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The Effects of a Three-Hour, After School Bout of Sedentary vs Active Behavior on Reward and Cognitive Control Activation in 8- to 9-Year-Old Children: A Randomized Crossover Study

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ABSTRACT

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PURPOSE: To compare the effects of after-school sedentary versus active play on activation in the reward and cognitive control regions of the brain to pictures of high- and low-calorie foods.

METHODS: 32 children (12 girls, 20 boys; age 8.7 ± 0.5 years; height 137.9 ± 6.9 cm; weight 32.4 ± 6.2 kg) participated in a randomized crossover study with counterbalanced treatment conditions. Conditions took place on separate days after school and included three hours of active or sedentary play. After each condition, neural activation in reward and cognitive control regions of the brain were assessed using functional magnetic resonance imaging (fMRI) while participants completed a go/no-go task involving pictures of high- and low-calorie foods. General response inhibition was measured by the Stroop task. Hunger was measured upon arrival to the testing facility and just prior to fMRI scans. Mixed effects models were used to evaluate main and interaction effects.

RESULTS: Significant stimulus by condition interactions were found in the right superior parietal cortex, right postcentral gyrus and accumbens area ($p < 0.05$). High- versus low-calorie pictures of food elicited significantly different activation bilaterally in the orbitofrontal cortex ($p < 0.01$). Stroop task performance diminished significantly following the sedentary condition compared to the active condition ($F = 6.79$, $p < 0.01$). Subjective feelings of hunger were not different between conditions at any point.

CONCLUSION: Sedentary behavior significantly decreased response inhibition and brain activation to pictures of high-calorie foods in areas of the brain important to the modulation of food intake. Decreased attention, reward, and response inhibition, following sedentary behavior, may contribute to disinhibited eating that can lead to overweight and obesity.

Keywords: sedentary behavior, response inhibition, fMRI, go/no-go task, obese

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Introduction

Historically, the reward center has played an important role in survival during times of energy scarcity.[1–3] High-calorie foods elicit a reward response from brain structures in and immediately around the midbrain.[3–11] Functions produced by the midbrain, such as breathing, heart rhythm and digestion, are usually automatic, but can be influenced by other parts of the brain. Viewing high-calorie foods automatically elicits increased reward response.[5,7–9,12–14] This is suggested to be essential to learning which foods are energy rich and are therefore able to sustain the body for a longer period of time.[15] However, in most developed countries, the nutritional environment is much more energy abundant than in any other time in recorded history. The challenge has changed from finding rewarding foods to moderating the intake of rewarding foods.

In the same nutritional environment, a portion of the population maintains healthy weight and relatively low rates of chronic disease, but a significant portion of the population suffers from chronic diseases related to obesity. While there are several factors that may account for the disparity, one influential factor may be the ability to control the impulse, produced by reward, to consume high-calorie foods. In adults as well as children, those who are obese have less impulse control, compared to those who are healthy weight. [5,8,13] In an environment that is energy abundant, less impulse control can lead to obesity. Though the role of sedentary behavior in impulse control has not yet been investigated, increased sedentary behavior in children has been shown to be correlated with both increased food intake and obesity.[16,17]

Impulse control is one of the many functions of the cognitive control system of the brain.[18] Impulsivity is measured by the degree to which the inhibition, produced by cognitive control regions of the brain, is overpowered by activation in reward regions of the brain.

Increased impulsivity has been shown to be highly correlated to weight status.[4–6] Physical activity interventions have investigated the effects of behavior on brain reward and cognitive control activation, however, these effects have not yet been investigated in the context of sedentary behavior.

Moderation of impulsive behavior occurs in the cognitive control regions of the brain which include the prefrontal, dorsolateral prefrontal, orbitofrontal, posterior parietal, and anterior cingulate cortices, amygdala and hippocampus.[6,8,10,13,19–23] Impulse control is produced in the prefrontal, orbitofrontal and anterior cingulate cortices.[4,24–26] To perform its many executive functions, such as planning, problem solving and attentional control, the cognitive control system receives information from multiple brain structures, such as those dealing with memory, emotion, and reward.[5,21,27]

Reward and cognitive control have both been shown to be altered by physical activity. Literature on physical activity and reward, however, is limited. A thorough search showed only two studies, which both tested young, fit adults.[28,29] Both studies used a randomized, counterbalanced crossover design and compared the blood oxygen level dependent (BOLD) response in reward regions of the brain to high- and low-calorie pictures of food after high intensity exercise. Both studies had participants exercise at a high intensity for 60 minutes. One study used a cycle ergometer and the other used a treadmill. The results from both studies demonstrated that the neural response to pictures of high-calorie foods was reduced, compared to no exercise, in reward regions such as the insula, putamen, and rolandic operculum.[28,29] While these findings are interesting, the literature that investigates the effects of less strenuous physical activity on reward activation to food cues is still limited, especially in children.

The effect of physical activity on cognitive control has been more thoroughly studied, however, most fMRI studies have used longitudinal designs and non-reward-related visual stimuli, such as geometric shapes.[19,21] There is only one other study in children on the effect of acute physical activity on brain activation, using reward-related stimuli. In the study by Masterson et al., participants were scanned by fMRI following 30 minutes of walking on a treadmill at a moderate intensity and after 30 minutes of sedentary behavior, consisting of reading books or playing games.[30] The results of this study showed that, after exercise, there was greater activation in both the hippocampus and right medial temporal lobe to pictures of high-calorie foods. In the same brain regions, activation was reduced to pictures of low-calorie foods. The study provided evidence for the role that an acute bout of exercise may play in the regulating eating behaviors in children.

While physical activity has been shown to influence activity in regions of the brain implicated in the regulation of eating behaviors in children, literature investigating the effect of sedentary behavior on these regions is limited. Sedentary behavior is an independent risk factor, separate from physical activity and diet, for obesity and multiple health problems.[31,32] As children age, the time they spend daily engaged in sedentary behaviors increases.[32–34]

Given current trends of prolonged sitting after school, it is important to understand how a single sedentary bout affects regions of the brain related to a child's desire to consume food. Aside from customary sitting in school, children engage in activities that require minimal physical effort after school.[32] Sedentary time reduces energy expenditure and increases energy intake in children.[16,31,32] Research describing the effect of sedentary behavior on neural response to food cues is needed. The purpose of this study was to compare the effects of after-school sedentary versus active play on activation in the reward and cognitive control regions of the brain to pictures of high- and low-calorie foods.

Methods

Research Design

The present study used a randomized crossover experimental design. Children participated in two separate, three-hour bouts of active behavior and sedentary behavior. Testing occurred at approximately the same time of day, on the same day of the week, one week apart for each condition. Active and sedentary conditions were conducted in random order. After completing the experimental condition on each day, blood oxygen level dependent (BOLD) response to pictures of food was measured by fMRI while participants performed a go/no-go task. The dependent variables included reward and cognitive control center BOLD response to pictures of food during the go/no-go task. Details of the testing measures are found below.

Participants

Thirty-two children between the ages of 8 and 9 years old were recruited to participate in this study. Participants included male and female children from several cities surrounding the university, with rolling admission until the desired number of participants completed the protocol. Recruitment was accomplished through flyers, visits to public recreation centers, and by word of mouth. Potential participants filled out an online demographic survey, which included age, gender, height, weight, and other demographic data. Participants were required to have normal or corrected-to-normal vision and to qualify to participate in strenuous physical activity, with no current orthopedic impairments, based on the physical activity readiness questionnaire (PAR-Q; see appendix 1). The study was approved by the institutional review board of the university.

Inclusion criteria.

- Children aged 8 to 9 years old
- Able to participate in physical activity without restriction
- Right handed, according to MRI convention

Exclusion criteria.

- Diagnosed with a neurological disorder, i.e., autism, attention deficit hyperactivity disorder (ADHD), depression, and any other disorders.
- < 5th or > 97th percentile of recommended BMI for age
- Previous incident of traumatic brain injury
- Taking mood altering medications

Procedures

After inclusion screening, parents of participants were contacted by phone to confirm understanding of the protocol and to schedule their child's two visits to the lab. An email was sent with electronic copies of consent and assent forms for parents and participants to review and a menu from which to select meals for the days of testing (see appendix 3). Initial consent and assent were given with a reply in the affirmative to the email. Food was dropped off to the participant's house on the day before testing for each condition. Participants also received an accelerometer to wear beginning at 7:00 a.m. on the day of testing for each condition, as an objective measure of the testing day's activity level. Upon arrival to the testing facility, participants signed a paper assent form and parents of participants signed a paper consent form. Understanding of protocol and expectations by both the participants and the parents was confirmed before beginning the experiment.

Participants received a standardized breakfast and lunch on the day prior to entering the testing facility. Participants were counseled to eat all the food provided for breakfast and lunch on the day of testing and to come adequately hydrated. Upon arrival to the testing facility, a standardized snack was provided before the experimental condition began. Parents were notified that dinner would not be provided to the participants, which meant that the children would not be available to eat dinner until sometime between 7:00 and 8:30 p.m.

Active condition. During the active condition, participants sat or rested for no more than 5 minutes in each hour. Participants engaged in various activities that kept them from being sedentary for 3 hours. The active day included various activities to keep participants on their feet, such as beanbag toss, basketball, soccer, volleyball, walking the track, Pokémon Go, and a brief fitness test. The purpose of the active condition was for participants to not be sedentary. To avoid exhaustion from overactivity confounding fMRI results, participants were instructed that the emphasis of these activities was on enjoyment and safety, not competition or skill enhancement.[21]

Sedentary condition. During the sedentary condition, participants were sitting or reclining, with no more than 5 minutes in each hour of standing or walking. Participants were sitting to play computer games (Minecraft or Viva Pinata) and to watch a G-rated film during the 3-hour block. Gaming occurred in the first hour and a half and, in the last hour and a half, participants viewed one of five movie choices: Aladdin, Cars, How to Train Your Dragon, Monsters, Inc., or Tangled. Children were allowed restroom and water fountain breaks as necessary, but breaks were limited as much as possible to keep participants sedentary. After completing each experimental condition, and before entering the scanner, participants completed the Stroop task.

A second standardized snack was provided two hours before beginning the fMRI scan.[35] The snacks and meals consisted of items previously selected by each participant from the menu found in appendix 3. Water was available throughout the experimental condition on both testing days. It was required that each participant sleep for at least eight hours on the night preceding the day of testing in each condition. The breakfast and lunch provided consisted of a selected main course for lunch along with fruits and vegetables the participant consented to consume. Meals and snacks were identical on both testing days with the total energy breakdown of 25%, 25%, 12.5% and 12.5%, respectively, to provide 75% of the daily macronutrient requirements. To calculate the energy requirements of the children, equations for boys and girls from the Food and Agriculture Organization were used.[53]

Following the 3-hour bout of sedentary or active behavior, participants were taken to the magnet room for an additional 30 minutes of testing. Upon arrival to the facility, and directly before entering the magnet, hunger and satiety of participants were subjectively assessed by the means of Teddy the Bear (see appendix 4). [8,36,37,38] This measurement was performed to verify that children entered each condition and the testing with similar feelings of hunger, since feelings of hunger might alter neural response to visual cues of food. According to standard procedure, an MRI Screening Form was filled out before each time a participant entered the magnet. Once inside the bore of the magnet, a computerized task acted as stimulus for the objective assessment of reward and cognitive control response to pictures of food.

Participants arrived between 3:30 and 5:00 p.m. for the experimental condition and fMRI scans occurred in the evening, with each scan beginning between the hours of 6:30 and 8:00 p.m. Objective fMRI measurements of reward and cognitive control response during go/no-go tasks were inferred by the measurement of the BOLD response in respective regions of the brain. For food images, participants answered "yes" or "no" to the question: "Is this a healthy food?" by pressing a button or by withholding a button push, respectively. Participants were instructed to push the button when they see a healthy food and to do nothing when they see an unhealthy food. Because not all children between the ages of 8 and 9 are familiar with identifying high- and low-calorie foods, the question proposed allowed participants to identify foods that appear rewarding to them. In this way, the assessment of reward and cognitive control response was not confounded by the participants' ability to immediately master a novel skill.[39] Analysis of the fMRI data was completed at the MRI facility at the university.

The pictures of food have been published previously and are based on the work of Killgore (2003).[13] The go/no-go task included pictures of high-calorie foods (such as candy, pastries and ice cream) (n = 120), low-calorie foods (such as vegetables, fish, and whole grains) (n = 120). Each picture was projected for approximately 0.5 second with a black fixation cross on a white background shown for 7 to 12 seconds between pictures. High-calorie and low-calorie food pictures were randomized into two groups of 60 pictures. One block of each was randomized to the sedentary and active conditions.

Each group of pictures had 24 blocks in total, consisting of 10 pictures each. The data was collected in 3 runs of 4-minute lengths with 18 pictures per run and approximately one minute to rest between runs to minimize participant movement during scans. To limit habituation, no image was shown twice. The amplitude of BOLD responses to pictures of food represented activation as outcomes for reward and cognitive control response. BOLD response was measured in regions of interest determined before measurements were taken for an a priori hypothesis.

Measurements

To answer the question whether or not after school activity levels influence the brain's reactivity to food cues, the following parameters were measured: activity levels, reward and cognitive control in regions of interest, hunger, self-reported impulsivity and inhibitory control. Methods associated with these measurements are described below.

Sedentary behavior and physical activity. Activity counts, measured by accelerometer, were recorded for each participant using ActiGraph accelerometry (Pensacola, FL). We made objective measures of children's sedentary behavior and moderate-to-vigorous physical activity levels, which were analyzed using ActiLife 6 software (Pensacola, FL). Validity and reliability of this accelerometer model have been supported in the literature.[40]

The Actigraph GT3X accelerometer was used as an objective measurement of activity levels on each testing day, beginning at 7:00 a.m. and ending after the experimental active or sedentary bout. Energy expenditure measured by these accelerometers has shown good correlations ($r = 0.74$ to 0.95) during walking, running, and other defined activities.[40] Participants wore the accelerometer on the right side of the body, at the level of the umbilicus and above the anterior iliac spine. The accelerometer was worn, beginning at 7:00 a.m., on the day of testing until the completion of the 3-hour experimental condition, removing it for water activities only. Participants were asked about any nonwear time and answers were recorded in their file.

A day's data was considered complete if the participant wore the monitor for at least 75% of the time between 7:00 a.m. and the end of the 3-hour experimental condition. Nonwear time was conservatively defined as 20 or more minutes of consecutive zeros. No participants were removed from this study for insufficient wear-time, as the measure was only a covariate in this study. Accelerometer data was collected in 60-second epochs. Standard activity cut points for children were used: vigorous activity (> 6500 counts/min), moderate activity (1500–6499 counts/min), light activity (100–1499 counts/min), and sedentary (< 100 counts/min).[41]

Reward and cognitive control. The BYU MRI Facility houses a Siemens TIM-Trio 3.0T MRI scanner (Siemens Trio, Erlangen, Germany) which was used for this study. Each subject received two scans (~30 min each), following sedentary and active experimental conditions, in the fMRI machine. The following parameters were used to obtain a T1-weighted MPRAGE structural scan for each subject: TE = 2.26 ms; T = 1900 ms; flip angle = 9°; matrix size = 256 × 215 mm; field of view = 218 × 250 mm; 176 slices; slice thickness = 1mm; voxel size = .977 × .977 × 1; 1 total acquisition. Localization of functional scans, Talairach transformation, and coregistration with the fMRI data were based on this structural scan. T2*-weighted images were obtained using the following parameters: TE = 28 ms; TR = 2000 ms; flip angle = 90°; matrix size = 64 × 64; field of view = 220 × 220 mm; 40 slices; slice thickness = 3 mm; voxel size = 3.4 × 3.4 × 3 mm; 270 total acquisitions. Analysis of Functional NeuroImages (AFNI) software was used to process and analyze fMRI data. Appropriate corrections, filtering, and normalization functions were performed.

Stimuli were displayed on an MRI-compatible computer screen that was viewed by participants through a mirror attached to the head coil. Before testing began, the mirror was adjusted, as necessary, for each participant to have had an optimal view of the reflection of the monitor. Participants were instructed to remain still and awake with their eyes open during scanning. They were informed that there were breaks between trials that would allow them to adjust slightly before being expected to be still for the next trial. Instructions emphasized that the participant view each picture attentively, even if some images might be unpleasant to them. Participants were warned about the possible side effects (dizziness, heating, nerve stimulation, claustrophobia) of being inside of the scanner, but that side effects were unlikely. In the highly unlikely case that severe side effects made it necessary, participants were given a panic balloon with which they had the ability to signal the researcher to stop the scanning session, in an emergency.

Regions of interest involved in both reward and cognitive control. Regions of interest were defined using a child template. The dorsal striatum, caudate and putamen are structures known to be related to habit learning, addiction, positive reward expectations and exposure to cues with increased incentive value among obese groups relative to lean cohorts.[11,28,35,36,42,43]

Reward regions of interest. Previous studies have identified the insula, nucleus accumbens and ventral tegmental area to be regions highly correlated with food reward response.[2,4,8,11,12,28,35,36,44–46]

Cognitive control regions of interest. Prefrontal, orbitofrontal and anterior cingulate cortices have all been identified in previous studies as correlating with increased cognitive control. The right anterior prefrontal and posterior parietal cortices are also correlated with increased cognitive control, though differentially from other regions of interest, namely the anterior and lateral prefrontal and orbitofrontal cortices, anterior cingulate cortex, hippocampus, and amygdala.[6,19,21,23,36,39,42,47,48]

Data Analysis

The MRI data were preprocessed and analyzed using the Analysis of Functional NeuroImages (AFNI) suite of software. All functional runs were time shifted, corrected for participant motion, and spatially filtered using a 5 mm FWHM Gaussian kernel. To model single-subject BOLD response to pictures of food, following after-school activity, 3dDeconvolve was performed. Mixed effects analysis of variance was used to evaluate the main and interactive effects for the regional analysis of the brain. Using Monte Carlo simulations, the exploratory whole brain analysis simulated a combination of significant activation of $p < 0.01$ for a cluster size of > 30 contiguous voxels, giving an overall $p < 0.05$. To measure the effect of activity level on BOLD activation amplitudes in response to picture type (high- versus low-calorie), whole-brain, group-level analysis of variance was conducted with activity level (sedentary, active) and stimulus type (high-, low-calorie) as fixed factors and participants as a random factor. Mixed effects analysis was also used to analyze the results of Stroop performance (reading, color naming, and incongruent word color reading), hunger rating, and physical activity (total, during and after school). The least squared means procedure was used to evaluate significant main and interactive effects. Means and standard deviations were reported for all variables of interest. PC-SAS version 9.4 was used for the mixed effects modeling.

Results

Participant Characteristics

Forty-two children were assessed for eligibility, 39 participants were randomized, with 32 of the participants finishing the study (see Figure 1). The primary reason for drop out was because the participants discontinued correspondence with the research staff. Twelve girls and twenty boys completed both sedentary and active conditions. Table 1 summarizes participant characteristics. The mean age was 8.7 ± 0.4 years and was similar for boys and girls.

The influence of gender was assessed for all outcomes of interest. There were no differences between boys and girls for any variable of interest nor was there any significant gender-by-condition interactions observed. As a result, gender was removed from all statistical models and all participants were analyzed together.

Activity

Physical activity patterns were not different during the school day for either test condition (see Figure 2). As expected, steps ($F = 335.31$, $p < 0.01$) and moderate-to-vigorous physical activity ($F = 228.63$, $p < 0.01$) were significantly lower after school on the sedentary compared to the active day (see Table 2). The number of steps taken after school was 94% lower on the sedentary day, compared to the active day.

Participants rated their sensations of hunger by the discrete measure with Teddy the Bear upon arrival to the MRI facility and before entering the MRI scanner. The result of the least squared means procedure showed no significant differences between condition, upon arrival to the testing facility ($p = 0.82$) nor after three hours of active or sedentary play, before entering the scanner ($p = 0.45$).

Response Inhibition

There was a significant condition-by-test interaction for the Stroop word color task ($F = 4.25$ and $p = 0.04$). The least square means follow-up test showed that following the sedentary test days participants scored lower on the incongruent task compared to the active test days ($F = 6.79$, $p = 0.01$). There was no difference for the reading or color naming tasks between the days. The full results of the Stroop task are detailed in Table 3.

Reward and Cognitive Control Activation

There was no main effect for condition observed for any region of the brain in either the a priori regional or exploratory whole-brain analysis. The regional analysis showed a significant stimulus-by-condition interaction in the right superior parietal cortex, right postcentral gyrus and accumbens area ($p < 0.05$; see Figure 3). The whole-brain analysis confirmed the results of the first two areas, but was not sensitive enough to confirm the interaction in the accumbens area (p

< 0.01: see Figures 5). Region-of-interest analysis also showed a significant main effect of picture type, bilaterally, in the lateral orbitofrontal cortex ($p < 0.05$; See Figure 4). Whole-brain analysis confirmed the significant main effect for picture type in the orbitofrontal cortex (bilaterally), and also showed significance for picture type in the supplementary motor cortex and primary somatosensory cortex, with higher activation to pictures of high- versus low-calorie food ($p < 0.01$; see Figure 6). For a list of all regions of interest analyzed see Table 4.

Discussion

The study was designed to evaluate the neural implications of increased sedentary play after school since children tend to have greater autonomy during this time of the day, especially when compared to time in school. According to the structured days hypothesis, this greater autonomy tends to result in behaviors that are less favorable to weight management.[49] This includes sitting, watching TV, playing sedentary games and unregulated eating. In addition, it is likely that these behaviors are not independent and that more time spent in sedentary activities influences neural responses to food cues. The findings of this study confirm this observation and demonstrate that activity choice can alter neural responses to food.

Though the fMRI literature exploring the effects of sedentary behavior in children is limited, the hypotheses of this study were based on the premise that the brain is inert matter governed by predictable principles. Thus, prospective studies comparing neural response to food cues by weight status, and longitudinal studies evaluating after-school exercise interventions among children, informed hypotheses on the effect of after-school activity choices on response to food cues.[6,7,19,21,23] The studies evaluating the relationship between weight status and neural response to food cues reported a positive correlation between neural activation in regions of the brain related to reward and cognitive control.[6,8,13,23] Additionally, physical activity interventions demonstrated increased cognitive control with both increased and decreased activation in cognitive control regions of the brain.[8,19,23] These two observations led to the hypothesis that sedentary behavior would result in activation patterns similar to obese and opposite to post-physical-activity activation, with increased activation to high-calorie stimuli in reward regions of the brain and both increased and decreased activation to high-calorie foods in cognitive control regions.

While the results of this study did not support the main effect of condition that was hypothesized, there were significant interactions and a significant main effect of stimulus. Both the whole-brain and regions-of-interest analyses showed a significant main effect for stimulus (high- and low-calorie foods) in the orbitofrontal cortex and a stimulus-by-condition interaction in the right postcentral gyrus and right superior parietal cortex. Along with those cognitive control region results, the regional analysis was sensitive enough to show a significant stimulus-by-condition interaction in the reward area of the accumbens. These findings suggest that the type of activity engaged in after school can elicit different responses to high- and low-calorie foods in regions of the brain involved in modulating food intake.

The lack of an observed main effect of condition in cognitive control and reward regions of the brain was caused by a reversal in activation patterns to high- and low-calorie foods cues on the sedentary versus the active day. In both reward and cognitive control regions in the brain, there was higher activation toward low-calorie stimuli following the sedentary condition and higher activation toward high-calorie stimuli followed the active condition. This resulted in a crossover activation pattern and a null finding for condition, but a significant condition by stimulus interaction (see Figure 3).

Currently, there is limited data evaluating how sedentary behavior influences activation in reward and cognitive control regions of the brain to pictures of food. The only previous study in children was conducted in the morning and included a go/no-go task while viewing stimuli that included pictures of food.[30] The two conditions were 30 minutes of playing seated games or reading books compared to walking on a treadmill at ~67% max heart rate. A significant stimulus-by-condition interaction (picture type) was found with a crossover activation pattern in the hippocampus. They also found decreased activation in the postcentral gyrus and increased activation in the insula to pictures of food, following the control condition compared to exercise. When the pictures of food were separated for analysis by calorie content within each condition, both areas resulted in higher activation toward high-calorie stimuli and lower activation toward low-calorie stimuli.

We observed a similar activation pattern in the hippocampus, observing higher activation to low-calorie stimuli on the sedentary day and higher activation to high-calorie stimuli on the active day. However our results were weaker and did not reach significance ($p = 0.09$). While our results were the same following activity, they were opposite following sedentary play in the right postcentral gyrus, right superior parietal cortex, and accumbens area ($p = 0.05$).

Though the study by Masterson et al.[50] and the present study were conducted in similar aged children using similar stimuli, the difference in findings may be due to a combination of the time of day the participants were scanned and the duration and intensity of the intervention. Specifically, the intervention in our study was six times longer and at a lower absolute intensity. In addition, the time of day has been shown to influence neural responses to visual food cues.[51] Thus, the neural response in the morning may be different than the neural response after school.

Interpreting activation changes in regions of the brain related to reward has become more difficult in recent years. Increased activation in areas of the midbrain such as the nucleus accumbens, caudate and putamen, has generally been interpreted to mean increased reward.[6,13,23,27,30,43,52] However, the concept of reward processing has brought into question whether increased reward activation really does indicate increased reward. Since what the activation of reward processing looks like is not yet clear, both increased and decreased reward processing have been suggested to contribute to the development of obesity.[9,43] In the present study, a significant stimulus-by-condition interaction was observed with decreased activation toward high-calorie stimuli in the accumbens area following sedentary play. Decreased activation may be due to decreased reward processing. Decreased reward processing, including decreased attention to food stimuli and response in the nucleus accumbens to food stimuli, is suggested to be an obesogenic activation pattern.[9–11]

The interpretation of cognitive control system activation is even more complicated. Different regions in the system have varying functions (i.e., attention, planning, executive control, and other cognitive functions) and increased BOLD response is the same whether neural firing causes excitation or inhibition. We hypothesized a dynamic interplay among cognitive control regions, with increased activation in some areas and decreased activation in others, which was confirmed by the results (see Figure 4).[21] The two previous fMRI studies conducted to evaluate both reward and cognitive control, using pictures of food following sedentary and active behavior, in fit adults saw increased orbitofrontal activation to high-calorie foods after rest.[28,29] In a longitudinal exercise study among children, Davis et al. employed a cognitive control task that demonstrated increased cognitive control with decreased activation bilaterally in the parietal cortex.

Results of the present study did not refute those findings with significant main effects of condition; however, the data trended opposite. There was a trend toward decreased orbitofrontal activation to high-calorie stimuli following sedentary versus active play and decreased cognitive control with a significant interaction of decreased parietal activation to high-calorie stimuli following sedentary play. These findings suggest decreased attention and greater conflict in the decision center. The greater conflict, indicated by increased activation toward the high-calorie stimuli, may have been due to decreased proficiency in performing the task of withholding the button push.[6,19,23]

To help interpret the results and determine whether decreased cognitive control was indicated by increased or decreased activation in a given cognitive control region of the brain, we administered the Stroop task at the completion of each experimental condition. Results of the Stroop task confirmed diminished cognitive control, specifically response inhibition, following sedentary compared to active after-school play.

As with any study, the present study had some limitations that should be considered when interpreting the results. First, it is possible that performing the Stroop task directly before the fMRI may have primed the cognitive control regions of the brain. However, the results of the Stroop task were valuable to the interpretation of the fMRI results.[48] In addition, using both high- and low-calorie images for the fMRI task, in contrast to food and nonfood objects, may have made changes between the two experimental conditions less evident. While this may have impacted the magnitude of the results, using high- and low-calorie food images allowed us to evaluate how the brain responds to pictures of foods with different reward value, which may be more salient to food choice and energy balance. Finally, while the narrow age range of this study minimized developmental noise in the data, it does not allow results to be generalized to children that are younger and older than 8 to 9 years old.

Along with these limitations, the present study has several strengths. This is the first study to investigate the effect of acute after-school sedentary compared to active play on neural responses to food cues using fMRI in children. On the days of testing, energy consumption was standardized with nutrient balanced meals designed using energy expenditure equations for children from the Food and Agricultural Organization, and energy expenditure was objectively measured by accelerometry. These measures confirmed that energy intake and physical activity were similar during both school days and that physical activity was different after school between experimental days. Finally, when performing the fMRI task, the question participants responded to was designed to avoid the confounding of novelty. Since 8- to 9-year-old children may not yet be familiar with the terms “high-calorie” and “low-calorie,” the terms “healthy” and “unhealthy” were used instead.

Conclusion

This study demonstrated the acute neural implications of a lack of compensation for imposed sedentary time during school.[41] After-school sedentary play decreased response inhibition and produced a significant interaction of decreased activation to pictures of high-calorie foods in brain regions responsible for reward and attention. Increased activation to high-calorie stimuli in the decision center of the brain may have been due to increased conflict produced by decreased proficiency in task performance. These changes in activation patterns add to an expanding body of fMRI literature that addresses disinhibited eating and the development of obesity in children. Findings from the present study suggest that changes in neural activation toward food cues, due to sedentary behavior, are one potential mechanism that contributes to the development of obese-correlated brain activation patterns that may lead to obese brain morphology.[6,9,27,53] Future studies that employ a longitudinal design are needed among children to evaluate how decreased reward processing alters brain activation patterns in reward and cognitive control regions of the brain.

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Table 1. *Participant demographic data*

	Girls *N = 12*	*Boys* *N = 20*	*Combined* *N = 32*
Age (y)	8.7 ± 0.5	8.7 ± 0.5	8.7 ± 0.48
Height (cm)	138.2 ± 9.1	137.7 ± 5.5	137.9 ± 6.9
Weight (kg)	32.3 ± 7.2	32.5 ± 5.7	32.4 ± 6.2
BMI (kg m^{-2})	16.7 ± 1.8	17.1 ± 2.5	16.9 ± 2.2

Means ± standard deviations
No significant difference between genders for any variable
Abbreviations: y = year; cm = centimeters; kg = kilograms

Table 2. *Intervention after-school physical activity patterns*

Activity Level	*Active*	*Sedentary*	*F-value*	*P*
Steps	11177 ± 2129	1570 ± 907	364.95	< 0.01
Sedentary (min)	95 ± 31	204 ± 50	90.62	< 0.01
Light (min)	95 ± 25	75 ± 33	7.30	< 0.01
MVPA (min)	106 ± 28	11 ± 9	238.06	< 0.01

Means ± standard deviations
F- and P-values refer to the difference between steps and minutes spent in each after-school condition
Abbreviations: min = minutes, MVPA = moderate-to-vigorous activity

Table 3. *Stroop scores following three-hour active versus sedentary play intervention, after school*

Condition	*Active*	*Sedentary*	*F-value*	*P*
Name Word	69.3 ± 14.8	68.3 ± 13.3	0.30	0.59
Name Color	48.4 ± 8.6	48 ± 8.5	0.07	0.79
Incongruent	30.7 ± 7.3	27 ± 7.3	6.79	0.01

Means ± standard deviations
F- and P-values refer to the difference between Stroop task performance on each condition following the sedentary compared to active after-school experimental days.

Table 4. *Regional analysis activation in beta values*

Region of Interest	*Act-Hi*	*Act-Lo*	*Sed-Hi*	*Sed-Lo*	*Stimulus*	*Stimulus by Condition*
Right Medial Orbitofrontal Cortex	0.40	-0.10	0.20	-0.12	3.22**	
Left Medial Orbitofrontal Cortex	0.52	-0.12	0.16	-0.08	3.56**	
Right Lateral Orbitofrontal Cortex	0.73	-0.03	0.41	0.10	7.95*	
Left Later Orbitofrontal Cortex	0.74	-0.09	0.39	0.11	6.48*	
Right Hippocampus	0.94	0.04	0.54	0.52	1.79	
Left Hippocampus	0.75	-0.16	0.28	0.50		3.00**
Right Postcentral Gyrus	0.19	0.01	-0.16	0.60		4.54*
Left Postcentral Gyrus	0.27	0.06	-0.20	0.73		3.83**
Right Superior Parietal Cortex	0.62	0.06	0.14	0.71		6.70*
Left Superior Parietal Cortex	0.66	0.15	0.17	0.74		3.40**
Accumbens Area	0.64	-0.18	-0.01	0.49		4.20*
Right Caudate	0.58	-0.04	0.52	0.68		1.97
Left Caudate	0.67	-0.26	0.05	0.64		3.72**
Right Putamen	0.58	-0.04	0.52	0.68		1.97
Left Putamen	0.67	-0.11	0.43	0.79		2.58
Right Insula	0.57	0.02	0.52	0.66		1.32
Left Insula	0.62	-0.15	0.39	0.74		2.08

*Indicates significance with $p < 0.05$
**Indicates significance with $p < 0.10$
The stimulus and stimulus by condition interaction are F-values.

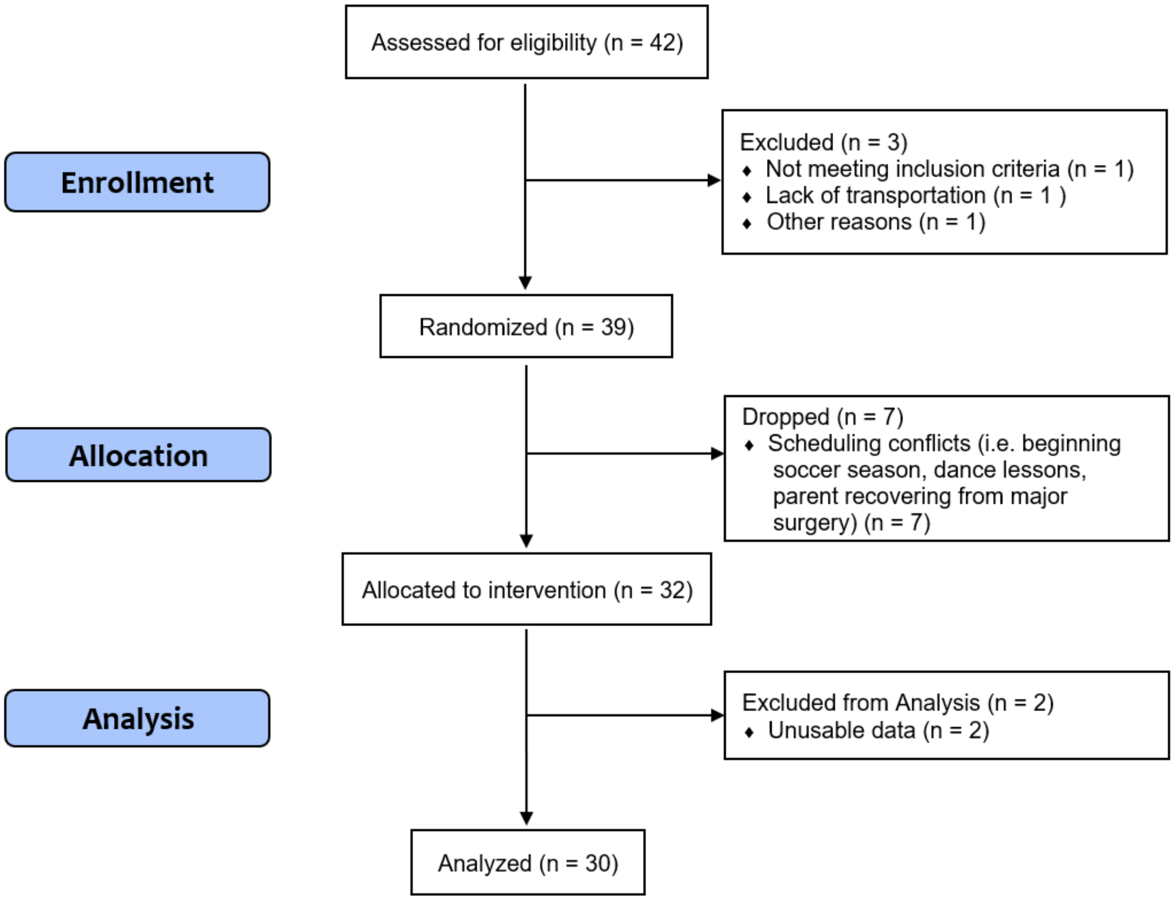

Figure 1. *Participant flow diagram*

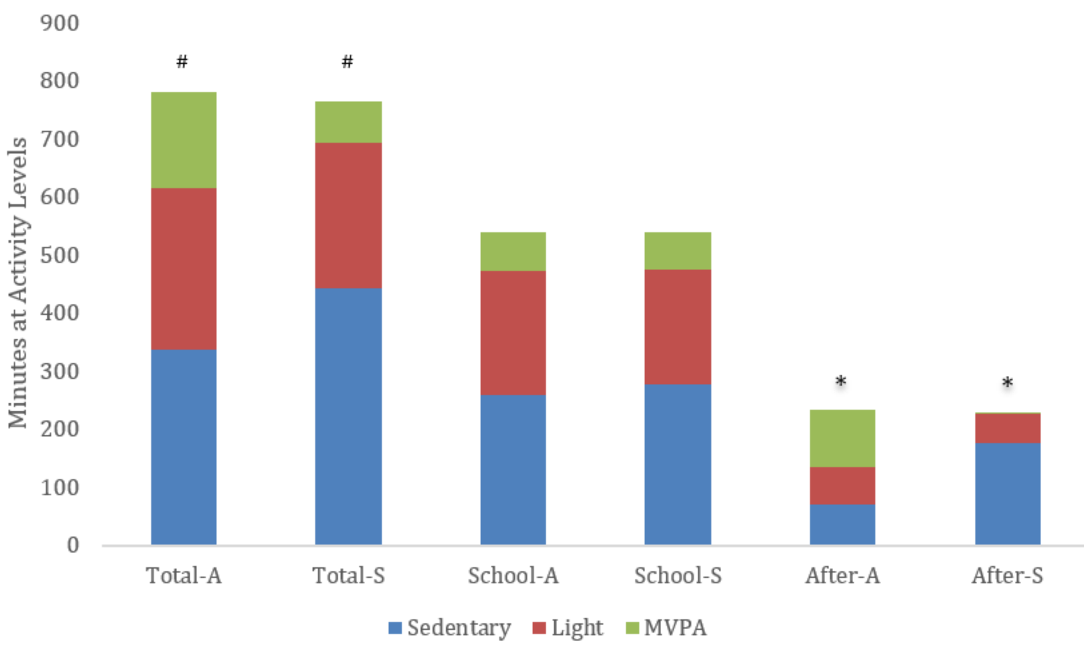

Figure 2. *Accelerometer minutes at multiple activity levels*

Abbreviations:
MVPA = moderate-to-vigorous physical activity;
School = school day;
After = after school;
A = active;
S = sedentary

No significant differences were observed between activity patterns during the school day.
[#]Indicates a significant difference between conditions for sedentary and MVPA for total activity ($p < 0.01$). Light was not different
*Indicates a significant difference between conditions for sedentary, light and MVPA during the afterschool intervention ($p < 0.01$)

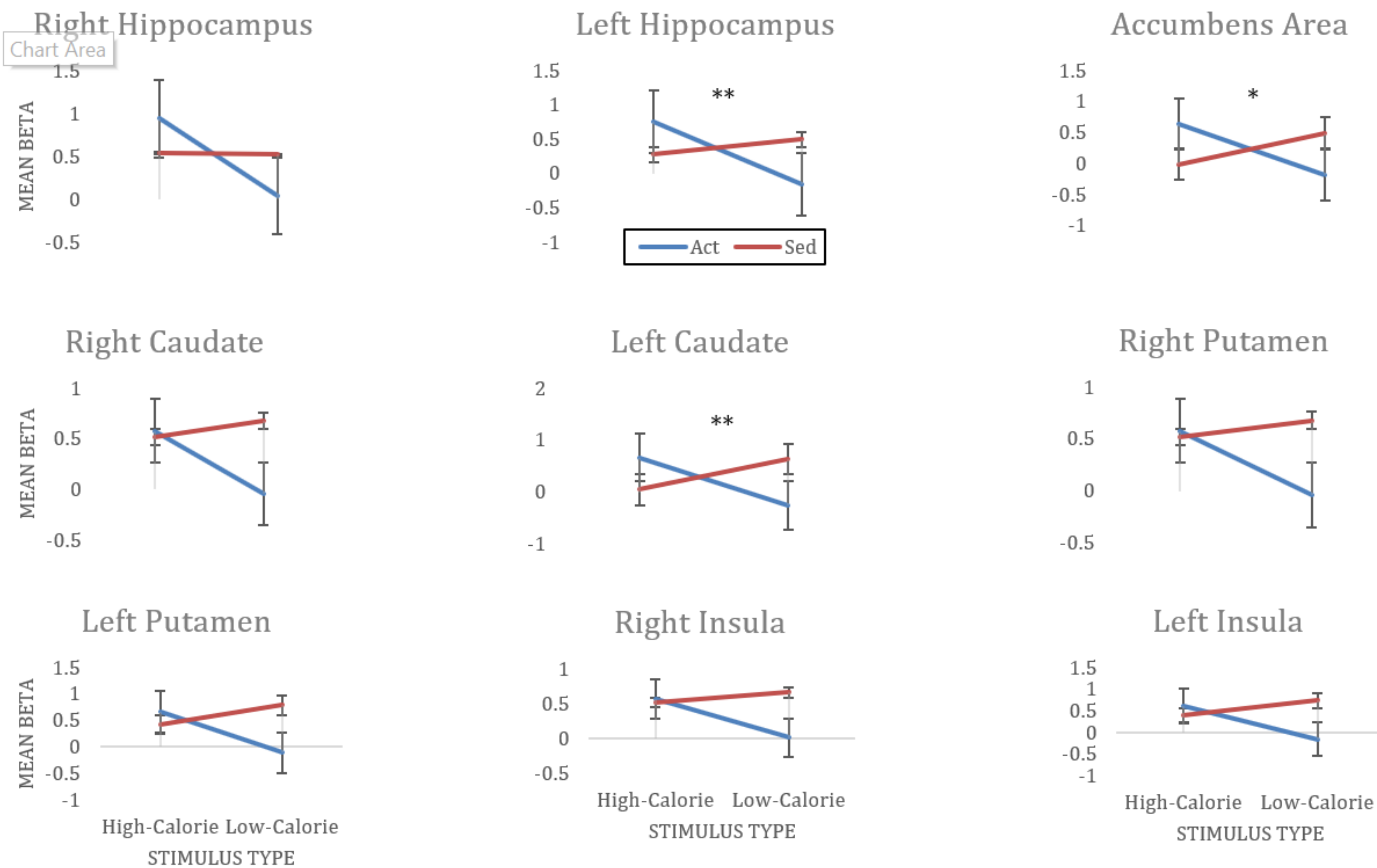

Figure 3. *Mean beta values graphed to illustrate the stimulus by condition interaction in reward regions of the brain. (For stimulus by condition interaction, *indicates significance with $p < 0.05$, **indicates significance with $p < 0.10$)*

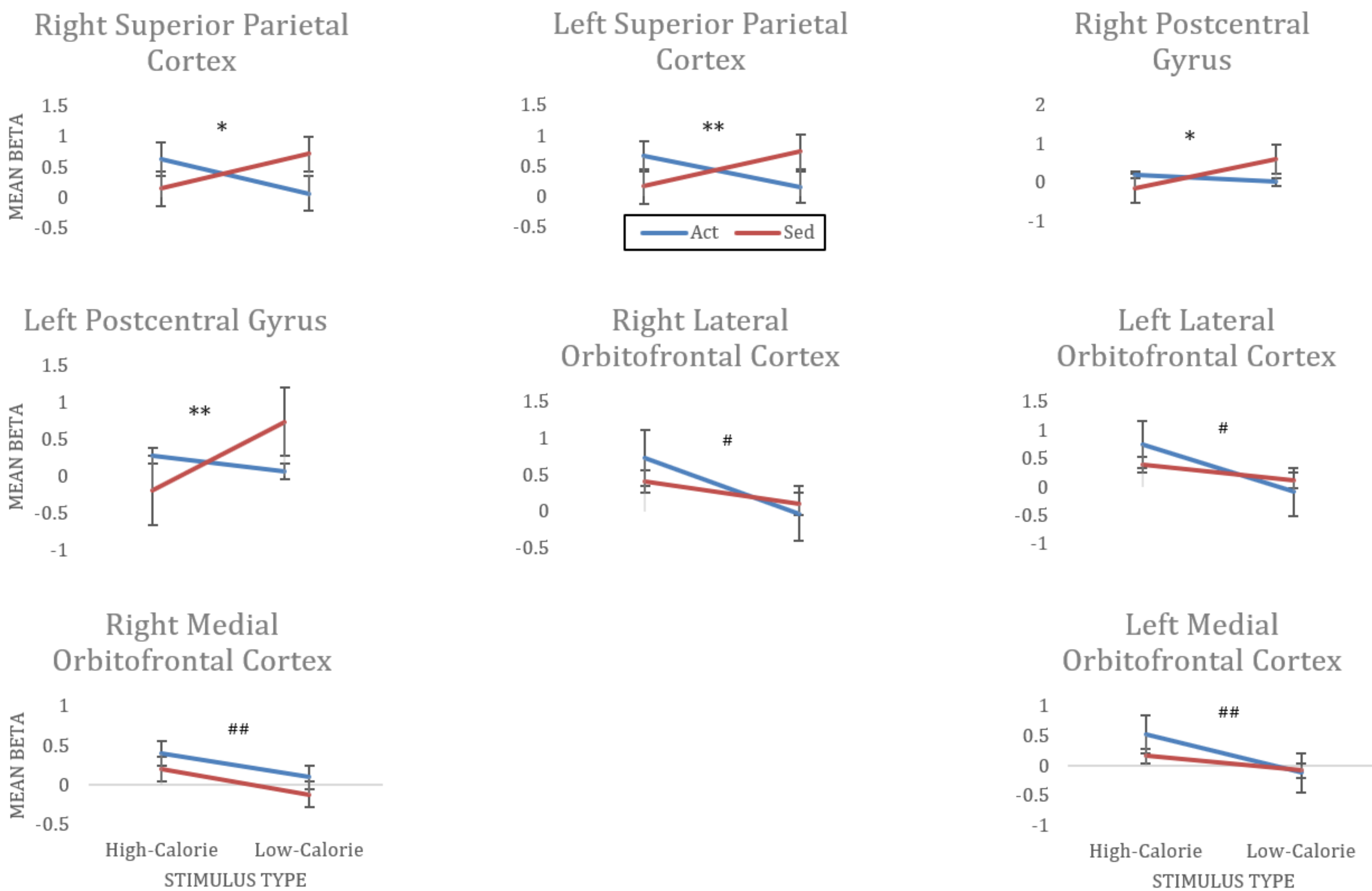

Figure 4. *Mean beta values graphed to illustrate the stimulus by condition interaction and main effect of stimulus in cognitive control regions of the brain. (For stimulus by condition interaction, *indicates significance with $p < 0.05$, **indicates significance with $p < 0.10$. For the main effect of stimulus, #indicates significance with $p < 0.05$, ##indicates significance with $p < 0.10$)*

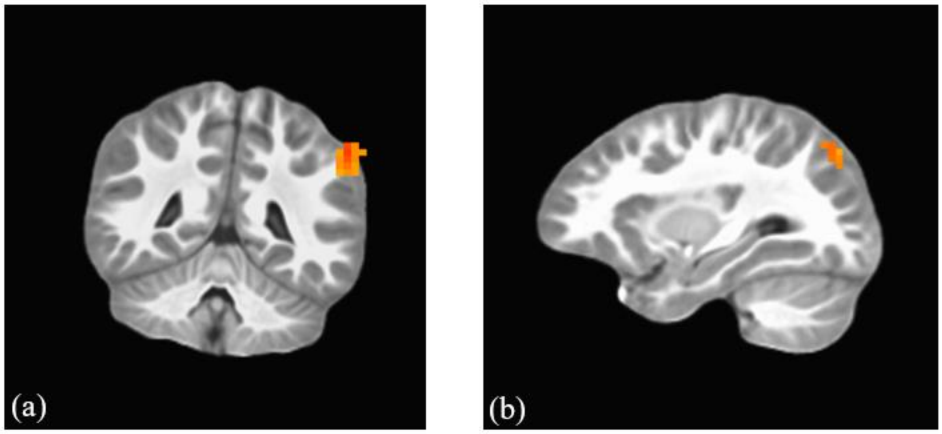

Figure 5. *Significant clusters of activation in a whole-brain analysis for the stimulus by condition interaction. Activation to high-calorie stimuli decreased following sedentary play and increased following active play in the (a) superior parietal cortex and (b) post-central gyrus.*

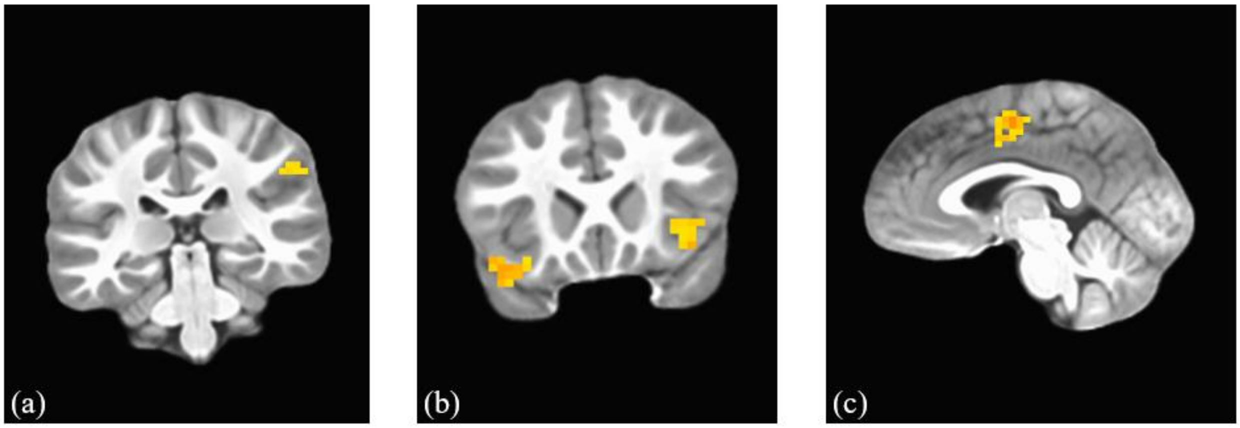

Figure 6. *Significant clusters of activation in a whole-brain analysis for the main effect of stimulus. Activation to high-calorie stimuli was greater than activation to low-calorie stimuli, regardless of condition, in the (a) right parietal cortex, (b) bilateral orbitofrontal cortex, and (c) primary motor cortex.*

Appendix 1

Children's PAR-Q Screening Form

Child's Name: ________________________

Child's Date of Birth: _______________

Address: _____________________________

Parent/guardian name: ____________________

**Emergency Contact Details Name/Relationship ______________________

Cell phone: ___________________________

Home phone: __________________________

Health Questions:

Does your child have or has he or she ever experienced any of the following? Please Circle:

High or Low Blood Pressure: Y / N

Elevated blood cholesterol: Y / N

Diabetes: Y / N

Chest pain brought on by physical exertion: Y / N

Childhood epilepsy: Y / N

Dizziness or fainting: Y / N

A bone, joint, or muscular problems with arthritis: Y / N

Asthma or respiratory Problems: Y / N

Any sustained injuries or illness: Y / N

Any allergies: Y / N

Is your child taking any medication: Y / N

Has your doctor ever advised your child to exercise: Y / N

Is there any reason not mentioned above why any type or physical activity may not be suitable for your child: Y / N

Any Special dietary needs for your child: Y / N

If answered 'YES' to any of the above questions, please give full details here:

Appendix 2

The Three-Factor Eating Questionnaire — Revised 18-Item

(Karlsson et. al. 2000)

1. When I smell a sizzling steak or juicy piece of meat, I find it very difficult to keep from eating, even if I have just finished a meal.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

2. I deliberately take small helpings as a means of controlling my weight.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

3. When I feel anxious, I find myself eating.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

4. Sometimes when I start eating, I just can't seem to stop.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

5. Being with someone who is eating often makes me hungry enough to eat also.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

6. When I feel blue, I often overeat.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

7. When I see a real delicacy, I often get so hungry that I have to eat right away.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

8. I get so hungry that my stomach often seems like a bottomless pit.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

9. I am always hungry so it is hard for me to stop eating before I finish the food on my plate.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

10. When I feel lonely, I console myself by eating.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

11. I consciously hold back at meals in order not to weight gain.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

12. I do not eat some foods because they make me fat.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

13. I am always hungry enough to eat at any time.

Definitely true (4)/ mostly true (3)/ mostly false (2)/ definitely false (1)

14. How often do you feel hungry?

Only at meal times (1)/ sometimes between meals (2)/ often between meals (3)/almost always (4)

15. How frequently do you avoid "stocking up" on tempting foods?

Almost never (1)/ seldom (2)/ usually (3)/ almost always (4)

16. How likely are you to consciously eat less than you want?

Unlikely (1)/ slightly likely (2)/ moderately likely (3)/ very likely (4)

17. Do you go on eating binges though you are not hungry?

Never (1)/ rarely (2)/ sometimes (3)/ at least once a week (4)

18. On a scale of 1 to 8, where 1 means no restraint in eating (eating whatever you want, whenever you want it) and 8 means total restraint (constantly limiting food intake and never "giving in"), what number would you give yourself?

The 1 – 2 scores were coded 1; 3 – 4 scores were coded 2; 5 – 6 scores were coded3; 7 – 8 scores were coded 4.

The cognitive restraint scale was composed of items 2, 11, 12, 15, 16, and 18. The uncontrolled eating scale was composed of items 1, 4, 5, 7, 8, 9, 13, 14, and 17. The emotional eating scale was composed of items 3, 6, and 10.

Appendix 3

Breakfast: main course, drink

1. Egg, sausage, cheese english muffin (1 Jimmy Dean - 350 kcal) 2. Eggo waffles (2 chocolate chip - 200 kcal, 2 homestyle - 190 kcal) 3. Oatmeal w/maple and brown sugar (Quaker instant 1 package 160 kcal) 4. Bagel and a. Cream cheese (2 tbsp - 80 kcal) b. Butter (1tbsp - 100 kcal) c. Jelly (1 tbsp - 50 kcal) d. Peanut butter (2 tbsp - 100 kcal)

i. Milk (8 oz. 2% - 140 kcal) ii. Apple juice (8 oz 100% - 110 kcal) iii. Orange juice (8 oz 100% - 110 kcal) iv. Water (8 oz 100% - 0 kcal)

Lunch: main course, drink, vegetable, fruit

1. Ham sandwich (300 kcal) 2. Ham wrap (180 kcal) 3. Turkey sandwich (310 kcal) 4. Turkey wrap (185 kcal)

a. Cheese (1 slice - 95 kcal) b. Mayonnaise (1 tbsp 180 - kcal) c. Mustard (1 tsp - 80 kcal) d. Chips (lays classic bag - 160 kcal) c. Cookies (chips ahoy 3 cookies - 160 kcal)
i. Milk (8 oz. 2% - 140 kcal) ii. Apple juice (8 oz 100% - 110 kcal) iii. Orange juice (8 oz 100% - 110 kcal) iv. Water (8 oz 100% - 0 kcal)

Vegetables: one plus fruit or two

1. Celery sticks (10 4" sticks - 35 kcal) 2. Baby carrots (1 cup - 50 kcal) 3. Sweet peppers (1 pepper - 15 kcal)
   a. Peanut butter (2 tbsp - 100 kcal) b. Ranch dressing (2 tbsp - 140 kcal)

Fruits: one plus vegetable or none

1. Apple (1 medium - 50 kcal) 2. Banana (1 medium - 105 kcal) 3. Berries (1 cup - 135 kcal)

Snack: One sandwich and one side

1. Peanut butter and jelly sandwich (uncrustable - 305 kcal) 2. Meat and cheese sandwich (1 sandwich - 300 kcal)

a. 2. Baby carrots (1 cup - 50 kcal) b. Apple slices (1 cup - 70 kcal) c. Cheese stick (1 piece - 50 kcal)

Appendix 4

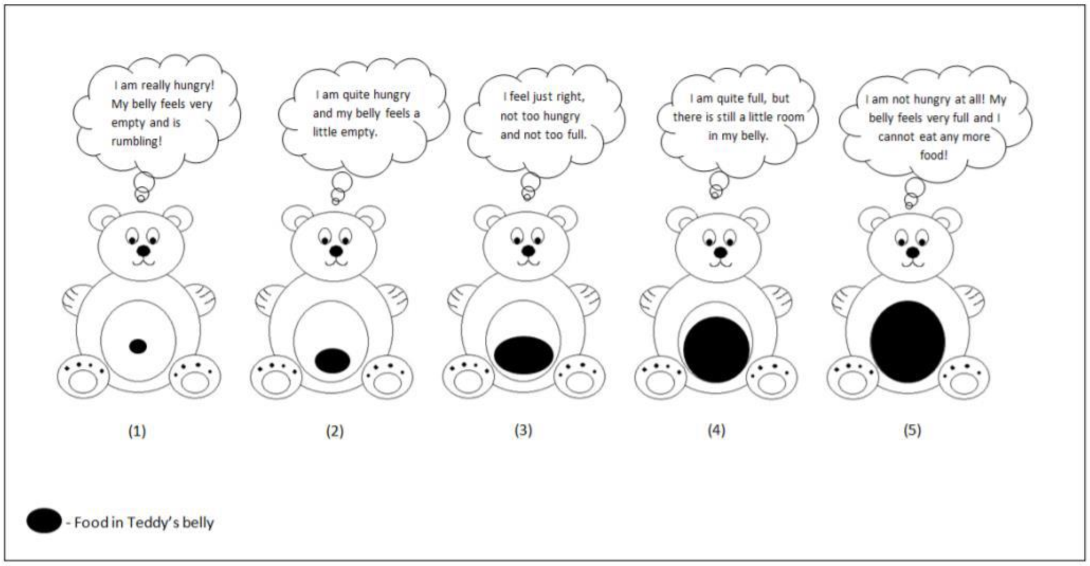

Figure 1. Hunger and Satiety Rating Scale: Teddy the Bear