Insular Cortex Activity During Food-Specific Inhibitory Control Is Associated With Academic Achievement in Children

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Keywords: Childhood obesity, response inhibition, impulsive reaction, somatic maturation, cardiorespiratory fitness, BOLD signal

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Abstract

Background/objectives: Inhibitory control (IC) is usually poorer in children with overweight and obesity and has been associated with unhealthy eating behaviors and lower academic achievement. Food-specific IC tasks depicting salient unhealthy foods may be more sensitive to predicting fat accumulation and unhealthy behaviors than traditional IC tasks. However, the neural activation patterns in response to food-specific IC remain unclear, especially in developing children`s brains. Here, we investigated brain activity associated with food-specific IC in children with accumulated fat mass. **Subjects/Methods:** 36 children with overweight and obesity performed a food-specific Go/No-Go task in an MRI scanner. We assessed the children's body composition with dual-energy x-ray absorptiometry, academic achievement, somatic maturation, and cardiorespiratory fitness. **Results:** The left insular cortex was significantly activated during successful inhibition of palatable food cues and was associated with higher academic achievement. Also, linear regression showed that academic achievement correlated with insular cortex activation even when controlling for somatic maturation, cognitive performance, and cardiorespiratory fitness. **Conclusion:** Our results indicate that insular cortex activation, an area known for rational and emotional processing, is associated with successful inhibitory control in response to food images in children with overweight and obesity, while academic performance seems to play a role in the magnitude of this activation.

Keywords: Childhood obesity, response inhibition, impulsive reaction, somatic maturation, cardiorespiratory fitness, BOLD signal.

1. INTRODUCTION

Establishing healthy decision-making at an early age is essential to benefit adult individuals' health (Casey et al., 2011). Inhibitory control (IC) is one of the executive functions usually derived from the prefrontal cortex (PFC) that has been suggested to play a crucial role in healthy behaviors and academic development (Q. Liu et al., 2015). Defined as the ability to keep the attention and focus on goal-oriented information and inhibit automatic goal-incongruent information (Diamond, 2013), IC can be crucial in children avoiding salient unhealthy foods (Martin & Davidson, 2014) and distractions during school classes (St Clair-Thompson & Gathercole, 2006). The developing children's brain is known to have impaired IC compared to healthy adults (Bunge et al., 2002) and maybe even more affected when associated with accumulated fat mass (Kamijo et al., 2012) and decreased cardiorespiratory fitness (Hsieh et al., 2020). Despite the known influence of IC on children's healthy behavior, the neurofunctional mechanisms associated with IC to salient unhealthy food are unknown.

Functional magnetic resonance imaging (fMRI) studies have investigated brain responses to exposure to high-calorie food images in children and adolescents. These studies have shown increased activity of cognitive- (orbitofrontal cortex, fusiform gyrus, and superior parietal lobule) and emotional- (insula and amygdala) related brain areas when participants are facing palatable foods (Davids et al., 2010; van Meer et al., 2015). In addition, PFC cognitive areas have been activated in children performing traditional IC tasks (i.e., Stroop, Flanker, and Go/No-Go tasks) (Adleman et al., 2002; Bunge et al., 2002; Casey et al., 1997; Durston et al., 2002). The neural processes required during these tasks involve the inhibition of automatic responses to incongruent information such as color (Stroop), the direction of an arrow (Flanker), or a motor response (Go/No-Go), all of which require a top-down PFC control (Chiu, 2019). However, it has been suggested that adding specific context to conditions during these cognitive tasks may increase the capacity to predict behavior and health-related outcomes (da Costa et al., 2019; Price et al., 2016). One of the possible reasons for such association is that salient stimulus of food cues on IC tasks may trigger physiological arousal responses and dopamine release related to feelings of craving that have been shown to predict eating behaviors (Boswell & Kober, 2016). Therefore, these specific food cues seem to better simulate a real-world obesogenic environment than letters, arrows, or colors, which are often used in traditional IC tasks.

It is essential to highlight that different factors may influence children's brain structure and function, such as somatic maturation, body composition, and cardiorespiratory fitness. When compared to adults, children's brain networks are more diffuse with short-range connections (Kelly et al., 2009). These networks also exhibit immature PFC activation, directly affecting cognitive processing, including IC (Bunge et al., 2002) and academic achievement (Chaddock-Heyman et al., 2018). In addition, it has been shown that overweight children have reduced cortical thickness on the PFC (Ronan et al., 2020), poorer inhibitory control (Houben et al., 2014; Nederkoorn et al., 2012) and fat mass is inversely associated with inhibitory control (Kamijo et al., 2012) and cardiorespiratory fitness (Langer et al., 2020). On the other hand, children with higher levels of cardiorespiratory fitness have faster reaction time and more efficient neuroelectric activity (showed by a larger P300 amplitude) during IC tasks (Mora-Gonzalez et al., 2020) and superior academic achievement and overall cognition (Hillman et al., 2008). Hence, we believe that investigating the relationship between somatic maturation, body composition, and cardiorespiratory fitness with brain areas activated during food-specific IC may further elucidate endogenous factors that affect the inhibition processing in children with accumulated fat mass.

Here, we investigate brain activity associated with IC to salient unhealthy food pictures by having 8-12-year-old children overweight and obese performing a food-specific Go/No-Go task in an MRI scanner. We predict that PFC brain areas would be significantly activated during successful inhibition trials and that successful inhibition will be associated with cardiorespiratory fitness, academic achievement, somatic maturation, and fat-free mass while inversely associated with fat mass.

2. METHODS

2.1. Participants

Thirty-six children (18 girls and 17 boys) aged between 8 and 12 years old met the following inclusion criteria: absence of cardiovascular risk or physical limitation accessed by the physical activity readiness questionnaire (PAR-Q) (Thomas et al., 1992); regularly educated without any significant cognitive impairment, and free of any medication. Initially, children and parents were informed about the project's aims, procedures, and risks and were invited to participate in the study. If children and parents agreed to participate, both signed informed consent. All children were recruited from a private school located in the urbanized area of Natal/RN, Brazil. The study followed the standards of the Declaration of Helsinki and was approved by the local ethics committee.

2.2. Study design

In the first meeting at the school, the food-specific IC task was practiced inside an adapted plastic-made MRI simulator for initial familiarization purposes. Children that presented any claustrophobic sign were not included in the study. Within one week apart, the first testing session was carried out at the Department of Physical Education at the

Federal University of Rio Grande do Norte. We assessed demographic, anthropometric, hemodynamic information, body composition, academic achievement, and cardiorespiratory fitness. In a follow-up session, children visited the University's Hospital to perform Go/No-Go food-specific IC task in a real MRI scanner.

2.3. Body composition, Anthropometric and Hemodynamics

A dual-energy x-ray absorptiometry (iDXA) (GE Healthcare Lunar, Madison, WI, USA) and version 13.6 enCore™2011 software (GE Healthcare Lunar) were used to measure body composition. For about seven minutes, the children remained in a supine position on the machine wearing light clothing and no shoes. Fat mass, bone mineral content, and lean soft tissue were determined based on total body measurements. The fat mass percentage was calculated based on the total body weight and fat mass values. Hip and waist circumference (cm) were measured and used to calculate the waist-hip ratio (WHR). Body mass index (BMI) was calculated by weight / $(\text{height})^2$. Bodyweight (kg) and total height (cm) were also measured to estimate the BMI. For hemodynamics, children were asked to sit and rest for five minutes. Then, blood pressure was assessed three times, two minutes apart, using a validated automatic blood pressure monitor and specific cuff for children (Takahashi et al., 2011). The average of the three measurements of both systolic and diastolic blood pressure was used for data analysis.

2.4. Somatic Maturation

Using seated height and leg length, we calculated the pubertal timing measures according to a standardized equation to estimate somatic maturation. The estimated results from this measurement represent the distance in years from/to reach the peak height velocity (PHV). For negative maturity offset prediction, the individual classification was considered as pre-PHV and positive prediction as post-PHV (Mirwald et al., 2002).

2.5. Cardiorespiratory Fitness

The multistage shuttle-run, a progressive effort test suggested by Léger (1984), was used to estimate cardiorespiratory fitness. The children should run between two cones 20 meters apart. The displacement rhythm should follow sound signals emitted by an audio file recorded specifically for this test. The test ends when the child cannot run between the cones, according to the recording time frame. A validated equation (Léger et al., 1984) was applied to calculate the estimated maximum oxygen consumption (VO_2max). This procedure has been widely used as a cardiorespiratory fitness marker with approved reliability and validity (N. Y.-S. Liu et al., 1992).

2.6. Academic Achievement

The academic achievement test (AAT) is a psychometric instrument widely applied to children's reading, writing, and arithmetic abilities. This test has been used for children of the same nationality in other brain and behavior-related studies (Boscariol et al., 2011; Fonseca et al., 2007). A total academic achievement composite variable was calculated by adding the performance of the three abilities evaluated (reading + writing + arithmetic). These subtests have shown good internal reliability (Cronbach's $\alpha = 0.77$).

2.7. Food-specific inhibitory control

Before undergoing the fMRI cognitive task, children answered a visual scale to measure how hungry they were (0 (not hungry at all - 10 (very hungry)). A Go/No-Go task adapted from (Price et al., 2016) was used while acquiring functional MRI data (blood-oxygen-level-dependent (BOLD)). Two No-Go conditions were examined: a food-specific where caloric food pictures were used as No-Go stimulus, and a generic condition where pictures of toys were used as No-Go stimulus. In both cases, pictures of random objects (neutral) were used as Go stimuli. Children were instructed to press a button with their right index finger as quickly as possible whenever they saw a neutral object picture while withholding for toys or food pictures. Six fMRI runs, three of each condition, were carried out. Each run consisted of 50 trials. For each trial, a fixation cross was presented for intervals ranging from 350 to 800 ms followed by a picture of an object (Go trial, 80% occurrence) or a picture of a caloric food/toy (No-Go trial, 20% occurrence) for 750 ms followed by a blank screen presented for a variable interval to complete a total time of 2000 ms (Figure 1). A set of 10 food, 10 toys, and 20 objects pictures were used. The Go/No-Go trials sequence followed a pseudo-randomized order, in which each food or toy picture was preceded by three, four, or five neutral images. The whole test, including both conditions, lasted about 11 min. Cognitive performance was measured by the number of errors (commission errors). Response time (RT) on Go trials was used as a control by comparing the time response between the food-specific and general inhibitory tasks. In addition, we also checked if the same amount of time was used to avoid the No-Go condition. Instructions were standardized, and a short preceding practice trial assured comprehension and willingness.

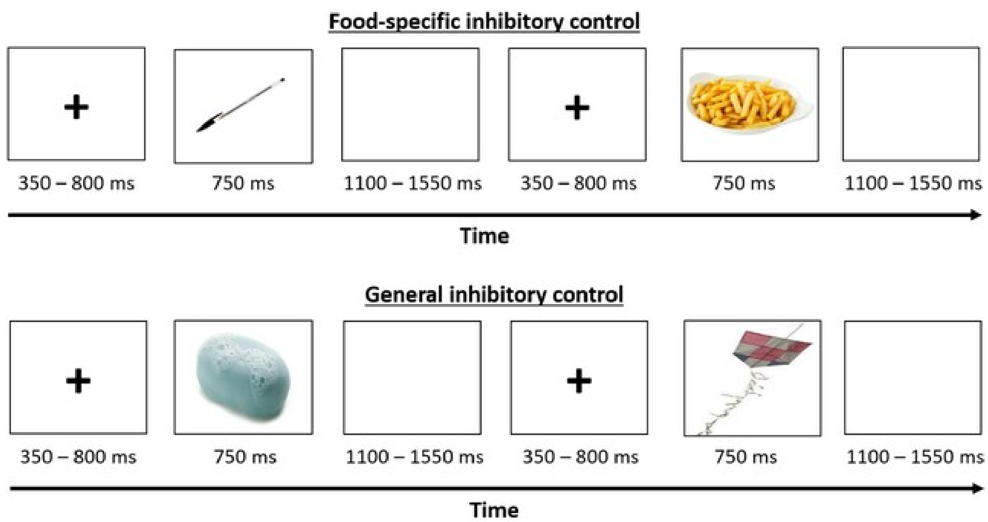

Figure 1. Food-specific and general inhibitory control tasks performed by children inside an MRI scanner.

2.8. Image acquisition

Images were acquired in a 1.5 Tesla MRI scanner (General Electric, USA). For functional MRI datasets, a total of 55 volumes were acquired, each with 34 slices, using an EPI sequence with the following parameters: TR = 2000 ms; TE = 35 ms; ; flip angle = 60º; FOV = 240 mm; matrix 64 x 64; slice thickness = 3 mm; gap = 0.3 mm. Whole-brain high resolution T1-weighted anatomical images were acquired using a FSPGR BRAVO sequence: TR = 12.7ms; TE = 5.3 ms; flip angle = 60°; matrix 320 x 320; FOV = 240 mm, voxel size = 1 mm x 1 mm x 1 mm, number of slices = 128. Stimuli were programmed using Psychopy software v.1.79 (Peirce et al., 2019) and presented through video goggles coupled in the head coil (NordicNeuroLab, Bergen Norway) and a fiber optic response collection device (NordicNeuroLab, Bergen, Norway). A cartoon was displayed during the T1-weighted images acquisition to prevent boredom and restlessness.

2.9. fMRI analysis

The fMRI Go/No-Go protocol was analyzed using SPM12 (Statistical Parametric Mapping, UK). The first five volumes were discarded to allow for T1 stabilization. Preprocessing steps included head motion correction, slice timing correction, spatial smoothing (8-mm FWHM Gaussian kernel), and a high-pass filter (128 seconds). Functional images were coregistered to each subject's anatomical scan, normalized into standardized MNI space, and resampled to voxels of 2 mm^3.

A first-level fixed-effects model was set up for each subject using a general linear model and an event-related design. Two regressors corresponding to the onsets for each

Go and No-Go trial (only corrected trials were analyzed) were convolved with a canonical hemodynamic response function. Periods of the fixation cross and blank screen were defined as the baseline. The model also included the six motion parameters as regressors of no interest. Contrast images were calculated using t-statistics for No-Go maps *versus* Go maps separately for each condition (food and toys).

Food-specific and general inhibitory controls were assessed in a second-level analysis through voxel-wise one-sample t-tests. Two statistical thresholds were considered: i) a less restrictive threshold: $p<0.010$ uncorrected; cluster-extent threshold: $p<0.05$ uncorrected, and ii) a more restrictive threshold: $p<0.010$ uncorrected; cluster-extent threshold: $p<0.05$ FWE corrected. Differences between conditions (food and toys) were evaluated using voxel-wise two-sample paired t-tests and a statistical threshold: $p<0.01$ uncorrected; cluster-extent threshold: $p<0.05$ uncorrected.

To further investigate the relationship between neural changes and behavioral measures, mean β-values for each cluster that surpassed the statistical threshold from the previous analysis were extracted from each participant's contrast image of No-Go > Go conditions (food and toys), using the MarsBaR toolbox in SPM12.

2.10. Statistical Analyses

Data are expressed as mean and standard deviation (SD). Shapiro-Wilk test was used for testing data normality. Paired Wilcoxon and t-test were used to verify differences between the number of errors and response time (RT) in the two conditions of the cognitive test (food *vs.* toys trials). Pearson or Spearman correlations were conducted between individual fMRI β-values with the independent variables (VO_2 max, fat mass, fat-free mass, number of errors on the cognitive test, PHV, and AAT). Significant correlations were added as covariables in the linear regression analysis model. Two separate linear regression analyses were used to investigate the independent contributions of the possible predictor variables to the variance in the ROI brain activity. For non-parametric variables, Blom's transformation was completed to achieve homogeneity and normality. Assumptions of equality of variance, independence, linearity, and normality were plotted, inspected, and verified using studentized residuals. Multicollinearity was not observed among any of the independent variables. The significance level was set at $p < 0.05$.

3. RESULTS

3.1. General characteristics

One child was excluded from the analysis due to excessive fMRI motion artifacts. Hence, data from 35 children (Age: 10.11 ± 1.32 years) was analyzed in the study. Before the MRI session, children reported 4.6 ± 0.3 on the visual hunger scale (0 = not hungry at all; -10 = very hungry). Table 1 illustrates the general characteristics of the final sample. According to World Health Organization (WHO) reference values, average BMI results show values greater (BMI= 21.35 ± 1.11) than 95th percentile for boys (obese) and between (BMI = 20.28 ± 0.83) 85th and 95th percentile for girls (overweight) (de Onis et al., 2007).

Table 1. Sample characteristics, body composition, cardiorespiratory fitness, hemodynamic responses, and academic achievement in the total sample (n=35)

Variables	Total (n = 35) Mean ± SD	Boys (n = 17) Mean ± SD	Girls (n = 18) Mean ± SD
Age (years)	10.11 ± 1.32	10.26 ± 0.26	10.05 ± 0.38
PHV (years)	-3.41 ± 1.44	-2.93 ± 0.24	-3.8 ± 0.41
BMI (kg/m^2)	20.76 ± 3.70	21.35 ± 1.11	20.28 ± 0.83

WHR (cm)	0.85 ± 0.06	0.88 ± 0.12	0.81 ± 0.01
SBP (mmHg)	109.77 ± 21.90	114.54 ± 2.56	112.03 ± 2.97
DBP (mmHg)	62.93 ± 12.83	65.79 ± 1.35	65.43 ± 1.8
Fat-free mass (kg)	26.65 ± 6.31	27.75 ± 1.62	25.36 ± 1.53
Fat mass (%)	36.70 ± 7.60	36.06 ± 2.25	37.94 ± 1.48
VO_2max (ml/kg/min)	32.01 ± 4.18	31.60 ± 0.81	31.93 ± 1.24
Writing (a.u)	20.32 ± 4.92	21.33 ± 0.96	18.94 ± 1.36
Reading (a.u)	64.00 ± 7.02	64.53 ± 1.40	63.82 ± 1.97
Math (a.u)	11.24 ± 3.01	10.93 ± 0.75	11.00 ± 0.79
AAT total (a.u)	91.82 ± 19.60	96.80 ± 2.68	93.76 ± 3.70

PHV: peak height velocity, BMI: Body max index; WHR: Waist hip ratio; SBP: Systolic Blood pressure; DBP: Diastolic blood pressure; VO_2max: maximal oxygen uptake; AAT: academic achievement test.

3.2. Go/No-Go task: behavioral results

No significant differences were found between the number of errors during the No-Go food trials and the number of errors during the No-Go toys' trials (Z=-138.79, p>0.05; 4.2±3.0 errors *vs.* 4.7±3.6 errors). Paired t-test showed no differences on RT for go trials (objects) between food and toys conditions (t(34)=1.3, p=0.18; 0.516 ± 0.085 ms *vs* 0.511 ± 0.081ms).

3.3. Go/No-Go task: fMRI results

Figure 2 presents the statistical map for the contrasts No-Go (food) *vs*. Go and No-Go (toys) *vs*. Go contrasts. For both contrasts, we found the increased bilateral activity of the insula. We did not find significant differences between No-Go conditions (food vs. toys, p>0.05). Furthermore, a cluster in the left insula remained significant when using a more restrictive p-value threshold (FWE<0.05), although only when comparing No-Go (food) *vs*. Go (Figure 3 and Table 1 (supplementary material)). No significant differences were observed for the No-Go (toys) *vs*. Go comparison (p>0.05).

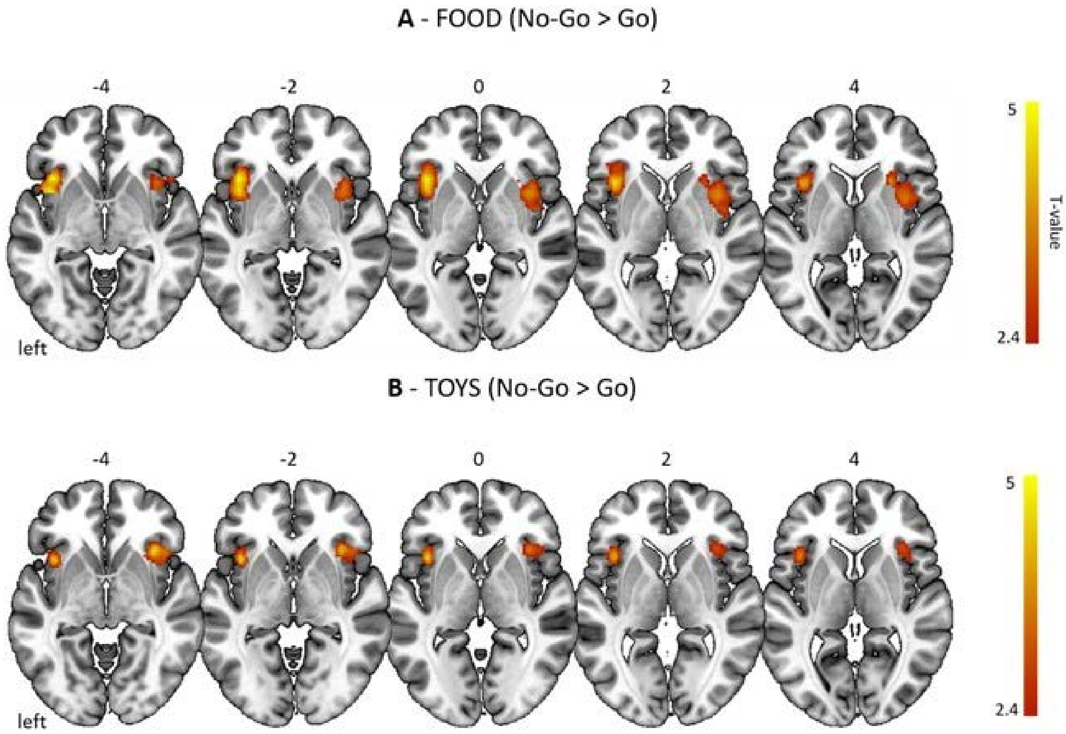

Figure 2. Brain areas with significantly increased activity in children while performing a food and toys specific inhibitory control task (No-Go>Go) (p< 0.001). Panel **A** describes areas with significantly increased activity for the contrast No-Go (food pictures) *vs.* Go. Panel **B** shows areas with significantly increased activity for the contrast No-Go (toy pictures) *vs.* Go.

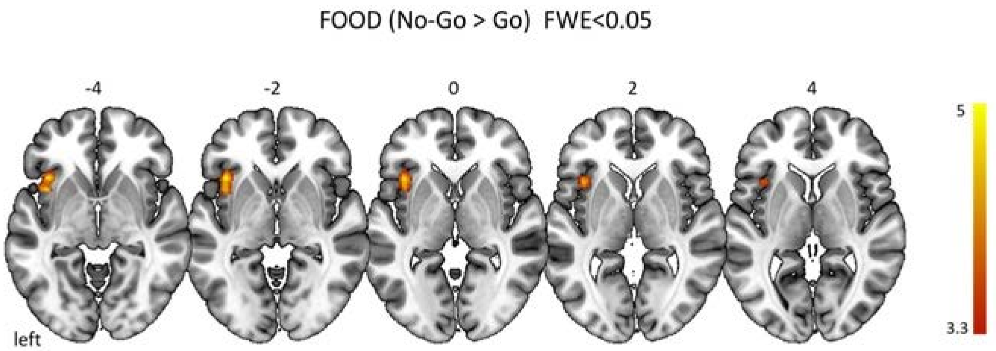

Figure 3. Brain areas with significantly increased activity during food-specific inhibitory tasks contrasting No-Go (food) *vs.* Go (FWE<0.05) in children. Extent Threshold: 147 voxels.; cluster size 441mm^3 (n = 35).

Significant positive correlations were found between the number of errors for food (r = 0.348, p=0.04) and toy (r = 0.410, p=0.015) trials during No-Go conditions with the activity of the right insula. Academic achievement (r = 0.443, p=0.009) was correlated with the left insula activity for the food condition. No correlations were found between VO_2max, fat mass, fat-free mass, and PHV (Table 4 supplementary material). Figure 4 supplementary material) shows the scatter plots of significant correlations between the left insular cortex activation (BOLD signal, FEW<0.05) and academic achievement.

Table 2 summarizes linear regression analyses results for the left insula activity for the food inhibition condition (FWE<0.05).

Table 2. Linear regression analysis between the left insula activity during successful food-specific inhibitory control and academic achievement controlled by somatic maturation, cognitive performance, and cardiorespiratory fitness in children.

Predictors	**Left insula activity**		
	β	**ΔR^2**	***P***
Model 1		0.22	0.056
AAT total	0.458		0.012
VO_2max	0.066		0.716
Error Food	0.112		0.519
Model 2		0.22	0.054
AAT total	0.489		0.009
PHV	-0.166		0.367

Error Toys	0.005	0.976

AAT: Academic achievement test; PHV: Peak height velocity; VO_2max: maximal oxygen uptake

Results show that AAT predicts left insula activity even when controlling for potential cofounders PHV and toy errors (t=2.78; β=0.489; p = 0.009) on model 1 and VO_2max and food errors on model 2 (t=2.69; β=0.458; p = 0012).

4. DISCUSSION

The present study showed that the insula activity was significantly increased for successful food-specific IC in children. This process seems more prominent in the left hemisphere as only the left insula cluster remained significant with a more restricted statistical threshold (FWE<0.05). Moreover, insula activity during the food-specific IC was correlated with academic achievement. Linear regression analysis indicated that academic achievement predicted left insula activity even when controlling for somatic maturation, cardiorespiratory fitness, and cognitive performance. Thus, different from studies that investigate the brain responses to cues of high palatable foods or non-specific inhibitory control, our study provides novel evidence of children's brain functioning when avoiding automatic responses to salient unhealthy food and the possible role of academic achievement in this process.

To our knowledge, this is the first study to investigate brain function in response to food-specific IC in children with overweight and obesity. Previous fMRI studies using traditional Go/No-Go IC tasks have mainly shown increased activity in the PFC areas in children, although these studies had different age ranges and small sample sizes relative to our study: 7-12 Age years, 5 females and 4 males) (Casey et al., 1997), 6 to 10 years old, 10 males (Durston et al., 2002), (Age 6-7 years old, 3 males and 7 females) (Réveillon et al., 2013). These results led us to hypothesize that PFC areas would selectively increase their activity during successful inhibition in children. However, our findings with similar ages and larger sample size, including boys and girls, do not support previous studies since we did not find any PFC areas activation during successful inhibition. Instead, we have found significantly increased activity in the insula during successful inhibition (No-Go>Go) during food-specific IC test in children (n=35; 8-12 years old, 17 males and 18 females). Interestingly, one study with teenage girls (n=39; Age 15.7 ± 0.93 years) using a food-specific IC test reported activation of the superior and inferior frontal gyrus, anterior insula, and frontal operculum for the condition No-Go>Go, and insula activity for the condition No-Go>baseline (fixation cross) (Batterink et al., 2010). These results are more aligned with ours as they used a food-specific IC paradigm rather than traditional IC tests. In addition, larger sample sizes have been suggested to increase the statistical power and replicability of task-based fMRI studies (Turner et al., 2018), thus, we believe the larger sample size and the evenly distributed sex, compared to previous studies, strengthen our findings. In fact, the PFC is the last area to achieve full development (Giedd et al., 1999). This delayed PFC maturation is explained by the rate of myelination and synaptogenesis of the developing brain (Casey et al., 2011). Thus, children's developing brains might be less susceptible to inhibit food cues during early childhood (Bunge et al., 2002; van Meer et al., 2016) and may suggest other brain areas might be recruited in response to inhibition tasks to compensate for the non-activation of frontal areas (van Meer et al., 2016). Thus, we believe that the increased insula activity for the successful inhibition found in our study act as a compensatory mechanism as children's PFC is not fully developed. Moreover, since most of the children in our sample were considered behind the expected maturation for their age (-3.41 ± 1.44 years), our results may emphasize the need for non-PFC areas to process IC. However, future studies having children with different maturation characteristics are necessary to confirm this assumption.

At the interoceptive level, the insula is a network hub that integrates visceral information from bodily state changes, such as blood pressure, heart rate, temperature, hunger, thirst, and other factors related to the body's state that plays an essential role in autonomic regulation and awareness of physiological changes (A. D. Craig, 2002). In addition, the left insula has been suggested as a key processing area for affect and comfort/pleasure feelings (i.e., happy side). Conversely, the right insula has been associated with discomfort/displeasure responses (A. D. B. Craig, 2009). Moreover, the insula has connections with the orbitofrontal and anterior cingulate cortices, which, according to the somatic marker hypothesis, influence cognitive functions by rational and emotional drives (A. D. B. Craig, 2009). For instance, high caloric food cues have been shown to increase insula activity in adults with obesity, whereas leaner adults show higher connectivity with the orbitofrontal and anterior cingulate cortex at resting state (Frank et al., 2013). Hence, we believe that the increased left insula activity (identified with a more restrictive statistic threshold; figure 3) during successful inhibition in our study can be related to a higher positive affect and emotional significance of salient unhealthy food cues.

Furthermore, we suggest that the activation of the left insula during food-specific IC and its positive relationship with academic achievement make this area an essential candidate for future eating-behaviors studies and educational interventions in children. For example, food-specific Go/No-Go inhibitory control training have shown to reduce high-calorie food evaluation and activity in reward related brain areas (Yang et al., 2021). In addition, improved academic achievement during childhood may predict later successes at vocational, graduate, and professional levels (Kuncel & Hezlett, 2007).

However, body weight increase may be related to poorer academic achievement (Kenney et al., 2015). Thus, IC can be essential to successful academic achievement by inhibiting inappropriate responses and ignoring irrelevant information while in the learning environment. Also, it is suggested that emotional regulation and positive emotions can be predictive of higher academic achievement (Valiente et al., 2012). Thereby encouraging teachers to use strategies to guarantee that children would learn how to deal with negative emotions and avoid eating unhealthy and salient food. Therefore, our results suggest that school-age children with higher academic achievement might have enhanced emotion regulation for food-specific IC. These results can be significant for childhood obesity prevention and IC training (e.g., teaching children that food cues might trigger automatic emotional responses that can be inhibited).

Strong reward responsiveness to food and insufficient inhibitory mechanisms are also proposed to obesity (de Klerk et al., 2022). Other interventions for preventing obesity, such as physical activity and diet, have shown to be effective strategies to maintain healthy body composition and improve brain and cognitive functions (González-Muniesa et al., 2017). Notably, higher physical activity levels may enhance structural and functional neural processing through increased cerebral blood flow and the release of neurotrophic factors (Stillman et al., 2020), which could ultimately lead to improve PFC function and consequently higher inhibitory control for palatable foods (Klerk,2022). For instance, inhibitory control have shown do mediate PFC function and exercise performance in overweight and obese individuals (da Silva et al., 2022). However, we did not find a significant relationship between cardiorespiratory fitness, body composition variables, and insular activity during successful IC. That might be due to the assessment of the VO_2 max used here, which is an indirect measure and might not be sensitive enough to capture a relationship between brain activity and cardiorespiratory fitness level.

Laboratory-based tests of VO_2max or a larger sample size might be needed to further explore this relationship.

Contrary to other studies using BMI to examine the association between weight gain and body composition with brain activity and IC (Batterink et al., 2010; Houben et al., 2014; Volkow et al., 2009), we used fat mass and fat-free mass obtained by DXA measurement. These measurements are more accurate markers of body composition. However, we did not find any relationship between these parameters and brain activity or IC. In fact, our sample had boys considered obese by BMI, girls overweight, and the overall sample average was considered overweight according to the WHO classifications (de Onis et al., 2007). The lack of an exclusive obese group for comparisons could be a limiting factor of our study for not finding those associations. Furthermore, WHO classifications have been criticized for yielding overestimation when accessing overweight and obesity in school-aged children (Gonzalez-Casanova et al., 2013; Kêkê et al., 2015), which could also directly influence the lack of association between BMI and body composition with brain activity.

5. CONCLUSION

Our results show that children with overweight and obesity between 8 to 12 years old activate mainly the left insular cortex when successfully inhibiting responses to food-specific stimuli. Furthermore, this left insular cortex activation was associated with academic achievement. These findings suggest that the insular cortex plays a role in food-specific IC and academic achievement in children facing emotional and to rational food-related cue processing. Despite not establishing a causal relationship, our findings provide important insights for future behavioral interventions to prevent and treat childhood obesity.

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