-term memory and intelligence. The PIAT in Math and Reading Comprehension were administered to children 5 years of age and older and measures reading and mathematics achievement.

Additional Explanatory Variables

We *a priori* identified several potential confounding variables that were hypothesized to be related to both obesity and cognitive test scores, based on previous studies.^{14,23,24,26} We considered sex, maternal education (≤ 12 years or >12 years of school), maternal race/ethnicity (because child-specific race/ethnicity was not collected), poverty level at the beginning of the study (family income $<100\%$ or $\geq 100\%$ of the federal poverty level), maternal obesity (BMI ≥ 30), and HOME-SF (Home Observation Measurement of the Environment, Short Form) score, a widely used measure capturing multiple dimensions of children's home environments.^{33,37} The HOME-SF measures the quality of the child's home environment and is related to socioeconomic status and parental education as well as subsequent cognitive and physical development. Importantly, it includes both self-reported and directly observed measures of the child's home environment, such as maternal responsiveness, emotional support, presence of materials for learning, and variety of stimulation. Additionally, we considered height, which has been shown to be significantly associated with cognitive performance and likely serves as a marker for nutrition and general health^{38,39}

Statistical Analysis

Given the complex survey design of the NLSY79 and oversampling of certain demographic groups,³⁰ we used NLSY-provided sample weights in our descriptive statistics to derive population estimates from the survey sample. Data analysis was performed using SAS software (version

9.3; SAS Institute Inc., Cary, NC). The unadjusted association between obesity and cognitive scores was analyzed using a regression of cognitive scores at follow-up on change in obesity status from x to y. The predictor variable of interest was obesity status, using a categorical variable defined as never obese, always obese (obese at the beginning and end of the cohort period), became obese (non-obese at the beginning of the cohort period and obese at the end), and became nonobese (obese at the beginning of the cohort period and nonobese by the end). The reference group for all regression analyses was the never obese category. The outcome variables of interest were age-adjusted standardized percentile scores on each of the four cognitive tests (PPVT-R, PIAT Math, PIAT Reading, and WISC-R) at the follow-up time point. We also performed sex-specific analyses, given previous evidence for differing effects in boys and girls.^{18,19}

We then used a fixed-effects regression model to estimate the impact of changes in obesity status on changes in cognitive test scores from x to y and c to d. To adjust for additional time-varying confounding variables, we created a second fixed-effects model that included difference scores for height percentile and HOME score, which had the potential to change over the study period. The HOME score was included because it was highly correlated with the other separate sociodemographic variables (maternal education, poverty status, and so on) and most consistently measured at the beginning and end of each cohort period. Of note, there were no children with valid WISC-R scores in both 1994 and 2000 (those who were tested in 1994 were not retested in 2000). Therefore, we could not perform a fixed-effects regression for WISC scores in cohort 2.

We considered the possibility of clustering within families and recreated these regression models with a unique maternal identifier as the primary sampling unit; this had no significant impact on our results (results available upon request). We also created multivariate linear regression models, with categorical obesity status as the predictor variable and age-adjusted standardized percentile scores on the four cognitive assessments as the outcome variables, to compare with our fixed-effects models. These multivariate linear regression models included HOME score and height percentile as covariates and yielded similar results (available upon request).

Results

Data were available for 2672 children in cohort 1 and 1991 children in cohort 2 and their mothers (Table 1). Demographic differences (a higher proportion of mothers with >12 years of education and fewer households living under the federal poverty line) between the two cohorts largely reflect the age differences between mothers (mothers in cohort 2 were significantly older than those in cohort 1).³¹ Rates of maternal obesity were higher in cohort 2 (17.55%; 95% confidence interval [CI], 15.83–19.27) than in cohort 1 (13.72%; 95% CI, 12.4–15.03). The

Table 1. Baseline Characteristics of Children in Longitudinal Cohorts in 1998 and 1994^a

Variable	Cohort 1 ^b (n=2672)	Cohort 2 ^b (n=1991)
Age of child, mean (SD), years ^c	5.01 (1.91)	5.31 (1.88)
Age of mother, mean (SD), years ^c	27.66 (2.29)	32.99 (2.23)
Female sex, % (95% CI)	50.22 (47.89; 51.67) n = 1341	48.79 (46.59; 50.98) n = 978
Ethnicity, % (95% CI)		
White	72.84 (71.16; 74.52) n = 1174	83.83 (82.21; 85.45) n = 1157
Black	18.49 (17.02; 19.95) n = 906	11.13 (9.75; 12.51) n = 506
Hispanic	8.67 (7.61; 9.74) n = 592	5.05 (4.08; 6.01) n = 328
Household poverty (<100% FPL), % (95% CI) ^c	24.49 (22.75; 26.22) n = 777	12.75 (11.14; 14.35) n = 297
Mothers with > 12 years of education, % (95% CI) ^c	27.91 (26.92; 29.61) n = 687	49.10 (46.94; 51.3) n = 903
Maternal obesity, % (95% CI) ^c	13.72 (12.40; 15.03) n = 418	17.55 (15.83; 19.27) n = 406

^aWeighted estimates nationally represent US children born to mothers who were 14–21 years old in 1979. Numbers are unweighted samples.

^bChildren initially 2–8 years of age at the beginning of their respective study periods; 1988 for cohort 1 and 1994 for cohort 2.

^cMeasured in the first year of the cohort; 1988 for cohort 1 and 1994 for cohort 2.

SD, standard deviation; CI, confidence interval; FPL, federal poverty level.

Table 2. Anthropometrics at the Beginning and End of Each Cohort Period^a

	Cohort 1 ^b (n=2672)	Cohort 2 ^b (n=1991)
Prevalence of obesity ^c		
Obese at beginning ^d of cohort period, % (95% CI)	6.96 (6.00; 7.92)	12.12 (10.67; 13.56)
Obese at end ^e of cohort period, % (95% CI)	8.24 (7.20; 9.27)	16.47 (14.82; 18.12)
Changes in obesity status ^f		
Children who became obese, % (95% CI)	6.16 (5.25; 7.07)	11.56 (10.13; 12.99)
Children who remained obese, % (95% CI)	2.08 (1.54; 2.62)	4.76 (3.81; 5.71)
Children who moved out of obesity ^g , % (95% CI)	4.88 (4.07; 5.70)	7.34 (5.98; 8.24)

^aWeighted estimates nationally represent US children born to mothers who were 14–21 years old in 1979.

^bChildren initially ages 2–8 years at the beginning of their respective study periods; 1988 for cohort 1 and 1994 for cohort 2.

^cBMI ≥ 95th percentile.

^d1988 for cohort 1 and 1994 for cohort 2.

^e1994 for cohort 1 and 2000 for cohort 2.

^fChanges over the 6-year study period; from 1988 to 1994 for cohort 1 and from 1994 to 2000 for cohort 2.

^gObese at the beginning of the cohort period and nonobese at the end.

CI, confidence interval.

average age of children at the beginning of each of the study periods was similar: 5.10 years for cohort 1 and 5.31 for cohort 2.

Rates of obesity were higher in each cohort at the end of the study period (Table 2). In cohort 1, 6.96% (95% CI, 6.00–7.92) were obese at the beginning of the study period and 8.24 (95% CI, 7.2–9.27) were obese at the end. In cohort 2, 12.12% were obese at the beginning of the study period (95% CI, 10.67–13.56) and 16.47% were obese at the end (95% CI, 14.82–18.12). Children's obesity status also seemed fairly dynamic; this has been noted elsewhere.³¹ In cohort 1, over 11% of children changed obesity status, and in cohort 2, over 18% of children changed obesity status over the study period.

Unadjusted analyses for cohort 1 (Table 3) showed that those who were obese throughout the cohort period had significantly lower PIAT math scores than those who were never obese ($\beta = -7.48$; $p < 0.05$). In sex-specific analyses for PIAT math scores, boys who were always obese scored

significantly lower ($\beta = -16.45$; $p < 0.01$) than boys who were never obese. Unadjusted results for the PPVT, PIAT reading, and WISC were not significant. Unadjusted analyses for cohort 2 (Table 4) showed that those who became obese by the end of the cohort period had significantly lower PIAT math scores than those who were never obese ($\beta = -4.10$; $p < 0.05$). Girls who were always obese had lower PIAT reading scores than those who were never obese ($\beta = -11.23$; $p < 0.01$). Otherwise, similar to cohort 1, there was no significant association between cognitive test scores at the end of the study period and any of the three categorical markers of obesity status (those who were always obese, those who became obese, or those who became nonobese), relative to those who were never obese.

When a fixed-effects approach was used (Table 5), the significant results noted for PIAT math scores in cohort 1 were no longer significant. The sex-specific effects observed in PIAT math scores in boys were also no longer significant. The results observed for PIAT Math in cohort 2 were no longer significant when using a fixed-effects

Table 3. Unadjusted Association Between Change in Obesity Status From 1988 to 1994 and Test Scores in 1994, Cohort 1

	PPVT-R ^a β^b (95%CI)	N ^c	PIAT Math ^a β (95% CI)	N	PIAT Reading ^a β (95% CI)	N	WISC-R ^a β (95% CI)	N
Entire sample		780		2504		2642		2521
Always obese ^d	0.28 (−12.67; 13.22)		−7.48 (−14.00; −0.96)*		−6.73 (−13.64; 0.16)		−0.01 (−0.76; 0.73)	
Became obese ^e	−3.94 (−12.63; 4.75)		−3.75 (−7.94; 0.45)		−3.68 (−8.92; 1.56)		−0.25 (−0.72; 0.23)	
Became nonobese ^f	4.10 (−5.29; 13.49)		−1.94 (−6.75; 2.85)		0.30 (−1.35; 1.96)		−0.02 (−0.57; 0.52)	
Girls		422		1274		1257		1280
Always obese	−11.58 (−30.00; 6.45)		−1.24 (−9.59; 7.12)		−4.71 (−13.48; 4.07)		0.23 (−0.75; 1.21)	
Became obese	−7.6 (−19.07; 3.86)		−5.42 (−11.03; 0.18)		−2.63 (−9.75; 4.49)		−0.24 (−0.89; 0.42)	
Became nonobese	1.56 (−10.32; 13.45)		−2.77 (−9.55; 4.01)		−0.66 (−2.96; 1.64)		0.13 (−0.67; 0.92)	
Boys		358		1230		1205		1241
Always obese	12.10 (−6.01; 30.29)		−16.45 (−26.80; −6.10)**		−10.60 (−21.68; 0.48)		−0.46 (−1.61; 0.69)	
Became obese	1.32 (−12.05; 14.69)		−1.80 (−8.11; 4.50)		−4.97 (−12.66; 2.70)		−0.30 (−0.99; 0.40)	
Became nonobese	8.76 (−6.71; 24.23)		−1.12 (−4.63; 2.38)		1.29 (−1.08; 3.65)		−0.14 (−0.90; 0.62)	

^aDependent variables represent unweighted age-standardized scores at the end of the cohort period (1994).

^bScore relative to the never obese category.

^cNumber of valid observations.

^dCategorical variable representing children who were obese at the beginning and end of the cohort period.

^eCategorical variable representing children who became obese by the end of the cohort period.

^fCategorical variable representing children who were no longer obese by the end of the cohort period.

* $p < 0.05$; ** $p < 0.01$.

PPVT-R, Peabody Picture Vocabulary Test-Revised; PIAT, Peabody Individual Achievement Test in reading Comprehension and Mathematics; WISC-R, Wechsler Intelligence Scale for Children-Revised: Digit Span Subscale.

model (Table 6). Similarly, the sex-specific effects observed in PIAT reading scores in girls were no longer significant. Fixed-effects models additionally adjusted for HOME score and height percentile (Table 6) also showed no significant association between changes in test scores and changes in obesity status in either cohort.

Discussion

In our analyses of two nationally representative cohorts of children, we found little evidence for a significant longitudinal relationship between obesity and cognitive test scores. This was true both for the overall cohort and in sex-specific analyses. The significant unadjusted results for PIAT scores in cohorts 1 and 2 were no longer significant when using a fixed-effects model and adjusting for additional covariates. This is mainly an effect of consistent obesity and may reflect uncontrolled confounding, similar to results found in previous studies examining elementary school children^{14,26,27} rather than adolescents. It may be that the detrimental effects of obesity take several years to meaningfully impact cognitive and school performance, and the 6-year follow-up period for each cohort in this study failed to capture that. It may also be that psychoso-

cial effects on self-esteem and peer relationships are observed in older children and adolescents, as described in the literature,^{8,18} rather than elementary school children. Additionally, given the dynamic nature of growth in children and sometimes rapid shifts in height and weight, it is not uncommon for children to move in and out of different weight states throughout childhood. This may also partially explain why the literature thus far has mainly shown an effect of obesity on cognitive and academic performance in adolescents and young adults, who may have a more stable weight trajectory.

It also may be that effects are observed at the extreme ends of the obesity spectrum—those with a BMI >99th percentile. There were not enough children in this BMI category in either cohort to test this hypothesis. These children may be more likely to suffer from serious medical comorbidities (such as sleep apnea) that can impact overall learning and increase the likelihood of school absenteeism owing to illness and medical appointments.⁴

A difference between this study and several others examining the association between obesity status and cognitive performance is that the assessments were conducted in the home as opposed to in school. If the causal pathway linking a potential relationship between obesity and

Table 4. Unadjusted Association Between Change in Obesity Status from 1994 to 2000 and Test Scores in 2000, Cohort 2

	PPVT-R ^a β^b (95%CI)	N ^c	PIAT Math ^a β^b (95%CI)	N	PIAT Reading ^a β^b (95%CI)	N	WISC-R ^a β^b (95%CI)	N
Entire sample		597		1825		1811		1084
Always, obese ^d	-1.50 (-11.81; 8.81)		0.54 (-4.95; 6.04)		-6.13 (-11.73; -0.53)		-0.26 (-1.14; 0.61)	
Became obese ^e	-6.41 (-13.29; 0.46)		-4.10 (-8.09; -0.11)*		-4.07 (-8.14; 0.01)		-0.40 (-0.95; 0.14)	
Became nonobese ^f	-4.38 (-15.40; 7.12)		-1.57 (-6.71; 3.56)		-0.48 (-5.71; 4.74)		-0.63 (-1.32; 0.07)	
Girls		285		919		911		548
Always obese	-4.48 (-17.78; 8.80)		1.20 (-5.95; 8.55)		-11.23 (-18.62; 3.92)**		-0.22 (-1.38; 0.95)	
Became obese	-9.26 (-19.84; 1.30)		-3.64 (-9.74; 2.18)		-4.87 (-10.75; 1.03)		-0.48 (-1.26; 0.31)	
Became nonobese	1.71 (-14.67; 18.01)		4.42 (-2.58; 11.41)		5.37 (-1.66; 12.41)		-0.21 (-1.16; 0.73)	
Boys		312		906		900		536
Always obese	2.74 (-13.52; 19.01)		-0.21 (-8.56; 8.14)		-0.39 (-8.87; 8.07)		-0.31 (-1.61; 0.99)	
Became obese	-4.73 (-13.94; 4.48)		-4.79 (-10.31; 0.71)		-2.88 (-8.51; 2.74)		-0.25 (-1.01; 0.50)	
Became nonobese	-9.75 (-26.02; 6.51)		-3.74 (-7.79; 0.31)		-6.49 (-14.19; 1.21)		-1.01 (-2.03; 0.01)	

^aDependent variables represent unweighted age-standardized scores at the end of the cohort period (2000).

^bScore relative to the never obese category.

^cNumber of valid observations.

^dCategorical variable representing children who were obese at the beginning and end of the cohort period.

^eCategorical variable representing children who became obese by the end of the cohort period.

^fCategorical variable representing children who were no longer obese by the end of the cohort period.

* $p < 0.05$; ** $p < 0.01$.

PPVT-R, Peabody Picture Vocabulary Test-Revised; PIAT, Peabody Individual Achievement Test in reading Comprehension and Mathematics; WISC-R, Wechsler Intelligence Scale for Children-Revised: Digit Span Subscale.

Table 5. Fixed-Effects Estimates of the Association Between Change in Obesity Status and Change in Test Scores from 1988 to 1994, Cohort 1

	PPVT-R ^a β (95% CI)	N ^b	PIAT Math ^a β (95% CI)	N	PIAT Reading ^a β (95% CI)	N	WISC-R ^a β (95% CI)	N
Model 1 ^c								
Entire sample	0.59 (5.52; 6.71)	514	2.29 (-2.47; 7.05)	1268	0.27 (-5.53; 6.01)	785	-0.25 (-1.02; 0.52)	500
Girls	2.49 (-5.23; 10.21)	274	1.49 (-4.79; 7.78)	647	1.40 (-6.57; 9.38)	409	-0.46 (-1.53; 0.62)	239
Boys	-1.59 (-11.36; 8.18)	240	3.21 (-4.02; 10.44)	621	-1.12 (-9.59; 7.34)	376	-0.07 (-1.18; 1.03)	261
Model 2 ^d								
Entire sample	1.47 (-4.83; 7.76)	503	2.54 (-2.41; 7.57)	1218	0.49 (-5.50; 6.50)	759	-0.03 (-0.82; 0.75)	482
Girls	3.12 (-4.76; 11.01)	271	0.61 (-6.05; 7.28)	620	1.44 (-6.87; 9.75)	393	-0.17 (-1.27; 0.93)	227
Boys	-0.31 (-10.58; 9.97)	232	4.60 (-2.91; 12.12)	598	-0.64 (-9.30; 8.01)	366	0.06 (-1.07; 1.19)	255

^aDependent variables represent age-standardized difference scores (score in 1994 - score in 1988).

^bNumber of valid observations.

^cFixed-effects model, includes within-subject difference scores for the exposure (obesity) and outcome (test scores) over the study period; all time-invariant child, family, and household characteristics that impact both obesity status and cognitive test scores are effectively cancelled out of the regression equation.

^dFixed-effects model with additional time-variant confounders: height percentile and HOME percentile score.

PPVT-R, Peabody Picture Vocabulary Test-Revised; PIAT, Peabody Individual Achievement Test in reading Comprehension and Mathematics; WISC-R, Wechsler Intelligence Scale for Children-Revised: Digit Span Subscale.

Table 6. Fixed-Effects Estimates of the Association Between Change in Obesity Status and Change in Test Scores From 1994 to 2000, Cohort 2

	PPVT-R ^a β (95%CI)	N ^b	PIAT Math ^a β (95%CI)	N	PIAT Reading ^a β (95%CI)	N
Model 1 ^c						
Entire Sample	4.32 (−1.68; 10.32)	339	0.78 (−3.21; 4.76)	1028	−1.13 (−6.61; 4.35)	652
Girls	8.82 (−0.84; 18.48)	159	0.92 (−4.79; 6.65)	508	−2.98 (−10.89; 4.92)	323
Boys	1.71 (−5.84; 9.26)	180	−0.01 (−5.57; 5.56)	520	−0.74 (−8.15; 6.68)	329
Model 2 ^d						
Entire Sample	6.21 (−0.23; 12.65)	317	0.39 (−3.75; 4.53)	998	−1.24 (−6.98; 4.43)	638
Girls	9.96 (−0.65; 20.58)	149	1.11 (−4.81; 7.05)	490	−1.39 (−9.61; 6.82)	314
Boys	3.67 (−4.44; 11.79)	168	−0.87 (−6.67; 4.94)	508	−2.81 (−10.54; 4.92)	324

^aDependent variables represent age-standardized difference scores (score in 2000–score in 1994).

^bNumber of valid observations.

^cFixed-effects model, includes within-subject difference scores for the exposure (obesity) and outcome (test scores) over the study period; all time-invariant child, family, and household characteristics that impact both obesity status and cognitive test scores are effectively cancelled out of the regression equation.

^dFixed-effects model with additional time-variant confounders: height percentile and HOME percentile score.

PPVT-R, Peabody Picture Vocabulary Test-Revised; PIAT, Peabody Individual Achievement Test in reading Comprehension and Mathematics; WISC-R, Wechsler Intelligence Scale for Children-Revised: Digit Span Subscale.

cognitive performance involves altered self-esteem, shame, or self-perception among peers, a detrimental impact on performance may only be observed in school or other settings among peers. If home is be a more comfortable environment for obese children, where they are not subject to weight-based teasing or bullying, then school assessments may be more sensitive in identifying changes in performance. Relative performance on home- versus school-based cognitive assessments in obese children has never been studied, but presents an interesting direction for future research.

Another difference between this study and others examining the association between obesity and cognitive performance is the consideration of height. Several studies have shown an association between relative height and earnings in adults as well as cognitive performance in children.^{38,39} The pathway for such an association in children is unclear; some have suggested that it is a reflection of early life or even fetal experiences and exposures³⁹; if this is the case, then its inclusion in our fixed-effects models was redundant, given that these exposures were already established for each child at the beginning of the cohort and unlikely to change. If, however, relative height acts as a marker for current nutritional status, then it may fluctuate over time and therefore merits inclusion in a fixed-effects model. Further research is needed to better understand children's growth trajectories as they become obese and how this interacts with overall nutrition.

Strengths of this study include the prospective, longitudinal nature of data collection, use of multiple well-validated measures of cognitive achievement, and a rich

set of socioeconomic covariates. An analytical approach addressing the endogeneity of obesity and the use of a fixed-effects model eliminating the potential confounding arising from stable and time-invariant characteristics, even those that are unobserved, is another strength of this study.

Limitations include lack of directly measured data on several important mediating or confounding variables, including physical activity,⁴⁰ sleep,⁴¹ and screen time.⁴² Also, whereas the majority of heights and weights were directly measured, over 20% of participants had self-reported anthropometrics.

The age of the data is another potential limitation. Though the cognitive tests are still valid and used today, other factors that impact children's performance on these assessments may have changed over time. Notably, the prevalence of obesity in our cohorts (particularly in cohort 1) is lower than that observed today. The impact on our analyses depends somewhat on the mechanism driving a link between obesity and cognitive outcomes. For example, if the mechanism is altered self-esteem and peer relationships, then being obese in a lower-prevalence era may be more detrimental than it is today, when obesity is more common. On the other hand, if there is a physiological or direct neurocognitive effect, then the population prevalence of obesity may be less likely to impact the relationship between obesity and cognitive outcomes in an individual child.

The lower obesity prevalence may have impacted our ability to detect a relationship between obesity and cognitive test scores, especially given that the initial sample size, though large, decreased considerably when using a

fixed-effects model. This is owing both to the complex scheduling of assessments across children—which was impacted by both age and the presence of previous valid scores—and the use of a fixed-effects model, which required all children to have two valid scores at the same points at the beginning and end of the cohort period. Owing to these constraints, we also could not perform ethnic-specific analyses, though previous work has shown that the effects of childhood obesity on cognitive ability may be more readily identified when analyzing separately by race.²⁴

Another disadvantage of using a fixed-effects model is that it does not deal explicitly with reverse causation—that is, the possibility that changes in cognitive ability or performance impact obesity status.^{21,24} Additionally, it is important to note that variables omitted from a fixed-effects analysis must not only be stable over time, but the strength of the associations for the fixed effects must also be constant over time.²⁵ Likewise, a fixed-effects approach does not address time-varying characteristics that affect both obesity and child outcomes, which must be controlled for separately. There may be changing qualities of the home or family environment that are not measurable and bias estimates of the relationship between obesity and cognitive scores. This was partially addressed through the use of the HOME score, but there may be additional dynamic characteristics that were not captured in our model.

Our study adds to our understanding of the association between childhood obesity and cognitive outcomes by including four well-validated, objective assessments and spanning a range of cognitive dimensions (mathematics and reading achievement, verbal ability, and working memory). In fact, to our knowledge, this is one of the first studies to evaluate the relationship between childhood obesity and performance on a measure of short-term memory (the WISC-R). Additionally, unlike previous studies, we include a broad age range, with assessments spanning from preschool to adolescence.

Conclusion

Evidence for a direct causal relationship between obesity and cognitive outcomes in children remains inconsistent. Ongoing study of the potential relationship between obesity and cognitive outcomes throughout childhood is clearly warranted. Greater attention toward a theoretical model of the association between obesity and cognition in childhood, with particular attention toward how fluctuating growth trajectories in children impact the possible timing of such an association, is crucial. In particular, these relationships should be further studied in the children at the furthest end of the obesity spectrum (BMI $\geq$ 99th percentile).

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Address correspondence to:

Amna Sadaf Afzal, MD, MS

The Children's Hospital at Montefiore

Division of Pediatric Gastroenterology and Nutrition

111 East 210th Street

Rosenthal Pavilion

Bronx, NY 10467

E-mail: aafzal@montefiore.org