



Sleep Disturbances, Obesity, and Cognitive Function in Childhood: A Mediation Analysis

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ABSTRACT

Background: Childhood cognitive development is influenced by biological and environmental factors. One such factor, obesity, impairs cognitive development and is associated with sleep disturbances.

Objectives: We aimed to examine the mediating role of sleep disturbances on the relation between BMI and cognitive function in children.

Methods: A total of 9951 children aged 9–10 y were included in this cross-sectional study. Children were recruited from the longitudinal ABCD (Adolescent Brain Cognitive Development) Study. Cognitive development was assessed using metrics for fluid, crystallized, and total cognitive function. Mediation analyses were conducted via linear regression modeling, with adjustment for potential confounders (sex, age, ethnicity, household income, parental education, and self-reported physical activity) for each of the 3 outcomes. Mediation significance was determined by bootstrapping.

Results: A statistically significant inverse association was found between BMI and total ($\beta = -0.41, P < 0.001$) and fluid ($\beta = -0.49, P < 0.001$) cognition, but not for crystallized cognition. Total sleep disturbances partially mediated the association between BMI and fluid cognition (indirect effect: $-0.02, P = 0.002$; proportion of the total effect: $0.05, P = 0.002$), but no mediation was found in the association between BMI and total cognition.

Conclusions: Sleep disturbances partially mediate the effect of childhood obesity on cognitive function, particularly in fluid cognitions. Future work is necessary to understand the effects of sleep disturbances and obesity on reduced childhood cognition throughout time, predominantly across the life course. *Curr Dev Nutr* 2021;5:nzab119.

Keywords: BMI, obesity, childhood, sleep disturbances, cognitive function, fluid cognition, crystallized cognition, mediation analysis

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Abbreviations used: ABCD, Adolescent Brain Cognitive Development; ACME, average causal mediation effect; ADE, average direct effect.

Introduction

Neurocognitive development is critical in childhood. During this period of life, a dynamic restructuring of the neural structures takes place, where neurons undergo an initial overproduction, and later pruning of the synapses during puberty, resulting in more efficient neural processing (1). Optimal childhood cognitive development allows for the improvement and control of abilities within multiple domains, in addition to the successful foundation of the skills required in adulthood (2, 3). Within these domains, there are abilities associated to biological processes that comprise problem solving, immediate learning, and comprehension tasks, known as fluid cognition. Fluid cognition includes tasks related to executive function, attention, cognitive flexibility, working and episodic memory, and processing speed (4). The ability to utilize information that is acquired through experience, cultural exposure,

and education, such as verbal knowledge and language skills, pertains to crystallized cognition (5). Thus, crystallized cognition is associated with long-term abilities, whereas fluid cognitive abilities serve as the building blocks of crystallized cognition.

Moreover, total cognition measures the composite of all neurocognitive abilities, which is important to understand adaptative functioning during childhood and across the life span (6).

Cognition is a developmental process that can be altered by the interaction of biological, genetic, and environmental factors (7–10). One such factor, obesity, has been associated with poorer cognitive performance and altered brain plasticity across the life span (11, 12). Obesity has also been linked to physiological and psychological consequences, including poor motor function, a higher risk of comorbidities (such as type 2 diabetes mellitus, hypertension, dyslipidemia, and obstructive sleep apnea), and emotional and social difficulties among children and

adolescents (13–16). In the United States, ~18.4% of children aged 6–11 y and 20.6% of children and adolescents aged 12–19 y have been classified with obesity (17). Owing to the deleterious effects of obesity on childhood cognitive development and the growing childhood obesity epidemic in the United States and worldwide, understanding the many elements of obesity's impact on cognition is needed.

Furthermore, obesity is associated with the development of sleep disorders (18). Poor sleep has increasingly become a common problem in children (19). Sleep is critical to supporting several biological functions, including cardiovascular, endocrine, and immune processes (20–22). Neural and cognitive processes, such as learning and memorizing, are directly related to healthy sleep patterns (18). Multiple studies have found that poor sleep patterns compromise cognition and mental health, as well as other developmental processes such as emotional control and metabolic regulation (23–25). Previous studies have examined the relation between obesity, obstructive sleep apnea, and executive function and attention, but findings have been inconclusive. This may be due to important study limitations including small sample sizes, lack of adjustment for confounders, as well as the inability to test for interaction and/or mediation effects (26–28).

Considering that previous studies have been limited to focusing on specific sleep disorders and cognitive tasks, this study examines the role of overall sleep disturbances in the association between obesity and 1) total, 2) crystallized, and 3) fluid cognition. Specifically, this study sought to understand the potential mediation effect of sleep disturbances on the obesity–cognition pathway.

Methods

Participants

This cross-sectional analysis included a total of 9951 children aged 9–10 y from the ABCD (Adolescent Brain Cognitive Development) Study, a longitudinal and demographically diverse data set with >11,800 children, recruited from 21 centers across the United States. Children were recruited through the school system, mailing lists at the catchment areas, enrollment of affiliates, referrals, and summer recruitment (29). The sampling scheme included considerations of age, gender, race, socioeconomic status, and urbanicity to reflect the distribution of the US population. The ABCD Study design and recruitment details are described elsewhere (29). For the analysis, children with missing data ($n = 1924$) and/or implausible values (BMI z score > 5 , after reviewing height and weight values; $n = 6$) were excluded. This study received approval from the Indiana University Institutional Review Board.

Weight status

BMI (in kg/m^2) was calculated for each child by dividing their weight in kilograms by their squared height in meters. WHO Anthro-plus was used to calculate the BMI-for-age and gender z scores (SD scores) (30, 31). Following the WHO recommendations, BMI-for-age was then categorized based on the z score cutoffs of < -2.0 , > 1.0 , and > 2.0 to classify children as underweight, overweight, and obese, respectively (32).

Sleep disturbances

Sleep disturbances were assessed using the Sleep Disturbance Scale for Children and were reported by parents. The Sleep Disturbance Scale

for Children is a questionnaire designed to categorize sleep disorders. It includes 27 items, each rated on a 5-point Likert scale. These 27 items score 5 subdomains that include disorders of initiating and maintaining sleep, disorders of sleep somnolence, sleep breathing disorders, sleep-wake transition disorders, disorders of arousal, and sleep hyperhydrosis (33). The analysis focused on the sleep disturbance total score, which ranges from 26 to 130 points [based on the Sleep Disturbance Scale for Children punctuation system (1–5)], and summed the scores of all subdomains.

Cognitive function

The ABCD Study has a detailed neurocognitive battery that includes visual acuity, handedness, laterality, and neurocognitive development (34, 35). This study was focused on the neurocognitive development area, i.e., the scores of the cognitive tests that comprised the NIH Toolbox. The NIH Toolbox was used to determine cognitive functionality (36, 37). The NIH Toolbox consists of 7 cognitive tasks which cover the 6 cognitive domains: episodic memory (Picture Sequence Memory task), executive function (Flanker Inhibitory Control and Attention, Dimensional Change Card Sort tasks), attention (Flanker Inhibitory Control and Attention task), working memory (List Sorting Working Memory task), processing speed (Pattern Comparison Processing Speed task), and language abilities (Picture Vocabulary, Oral Reading Recognition tasks) (34, 35). The tasks were scored and used to generate 3 composite scores: fluid, crystallized, and total cognitive abilities (6). Fluid cognition includes 5 domains: episodic memory, executive function, attention, working memory, and processing speed; whereas crystallized cognition is particularly focused on language abilities.

For this analysis, the age-corrected cognitive scores available in the ABCD Study data set were used. The age-corrected standard scores, derived from a normative sample of 2917 children and adolescents, account for the performance of individuals in the same age group, and consider the effect of age, as the neurodevelopmental stages change during childhood (38).

Potential confounders

Based on previous literature, several potential confounders were included in the analysis (39, 40). More specifically, sex (female and male), age (as a continuous variable; mo), race [white, black, and other races (including Native American, Pacific Islanders, Asians, and others)], combined household income (categorized as $\leq \$15,999$; $\$16,000$ – $\$34,999$; $\$34,500$ – $\$49,999$; $\$50,000$ – $\$74,999$; $\$75,000$ – $\$99,999$; $\$100,000$ – $\$199,999$; and $\geq \$200,000$), parental education (categorized as less than high school degree; completed high school/General Educational Development; some college; undergraduate/occupational degree; graduate degree), and self-reported physical activity (as the number of days that the participant was active for ≥ 60 min/d) were included in the analyses.

Statistical analysis

A mediation analysis was conducted to determine whether sleep disturbances mediate the relation between BMI and cognitive function. Figure 1 shows a direct acyclic graph of the hypothesized relation. Potential mediation effects were assessed using the multivariate linear regression methods described by Baron and Kenny (41). Modeling included 1) BMI on cognitive function (separately modeled for the

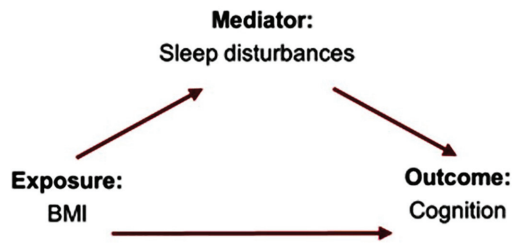


FIGURE 1 Direct acyclic graph of the potential mediation effect of sleep disturbances on the association between BMI and cognition composite scores.

total, fluid, and crystallized composite scores); 2) BMI on the sleep disturbances total score; and 3) a regression of the 3 cognitive composite scores on the sleep disturbances total score. In addition, it was determined whether the sleep disturbances total score was a significant mediator of cognitive function in the full model (including BMI). Covariate significance was assessed through a backward elimination stepwise regression. All potential confounders, including age, sex, physical activity, family income, parents' education, and race, were included as significant covariates in the full-sample and stratified models. Descriptive statistical analyses were performed for these covariates. A chi-square test was applied for the categorical covariates and a one-way ANOVA was applied for the continuous covariates. All analyses were conducted in R version 3.6.0, using the "mediation" package (42, 43). The mediation significance was assessed with the Hayes and Preacher method by bootstrapping (44), with 1000 simulation samples used to generate 95% CIs for the indirect effect [average causal mediator effect (ACME)] and the average direct effect (ADE). Standardized regression coefficients and their corresponding 95% CIs were reported in this study.

Results

A total of 9951 children were included in the analysis. **Table 1** shows the demographic characteristics of the sample. Mean \pm SD age in the overall sample was 9.91 ± 0.62 y, with statistically significant differences between BMI categories. In this analysis, 52.23% of the participants were male and 66.2% of the children in the overall sample were identified as white; however, distribution by BMI categories varied between sex and race ($P < 0.01$). Children with normal BMI (≤ 1 SD) had a higher mean number of hours spent in physical activity than children with overweight or obesity ($P < 0.01$). Statistically significant differences were also found regarding family income and parents' education between BMI categories ($P = 0.69$ and $P = 0.37$, respectively). Compared with children with a normal BMI, children with overweight (>1 SD to ≤ 2 SD) or obesity (>2 SD) had a statistically significantly higher total score in sleep disturbances. Cognition scores were statistically higher in children with normal BMI than in children with overweight and obesity ($P < 0.01$).

This analysis explored the association of BMI with total, fluid, and crystallized cognition, and the effect of sleep disturbances as a mediator. **Table 2** shows these results. In the preliminary analysis, it was found that higher BMI was positively associated with sleep disturbances. After adjusting for potential confounders, attenuated inverse statistically

significant associations of BMI with fluid cognition and total cognition were found. When sleep disturbances total score was included in the model, no mediation effect was found in the associations of BMI with total and crystallized cognition, but a small partial mediation effect of sleep disturbance was found in the association between BMI and fluid cognition. Sleep disturbances had an ACME of -0.02 ($P < 0.01$) and an ADE of -0.46 ($P < 0.01$) on the association between BMI and fluid cognition, and the proportion of the total effect caused by sleep disturbances was 0.05 ($P < 0.01$). **Figure 2** shows the mediation significance of sleep disturbances in the overall sample.

Discussion

A statistically significant, although partial, mediation effect of sleep disturbances on the association between BMI and fluid cognition was found. There was no significant mediation for total or crystallized cognition. These results can be explained by the influence of biological and external factors on fluid cognition, which comprise a series of cognitive processes that develop during late childhood. Fluid cognition is sensitive to changes in neurobiological integrity and other factors, such as sleep quality and weight status, which can alter the brain structure and its function (6). Previous studies have shown that obesity was associated with the impairment of inhibition, cognitive flexibility, working memory, and planning. Incremental increases in BMI have been associated with a decline in individual cognitive performance among both children and adults (45–49). Moreover, neuroimaging literature has shown that an increased BMI is associated with reduced cortical thickness in the prefrontal region, which is involved in fluid cognition, and with lower executive function, processes involved in fluid cognition (39, 50). In addition, sleep quality and quantity are also linked to metabolic and endocrine disorders affected by obesity (39, 50–53). The quality and quantity of sleep are fundamental for memory consolidation, and sleep deprivation can affect the brain's reaction time and information processing (36). Poor sleep can negatively affect cognitive processes related to fluid cognition that include learning, cognitive performance, IQ measures, and self-regulatory abilities (54–56). These findings align with the results presented in the current study, suggesting the importance of sleep disturbances for fluid cognition. Moreover, the results in this analysis support and complement the evidence found in a recent study conducted with the ABCD data set, which found that fewer hours of sleep were related to reduced fluid cognition in children (57).

Finally, the results in this study are supported by previous studies that have explored the BMI, sleep, and cognition axis. A previous small-sample study showed that apnea, a specific sleep disturbance, can worsen the effect of obesity on cognitive function, particularly mental processing (58). In addition, other studies have shown that worse sleep behaviors are associated with reduced gray matter volume and cognitive performance (59, 60). One advantage of the present study is that it incorporates several types of sleep disturbances in the analysis, which strengthen the findings from previous studies.

This study has several limitations that may limit the interpretation of our findings. First, the cross-sectional study design does not permit the examination of causal relations owing to the lack of temporality, owing to measurement of the exposure and outcome at the same time point, and not measuring the exposure before the occurrence of the outcome.

TABLE 1 Descriptive characteristics of the ABCD (Adolescent Brain Cognitive Development) Study participants¹

	Overall (n = 9951)	BMI-for-age SD scores			P value
		≤1 SD (n = 6208)	>1 SD to ≤2 SD (n = 2005)	>2 SD (n = 1738)	
Age, mo	118.96 ± 7.43	119.12 ± 7.45	118.78 ± 7.43	118.57 ± 7.35	0.01
Physical activity, d	3.55 ± 2.31	3.68 ± 2.31	3.46 ± 2.29	3.20 ± 2.29	<0.01
Sex					<0.01
Male	5197 (52.23)	3178 (51.19)	1047 (52.22)	972 (55.93)	
Female	4754 (47.77)	3030 (48.81)	958 (47.78)	766 (44.07)	
Race					<0.01
Black	1434 (14.41)	674 (10.86)	329 (16.41)	431 (24.80)	
Other white	1928 (19.37)	1132 (18.23)	407 (20.30)	389 (22.38)	
White	6589 (66.21)	4402 (70.91)	1269 (63.29)	918 (52.82)	
Family income, \$					<0.01
≤15,999	960 (9.45)	425 (6.85)	218 (10.87)	317 (18.24)	
16,000–34,999	1047 (10.52)	524 (8.44)	244 (12.17)	279 (16.05)	
35,000–49,999	838 (8.43)	442 (7.12)	208 (10.37)	188 (10.82)	
50,000–74,999	1388 (13.95)	823 (13.26)	287 (14.31)	278 (16.00)	
75,000–99,999	1458 (14.65)	930 (14.98)	297 (14.81)	231 (13.29)	
100,000–199,999	3087 (31.03)	2167 (34.91)	560 (27.93)	360 (20.71)	
≥200,000	1173 (11.79)	897 (14.45)	191 (9.53)	85 (4.89)	
Parental education					<0.01
Less than high school	507 (5.09)	224 (3.61)	120 (5.98)	163 (9.38)	
High school	941 (9.46)	451 (7.26)	192 (9.58)	298 (17.15)	
Some college	1602 (16.10)	886 (14.27)	368 (18.35)	348 (20.02)	
College degree	4215 (42.36)	2745 (44.22)	820 (40.90)	650 (37.40)	
Graduate degree	2686 (26.99)	1902 (30.64)	505 (25.19)	279 (16.05)	
Sleep disturbances total score	36.47 ± 8.04	35.97 ± 7.39	37.17 ± 9.09	37.47 ± 8.82	<0.01
Total cognition score	101.34 ± 17.80	103.20 ± 17.74	99.87 ± 17.46	96.40 ± 17.28	<0.01
Fluid cognition score	96.24 ± 17.27	97.72 ± 17.23	95.10 ± 17.04	92.25 ± 16.96	<0.01
Crystallized cognition score	106.46 ± 18.24	108.07 ± 18.40	105.14 ± 17.85	102.22 ± 17.25	<0.01

¹Values are mean ± SD or n (%) unless indicated otherwise. P values are for any difference across race (white, African American, and other races) using ANOVA or chi-square test, as appropriate.

Second, sleep disturbances were collected through the widely used Sleep Disturbance Scale for Children. Nonetheless, the sleep outcomes might be underestimated because the scale was based on parental report and not clinical measurements. In addition, the use of gold-standard techniques for body composition, such as DXA, was unavailable. However, BMI is a valid surrogate estimate that allows a representation of the population weight distribution in large samples, like the ABCD Study. Furthermore, this analysis was developed with the baseline measurements of the ABCD Study. The baseline sample only included children aged 9–10 y, which limits the generalizability of the results beyond these ages. In addition, nutrient and energy intake measurements were not available in the baseline data set, which limits the potential adjustment for energy and nutrient intakes. Other potential confounders such as caffeine were not included in the study, because the available information was

not detailed enough and could potentially have introduced bias into the analysis. Finally, physical activity was self-reported in this data release, which could potentially have created report bias.

This analysis suggests that sleep disturbances partially mediate the effect of childhood obesity on cognitive function, particularly as it pertains to fluid cognition. Future work is needed to understand the effects of sleep disturbances and obesity on reduced childhood cognition over time, predominantly across the life course, and particularly on fluid cognition.

Fluid cognition is critical for neurodevelopment. The fluid abilities developed during childhood support crystallized cognition. During childhood, individuals acquire the knowledge that is needed for long-term memory, message decoding, and comprehension, which are abilities that are fundamental in life. Understanding the effect of sleep

TABLE 2 β Coefficients from the linear regression approach for the mediation effect of sleep disturbances in the association of BMI and cognitive scores¹

Sample	Cognitive test	Exposure to mediator (β, α)	Exposure to outcome (β, α)	Mediator to outcome (β, α)	Exposure to outcome, adjusted by mediator (β, α)
Total sample	Fluid cognition	0.38 (<0.001)	−0.49 (<0.01)	−0.07 (<0.01)	−0.47 (<0.01)
	Crystallized cognition		−0.20 (0.12)	0.05 (0.01)	−0.21 (0.09)
	Total cognition		−0.41 (<0.01)	−0.01 (0.71)	−0.41 (<0.01)

¹All models were adjusted for age, sex, physical activity, family income, parents' education, and race.

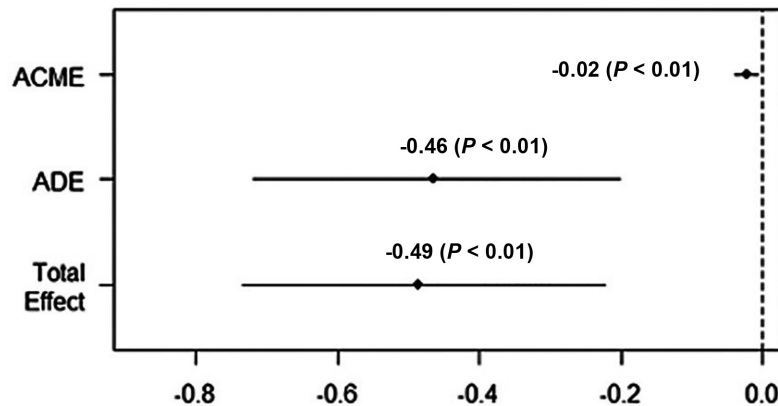


FIGURE 2 Sleep disturbances' mediation significance in the association between BMI and fluid cognition, for the overall sample. ACME, average causal mediation effect/indirect effect; ADE, average direct effect.

disturbance patterns in the association between obesity and fluid cognition in childhood may lead to appropriate interventions to improve the developmental conditions that could enhance neurodevelopment in children.

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Data Availability

The data that support this study are openly available in the National Institute of Mental Health Data Archive (NDA). The ABCD Study data repository will grow and change over time.

References

1. Stiles J, Brown TT, Haist F, Jernigan TL. Brain and cognitive development. In: Liben LS, Müller U, editors. Handbook of child psychology and

developmental science. Vol. 2, Cognitive processes. 7th ed. Hoboken, NJ: Wiley; 2015. p. 9–62.

- Committee on the Science of Children Birth to Age 8: Deepening and Broadening the Foundation for Success, Board on Children, Youth, and Families, Institute of Medicine, National Research Council, Allen LR, Kelly BB, editors. Transforming the workforce for children birth through age 8: a unifying foundation. Washington (DC): National Academies Press (US); Child Development and Early Learning; 2015.
- Carson V, Hunter S, Kuzik N, Wiebe SA, Spence JC, Friedman A, Tremblay MS, Slater L, Hinkley T. Systematic review of physical activity and cognitive development in early childhood. *J Sci Med Sport* 2016;19(7): 573–8.
- Garon N, Bryson SE, Smith IM. Executive function in preschoolers: a review using an integrative framework. *Psychol Bull* 2008;134(1): 31–60.
- Tomasello M. Language development. In: Goswami U, editor. The Wiley-Blackwell handbook of childhood cognitive development. 2nd ed. Hoboken, NJ: Wiley-Blackwell; 2010. p. 239–57.
- Akshoomoff N, Beaumont JL, Bauer PJ, Dikmen SS, Gershon RC, Mungas D, Slotkin J, Tulskey D, Weintraub S, Zelazo PD, et al. NIH Toolbox Cognition Battery (CB): composite scores of crystallized, fluid, and overall cognition. *Monogr Soc Res Child Dev* 2013;78(4):119–32.
- Briley DA, Tucker-Drob EM. Comparing the developmental genetics of cognition and personality over the life span. *J Pers* 2017;85(1): 51–64.
- Mollon J, Knowles EEM, Mathias SR, Gur R, Peralta JM, Weiner DJ, Robinson EB, Gur RE, Blangero J, Almasy L, et al. Genetic influence on cognitive development between childhood and adulthood. *Mol Psychiatry* 2021;26(2):656–65.
- MAL-ED Network Investigators. Early childhood cognitive development is affected by interactions among illness, diet, enteropathogens and the home environment: findings from the MAL-ED birth cohort study. *BMJ Glob Health* 2018;3(4):e000752.
- Georgieff MK. Nutrition and the developing brain: nutrient priorities and measurement. *Am J Clin Nutr* 2007;85(2):614S–20S.
- Prickett C, Brennan L, Stolwyk R. Examining the relationship between obesity and cognitive function: a systematic literature review. *Obes Res Clin Pract* 2015;9(2):93–113.
- Wang C, Chan JSY, Ren L, Yan JH. Obesity reduces cognitive and motor functions across the lifespan. *Neural Plast* 2016;2473081.
- Kyrou I, Randeve HS, Tsigos C, Kaltsas G, Weickert MO. Clinical problems caused by obesity. In: Feingold KR, Anawalt B, Boyce A, Chrousos G, de Herder WW, Dhatariya K, Dungan K, Grossman A, Hershman JM, Hofland J, et al. editors. Endotext [Internet]. South Dartmouth, MA: MDText.com, Inc.; 2000. [cited 20 June, 2021] Available from: <https://www.ncbi.nlm.nih.gov/books/NBK278973/>.

14. Rankin J, Matthews L, Cobley S, Han A, Sanders R, Wiltshire HD, Baker JS. Psychological consequences of childhood obesity: psychiatric comorbidity and prevention. *Adolesc Health Med Ther* 2016;7:125–46.
15. Pulgarón ER. Childhood obesity: a review of increased risk for physical and psychological comorbidities. *Clin Ther* 2013;35(1):A18–32.
16. Kumar S, Kelly AS. Review of childhood obesity: from epidemiology, etiology, and comorbidities to clinical assessment and treatment. *Mayo Clin Proc* 2017;92(2):251–65.
17. CDC. Promoting health for children and adolescents [Internet]. Atlanta, GA: CDC; c2020 [cited 20 June, 2021]. Available from: .
18. Bonanno L, Metro D, Papa M, Finzi G, Maviglia A, Sottile F, Corallo F, Manasseri L. Assessment of sleep and obesity in adults and children: observational study. *Medicine (Baltimore)* 2019;98(46):e17642.
19. Miller AL, Lumeng JC, LeBourgeois MK. Sleep patterns and obesity in childhood. *Curr Opin Endocrinol Diabetes Obes* 2015;22(1):41–7.
20. Besedovsky L, Lange T, Born J. Sleep and immune function. *Pflügers Arch* 2012;463(1):121–37.
21. Thosar SS, Butler MP, Shea SA. Role of the circadian system in cardiovascular disease. *J Clin Invest* 2018;128(6):2157–67.
22. Morris CJ, Aeschbach D, Scheer FA. Circadian system, sleep and endocrinology. *Mol Cell Endocrinol* 2012;349(1):91–104.
23. Short MA, Blunden S, Rigney G, Matricciani L, Coussens S, Reynolds CM, Galland B. Cognition and objectively measured sleep duration in children: a systematic review and meta-analysis. *Sleep Health* 2018;4(3):292–300.
24. Philbrook LE, Hinnant JB, Elmore-Staton L, Buckhalt JA, El-Sheikh M. Sleep and cognitive functioning in childhood: ethnicity, socioeconomic status, and sex as moderators. *Dev Psychol* 2017;53(7):1276–85.
25. El-Sheikh M, Philbrook LE, Kelly RJ, Hinnant JB, Buckhalt JA. What does a good night's sleep mean? Nonlinear relations between sleep and children's cognitive functioning and mental health. *Sleep* 2019;42(6):zsz078. Erratum in: *Sleep* 2019;42(12):zsz195.
26. Watach AJ, Radcliffe J, Xanthopoulos MS, Novick MB, Sawyer AM. Executive function impairments in adolescents with obesity and obstructive sleep apnea syndrome. *Biol Res Nurs* 2019;21(4):377–83.
27. Xanthopoulos MS, Gallagher PR, Berkowitz RI, Radcliffe J, Bradford R, Marcus CL. Neurobehavioral functioning in adolescents with and without obesity and obstructive sleep apnea. *Sleep* 2015;38(3):401–10.
28. Tan E, Healey D, Schaughency E, Dawes P, Galland B. Neurobehavioural correlates in older children and adolescents with obesity and obstructive sleep apnoea. *J Paediatr Child Health* 2014;50(1):16–23.
29. Garavan H, Bartsch H, Conway K, Decastro A, Goldstein RZ, Heeringa S, Jernigan T, Potter A, Thompson W, Zahs D. Recruiting the ABCD sample: design considerations and procedures. *Dev Cogn Neurosci* 2018;32:16–22.
30. World Health Organization. Growth reference data for 5–19 years [Internet]. Geneva, Switzerland: WHO; 2009. [cited 20 June, 2021]. Available from: <http://www.who.int/growthref/tools/en/>.
31. de Onis M, Blössner M. The World Health Organization Global Database on Child Growth and Malnutrition: methodology and applications. *Int J Epidemiol* 2003;32(4):518–26.
32. de Onis M, Lobstein T. Defining obesity risk status in the general childhood population: which cut-offs should we use? *Int J Pediatr Obes* 2010;5(6):458–60.
33. Bruni O, Ottaviano S, Guidetti V, Romoli M, Innocenzi M, Cortesi F, Giannotti F. The Sleep Disturbance Scale for Children (SDSC). Construction and validation of an instrument to evaluate sleep disturbances in childhood and adolescence. *J Sleep Res* 1996;5(4):251–61.
34. Luciana M, Bjork JM, Nagel BJ, Barch DM, Gonzalez R, Nixon SJ, Banich MT. Adolescent neurocognitive development and impacts of substance use: overview of the adolescent brain cognitive development (ABCD) baseline neurocognition battery. *Dev Cogn Neurosci* 2018;32:67–79.
35. Lisdahl KM, Sher KJ, Conway KP, Gonzalez R, Feldstein Ewing SW, Nixon SJ, Tapert S, Bartsch H, Goldstein RZ, Heitzeg M. Adolescent brain cognitive development (ABCD) study: overview of substance use assessment methods. *Dev Cogn Neurosci* 2018;32:80–96.
36. Weintraub S, Dikmen SS, Heaton RK, Tulsky DS, Zelazo PD, Bauer PJ, Carlozzi NE, Slotkin J, Blitz D, Wallner-Allen K, et al. Cognition assessment using the NIH Toolbox. *Neurology* 2013;80(11 Supplement 3):S54–64.
37. Weintraub S, Dikmen SS, Heaton RK, Tulsky DS, Zelazo PD, Slotkin J, Carlozzi NE, Bauer PJ, Wallner-Allen K, Fox N, et al. The cognition battery of the NIH toolbox for assessment of neurological and behavioral function: validation in an adult sample. *J Int Neuropsychol Soc* 2014;20(6):567–78.
38. Casaletto KB, Umlauf A, Marquine M, Beaumont JL, Mungas D, Gershon R, Slotkin J, Akshoomoff N, Heaton RK. Demographically corrected normative standards for the Spanish language version of the NIH Toolbox Cognition Battery. *J Int Neuropsychol Soc* 2016;22(3):364–74.
39. Ronan L, Alexander-Bloch A, Fletcher PC. Childhood obesity, cortical structure, and executive function in healthy children. *Cereb Cortex* 2020;30(4):2519–28.
40. Pearce AL, Mackey E, Nadler EP, Vaidya CJ. Sleep health and psychopathology mediate executive deficits in pediatric obesity. *Child Obes* 2018;14(3):189–96.
41. Baron RM, Kenny DA. The moderator–mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. *J Pers Soc Psychol* 1986;51(6):1173–82.
42. R Core Team. R: a language and environment for statistical computing [Internet]. Version 3.6.0 [Software]. Vienna, Austria: R Foundation for Statistical Computing; 2020. Available from: <https://www.R-project.org/>.
43. Tingley D, Yamamoto T, Hirose K, Keele L, Imai K. Mediation: R package for causal mediation analysis. Version 4.5.0 [Software]. *J Stat Soft* 2014;59(5):1–38.
44. Hayes AF. Beyond Baron and Kenny: statistical mediation analysis in the new millennium. *Commun Monogr* 2009;76(4):408–20.
45. Yang Y, Shields GS, Guo C, Liu Y. Executive function performance in obesity and overweight individuals: a meta-analysis and review. *Neurosci Biobehav Rev* 2018;84:225–44.
46. Liang J, Matheson BE, Kaye WH, Boutelle KN. Neurocognitive correlates of obesity and obesity-related behaviors in children and adolescents. *Int J Obes* 2014;38(4):494–506.
47. Bocarsly ME, Fasolino M, Kane GA, LaMarca EA, Kirschen GW, Karatsoreos IN, McEwen BS, Gould E. Obesity diminishes synaptic markers, alters microglial morphology, and impairs cognitive function. *Proc Natl Acad Sci U S A* 2015;112(51):15731–6.
48. Vainik U, Dagher A, Dubé L, Fellows LK. Neurobehavioural correlates of body mass index and eating behaviours in adults: a systematic review. *Neurosci Biobehav Rev* 2013;37(3):279–99.
49. Smith E, Hay P, Campbell L, Trollor JN. A review of the association between obesity and cognitive function across the lifespan: implications for novel approaches to prevention and treatment. *Obes Rev* 2011;12(9):740–55.
50. Laurent JS, Watts R, Adise S, Allgaier N, Chaarani B, Garavan H, Potter A, Mackey S. Associations among body mass index, cortical thickness, and executive function in children. *JAMA Pediatr* 2020;174(2):170–7.
51. Garaulet M, Ortega FB, Ruiz JR, Rey-López JP, Béghin L, Manios Y, Cuenca-García M, Plada M, Diethelm K, Kafatos A, et al. Short sleep duration is associated with increased obesity markers in European adolescents: effect of physical activity and dietary habits. The HELENA study. *Int J Obes* 2011;35(10):1308–17.
52. Yoong SL, Chai LK, Williams CM, Wiggers J, Finch M, Wolfenden L. Systematic review and meta-analysis of interventions targeting sleep and their impact on child body mass index, diet, and physical activity. *Obesity* 2016;24(5):1140–7.
53. Aldabal L, Bahammam AS. Metabolic, endocrine, and immune consequences of sleep deprivation. *Open Respir Med J* 2011;5(1):31–43.
54. Hill CM, Hogan AM, Karmiloff-Smith A. To sleep, perchance to enrich learning? *Arch Dis Child* 2007;92(7):637–43.
55. Bernier A, Beauchamp MH, Bouvette-Turcot AA, Carlson SM, Carrier J. Sleep and cognition in preschool years: specific links to executive functioning. *Child Dev* 2013;84(5):1542–53.
56. Ravid S, Afek I, Suraiya S, Shahar E, Pillar G. Sleep disturbances are associated with reduced school achievements in first-grade pupils. *Dev Neuropsychol* 2009;34(5):574–87.

57. Kirlic N, Colaizzi JM, Cosgrove KT, Cohen ZP, Yeh H-W, Breslin F, Morris AS, Aupperle RL, Singh MK, Paulus MP. Extracurricular activities, screen media activity, and sleep may be modifiable factors related to children's cognitive functioning: evidence from the ABCD Study®. *Child Dev* 2021;92(5):2035–52.
58. Spruyt K, Gozal D. A mediation model linking body weight, cognition, and sleep-disordered breathing. *Am J Respir Crit Care Med* 2012;185(2):199–205.
59. Migueles JH, Martinez-Nicolas A, Cadenas-Sanchez C, Esteban-Cornejo I, Muntaner-Mas A, Mora-Gonzalez J, Rodriguez-Ayllon M, Madrid JA, Rol MA, Hillman CH, et al. Activity-rest circadian pattern and academic achievement, executive function, and intelligence in children with obesity. *Scand J Med Sci Sports* 2021;31(3):653–64.
60. Migueles JH, Cadenas-Sanchez C, Esteban-Cornejo I, Mora-Gonzalez J, Rodriguez-Ayllon M, Solis-Urra P, Erickson KI, Kramer AF, Hillman CH, Catena A, et al. Associations of sleep with gray matter volume and their implications for academic achievement, executive function and intelligence in children with overweight/obesity. *Pediatr Obes* 2021;16(2):e12707.
61. ABCD Consortium. Adolescent Brain Cognitive DevelopmentSM (ABCD) Study, ABCD consortium, 2019 [Internet]. Curated Annual Release 2.0, NIMH Data Archive. NIMH Data Archive 2019 [cited 20 June, 2021]. Available from: <https://nda.nih.gov/abcd>