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Research article

Eating behavior-mediated association between attention deficit hyperactivity disorder and body fat mass

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A R T I C L E I N F O

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A B S T R A C T

Background: Adverse eating behaviors and a high rate of obesity have been identified among children diagnosed with attention deficit hyperactivity disorder (ADHD). In this study, we investigate the relationships between eating behaviors and body fat mass among children with ADHD.
Methods: All participants were recruited from the Children's Health Care Department of the Children's Hospital of Nanjing Medical University from June 2019 to June 2020. ADHD was diagnosed according to the diagnostic criteria of the 5th edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) by psychiatrists. Core ADHD symptoms defined by the DSM-5 were inattention and hyperactivity/impulsivity. The anthropomorphic indices defined by the World Health Organization (WHO) were utilized in this study (body mass index [BMI], underweight, normal body mass, overweight, obesity, short stature). Body fat mass, fat mass percentage (FM%), skeletal muscle mass, skeletal muscle mass percentage (SMM%) were tested via body composition meter, and eating behaviors were assessed by parents using the Chinese version of the Children's Eating Behavior Questionnaire (CEBQ). The CEBQ was comprised of subscales related to food avoidant behaviors (satiety responsiveness, slowness in eating, fussiness, and emotional undereating) and food approach behaviors (food responsiveness, enjoyment of Food, desire to drink, and emotional overeating). The associations among ADHD, obesity and adverse eating behavior were tested through correlation analysis, and a mediating effect model was established to explore the effect of eating behaviors.
Results: A total of 548 participants aged 4–12 years were recruited. Among them, 396 were diagnosed with ADHD, with the remaining 152 enrolled in a control group. Compared with the control group, the ADHD group had higher incidences of overweight (22.5% vs. 14.5%) and obesity (13.4% vs. 8.6%) ($p < 0.05$). The ADHD group was more likely to display "slowness in eating" (11.01 ± 3.32 vs. 9.74 ± 2.95), "fussiness" (15.61 ± 3.54 vs. 15.03 ± 2.84), "food responsiveness" (11.96 ± 4.81 vs. 9.88 ± 3.71) and "desire to drink" (8.34 ± 3.46 vs. 6.58 ± 2.72) ($p < 0.05$). Moreover, The FM% of children with ADHD was positively correlated with inattention ($\beta = 0.336$, 95% *CI*: 0.001 to 0.673) and "food responsiveness" ($\beta = 0.509$, 95% *CI*: 0.352 to 0.665) in the multiple linear regression model. The mediation effect model showed that "food responsiveness" accounted for a significant portion (64.2%) of the mediating effect.

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Conclusion: Children with ADHD had higher prevalence of overweight and obesity. As an important risk factor, food responsiveness may connect core symptoms of ADHD with obesity.

1. Introduction

Attention deficit hyperactivity disorder (ADHD) is a common neurodevelopmental disorder with a prevalence of 2–7% around the world [1]. In China, about 5.70–6.26% of children are diagnosed with ADHD depending on different investigation reports [2]. The core symptoms of ADHD may persist into adolescence, and 30–70% of participants still have significant symptoms even in adulthood [3]. At present, the mechanism of ADHD is not very clear. Neurobiochemical studies have confirmed the presence of dopamine dysfunction in children with ADHD, that is, a low level of dopamine in the brain leads to inattention, hyperactivity, and impulsive behavior [4]. Eating behaviors in childhood are significant for children to obtain adequate nutrition for growth and development, while adverse eating behaviors may lead to underweight, overweight, or obesity [5]. More than 50% of children with ADHD have adverse eating behaviors, such as picky eating, long duration of eating, and emotional eating [6]. Rios-Hernandez et al. found excessive consumption of sweeteners, candies, and soft drinks, together with low intake of fat-rich fish by children with ADHD [7]. A study with a large sample of children aged 5–12 years revealed that more than 40% of those with ADHD exhibited binge-eating behaviors at least once a week [8]. Children with ADHD and adverse eating behaviors also have a higher risk of disordered eating as they enter adulthood [9]. There is evidence that inattention among children diagnosed with ADHD may lead to excessive fidgeting during mealtimes, which would lengthen eating time and slow down eating [10]. Behavioral problems, such as hyperactivity and impulsivity among children with ADHD, can trigger emotional or binge eating [11]. Furthermore, the prevalence of obesity among adolescents with ADHD is significantly higher than that in among adolescents without ADHD [12]. Other studies have also shown that overweight and obese children with ADHD are more prone to food preference and responsiveness [8]. Therefore, the clinical treatment of ADHD should focus not only on the core symptoms of ADHD, but also on adverse eating behaviors.

In recent years, growth deviation in children with ADHD has attracted the attention of clinicians and scholars. The incidence of obesity in these children is higher than that in the general population. Obesity not only increases the risk of hypertension and hyperglycemia, but may also impair psychosocial behaviors, such as recreation or communication with family members and friends [12, 13]. A meta-analysis showed that participants with ADHD who received medication had a lower prevalence of obesity than those who did not, which may be related to the appetite-suppressing effects of central stimulants [12]. In addition, about 10% of children with ADHD developed short stature in early adolescence, compared to 1% in the control group [14].

Therefore, we hypothesized that adverse eating behaviors might accompany with children with ADHD and exert adverse effects on their body weight and height. We also hypothesized that the clinical symptoms of ADHD might in turn aggravate adverse eating behaviors. We investigated the clinical characteristics of children with ADHD, including ADHD-related symptoms, nutritional status, and eating behaviors, in an effort to delineate the relationships among ADHD, overweight/obesity and eating behaviors.

2. Methods

2.1. Participants and procedures

Research team included pediatricians, psychiatrists, technicians, and dietitians who were responsible for participant counseling, questionnaires, physical examinations, dietary surveys, dietary behavior assessments, respectively. A psychiatrist determines and rules out the diagnosis of ADHD based on all reports and DSM-5.

2.1.1. Participants and inclusion criteria

Participants aged 4–12 years were recruited from the Department of Children's Health Care of the Children's Hospital of Nanjing Medical University from June 2019 to June 2020. Preschool children aged 3–5 years, and school-age children aged 6–12 years. Included in the ADHD group were those who: (1) met the diagnostic criteria for ADHD in the 5th edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5); (2) were not taking any ADHD-related medications, psychotropic or hormone drugs by psychiatrists interviewing their parents; (3) were in the company of their parents, and both children and parents were willing to cooperate and follow relevant regulations; and (4) were able to fill out the questionnaires, read and understand Chinese, and communicate normally. Exclusion criteria included: (1) developmental delay; and (2) ADHD symptoms caused by organic diseases or drugs (e.g., hyperthyroidism, epilepsy); Other comorbidities of ADHD were not exclusion criteria. The control group included healthy children who did not meet the DSM-5 diagnostic criteria for ADHD according to the results of physical and psychological examinations. The study was approved by the Medical Ethics Committee of the Children's Hospital of Nanjing Medical University. The children and their parents voluntarily participated in this study and the parents signed informed consent forms.

2.1.2. Diagnosis of ADHD and comorbidities

After interviewing the children and their parents, psychiatrists made the clinical diagnosis based on the diagnostic criteria for ADHD and comorbidities in the DSM-5 [15]. In the DSM-5 scoring system, there were 9 items for inattention and 9 items for hyperactivity and impulsivity. Each item scored "1" for "yes" or "0" for "no". Inattention and/or hyperactivity and impulsivity were diagnosed when the score was 6 or more, and the symptoms should last for 6 months or longer.

2.1.3. Anthropometric measures

The technician measured the children's body height and weight. BMI was calculated by dividing body weight (in kilograms) by the square of height (in meters). BMI standard deviation score (BMI-SDS) was calculated according to the guidelines of the World Health Organization (WHO) [16]. Short stature (Height–SDS ≤ -2), underweight (BMI–SDS ≤ -2), normal weight ($-2 <$ BMI-SDS <1), overweight ($1 \leq$ BMI-SDS <2), and obese (BMI-SDS ≥ 2) were defined according to the WHO Child Growth Standards [16]. Body fat mass (FM) and fat mass percentage (FM%), skeletal muscle mass (SMM) and skeletal muscle mass percentage (SMM%) were calculated using a body composition meter (InBody J20, Biospace, Korea) [17].

2.1.4. Children's eating behavior questionnaire (CEBQ)

The CEBQ, developed by Jane Wardle et al., in 2001, has been widely used to evaluate the eating behaviors of children aged 2–13 years. Surveys based on the CEBQ have achieved good internal consistency and test-retest reliability and reasonable structural validity [18,19]. The Chinese version of the CEBQ has good retest reliability (74–91%) and reasonable structural validity (52–64%) [20]. The CEBQ includes 35 items covering eight dimensions: "satiety responsiveness (SR)", "slowness in eating (SE)", "fussiness (FU)", "emotional undereating (EU)", "food responsiveness (FR)", "enjoyment of food (EF)", "desire to drink (DD)", and "emotional overeating (EO)". The first four subscales (SR, SE, FU and EU) are "food-avoidant" subscales related to negative inclinations to food intake while the other four subscales (FR, EF, DD and EO) are considered as "food-approach" subscales that indicate positive inclinations for eating. Each item in the CEBQ scored 1, 2, 3, 4, or 5, indicating "never", "occasionally", "sometimes", "often", and "always", respectively. In this study, the psychiatrists explained the questionnaire to the parents before the parents completed it. Table 1 presents the dimensions and their associated items.

2.1.5. Covariates

The demographic information was collected through a self-designed questionnaire and included participants' gender, age, date of birth, daily screen time, parents' education level, annual family income.

The weight and height of parents were measured by the technician as well. Parents' BMIs were calculated and grouped into four

Table 1
Children's eating behavior questionnaire (CEBQ) items.

Food avoidant behaviors	Items
Satiety responsiveness (SR)	My child gets full easily.
	My child has a big appetite.
	My child leaves food on his/her plate at the end of a meal.
	My child gets full before his/her meal is finished.
	My child cannot eat a meal if he/she has had a snack just before.
Slowness in eating (SE)	My child eats slowly.
	My child takes more than 30 min to finish a meal.
	My child eats more and more slowly during the course of a meal.
	My child finishes his/her meal very quickly.
Fussiness (FU)	My child enjoys tasting new foods.
	My child enjoys a wide variety of foods.
	My child is interested in tasting foods he/she hasn't tasted before.
	My child refuses new foods at first.
	My child decides that he/she doesn't like food, even without tasting it.
	My child is difficult to please with meals
Emotional undereating (EU)	My child eats less when he/she is upset.
	My child eats less when he/she is angry.
	My child eats less when he/she is tired.
	My child eats more when he/she is happy.
Food approach behaviors	
Food responsiveness (FR)	My child's always asking for food.
	If given the chance, my child would always have food in his/her mouth.
	Given the choice, my child would eat most of the time.
	If allowed to, my child would eat too much.
	Even if my child is full, he/she finds room to eat his/her favorite food.
Enjoyment of food (EF)	My child enjoys eating.
	My child loves food.
	My child is interested in food.
	My child looks forward to mealtimes.
Desire to drink (DD)	If given the chance, my child would always be having a drink.
	If given the chance, my child would drink continuously throughout the day.
	My child is always asking for a drink.
Emotional overeating (EO)	My child eats more when anxious.
	My child eats more when annoyed.
	My child eats more when worried.
	My child eats more when s/he has nothing else.

subgroups: underweight (BMI <18.5 kg/m^2), normal weight (18.5 kg/m^2 ≤ BMI <24 kg/m^2), overweight (24 kg/m^2 ≤ BMI <28 kg/m^2), and obese (BMI ≥28 kg/m^2).

2.2. Statistics

EpiData 4.4 was used to input participant information, and data analysis was performed using SPSS 26.0. The Shapiro-Wilk test was used to determine the normality of the data. Normally distributed data were expressed as mean ± standard deviation ($\bar{x}$ ± SD), and the median was used to express the data in non-normal distribution. Independent samples *t*-test was used to compare variables in normal distribution and the Mann-Whitney *U* test was applied to compare variables in non-normal distribution. In addition, the Chi-square test was used to compare the categorical variables. Pearson correlation tests were performed to explore the correlations among eating behavior scores, physical indicators, and DSM-5 scores of participants with ADHD. Partial correlation analysis was employed to control the confounding factors, such as parents' education level, electronic screen time, and annual household income.

Linear and logistic regression models were used to examine the relationships among inattention score, food responsiveness, and FM %. The data for the ADHD group were submitted to a regression model. We estimated the relationship between inattention score and FM% by using the multiple linear regression model adjusted for parents' education level, BMI, and household income. We also investigated the association between food responsiveness and FM% of children with ADHD in a linear and logistic regression model and the association between inattention score and food responsiveness in a regression model adjusted for possible confounding variables. The moderating effect of inattention score on FM% was measured by food responsiveness adjusted models. A two-tailed *p*-value <0.05 was considered statistically significant.

3. Results

3.1. Demographics

A total of 548 participants aged 4–12 years old were recruited. There were 29 pre-school and 367 school-aged children in ADHD group, and 7 pre-school and 145 school-aged children in control group. There were no significant differences in gender, age, and parents' physical status between the two groups ($p > 0.05$). Parents' education level and annual family income in the ADHD group were lower than those in the control group ($p < 0.01$).

The rates of overweight and obesity in the ADHD group were higher than those in the control group (35.9% vs. 23.0%, $p < 0.001$). There was no statistical difference in the rate of short stature and underweight between the two groups ($p > 0.05$). Body composition analysis showed that the ADHD group had a higher FM% and a lower SMM% than the control group ($p < 0.05$). Table 2 presents the descriptive characteristics of the sample.

Table 2
Demographic information and growth status of children in the ADHD and control groups (median [25th, 75th] or x ± S).

Demographic information	Control group (n = 152)	ADHD group (n = 396)	χ^2/t/Z	p
Gender Male (%)	122 (80.3)	331 (83.6)	0.846	0.358
Age (years)	7.8 (7.0,9.2)	7.9 (6.9,9.17)	0.446	0.656
DSM-5				
Inattention score	3.43 ± 1.44	7.19 ± 1.58	−25.526	<0.01
Hyperactivity-impulsivity score	2.32 ± 1.55	5.95 ± 2.44	−20.755	<0.01
Child's screen time (h/d)	1.0 (0.5, 1.5)	1 (0.5, 2.0)	−2.334	0.020
BMI (kg/m^2)	16.00 (14.58, 17.63)	16.60 (15.00, 19.18)	−2.536	0.011
BMI-SDS	0.10 (−0.81, 0.90)	0.42 (−0.52, 1.37)	−2.816	0.005
Child's growth status (%)				
Short stature	1 (0.7)	9 (2.3)	1.599	0.206
Underweight	4 (2.6)	7 (1.8)	0.417	0.519
Normal body mass	113 (74.3)	247 (62.4)	6.981	0.008
Overweight/obese	35 (23.0)	142 (35.9)	8.271	0.004
Body composition analysis				
Body fat percentage (%)	17.05 (13.43, 22.30)	19.05 (13.83, 26.08)	−1.992	0.046
Percentage of skeletal muscle (%)	40.79 (38.58, 43.10)	40.04 (36.70, 42.51)	−2.343	0.019
Father's BMI	24.4 ± 3.47	24.88 ± 3.41	1.986	0.159
Mother's BMI	21.81 ± 3.05	22.36 ± 3.14	3.312	0.069
Father's education level[a]	29/25/79/15	106/122/146/6	36.923	<0.001
Mother's education level[a]	29/34/80/8	89/148/137/7	21.545	<0.001
Annual family income			10.579	0.001
<150,000	78 (53.1)	252 (68.3)		
≥150,000	69 (46.9)	117 (31.7)		

ADHD: attention deficit hyperactivity disorder; *DSM-5*: the 5th edition of the Diagnostic and Statistical Manual of Mental Disorders; *BMI*: body mass index; *BMI- SDS:* BMI Standard deviation score.

[a] Parents' education level (below high school/high school/bachelor's degree/master's degree and above).

3.2. Eating behaviors

Table 3 showed that the ADHD group had higher scores in "slowness in eating", "fussiness" "food responsiveness" and "desire to drink" compared to the control group. There were no differences in satiety responsiveness, emotional undereating, enjoyment of food, or emotional overeating between the two groups.

3.3. Association among ADHD symptoms, obesity and eating behaviors in participants with ADHD

Correlation analysis was conducted for DSM-5 scores, obese indexes, and the eating behavior scores of children with ADHD. As shown in Table 4, the score for "food responsiveness" was positively correlated with the inattention score and the hyperactivity-impulsivity score, and the "desire to drink" score was positively correlated with the hyperactivity-impulsivity score. The score for "slowness in eating" was negatively correlated with BMI-SDS and FM%, and the scores for "food responsiveness" and inattention were positively correlated with FM%. The score for "desire to drink" was not significantly correlated with BMI-SDS and FM%.

3.4. Mediation analysis

The multiple linear regression model showed that the inattention score was significantly associated with FM% in children with ADHD ($\beta = 0.505$, 95% CI: 0.167 to 0.843); this correlation remained in the adjusted model ($\beta = 0.336$, 95% CI: 0.001 to 0.673). See Table 5. In addition, the score for "food responsiveness" among children with ADHD was positively correlated with FM% in both unadjusted model and adjusted models. See Table 6. We also evaluated the mediating effect of "food responsiveness" in order to explore the relationships between inattention score and FM% among children with ADHD. Inattention score modulated "food responsiveness" but did not influence FM% directly ($\beta = 0.138$, 95% CI: 0.107 to 0.460) after adjusting "food responsiveness". "Food responsiveness" influenced FM% indirectly ($\beta = 0.218$, 95% CI: 0.116 to 0.340). See Table 7. Fig. 1 shows that "food responsiveness" accounted for a significant portion (64.2%) of the mediating effect.

4. Discussion

We found that children diagnosed with ADHD exhibited higher incidences of overweight/obesity, high body fat mass and eating behavior problems, such as prolonged eating, picky eating, abnormal food responsiveness, and great intake of beverages. There were significant relationships among eating behaviors, ADHD core symptoms, and BMI-SDS or FM%. Food responsiveness was confirmed as a significant factor that connected ADHD core symptoms with obesity.

4.1. ADHD and overweight/obesity

A large number of clinical investigations have shown that children diagnosed with ADHD have a higher risk for obesity. Martins-Silva et al. found correlations among children's BMI, body fat mass, and prevalence of ADHD (OR = 1.04, 1.05) in a 30-year study of 3630 individuals [21]. Bowling et al. observed that compared with a control group, children with ADHD at the age of 6 years had body fat mass significantly rising in the following three years [22]. Consistent with these reports, children with ADHD in the present study had higher BMI-SDS, and FM% and lower SMM% than the control group. High FM and low SMM pose negative impacts on metabolic rate and overall health [23], and childhood obesity exacerbates core ADHD symptoms by damaging children's psychosocial abilities, such as self-esteem [12]. Therefore, parents and clinicians should be concerned not only about the core symptoms of ADHD, but also the body weight of children.

Comparing 124 children diagnosed with ADHD and 109 children without ADHD aged 1–17 years in the United States, Spencer et al. found that 10% of children with ADHD developed short stature at a young age [14]. Hanc T et al. also found a lower value of BMI-Z score among preschool boys who had been diagnosed with ADHD [24]. We did not identify a higher incidence of short stature among our sample, possibly because of the limited number of preschool-aged children.

Table 3
Eating behaviors of children in the ADHD and control groups (x ± s).

CEBQ Scale	Control group ($n = 152$)	ADHD group ($n = 396$)	t	p
Food avoidant behaviors				
Satiety responsiveness	13.21 ± 3.09	13.68 ± 3.41	−1.495	0.135
slowness in eating	9.74 ± 2.95	11.01 ± 3.32	−4.107	<0.01
Fussiness	15.03 ± 2.84	15.61 ± 3.54	−1.993	0.047
Emotional undereating	10.03 ± 2.88	10.42 ± 3.65	−1.324	0.186
Food approach behaviors				
Food responsiveness	9.88 ± 3.71	11.96 ± 4.81	−5.403	<0.01
Enjoyment of food	11.61 ± 3.64	12.13 ± 4.03	−1.386	0.166
Desire to drink	6.58 ± 2.72	8.34 ± 3.46	−6.266	<0.01
Emotional overeating	6.11 ± 2.40	6.43 ± 2.78	−1.314	0.190

ADHD: attention deficit hyperactivity disorder; *CEBQ*: Children's Eating Behavior Questionnaire.

Table 4
Multivariate associations among ADHD symptoms, obesity, and eating behaviors in children with ADHD.

	1	2	3	4	5	6	7	8
1 Inattention score	–							
2 Hyperactivity-impulsivity score	0.083	–						
3 BMI-SDS	0.104	−0.035	–					
4 FM%	0.115 *	−0.094	0.807 **	–				
5 SMM%	−0.060	0.031	−0.628 **	−0.902 **	–			
6 Slowness in eating	−0.003	0.084	−0.422 **	−0.358 **	0.239 **	–		
7 Food responsiveness	0.124 *	0.123 *	0.224 **	0.266 **	−0.257 **	0.048	–	
8 Desire to drinks	0.104	0.122 *	0.055	0.108	−0.104	0.110 *	0.457 **	–

ADHD: attention deficit hyperactivity disorder; *BMI- SDS:* body mass index Standard deviation score; *FM%*: fat mass percentage; *SMM%*: Percentage of body muscle.
Note: *$p < 0.05$; **$p < 0.01$; adjusted for paternal/maternal education, child's screen time, and annual household income.

Table 5
Association between inattention score and FM% in children with ADHD.

	Model 1[a]			Model 2[b]		
	β	95% CI	*p*-values	*β*	95% CI	*p*-value
Inattention	0.505	(0.167, 0.843)	0.003	0.336	(0.001, 0.673)	0.050

ADHD: attention deficit hyperactivity disorder; *FM%*: fat mass percentage; *CI*: confidence interval.
[a] unadjusted model.
[b] adjusted model; adjusted for father's education level, mother's education level, father's BMI, mother's BMI, and household income.

Table 6
Association between food responsiveness and FM% among children with ADHD.

	Model 1[a]			Model 2[b]		
	β	*95% CI*	*P*-values	*β*	*95% CI*	*P*-values
food responsiveness	0.552	(0.391, 0.714)	<0.001	0.509	(0.352, 0.665)	<0.001

ADHD: attention deficit hyperactivity disorder*; FM%*: fat mass percentage; *CI*: confidence interval.
[a] unadjusted model.
[b] adjusted model; adjusted for father's education level, mother's education level, father's BMI, mother's BMI, and household income.

Table 7
Direct effect (DE) and indirect effect (IE) of inattention score and FM% mediated by food responsiveness in participants with ADHD.

	Model 1[a]			Model 2[b]		
	B	*95% CI*	*P*-values	*B*	*95% CI*	*P*-values
Indirect effect	0.217	(0.131, 0.342)	<0.001	0.218	(0.116, 0.340)	<0.001
Direct effect	0.279	(0.003, 0.581)	0.061	0.138	(−0.107, 0.460)	0.26
Total effect	0.496	(0.210, 0.813)	<0.001	0.356	(0.072, 0.710)	<0.001
Prop. Mediated	0.437	(0.229, 0.990)	<0.001	0.642	(0.285, 2.081)	<0.001

ADHD: attention deficit hyperactivity disorder; *FM%*: fat mass percentage; *CI*: confidence interval.
[a] unadjusted model.
[b] adjusted model, adjusted for father's education level, mother's education level, father's BMI, mother's BMI, and household income.

4.2. ADHD and eating behaviors

Eating behavioral issues are common among children with ADHD and vary with age. Consistent with previous research, the ADHD children in the current study exhibited multiple eating problems, such as "fussiness", "desire to drink", and "food responsiveness". Disordered eating is more obvious among school-age children and adolescents diagnosed with ADHD, who have more opportunities to get emotional eating and beverages [9,25]. El Archi et al. suggested that ADHD is associated with disordered eating, especially addiction-like emotional eating behaviors (i.e., binge eating, food addiction, and uncontrolled eating) [26]. During early childhood, children diagnosed with ADHD show strong preferences for greasy, salty, sweet foods, processed meat and soft drinks [27]. Fuemmeler et al. proposed that "slowness in eating" among 4-year-old children might be related to excessive fidgeting during eating, which lengthens the eating time [28]. In the current study, school-aged children in the ADHD group also exhibited "slowness in eating". Slow eating among this group may be caused by inattention because they were occupied by other issues during mealtime rather than eating itself. Children with ADHD who are hyperactive and impulsive in early childhood may also develop inattention that persists as they

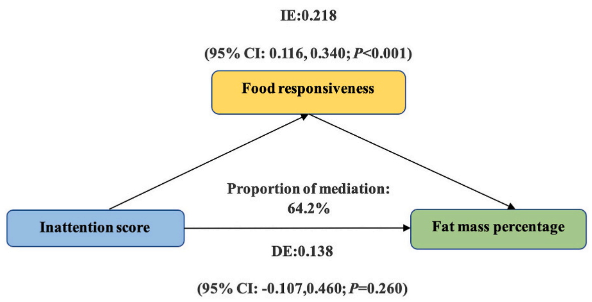

Fig. 1. Estimated proportion of the association between inattention score and FM% mediated by food responsiveness. The figure displays food responsiveness as the mediator, the estimate of the indirect effect (IE), the estimate of the direct effect (DE), and the proportion of mediation (IE/DE + IE). *IE*: indirect effect; *DE*: direct effect; *CI*: confidence interval; *FM%*: fat mass percentage.

mature, even after they cast away their hyperactive and impulsive behaviors.

These eating behavioral issues have been considered as risk factors for obesity among children without ADHD [29], but in children diagnosed with ADHD, these issues are more common and serious enough to exacerbate overnutrition and increase the risk of obesity among ADHD populations.

4.3. ADHD, overweight/obesity and food responsiveness

In the reward pathway of brain, dopamine neurons release the neurotransmitter dopamine and link with dopamine receptors on the surface of receptor cells. Dopamine can send pleasurable messages and regulate learning and motivation. Some dopamine molecules re-enter the sending cell via dopamine transporter (DAT) on the sending cell's membrane. A healthy brain has a moderate level of dopamine in the synaptic space, even in the absence of rewarding stimuli. When a reward is encountered, such as food, the pre-synaptic cell releases a larger amount of dopamine in a sudden burst; then dopamine transporters will quickly remove the excess, returning the amount of dopamine to the original level. However, ADHD participants have a low level of dopamine in the brain, due to high concentrations of DAT in some brain regions [30]. As a result, multiple core ADHD symptoms such as inattention and hyperactivity/impulsivity would emerge [4].

Previous studies have shown that prolonged use of electronic gadgets, sedentary lifestyle, and family socioeconomic status are strongly associated with obesity [31]. We found that inattention was positively correlated with FM% and "food responsiveness" score among children with ADHD after adjusting for confounders, including parental weight, height, education level, child's screen time, and annual household income. These findings are consistent with those of Leventakou et al. [8], who noted that overweight and obese children with ADHD are more prone to "food responsiveness", which may be related to DA deficiency caused by abnormal dopaminergic system. When dopamine secretion is insufficient, the body's response to satiety signals decreases, so the "food responsiveness" becomes stronger. For example, participants with ADHD had a stronger response to high-calorie/high-carbohydrate foods compared with controls [32]. When children with ADHD physically crave for these types of foods, the frequency and amount of food consumed also increase, which contributes to weight gain.

Our results indicated that "food responsiveness" among children with ADHD partially mediated the relationship between inattention score and FM%. This suggests that ADHD symptoms may alter the body's composition by influencing eating behaviors. Previous studies have confirmed that using stimulant medications) can correct their eating behaviors and optimize their body composition [12,33]. A prospective cohort study in the United States showed that core ADHD symptoms may occur first, followed by unhealthy dietary patterns, providing evidence of the causal relationship between ADHD symptoms and eating behaviors [28]. Long-term use of stimulants can enhance executive ability and reduce impulsivity, helping children to regulate their eating behaviors and promoting their physical growth. Therefore, clinicians need to improve participants' compliance with medication, especially in a long term.

In addition, a regular eating habit can improve attention and overweight/obesity [34]. Mini meals, through enhancing the frequency of eating, are recommended to manage body weight. It provides continuous stimulations to ADHD participants, thus alleviating the feeling of restlessness. Moreover, it also exerts a positive effect on body weight in obese participants. Scientific and regular exercises not only control body weight, but also increase neurotransmitter levels by stimulating specific brain regions to produce dopamine/norepinephrine receptors, thus alleviating the attention and binge eating due to the lack of dopamine in ADHD participants [35]. Therefore, the clinical management of children with ADHD should involve the use of stimulant (appetite-reducing) medications, non-stimulant (e.g., mood-stabilizing) medications, nutritional consultation on eating behaviors, exercise routiness, psychoeducation for children and parents, and coordination with all members of the treatment team.

5. Strengths and limitations of this study

To the best of our knowledge, this is the first study to investigate the mediating role of eating behaviors on core ADHD symptoms and fat mass of children with ADHD by using a mediation model. Our findings provide a basis for further explorations of the mechanisms and interventions for ADHD combined with obesity.

Some limitations in this study should be noted. First, the number of children visiting doctors in hospitals did decrease during the COVID-19 epidemic, especially among preschool children and the control group. The small sample size may limit the exploration of different patterns of eating behaviors in preschool and school-aged children with ADHD. Second, the general conditions of the enrolled children and their eating behaviors were collected from parent-reported questionnaires. Because the school-aged children usually had meals in school, there might be subjective reporting bias in the study. In future research, information from children's self-reports and teachers' feedback should be collected as well.

6. Conclusions

Children with ADHD have a higher risk of developing overweight/obesity, as well as harmful eating behaviors, including long-time eating, picky eating, and over-responsiveness to foods and drinks. There are significant associations between core ADHD symptoms, adverse eating behaviors, and body fat mass. Food responsiveness plays a mediating role between inattention and obesity.

Ethics approval and consent to participate

The study protocol was approved by the Medical Ethics Committee of the Children's Hospital of Nanjing Medical University (NMUB2018074).

Consent for publication

Not applicable.

Author contribution statement

Shujin Chen: Performed the experiments; Analyzed and interpreted the data; Contributed materials, analysis tools or data; Wrote the paper.

Dandan Wu: Conceived and designed the experiments; Wrote the paper.

Shuang Lin; Rong Huang; Rong Li; Yiyang Huang; Mengying Chen: Contributed reagents, materials, analysis tools or data.

Xiaonan Li: Conceived and designed the experiments；Revised the manuscript

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no competing interests.

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Appendix B. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2023.e13641.

Abbreviations

ADHD	Attention Deficit Hyperactivity Disorder
BMI	body mass index
BMI-SDS	BMI standard deviation score
CEBQ	Children's Eating Behavior Questionnaire
DA	dopamine
DAT	dopamine transporter
DSM-5	Diagnostic and Statistical Manual of Mental Disorders (Fifth Edition)

FM fat mass
FM% percentage of body fat
Height-SDS height standard deviation score
SMM skeletal muscle mass
SMM% percentage of body muscle
Weight-SDS weight standard deviation score

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