ARTICLE

Associations between inhibitory control, eating behaviours and adiposity in 6-year-old children

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Abstract

Background Lower inhibitory control has been associated with obesity. One prediction is that lower inhibitory control underlies eating behaviours that promote increased energy intakes. This study examined the relationships between children's inhibitory control measured using the Stop Signal Task (SST), body composition and eating behaviours, which included self-served portion size, number of servings, eating rate, and energy intake at lunch and in an eating in the absence of hunger (EAH) task.

Methods The sample included 255 6-year-old children from an Asian cohort. Stop-signal reaction time (SSRT) was used as an index of inhibitory control. Children participated in a recorded self-served lunchtime meal, followed by the EAH task where they were exposed to energy-dense snacks. Behavioural coding of oral processing was used to estimate eating rates (g/min). BMI, waist circumference and skinfolds were used as indices of adiposity.

Results Children with lower inhibitory control tended to self-serve larger food portions ($p = 0.054$), had multiple food servings ($p = 0.006$) and significantly faster eating rates ($p = 0.041$). Inhibitory control did not predict energy intake at lunch ($p = 0.17$) or during the EAH task ($p = 0.45$), and was unrelated to measures of adiposity ($p > 0.32$). Twenty percent of the children in the sample had problems focusing on the SST and were described as 'restless'. Post-hoc analysis revealed that these children had lower inhibitory control ($p < 0.001$) and consumed more energy during the EAH task ($p = 0.01$), but did not differ in any other key outcomes from the rest of the sample ($p > 0.1$).

Conclusions Children with lower inhibitory control showed a trend to select larger food portions, had multiple food servings and faster eating rates, but were equally as responsive to snacks served in the absence of hunger as children with better inhibitory control. Inhibitory control may impact a number of eating behaviours, not limited to energy-dense snacks.

Introduction

Growing up in an 'obesogenic' environment abundant in energy dense foods served in large portions is a risk factor for unhealthy weight gain during the first years of life [1, 2]. However, not all children exposed to such an environment develop obesity, suggesting that children differ in their self-regulation abilites and responsiveness to food cues [3, 4].

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One of the traits thought to increase children's vulnerability to the 'obesogenic' environment is ineffective impulse control around food [5] that may in part stem from deficits in inhibitory control [6, 7]. Inhibitory control is a facet of impulsivity describing a broader ability to suppress responses that are no longer needed or are in conflict with cognitive processes, commonly measured in response inhibition paradigms such as the Stop Signal Task (SST) or Go/No-Go Task (GNG) [5].

Poorer response inhibition in the SST and GNG task has been linked with higher weight and obesity prevalence, and poorer weight loss success in 7–13-year-old children, adolescents and adults [8–12]. Although inhibitory control can be harder to capture in younger age groups, preliminary evidence has also linked lower inhibitory control to higher BMI in girls as young as 4 years old [13], suggesting that it

may play a role in developing and maintaining obesity from early childhood.

To date, few studies have investigated the specific aspects of eating behaviour through which poorer inhibitory control might impact energy intake and weight status. Establishing associations between inhibitory control and specific eating behaviours will help identify targets for behaviour modification among vulnerable children. Adults with poorer response inhibition in the SST consumed more energy in a bogus taste test and purchased more calories from a virtual supermarket, consistent with the theory that poorer inhibitory control may underlie heightened responsiveness to external food cues [14, 15]. However, it has been suggested that this susceptibility may be more relevant in the presence but not in the absence of hunger, pointing to the idea that people with lower inhibitory control may be vulnerable to energy-dense snacks specifically when hungry [16]. On the contrary, a similar study conducted in 7–9 year olds showed that children with lower inhibitory control consumed more energy-dense snacks, compared to those with higher inhibitory control, both in the presence and in the absence of hunger [17]. This effect was not observed for medium or low-energy snacks that were also rated as less liked, suggesting that this increased susceptibility may be specific to palatable energy-dense foods. However, the authors reported that their satiety manipulation was not very effective and children reported moderate hunger after lunch, highlighting the need to re-examine these effects.

Overall, the evidence suggests that poor inhibitory control is linked with increased susceptibility to palatable energy-dense snacks in a laboratory context. Yet, little is known about its role in other important aspects of eating behaviour that impact energy intake and show large variation across individuals, such as portion selection decisions or the speed of eating. Research on portion size shows that children and adults tend to eat more when they are served larger food portions [18, 19] and this is not compensated for at subsequent meals, which over time can lead to weight gain [20–22]. It has been suggested that allowing children to self-serve their food could be a strategy to reduce intake from large portions [23]. However, there are large individual differences in self-served food portions and not all children eat less when allowed to self-select their meal size [24, 25]. Poor inhibitory control may be one of the underlying factors, leading some children to serve themselves more food when given the opportunity to select their own portion. Similarly, children's eating rates also show large variation that accounts for substantial differences in energy consumed at a meal [26], and these have been linked to their appetitive traits, such as higher food enjoyment and lower satiety responsiveness [27]. Evidence suggests that children increase their bite size, the primary driver of faster eating rates [28], when served larger food portions [29],

suggesting that faster eating may also reflect an aspect of increased responsiveness to external food cues that could be linked to poor inhibitory control.

The first aim of the current study was to investigate whether there is a relationship between 6 year old children's inhibitory control as measured by the SST and a range of eating behaviours, specifically: self-served portion size at lunch, eating rates, and energy intake at lunch during an eating in the absence of hunger (EAH) task, and cumulatively over these two eating occasions. The second aim was to investigate the relationship between children's inhibitory control and adiposity. We hypothesised that children with lower inhibitory control would select larger food portions at lunch, would eat at a faster rate and consume more energy during lunch, during the EAH task and more energy cumulatively. We further hypothesised that children with lower inhibitory control would have higher BMI, and higher skinfolds thickness and waist circumference.

Methods

Participants

The participants in this study were 406 children from the Growing Up in Singapore Towards healthy Outcomes (GUSTO) cohort, who completed the Stop Signal Task (SST) and participated in a lunchtime meal provided ad libitum, and the EAH task at age 6 years (range of 5 years 10 months to 6 years). Eligibility criteria and the GUSTO study profile are described in detail elsewhere [30]. Selection criteria for participation in this study are described in a flowchart provided as supplementary material (Appendix A). Children who consumed less than 50 g of food during lunch or who expressed hunger immediately afterwards were excluded as absence of hunger could not be assumed ($n = 151$; exclusion criteria based on Fisher and Birch [31]).

The final sample consisted of 255 children (127 boys, 128 girls), who were of Chinese ($n = 164$), Malay ($n = 50$) or Indian ($n = 41$) ethnicity. Children excluded from the sample did not differ from the final sample in sex, maternal education, BMI, measures of anthropometry or SST parameters ($p > 0.05$). Children of Malay ethnicity were more likely to be excluded, compared to children of Indian or Chinese ethnicity ($\chi^2 = 27.11$, $p < 0.001$). A slightly larger proportion of excluded children reported disliking the test food (20%), compared to those included in the analyses (11%; $\chi^2 = 15.5$, $p < 0.001$). Informed written consent was obtained from all participants and the study was approved by the National Healthcare Group Domain Specific Review Board and SingHealth Centralized Institutional Review Board.

Ad libitum lunchtime meal

Children consumed breakfast at home and were requested to fast for a minimum of 1 h before arriving at the study location. Children participated in other tasks for approximately 2 h prior to the lunchtime meal task, without access to food. Children consumed lunch alone without the parent or researcher present, in a test room equipped with child appropriate furniture and with three CCTV cameras. Children self-served a portion of vegetarian fried rice (1.86 kcal/g), which is a popular lunchtime food in Singapore, from a large bowl (800 g). Children were told that they could eat as much or as little as they wished, and they could serve themselves multiple times. The total portion served and consumed food was calculated from the leftovers in the serving bowl and on the child's plate. The number of food servings was recorded by the researcher who was observing the child from an adjacent room via CCTV. Children were given 20 min to consume the meal, but 10 min extensions were granted if that was not enough time (granted for 9 children). Children's hunger was assessed using a 5-point scale ranging from 'Very hungry' to 'Very full' both before and after lunch, and children's reported liking of the dish was assessed on a 3-point scale (yummy, OK, yucky) after lunch. The majority of children liked the test dish (89.4%).

Eating rate

Oral processing behaviours were coded using behavioural annotation software (ELAN 4.9.1, Max Planck Institute for Psycholinguistics, The Netherlands), described in detail elsewhere [26]. Children's bites, chews and swallows were coded throughout the meal, and were used to calculate the average eating rate (g/min) by dividing the total number of grams consumed per total time food spent in mouth. Video-coding was completed by a single trained coder, and 10% of the videos were randomly validated by a second trained coder, with two-way mixed effects model intra-class correlation coefficients showing excellent inter-rater reliability (ICC = 0.995, 95% CI [0.991, 0.997]).

Eating in the absence of hunger task

Approximately 20 min after lunch children took part in an EAH task, following the 'free access' protocol described by Fisher and Birch [31]. Two types of sweet (18 units of M&M, 4.83 kcal/g; 10 units of Hello Panda, 5.43 kcal/g) and two types of savoury (10 units of Rollercoster, 5.55 kcal/g; 2 units of Want Want, 4.83 kcal/g) snacks were placed in small bowls (310 kcal in total), and provided to children while they were playing with colouring papers and crayons. The researcher told the child that they had to briefly leave the room, and before leaving placed the bowls on the table within the child's

reach, and told them that they could have the snacks if they wished. The researcher returned after 5 min, which marked the end of the task. The food was weighed before and after the task to estimate the total energy consumed. Children rated liking of the snacks on a 3-point scale (yummy, OK, yucky). Individually each snack was accepted by the majority of children (98.4–99.6%).

Stop signal task (SST)

Children completed a computer-based language-independent SST from the Cambridge Neuropsychological Test of Automated Battery (CANTAB; Cambridge Cognition 2017), which has been previously used to assess response inhibition in a similar age group [17, 32, 33]. The SST requires children to take part in two concurrent tasks: a *Go* task and a *Stop* task. Children were instructed to press a left-hand button when they saw an arrow pointing to the left, and a right-hand button when the arrow pointed right (Go task; 75% of trials), and to withhold the response and not press the buttons when they heard an auditory 'beep' signal (Stop task; 25% of trials). The onset of the 'beep' signal varied and was either increased or decreased based on whether the previous attempt was successful or not. The task was presented in 5 blocks, block 1 was a practice block with 16 trials and blocks 2–5 were the main tasks, with 64 trials per block. The outcome measure of inhibitory control was taken as the stop signal reaction time (SSRT). SSRT was calculated as the mean reaction time on the Go trials (when there is no Stop signal) minus the mean delay on the Stop trials, from the last 50% of the trials. Higher SSRT indicated poorer response inhibition, akin to poorer inhibitory control.

Children were encouraged to try their best to press the buttons as fast as they could and to not press any buttons when they heard the beep, and were reminded of these instructions after each block. The researcher also took note if the child showed any unusual behaviours during the task.

Anthropometry

Child weight, height, waist circumference, and triceps, biceps, suprailiac and subscapular skinfold thickness were collected within 2 weeks of participating in the eating tasks, following the standard guidelines and using the recommended anatomical landmarks for children in this age group [34, 35]. Some data for individual measurements were missing due to lack of assent, with numbers outlined in the participant flowchart (Appendix A).

Height and weight were transformed to BMI *z*-scores (BMIz) corrected for age and sex according to WHO child growth standards [36], and were used to classify children as with healthy weight (BMI$_z$ ≤ 1.04; *n* = 183, 82.4%) or with overweight/obesity (BMI$_z$ > 1.04; *n* = 39, 17.6%),

equivalent to 85th percentile of BMIz [37–39]. Skinfold thickness in the four areas was summed as an indicator of whole-body adiposity (BA$_i$) and together with waist circumference were used as the main estimates of adiposity [39, 40].

Statistical analysis

SSRT scores were not normally distributed, so to improve normality these were log transformed. Most of the variables were treated as continuous, except for the number of servings children had at lunch, which was transformed to two categories, representing one serving (67.5% of the sample) or two servings or more (31.8% of the sample; 2 cases missing). The range of servings in the sample varied between 1–6. As an initial step, univariate regression analyses were performed to identify the potential covariates of the continuous study outcomes. Significant predictors and child sex were retained as covariates in the main analyses (summarised in tables). Logistic regression model with the same predictors was conducted to identify the potential covariates of the number of servings at lunch. No significant predictors were identified and child sex was the only variable retained as a covariate in the adjusted model.

Univariate linear regressions were conducted to investigate unadjusted associations between children's inhibitory control, their eating behaviours (excluding the number of self-servings made) and adiposity. Subsequently, hierarchical regression models were tested to investigate these associations, after adjusting for the previously identified covariates. Unadjusted and adjusted logistic regressions were conducted to examine whether inhibitory control predicted multiple portion servings at lunch. As the associations between poor inhibitory control and weight status might not show linear dependence, ANCOVA was computed to specifically compare SSRT among children with healthy weight and with overweight. Additional hierarchical regression analyses were conducted testing for potential interactions between SSRT and child sex, and no interactions were observed across any of the outcome variables (results not reported).

It was noted that 52 children (20.4 % of the sample) who completed the SST task were described in their task notes as being 'restless', 'fidgety', 'requested numerous breaks', 'complained of being tired or bored', 'chatty' or 'frustrated'. Additional exploratory post-hoc ANCOVAs were computed to investigate whether these children (hereafter referred to as 'restless') differed in any of the study outcomes from children who did not exhibit these behaviours during the task (described as 'typical' throughout), controlling for the previously identified covariates. For sensitivity, all a priori study aims were re-tested after excluding children described as 'restless' from the analyses. The results on the reduced sample ($n = 203$) did not differ significantly from those reported

(results not shown). All analyses were performed in IBM SPSS version 23.0. Tests are two-tailed and alpha level of 0.05 is considered significant.

Results

Inhibitory control and eating behaviours

Sample characteristics in the key study outcomes are presented in Table 1. Children tended to select larger portions than they consumed and leftover around 61 kcal (33 g) on average. The majority of children consumed some snacks during the EAH task (89.5%). There were significant sex differences in SSRT, portions selected and energy consumed at lunch, during the EAH and cumulatively.

The unadjusted and adjusted linear regression models are summarised in Table 2. In unadjusted analyses, children with lower inhibitory control served themselves larger portions of food at lunch and consumed lunch at faster rates. There was a trend for children with lower inhibitory control to consume more energy at lunch and cumulatively from lunch and the EAH task, but not independently during the EAH task. In unadjusted analyses children with higher SSRT had substantially increased odds to serve themselves multiple portions at lunch (OR = 14.9, 95% CI [2.1, 107.3]; b = 2.71, Wald $\chi^2(1) = 7.27$, $p = 0.007$).

Though the final models adjusted for covariates generally supported the unadjusted models, some of these associations were attenuated. Children with lower inhibitory control had significantly faster eating rates during the meal, and tended to serve themselves larger portions of food at lunch, although this association marginally missed the level of statistical significance ($p = 0.054$). The standardised regression coefficients indicated that for every 10% increase in SSRT children were self-serving 13.3 kcal more at lunch, and their eating rate was increasing by 1 g/min. Children with the scores in the top 10% of SSRT self-served up to 47% more food than the average selected portion at lunch, and had up to 69% higher eating rates than the average eating rate in this sample. The adjusted logistic regression confirmed that children with higher SSRT had 16-fold increased odds to serve themselves multiple portions at lunch (OR = 15.9, 95% CI [2.2, 115.8]; b = 2.76, Wald $\chi^2(1) = 7.42$, $p = 0.006$). Lower Inhibitory control was not associated with intake at lunch, during the EAH task or cumulative intake.

Inhibitory control and anthropometric measures

Table 2 summarises the results of regression models predicting measures of adiposity from children's SSRT scores. Both unadjusted and adjusted models showed that SSRT was not associated with children's BMIz, waist circumference or

Table 1 Sample characteristics in the main study outcomes (Mean ± SD) presented for the full sample and sex differences across the variables (*t*-tests)

	Sample	Boys (*n* = 127)	Girls (*n* = 128)
SSRT (ms)	376.6 ± 125.1	394.0 ± 126.8	359.2 ± 121.1*
Portion selection (kcal)	283.0 ± 153.5	316.8 ± 172.3	249.4 ± 124.0***
Eating rate (g/min)	14.4 ± 10.4	15.7 ± 9.2	13.2 ± 11.3
Lunch intake (kcal)	222.9 ± 125.7	245.5 ± 138.1	200.7 ± 108.0**
EAH (kcal)	60.2 ± 50.3	69.8 ± 54.8	50.7 ± 43.7***
Cumulative intake (kcal)	283.2 ± 142.7	315.3 ± 160.2	251.4 ± 114.8***
BMIz	−0.15 ± 1.35	−0.15 ± 1.14	−0.15 ± 1.31
BAi (cm)	30.5 ± 15.0	27.4 ± 12.1	33.2 ± 16.8**
Waist (cm)	53.5 ± 6.4	53.6 ± 5.9	53.4 ± 6.0

SSRT stop signal reaction time, *EAH* the eating in the absence of hunger task, *BAi* body adiposity index

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

BAi. Children with healthy weight did not differ from children with overweight in SSRT ($F (1, 218) = 0.51$, $p = 0.48$, $\eta_p^2 = 0.01$).

Post-hoc comparisons of 'typical' and 'restless' children

Children described as 'restless' during the SST task did not differ from children described as 'typical' in sex, ethnicity or maternal education (Chi-squared; $\chi^2 < 2.31$, $p > 0.18$). Table 3 summarises the differences between children described as 'restless' and those described as 'typical' across a range of SST parameters and study outcomes. 'Restless' children had higher SSRT compared to children with 'typical' behaviour. Further inspection of other SST parameters was conducted to understand the general performance of children described as 'restless' during the SST. This showed that 'restless' children had significantly higher mean response times and higher standard deviation of response times, both indicative of poorer attention and/or over-activity during the task.

Children described as 'restless' consumed on average 34% more calories during the EAH task compared to children with 'typical' behaviour, but did not differ significantly in any of the other key measures, including the number of servings at lunch (b = −0.19, Wald $\chi^2(1) = 0.30$, $p = 0.58$; adjusted for sex).

Discussion

Children with lower inhibitory control had increased odds of selecting multiple food portions at lunch and tended to

Table 2 Models (Beta and 95% CI, unadjusted and adjusted by covariates[a]) predicting child eating behaviours and adiposity from measure of their inhibitory control (SSRT)

Main outcome	Unadjusted		Adjusted	
	Beta [95% CI]	*p*	Beta [95% CI]	*p*
Portion served (kcal)[b]				
SSRT	165.7 [31.3, 300.2]	0.016	133.4 [−2.5, 269.3]	0.054
Eating rates (g/min)[c]				
SSRT	10.7 [1.6, 19.8]	0.021	9.9 [0.4, 19.3]	0.041
Lunch (kcal)[b]				
SSRT	103.2 [−7.4, 213.8]	0.067	77.0 [−32.9, 186.9]	0.17
EAH (kcal)[d]				
SSRT	26.8 [−17.7, 71.3]	0.24	17.0 [−27.4, 61.3]	0.45
Cumulative (kcal)[b]				
SSRT	130.0 [4.56, 255.4]	0.042	87.2 [−37.5, 211.9]	0.17
BMIz[e]				
SSRT	−0.3 [−1.6, 0.9]	0.59	−0.5 [−1.7, 0.8]	0.47
Waist (cm)[e]				
SSRT	−2.1 [−8.0, 3.8]	0.49	−3.0 [−8.9, 3.0]	0.32
BAi (cm)[e]				
SSRT	−4.1 [−18.4, 10.1]	0.57	−2.5 [−16.5, 11.4]	0.72

SSRT stop signal reaction time, *BAi* body adiposity index, *EAH* the eating in the absence of hunger task, *Beta* indicates unstandardised coefficients

[a]Variables considered as potential covariates of eating behaviours at lunch: child's sex, ethnicity, BMIz, child's reported liking of the rice, child's reported hunger before the meal, maternal education level and household income. Variables considered as potential covariates of intake during the EAH task: the same variables as for eating behaviours during lunch, and additionally intake (kcal) at lunch. Variables considered as potential covariates of SSRT: child's sex, ethnicity, maternal education, maternal age and household income. Variables considered as potential covariates of measures of anthropometry: child's sex, ethnicity, maternal education level and household income

[b]Adjusted for sex, BMI and child's reported liking of the rice

[c]Adjusted for sex and BMI

[d]Adjusted for sex

[e]Adjusted for sex and ethnicity

self-serve more calories overall, although this trend missed significance in the fully adjusted model. Children with lower inhibitory control also had faster eating rates, but they did not differ from children with higher inhibitory control in energy consumed at lunch, during the EAH task, or cumulative energy across the two eating occasions.

Table 3 ANCOVA summarising differences (Mean ± SEM) in the main study outcomes between children described as 'restless' and 'typical' during participation in the Stop Signal Task

Outcomes	Restless	Typical	F	sig.	η_p^b
SSRT[a] (ms)	433.5 ± 16.8	362.0 ± 8.5	14.45	<0.001	0.054
MRT[a] (ms)	1130.6 ± 47.3	875.3 ± 23.9	23.17	<0.001	0.084
SDRT[a] (ms)	1468.2 ± 211.0	471.6 ± 106.3	17.89	<0.001	0.066
Portion served (kcal)[b]	280.3 ± 21.0	278.51 ± 10.8	0.01	0.93	<0.01
Eating rates (g/min)[c]	14.5 ± 1.4	14.2 ± 0.8	0.09	0.76	<0.01
Lunch (kcal)[b]	213.7 ± 16.9	220.7 ± 8.7	0.13	0.71	<0.01
EAH (kcal)[a]	54.9 ± 4.8	40.89 ± 2.4	6.77	0.01	0.026
Cumulative (kcal)[b]	269.6 ± 18.1	261.43 ± 9.4	0.16	0.69	<0.01
BMIz[d]	0.13 ± 0.19	−0.23 ± 0.09	2.74	0.099	0.012
Waist (cm)[d]	54.5 ± 0.9	53.2 ± 0.5	1.51	0.22	0.010
BAi (cm)[d]	33.6 ± 2.1	29.6 ± 1.1	2.78	0.097	0.012

SSRT stop-signal reaction time, *MRT* mean response times, *SDRT* standard deviation of response times, *EAH* eating in the absence of hunger task, *BAi* body adiposity index, η_p^2 partial eta-squared

[a]Adjusted for sex

[b]Adjusted for sex, BMI and child's liking of rice

[c]Adjusted for sex and BMI

[d]Adjusted for sex and ethnicity

Exploratory post-hoc analysis revealed that children described as 'restless' during the SST had lower inhibitory control and consumed more energy during the EAH task, but did not differ in other eating behaviours from the rest of the sample. Finally, we found no evidence that inhibitory control was related to children's BMI or adiposity.

When allowed to select their own food, children with lower inhibitory control were significantly more likely to have multiple food servings and showed a trend to self-serve more food overall, highlighting specific eating behaviours through which poor inhibitory control may be expressed in a mealtime context. It has been previously hypothesised that lower inhibitory control undermines the control of eating behaviours as it increases susceptibility to external food cues. Yet, surprisingly little is known about the specific aspects of food behaviour through which poor inhibitory control is expressed. In adults, lower inhibitory control has been linked with higher intake of high-energy snacks, consistent with the idea that people with poorer inhibitory control may be more vulnerable to external food cues [14, 15]. Here, we provide evidence that among 6 year old children poor inhibitory control may increase susceptibility to multiple food approach behaviours, not restricted to palatable energy-dense snacks, and in this way promote larger portion sizes at meals. It has been previously suggested that encouraging children to select their own portions could be a strategy to reduce energy intake and promote better self-regulation [23]. However, the effectiveness of this strategy may be limited among children with lower inhibitory control, who when given the opportunity to self-serve their food, may be unduly influenced by external cues, and not necessarily select the appropriate amount or approach food multiple times. In this instance, children with lower inhibitory control may need more support from parents and caregivers to manage their portion sizes [41, 42].

Inhibitory control was also related to children's eating rates. It has been previously demonstrated that children increase their bite size in response to external food cues [29], supporting the idea that faster eating rates may reflect an aspect of increased responsiveness to external food cues that could stem, in-part, from lower inhibitory control. Faster rate of intake among children with lower inhibitory control may have additionally facilitated reaching for additional food portions after consuming the initial serving of the dish. Faster eating rates have been previously associated with higher energy intakes in children [26] and adults [43], highlighting that targeting this specific eating behaviour in intervention programmes could be beneficial for reducing energy intakes over time.

Although inhibitory control was linked to eating behaviours that are strong predictors of higher energy intakes, it was unrelated to energy consumed at lunch and to intake in the EAH task. This is surprising because the EAH task is commonly considered to be a measure of *disinhibited* eating and as such we expected that it would be well differentiated by an objective measure of inhibitory control. It has been previously demonstrated that children with lower inhibitory control show increased susceptibility to high-energy snacks both before lunch, and in the EAH paradigm after lunch [17]. Nevertheless, the authors noted that their satiety manipulation was not fully effective and some children reported moderate hunger after lunch, which might help to explain why these findings are inconsistent with the current study. The findings of the current study are consistent with

an earlier study in adults, which showed that inhibitory control may play a larger role in influencing eating behaviours when people report feeling hungry, but not in the absence of hunger [16]. Children with lower inhibitory control tended to select larger, and multiple food portions after a fasting period, and consumed food at faster rates, but did not consume more energy at lunch, when hunger sensations progressively subsided, or more energy during the EAH task, after they reported feeling full. It is possible that lower inhibitory control has a stronger influence over decision making at the initial phases of the meal. It should be noted that the majority of children in this sample consumed some snacks during the EAH task (89.5%), highlighting children's general tendency to respond to palatable snack food cues even when satiated, also observed in other studies [44, 45]. Consequently, it is possible that low data variability or time limits on this task affected sensitivity of the tests to detect individual differences.

Inhibitory control was not associated with measures of body composition in this sample. This is in line with another study conducted in children of similar age [17], and in a slightly younger sample where this association was seen among girls but not boys [13]. Research in older age groups generally supports the link between poorer inhibitory control and adiposity [10], suggesting that these associations might emerge in later stages of development, when children have greater control over their food environment, opportunities to habitually express this trait, and when they want to make active attempts to control their food intake for weight management.

One unexpected aspect of this study was that post-hoc analysis of SST data revealed that 20% of children in the sample showed some characteristics of behaviour described as 'restless'. Analysis of their SST parameters indicated that these children had lower inhibitory control, poorer attentiveness and were over-active during the test session, providing quantitative support for the split of children to 'restless' and 'typical' behaviour groups that was initially based on a qualitative comparison. The SST is a cognitively demanding task that requires the child's attention and focus. This may be to some extent challenging for children who are over-active, impulsive or have a shorter attention span. These children consumed more energy in the EAH task, highlighting potential links between executive function traits such as over-activity/inattention, poor inhibitory control, and vulnerability to external food cues. It has previously been suggested that higher levels of over-activity and inattention are facets of higher impulsivity [9, 46]. These traits have been linked to both faster and slower eating rates, higher intakes of fast food and soft drinks, and higher obesity risk in clinical samples of children with ADHD and non-clinical populations [47–49]. These results suggest that a sub-group of children who are both over-active/inattentive and have lower inhibitory control might be the most susceptible to EAH. As these were unplanned exploratory comparisons the results should be interpreted with caution.

Perhaps the most salient take-home point from these data is the need for intervention strategies that target multiple behaviours. Inhibitory control training has been shown to be effective in reducing short-term energy intakes in laboratory tasks [50, 51]. However, our results also demonstrate a need to target specific eating behaviours that affect energy intakes, such as selecting larger food portions, opportunities for children to have multiple food servings and faster eating rates. Previous research has shown that both eating rate and energy intake can be reduced when children receive within-meal feedback from external prompters of eating rates [52–54]. An alternative method is to modify food texture to produce 'slower foods' that promote smaller bites and encourage longer chewing cycles, or by promoting foods that are naturally 'slow' [55], which has been effective in reducing eating rates and energy intakes in adults [56]. Future research should focus on combined strategies to attenuate the risk of increased energy intake among children with lower inhibitory control.

The current study had a few limitations worth noting. Firstly, children were offered only a single food item at lunch, and some children did not consume a sufficient amount and were excluded from our analysis. It is possible that the single lunch option may have reduced the sensitivity of the lunch meal and subsequent EAH task as tools to detect differences in intake between children varying in inhibitory control who remained in the study. The lack of variety at lunch may have prompted children to eat more in the EAH task, which could explain why the majority of children in our sample showed some level of EAH. Nevertheless, limiting the number of lunch food choices allowed for a more accurate comparison of eating behaviours across the sample. Due to cross-sectional design, a causal relationship between the variables of interest cannot be established. Furthermore, this study utilised a single measure of inhibitory control and measured eating behaviours in the laboratory on one occasion, which might not reflect child's usual eating patterns. These associations should be additionally examined with alternatives measures of inhibitory control such as the Go/No-Go or Stroop test, as they might show different associations with eating behaviours. Finally, although representative of the Singaporean population, there was a relatively small number of children with BMIz over the 85th centile, which limited comparisons of child adiposity in the extreme range.

To conclude, children with lower inhibitory control took multiple food servings, showed a trend to self-serve more energy at lunch and consumed their meal at faster rates, highlighting potential behavioural manifestations of this trait. However, inhibitory control was unrelated to the actual energy consumed at lunch or during the EAH task, and was

not associated with child body composition. Within the current sample, 20% of the children showed behaviour characterised as 'restless' during the SST, and these children had lower inhibitory control and consumed more energy during the EAH task, highlighting a sub-group of children who may be particularly susceptible to high-energy snacks. These results have implications for our understanding of how individual differences in children's inhibitory control are associated with their eating behaviours, specifically portion selection and eating rates, indicating that a single individual trait may be linked to multiple aspects of eating.

Data availability

The datasets generated and/or analysed during the current study are not publicly available yet due to ongoing data collection, but are available from the corresponding author on reasonable request.

Compliance with ethical standards

References

1. Birch LL, Davison KK. Family environmental factors influencing the developing behavioral controls of food intake and childhood overweight. Pediatr Clin. 2001;48:893–907.
2. Stunkard AJ, Berkowitz RI, Schoeller D, Maislin G, Stallings VA. Predictors of body size in the first 2 y of life: a high-risk study of human obesity. Int J Obes Relat Metab Disord. 2004;28:503–13.
3. Llewellyn C, Wardle J. Behavioral susceptibility to obesity: gene-environment interplay in the development of weight. Physiol Behav. 2015;152(Pt B):494–501.
4. Anderson SE, Whitaker RC. Association of self-regulation with obesity in boys vs girls in a US National Sample. JAMA Pediatr. 2018;172:842–50.
5. Thamotharan S, Lange K, Zale EL, Huffhines L, Fields S. The role of impulsivity in pediatric obesity and weight status: a meta-analytic review. Clin Psychol Rev. 2013;33:253–62.
6. Guerrieri R, Nederkoorn C, Jansen A. How impulsiveness and variety influence food intake in a sample of healthy women. Appetite. 2007;48:119–22.
7. Nederkoorn C, Braet C, Van Eijs Y, Tanghe A, Jansen A. Why obese children cannot resist food: the role of impulsivity. Eat Behav. 2006;7:315–22.
8. Kamijo K, Khan NA, Pontifex MB, Scudder MR, Drollette ES, Raine LB, et al. The relation of adiposity to cognitive control and scholastic achievement in preadolescent children. Obesity . 2012;20:2406–11.
9. Pauli-Pott U, Albayrak Ö, Hebebrand J, Pott W. Association between inhibitory control capacity and body weight in overweight and obese children and adolescents: dependence on age and inhibitory control component. Child Neuropsychol. 2010;16:592–603.
10. Reinert KRS, Po'e EK, Barkin SL. The relationship between executive function and obesity in children and adolescents: a systematic literature review. J Obes. 2013;2013:820956.
11. Lavagnino L, Arnone D, Cao B, Soares JC, Selvaraj S. Inhibitory control in obesity and binge eating disorder: a systematic review and meta-analysis of neurocognitive and neuroimaging studies. Neurosci Biobehav Rev. 2016;68:714–26.

12. 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.

13. Levitan R, Rivera J, Silveira P, Steiner M, Gaudreau H, Hamilton J, et al. Gender differences in the association between stop-signal reaction times, body mass indices and/or spontaneous food intake in pre-school children: an early model of compromised inhibitory control and obesity. Int J Obes. 2015;39:614–9.

14. Guerrieri R, Nederkoorn C, Stankiewicz K, Alberts H, Geschwind N, Martijn C, et al. The influence of trait and induced state impulsivity on food intake in normal-weight healthy women. Appetite. 2007;49:66–73.

15. Nederkoorn C. Effects of sales promotions, weight status, and impulsivity on purchases in a supermarket. Obesity. 2014;22:E2–5.

16. Nederkoorn C, Guerrieri R, Havermans R, Roefs A, Jansen A. The interactive effect of hunger and impulsivity on food intake and purchase in a virtual supermarket. Int J Obes. 2009;33:905–12.

17. Nederkoorn C, Dassen FCM, Franken L, Resch C, Houben K. Impulsivity and overeating in children in the absence and presence of hunger. Appetite. 2015;93(Supplement C):57–61.

18. Fisher JO. Effects of age on children's intake of large and self-selected food portions. Obesity. 2007;15:403–12.

19. Roe LS, Kling SM, Rolls BJ. What is eaten when all of the foods at a meal are served in large portions? Appetite. 2016;99:1–9.

20. Kelly MT, Wallace JMW, Robson PJ, Rennie KL, Welch RW, Hannon-Fletcher MP, et al. Increased portion size leads to a sustained increase in energy intake over 4 d in normal-weight and overweight men and women. Br J Nutr. 2009;102:470–7.

21. French SA, Mitchell NR, Wolfson J, Harnack LJ, Jeffery RW, Gerlach AF, et al. Portion size effects on weight gain in a free living setting. Obesity . 2014;22:1400–5.

22. Syrad H, Llewellyn CH, Johnson L, Boniface D, Jebb SA, Van Jaarsveld CH, et al. Meal size is a critical driver of weight gain in early childhood. Sci Rep. 2016;6:28368.

23. Birch LL, Johnson SL, Andresen G, Peters JC, Schulte MC. The variability of young children's energy intake. N Engl J Med. 1991;324:232–5.

24. Savage JS, Haisfield L, Fisher JO, Marini M, Birch LL. Do children eat less at meals when allowed to serve themselves? Am J Clin Nutr. 2012;96:36–43.

25. McCrickerd K, Leong C, Forde CG. Preschool children's sensitivity to teacher-served portion size is linked to age related differences in leftovers. Appetite. 2017;114(Supplement C): 320–8.

26. Fogel A, Goh AT, Fries LR, Sadananthan SA, Velan SS, Michael N, et al. Faster eating rates are associated with higher energy intakes during an ad libitum meal, higher BMI and greater adiposity among 4.5-year-old children: results from the Growing Up in Singapore Towards Healthy Outcomes (GUSTO) cohort. Br J Nutr. 2017;117:1042–51.

27. Fogel A, Fries LR, McCrickerd K, Goh AT, Quah PL, Chan MJ, et al. Oral processing behaviours that promote children's energy intake are associated with parent-reported appetitive traits: Results from the GUSTO cohort. Appetite. 2018;126:8–15.

28. Fogel A, Goh AT, Fries LR, Sadananthan SA, Sendhil Velan S, Michael N, et al. A description of an 'obesogenic' eating style that promotes higher energy intake and is associated with greater adiposity in 4.5 year-old children: Results from the GUSTO cohort. Physiol Behav. 2017;176:107–16.

29. Fisher JO, Rolls BJ, Birch LL. Children's bite size and intake of an entrée are greater with large portions than with age-appropriate or self-selected portions. Am J Clin Nutr. 2003;77:1164–70.

30. Soh SE, Tint MT, Gluckman PD, Godfrey KM, Rifkin-Graboi A, Chan YH, et al. Cohort profile: growing up in singapore towards healthy outcomes (GUSTO) birth cohort study. Int J Epidemiol. 2014;43:1401–9.

31. Fisher JO, Birch LL. Eating in the absence of hunger and overweight in girls from 5 to 7 y of age. Am J Clin Nutr. 2002;76:226–31.

32. Phua DY-L, Rifkin-Graboi A, Saw S-M, Meaney MJ, Qiu A. Executive functions of six-year-old boys with normal birth weight and gestational age. PLoS ONE. 2012;7:e36502.

33. Luciana M, Nelson CA. Assessment of neuropsychological function through use of the Cambridge Neuropsychological Testing Automated Battery: performance in 4 to 12-year-old children. Dev Neuropsychol. 2002;22:595–624.

34. de Onis M, Onyango AW, Van den Broeck J, Chumlea CW, Martorell R. Measurement and standardization protocols for anthropometry used in the construction of a new international growth reference. Food Nutr Bull. 2004;25(1_suppl1):S27–S36.

35. Hamilton CM, Strader LC, Pratt JG, Maiese D, Hendershot T, Kwok RK, Hammond JA, Huggins W, Jackman D, Pan H, Nettles DS. The PhenX Toolkit: get the most from your measures. Am J Epidemiol. 2011;174:253–60.

36. WHO. Child growth standards. 2003. Accessed on: 1 September 2016. http://www.who.int/childgrowth/standards/Technical_report.pdf.

37. Wang Y, Chen HJ. Use of percentiles and z-scores in anthropometry. In: Handbook of anthropometry. Springer, New York, NY.; 2012. p. 29–48.

38. Centres for Disease Control and Prevention (CDC). Defining childhood obesity. 2015. https://www.cdc.gov/obesity/childhood/defining.html.

39. Berkowitz RI, Moore RH, Faith MS, Stallings VA, Kral TV, Stunkard AJ. Identification of an obese eating style in 4-year-old children born at high and low risk for obesity. Obesity. 2010;18:505–12.

40. Nightingale CM, Rudnicka AR, Owen CG, Cook DG, Whincup PH. Patterns of body size and adiposity among UK children of South Asian, black African-Caribbean and white European origin: Child Heart And health Study in England (CHASE Study). Int J Epidemiol. 2011;40:33–44.

41. Farrow CV. Do parental feeding practices moderate the relationships between impulsivity and eating in children? Eat Behav. 2012;13:150–3.

42. Bennett C, Blissett J. Parental monitoring may protect impulsive children from overeating. Pediatr Obes. 2017;12:414–21.

43. Robinson E, Almiron-Roig E, Rutters F, de Graaf C, Forde CG, Tudur Smith C, et al. A systematic review and meta-analysis examining the effect of eating rate on energy intake and hunger. Am J Clin Nutr. 2014;100:123–51.

44. Hill C, Llewellyn CH, Saxton J, Webber L, Semmler C, Carnell S, et al. Adiposity and'eating in the absence of hunger in children. Int J Obes. 2008;32:1499.

45. Moens E, Braet C. Predictors of disinhibited eating in children with and without overweight. Behav Res Ther. 2007;45:1357–68.

46. Braet C, Claus L, Verbeken S, Van Vlierberghe L. Impulsivity in overweight children. Eur Child Adolesc Psychiatry. 2007;16:473–83.

47. McWilliams L, Sayal K, Glazebrook C. Inattention and hyperactivity in children at risk of obesity: a community cross-sectional study. BMJ Open. 2013;3:e002871.

48. Holtkamp K, Konrad K, Müller B, Heussen N, Herpertz S, Herpertz-Dahlmann B, et al. Overweight and obesity in children with attention-deficit/hyperactivity disorder. Int J Obes. 2004;28:685–9.

49. Kim KM, Lim MH, Kwon H-J, Yoo S-J, Kim E-j, Kim JW, et al. Associations between attention-deficit/hyperactivity disorder symptoms and dietary habits in elementary school children. Appetite. 2018;127:274–9.

50. Jones A, Di Lemma LCG, Robinson E, Christiansen P, Nolan S, Tudur-Smith C, et al. Inhibitory control training for appetitive behaviour change: a meta-analytic investigation of mechanisms of action and moderators of effectiveness. Appetite. 2016;97:16–28.

51. Jiang Q, He D, Guan W, He X. Happy goat says: the effect of a food selection inhibitory control training game of children's response inhibition on eating behavior. Appetite. 2016;107:86–92.

52. Salazar Vázquez BY, Salazar Vazquez MA, López Gutiérrez G, Acosta Rosales K, Cabrales P, Vadillo-Ortega F, Intaglietta M, Pérez Tamayo R, Schmid-Schönbein GW. Control of overweight and obesity in childhood through education in meal time habits. the 'good manners for a healthy future' programme. Pediatric Obesity. 2016:6;484–490.

53. Hamilton-Shield J, Goodred J, Powell L, Thorn J, Banks J, Hollinghurst S, et al. Changing eating behaviours to treat childhood obesity in the community using Mandolean: the Community Mandolean randomised controlled trial (ComMando)—a pilot study. Health Technol Assess. 2014;18

54. Ford AL, Bergh C, Södersten P, Sabin MA, Hollinghurst S, Hunt LP, et al. Treatment of childhood obesity by retraining eating behaviour: randomised controlled trial. BMJ. 2010;340:250.

55. Forde C, Leong C, Chia-Ming E, McCrickerd K. Fast or slow-foods? Describing natural variations in oral processing characteristics across a wide range of Asian foods. Food Funct. 2017;8:595–606.

56. McCrickerd K, Lim CMH, Leong C, Chia EM, Forde CG. Texture-based differences in eating rate reduce the impact of increased energy density and large portions on meal size in adults. J Nutr. 2017;147:1208–17.

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