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Research paper

# The role of BMI on cognition following acute physical activity in preadolescent children

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ABSTRACT

*Background:* There is an increasing prevalence of physical inactivity during childhood, concurrent with a rise in obesity rates, which is associated with a variety of health problems. However, the extent to which increased body mass index (BMI) influences acute physical activity (PA) benefits on cognition in childhood remains unknown. The aim of this study was to examine whether BMI influences the effects of acute PA on inhibitory control task performance.

*Methods:* In a sample of 116 children pooled from four prior studies (ages 8-11; 51 females), demographic measures of age, sex, IQ, socioeconomic status, and aerobic fitness were considered along with BMI. Children participated in a counterbalanced, randomized crossover study, whereby they completed two different interventions; 20 minutes of treadmill walking (60-70% heart rate max) and restful reading (non-exercise control). Following each intervention, children performed a modified flanker task that manipulates inhibitory control demands. Correlations were conducted to determine the influence of demographic variables, fitness, and BMI on inhibitory control following each intervention. Subsequent hierarchical regression analyses were performed with significant demographic factors in the first step, aerobic fitness in the second step when significant, and BMI in the final step.

*Results:* Analyses indicated that children exhibited improved task performance ($p$'s $\leq 0.001$) and decreased interference ($p = 0.04$) following the walking intervention compared to the restful reading control condition, indicating greater benefits following acute PA across task condition, with selectively greater benefits for the task condition requiring greater inhibitory control. Regression analyses revealed that greater BMI was related to decreased performance following acute PA ($p = 0.001$); an association not observed following restful reading ($p$'s $\geq 0.11$). These results suggest that BMI negatively influences the effect of acute exercise on performance.

*Conclusion:* Confirming previous studies, these findings indicate beneficial effects of acute PA on a flanker task that modulates inhibitory control requirements, but the effects are significantly greater for task conditions requiring greater amounts of inhibitory control. Further, these beneficial effects of PA appear to be blunted in children with higher BMI. These findings suggest that the acute benefits of PA on cognition may not be fully realized in children with higher BMI.

## 1. Introduction

Today's children have become increasingly inactive and unfit, with >50% of children not meeting the recommended daily 60 min of moderate-to-vigorous physical activity (MVPA) [1]. Unfortunately, this trend co-occurs alongside an obesity epidemic in the United States, with more than a third of children considered obese (OB) [2]. Importantly, children who are OB engage in less MVPA than their healthy weight

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(HW) peers [3,4]. Obesity is characterized by an excess accumulation of adipose tissue and is clinically determined using body mass index (BMI; an individual's weight in kilograms divided by their height in meters squared ($kg/m^2$). Obesity in childhood is associated with various health concerns including, musculoskeletal, endocrine, and cardiovascular, among others [5]. Approximately 30% of OB children present with hypertension, of which 70% have at least one risk factor for cardiovascular disease [6]. These consequences extend to brain health, such that children with OB have poorer cognition than their HW peers, including deficits in academic achievement [7,8], attention [9,10], impulsivity [11,12], cognitive flexibility [13], and inhibition [14–16].

Inhibition refers to the ability to suppress task irrelevant information in the environment (i.e., perceptual interference), and inhibit a prepotent or impulsive response (i.e., response inhibition) That is, perceptual interference entails the ability to filter out interfering stimuli that would lead to erroneous responses, and response inhibition refers to the ability to withhold an incorrect response in favor of a correct response. One common class of laboratory tasks used to assess inhibitory control are flanker tasks [17], which utilize levels of stimulus and response patterns requiring the modulation of inhibition and selective attention for successful execution. That is, flanker tasks require attentional inhibition, or the ability to attend to and focus on relevant features of the stimulus environment while ignoring other, irrelevant features; as well as the inhibition of prepotent behavior responses [18–20]. During childhood, inhibition is particularly critical since it involves prolonged attention and control of one's actions [21,22]. Inhibitory control is paramount in the classroom, as this allows children to inhibit impulsive behavior, to stay on task, and thus perform well academically [23]. Children who struggle to maintain inhibitory control have lower mathematical abilities as they are unable to change strategies to complete the task [24]. Inhibition has also been shown to be associated with achievement in English and science, suggesting that inhibition supports general academic success [23,25].

Furthermore, some children display worse inhibitory control than their peers. For example, children with increased BMI often display poorer inhibition. That is, children with OB perform worse on tests of inhibitory control as evidenced by longer reaction times on a modified flanker task [12] as well as a Stroop task [16], which also modulates inhibitory control demands. These results suggests that children with OB are less able to modulate inhibitory control in order to meet the increased task demands relative to their NW peers [15]. Such effects extend to deficits in intraindividual response variability on inhibitory control tasks as well as academic performance with increased adiposity [26,27].

Available evidence indicates that one method to improve brain health and cognition in healthy children is physical activity (PA). Several studies examined the effects of acute exercise on cognition and indicated that 20-min of moderate intensity walking improved neural and behavioral correlates of inhibition and academic performance [28–30]. That is, following a bout of walking, children exhibited enhanced brain function, improved cognitive performance during tasks demanding variable amount of inhibition, and higher academic achievement in mathematics and reading compared to rest [28,31]. These findings extend to a variety of special populations as well. Following an acute bout of PA, children with ADHD experience specific benefits to inhibitory control [32,33]. Furthermore, acute PA appears particularly beneficial for children with ADHD as they exhibited facilitations in behavior as evidenced by post-error slowing following an acute bout of PA [29]. This beneficial effect of PA also includes cycling, such that youth with ADHD exhibited reductions in reaction time after moderate cycling, further corroborating the literature that a single exercise bout improves inhibitory control [34]. Additionally, benefits from acute PA have been observed in youth with autism spectrum disorder. Following various forms of brief bouts of PA, youth with autism exhibit improved cognition, particularly in inhibitory control [35], working memory, and attention [36–38]. Some findings suggest that the greatest benefits of acute PA are seen in children who perform poorly on inhibitory control tasks at baseline, suggesting that an acute bout of PA benefits children who need it most (i.e., lower performers) [30]. Interestingly, in one study, children with overweight walked on a treadmill and completed a mental flexibility task (a different aspect of executive control). Specifically, a switch task was performed, which required children to flexibly disengage the processing operations of one task and engage in operations involved in a second task [39]. The acute bout of PA did not modify the children's performance on this task [40]. Taken together, acute PA effects may be selectively beneficial to specific aspects of executive function, such as inhibition, rather than broadly beneficial across all aspects of executive function. Thus, moderate intensity walking may be a realistic and beneficial way to promote PA [41], combat childhood OB, enhance PA adherence, and acutely improve cognition [42]. However, to date, no such research has examined the role of BMI in relation to the acute benefits of PA on inhibitory control. The influence of BMI is critical, as children with increased body mass are frequently encouraged to engage in PA for physical health benefits, but it remains unknown whether acute bouts of PA are also favorable to short-term changes in cognitive function, as seen in HW children.

To answer this question, the current study involved a reanalysis of four data sets collected between 2006 and 2014 to investigate whether children with higher BMI responded differently to an acute bout of PA on inhibitory control. Therefore, the purpose of this study was to determine whether BMI modulated the observed transient beneficial effects found for inhibitory control following an acute bout of treadmill walking in preadolescent children. Based on prior research, it was hypothesized that acute PA would broadly benefit inhibition, but the effects would be especially pronounced during task conditions requiring greater amounts of inhibitory control. Since prior studies of acute PA interventions indicate that special populations of children appear to benefit most from acute exercise, it was hypothesized that greater acute benefits to inhibitory control would be observed in children with greater BMI following a single bout of PA.

## 2. Methods

### 2.1. Participants

Data from 116 preadolescent participants were re-analyzed from four prior studies conducted between 2009 and 2014 [28,29,43]. Studies were included in the dataset if they contained task performance data from a flanker task following two conditions: an acute aerobic exercise (i.e., walking) intervention and a resting control. Exclusion criteria included being outside the age range (8-11 years old), diagnoses of ADHD, an IQ score greater than 2 standard deviations below the norm, and task performance below 50%.

Demographic information can be found in Table 1. Demographic variables included age, socioeconomic status (SES), IQ, $VO_2$ relative (kg/ml/min) peak, $VO_2$ percentile, BMI ($kg/m^2$) and BMI percentile. For SES, a trichotomous index (i.e., 1-3 point scale) was calculated, which

**Table 1**
Participant demographics (Mean ± SE).

| Characteristic | |
|---|---|
| N, % female | 116, 44% |
| Age (years) | 9.88 ± 0.06 |
| SES | 2.34 ± 0.06 |
| IQ | 116.93 ± 1.11 |
| $VO_2$ relative (kg/ml/min) | 42.75 ± 0.65 |
| $VO_2$ percentile | 33.15 ± 2.80 |
| BMI ($kg/m^2$) | 18.38 ± 0.41 |
| BMI% | 55.95 ± 3.02 (12.1% OW, 14.7% OB) |

Note: IQ = intelligent quotient; SES = socioeconomic status; $VO_2$ = maximal oxygen volume included parents' highest level of education, number of parents in the household working full-time, and whether participants were enrolled in free or reduced-price meal program at school [44]. A score of 1 indicated low SES, a score of 2 indicated moderate SES and a score of 3 indicated high SES.

Two different IQ tests were administered across the four studies: the Kaufman Brief Intelligence Test (Kaufman and Kaufman,1990) and the Kaufman Brief Intelligence Test Second Edition (Kaufman and Kaufman, 2004). Each test was standardized on the same scale (mean = 100 ± 15). Multiple IQ scales have been used together and incorporated previously across a variety of studies and analyses [45–47]. Missing demographic variables were imputed via mean replacement: IQ (n = 3) and SES (n = 23).

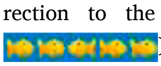
### 2.2. Cardiorespiratory Fitness ($VO_2$)

Cardiorespiratory fitness was measured as a $VO_2$peak [48]. Participants' oxygen consumption was measured using an indirect calorimetry system (ParvoMedics True Max 2400). Participants walked/ran at a constant speed on a treadmill with incline increases of 2.5% every 2 minutes until volitional exhaustion. Participants wore a heart rate (HR) monitor throughout the test to determine their maximal heart rate. Ratings of perceived exertion (RPE) were assessed every 2 min using the children's OMNI Scale [49], which uses a 0-10 pictorial scale to represent perceived physical effort. Relative peak oxygen consumption was expressed in milliliters per kilogram per minute and was based upon maximal effort defined by: (1) a plateau in oxygen uptake corresponding to an increase of less than 2 ml/kg/min despite an increase in exercise workload, (2) a peak HR ≥ 185 beats-per-minute [50], (3) respiratory exchange ratio (RER ≥ 1.0 [51], and/or (4) RPE ≥ 8 [49]. $VO_2$peak percentile ($VO_2$peak%) was then determined based on the participants' age, sex, and relative score from normative data [52].

### 2.3. BMI: Weight Status and Body Composition Assessment

Standing height and weight measurements were taken with participants wearing lightweight clothing and no shoes. Height and weight were measured using a Tanita WB-300 Plus digital scale (Tanita corp., Tokyo, Japan). BMI was calculated using each participant's weight (measured in kilograms (kg) and height (measured in meters) (m)) as $kg/m^2$.

### 2.4. Flanker Task

Inhibitory control was assessed using a modified version of the Eriksen flanker task [17]. Participants responded to the direction of a central target stimulus (i.e. fish or arrows depending on the version). The task requires an individual to distinguish a centrally presented stimulus amid lateral flanking stimuli. Interference was created by manipulating the congruency of the target and flanking stimuli, such that in the congruent condition, the target and flanking stimuli are the same, whereas in the incongruent condition, the target and the flanking stimuli require alternative behavioral responses. Incongruent trials require greater amounts of inhibitory control as the target and flanking stimuli activate multiple action schemas [53]. For congruent trials, there were five arrows or fish all oriented to point the same direction (e.g. >>>>> or <<<<<) (). Incongruent trials also had five arrows or fish, but the central stimulus faced in the opposite direction to the flanking stimuli (e.g. <<><< or >><>> or ). Both trials featured stimuli on either a blue (for fish) or black (for arrows) background of a computer screen. Children were seated 1m away from a computer, which ran Neuroscan Stim software (Compumedics, Charlotte, NC) and were instructed to respond using a response pad as quickly and accurately as possible on the side corresponding to the directionality of the central target stimulus. Congruency and directionality of target stimuli were equiprobable. Participants were given instructions, between 20-40 practice trials, and the opportunity to ask questions before the task began. The experimenter observed practice trials to verify that the participant understood the task and responded correctly. Task parameters (target direction, interstimulus interval, stimuli type, etc.) varied slightly across studies (see Table 2). The total duration of each task was approximately 7 minutes.

Performance variables were collected for the flanker task for congruent and incongruent trials. Accuracy was calculated as the percentage of correct responses. Mean reaction time (RT) was calculated for correct responses as the time in milliseconds (ms) from stimulus onset until response execution. Accuracy interference was calculated as congruent accuracy minus incongruent accuracy, with lower scores reflecting less interference and thus better performance. Mean RT interference was calculated as incongruent mean RT minus congruent mean RT, with smaller interference scores reflecting less interference and thus better performance.

### 2.5. Intervention Procedure

Participants completed two separate, randomized experimental conditions on two different days. The resting control condition lasted 20 minutes and consisted of participants reading in a seated position while conversations were kept to a minimum. The exercise intervention consisted of 20 min of walking on a treadmill at 60%-75% of their maximal heart rate determined during the cardiorespiratory fitness test. Approximately 20 minutes following both the rest and exercise conditions, participants performed a modified flanker task. The order of rest and exercise conditions was counterbalanced within each study across participants.

### 2.6. Statistical Analysis

All statistical analyses were performed with SPSS 25 (IBM, Armonk, New York) using a family-wise alpha threshold for all tests set at $p = 0.05$. Analyses of flanker task performance (response accuracy and reaction time) were conducted using multivariate repeated measures analyses of variance comparing performance following rest and exercise. The dependent variables of interest were assessed using separate 2 (Intervention: rest, exercise) x 2 (Congruency: congruent, incongruent). Post hoc comparisons were conducted using Bonferroni corrected independent- and paired-sample t-test. All factors were treated as dependent variables and analyses with three or more within subject levels used the Wilks' Lambda statistic.

A subsequent analytical approach employed regression analyses to characterize relationships between the primary measures within each intervention. Pearson correlations assessed bivariate relationships between BMI and task performance outcomes following each intervention. Next, separate stepwise linear regressions were conducted across participants to determine if BMI was associated with the dependent measures of interest following each intervention: accuracy, reaction time, and interference control on flanker tasks. For significant relationships (i.

**Table 2**
Task Descriptions.

| | Stimulus Type | Total Trials | Stimulus Presentation Duration | Inter-trial Interval (ITI) Duration |
|---|---|---|---|---|
| Study 1 | Arrow | 200 | 125 | 1100, 1300, 1500 |
| Study 2 | Arrow | 200 | 120 | 1100, 1300, 1500 |
| Study 3 | Arrow | 100 | 200 | 1500 |
| Study 4 | Fish | 200 | 200 | 1700 |

e., $p<0.05$), additional analyses were conducted within each intervention group (rest and exercise). In the first step, the dependent variables were regressed on any significantly correlated demographic variables (e. g., age, sex, IQ, SES). If no demographics variables were significantly correlated with the outcome, this step was skipped. The next step included $VO_2$ in the model. The final step included BMI in the model. The change in $R^2$ values between the steps was used to judge the independent contribution of these measures for explaining the variance in the dependent variables of interest beyond that of demographic variables.

## 3. Results

Correlations between flanker outcomes, demographic variables, and aerobic fitness are presented in Table 3. In general, age, SES, IQ, and $VO_2$peak% were most frequently correlated with flanker performance variables, such that older children, children of higher SES, and children with higher aerobic fitness exhibited superior flanker performance (see Table 3).

### 3.1. Repeated Measures

#### 3.1.1. Studies

The ANOVA revealed no significant differences in task performance across studies, *F's*(3, 115)≤2.63, *p's*>0.05. In regard to order effects, 57 children received the rest intervention first, and on a subsequent visit received the exercise intervention. Thus, 59 children first received the exercise intervention, and subsequently received the rest intervention. There were no order effects on accuracy, $F(1, 114)=0.76$, $p=0.39$, $\eta^2=0.01$ or Mean RT, $F(1, 114)=1.22$, $p=0.27$, $\eta^2=0.01$.

#### 3.1.2. Intervention heart rate

Confirming intervention efficacy, heart rate was significantly higher during exercise (64.83±0.42% of $VO_2$ max) than during rest (45.87±0.56% of $VO_2$ max), $t(115)=32.59$, $p < 0.001$.

#### 3.1.3. Accuracy

The ANOVA revealed main effects of intervention, $F(1, 115)=19.76$, $p\leq0.001$, $\eta^2=0.15$, with greater accuracy following exercise (91.47±0.54%) relative to following rest (88.77±0.72%) and Congruency, $F(1, 115)=127.84$, $p\leq0.001$, $\eta^2=0.53$, with higher accuracy for congruent (92.68±0.49%) relative to incongruent (87.56±0.70%) trials. These findings confirm previous individual reports [29,43,54]. Further, a 2-way interaction of Congruency x Intervention was observed, $F(1, 115)=4.21$, $p=0.04$, $\eta^2=0.04$. The interaction was decomposed by assessing Congruency within each Intervention as well as congruency between each intervention. Findings revealed that after rest and exercise, congruent and incongruent accuracy were significantly different from each other, *t's*(115)>8.85, $p<0.001$. Importantly, congruent accuracy was significantly lower after rest ((91.68±0.64%) compared to after exercise ((93.68±0.48%), $t(115)=3.67$, $p < 0.001$. Similarly, incongruent accuracy was significantly lower after rest (85.86±0.91%) compared to after exercise ((89.25±0.68%), $t(115)=4.15$, $p < 0.001$ (see Fig. 1). Lastly, interference scores indicated an effect of intervention, $t(115)=2.05$, $p=0.04$, such that there was less accuracy interference post-walking (4.42±0.46%) relative to post-restful reading (5.82±0.66%), suggesting a benefit of acute exercise on interference control (see Fig. 2).

#### 3.1.4. MeanRT

The ANOVA revealed main effects of congruency, $F(1, 115)=194.79$, $p\leq0.001$, $\eta^2=0.63$, with shorter congruent RT (516.93±7.9ms) relative to incongruent RT (550.04±8.17ms). There was no significant effect for mean RT interference between rest and exercise (p=0.52).

### 3.2. Regressions[1]

Any demographic variables were significantly correlated with each specific cognitive measure they were included in Step 1 (see Table 3). In order to determine the unique contribution of fitness, $VO_2$ was entered in Step 2. The final Step included BMI. Each regression was run with all children within each intervention.

#### 3.2.1. Post Rest congruent accuracy and BMI

The Step 1 regression analysis which included sex for post rest congruent accuracy was significant, adjusted $R^2=0.03$, $F(1, 114)=4.68$, $p=0.033$. Step 2 was non-significant, $\Delta R^2=0.003$, $F(1, 113)=2.478$, $p=0.09$, as was Step 3, $\Delta R^2=0.008$, $F(1, 112)=1.97$, $p=0.12$ (see Table 4 and Fig. 3).

#### 3.2.2. Post Rest incongruent accuracy and BMI

The Step 1 regression analysis which included age for post rest incongruent accuracy was significant, adjusted $R^2=0.04$, $F(1, 114)=5.71$, $p=0.02$. Step 2 was also significant, $\Delta R^2=0.04$, $F(1, 113)=5.713$, $p=0.004$, with the addition of $VO_2$ accounting for an incremental amount of variance in incongruent accuracy beyond associated demographic variables ($\beta=0.22$, $t(113)=2.37$, $p=0.02$). Step 3 was significant, $\Delta R^2=0.02$, $F(1, 112)=4.60$, $p=0.004$, however the addition of BMI ($\beta=-0.16$, $t(112)=-1.50$, $p=0.14$) did not account for an incremental amount of variance in incongruent accuracy beyond associated demographic variables and $VO_2$ (see Table 4 and Fig. 3).

#### 3.2.3. Post Rest accuracy interference and BMI

As no demographic variables significantly correlated with accuracy interference after rest, $VO_2$ was entered in Step 1. The Step 1 regression analysis for post rest accuracy interference was significant, adjusted $R^2=0.09$, $F(1, 114)=12.26$, $p=0.001$, with $VO_2$ accounting for an incremental amount of variance in accuracy interference ($\beta=-0.31$, $t(114)=-3.50$, $p=0.001$). Step 2 was also significant, $\Delta R^2=0.00$, $F(1, 113)=6.08$, $p=0.003$, but the addition of BMI did not account for an incremental amount of variance in accuracy interference beyond $VO_2$ ($\beta=-0.008$, $t(113)=-0.07$, $p=0.94$) (see Table 4).

#### 3.2.4. Post Exercise congruent accuracy and BMI

As no demographic variables significantly correlated with congruent accuracy after exercise, $VO_2$ was entered in Step 1. The Step 1 regression analysis for post exercise congruent accuracy was significant, adjusted $R^2=0.06$, $F(1, 114)=8.25$, $p=0.005$, with $VO_2$ accounting for an incremental amount of variance in congruent accuracy ($\beta=0.26$, $t(114)=2.87$, $p=0.005$). Step 2 was also significant, $\Delta R^2=0.07$, $F(1, 113)=9.03$, $p\leq0.001$, with the addition of BMI accounting for an incremental amount of variance in congruent accuracy after exercise, beyond accounting for $VO_2$, $\beta=-0.31$, $t(113)=-3.04$, $p=0.003$ (see Table 4 and Fig. 3).

#### 3.2.5. Post Exercise incongruent accuracy and BMI

The Step 1 regression analysis which included SES for post exercise incongruent accuracy was significant, adjusted $R^2=0.07$, $F(1, 114)=9.30$, $p=0.003$. Step 2 was also significant, $\Delta R^2=0.08$, $F(1, 113)=10.67$, $p\leq0.001$, with the addition of $VO_2$ accounting for an incremental amount of variance in incongruent accuracy after exercise beyond associated demographic variables, $\beta=0.29$, $t(113)=3.35$, $p=0.001$. Step 3 was also significant, $\Delta R^2=0.07$, $F(1, 112)=11.26$, $p\leq0.001$, with the addition of BMI, $\beta=-0.32$, $t(112)=-3.26$, $p=0.001$ accounting for an

[1] Significant effects of BMI do not change if the fitness measure ($VO_2$) is removed from the models.

**Table 3**
Correlations between demographic variables and task performance.

| | Sex | Age | SES | IQ | $VO_2$max relative | BMI |
|---|---|---|---|---|---|---|
| **After Rest** | | | | | | |
| Congruent Accuracy | -.199* | 0.142 | 0.152 | 0.045 | 0.025 | -0.137 |
| Incongruent Accuracy | -0.090 | .216* | 0.136 | -0.086 | .242** | -.210* |
| Accuracy Interference | -0.067 | -0.163 | -0.043 | 0.163 | -0.312** | 0.159 |
| Congruent MeanRT | -0.029 | -0.185* | -0.020 | -0.148 | 0.126 | -0.090 |
| Incongruent MeanRT | -0.047 | -0.215* | -0.076 | -0.111 | 0.102 | -0.104 |
| MeanRT Interference | 0.058 | 0.099 | 0.168 | -0.099 | 0.065 | 0.048 |
| **After Exercise** | | | | | | |
| Congruent Accuracy | -0.144 | 0.139 | 0.090 | 0.131 | .260** | -.362** |
| Incongruent Accuracy | -0.170 | 0.169 | .275** | 0.114 | .298** | -.390** |
| Accuracy Interference | 0.103 | -0.107 | -0.317** | -0.032 | -0.172 | 0.202* |
| Congruent MeanRT | -0.006 | -0.272** | -0.112 | -0.088 | 0.128 | -0.213* |
| Incongruent MeanRT | -0.025 | -0.291 | -0.149 | -0.051 | 0.105 | -0178 |
| MeanRT Interference | 0.057 | 0.082 | 0.123 | -0.105 | 0.059 | -0.085 |

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

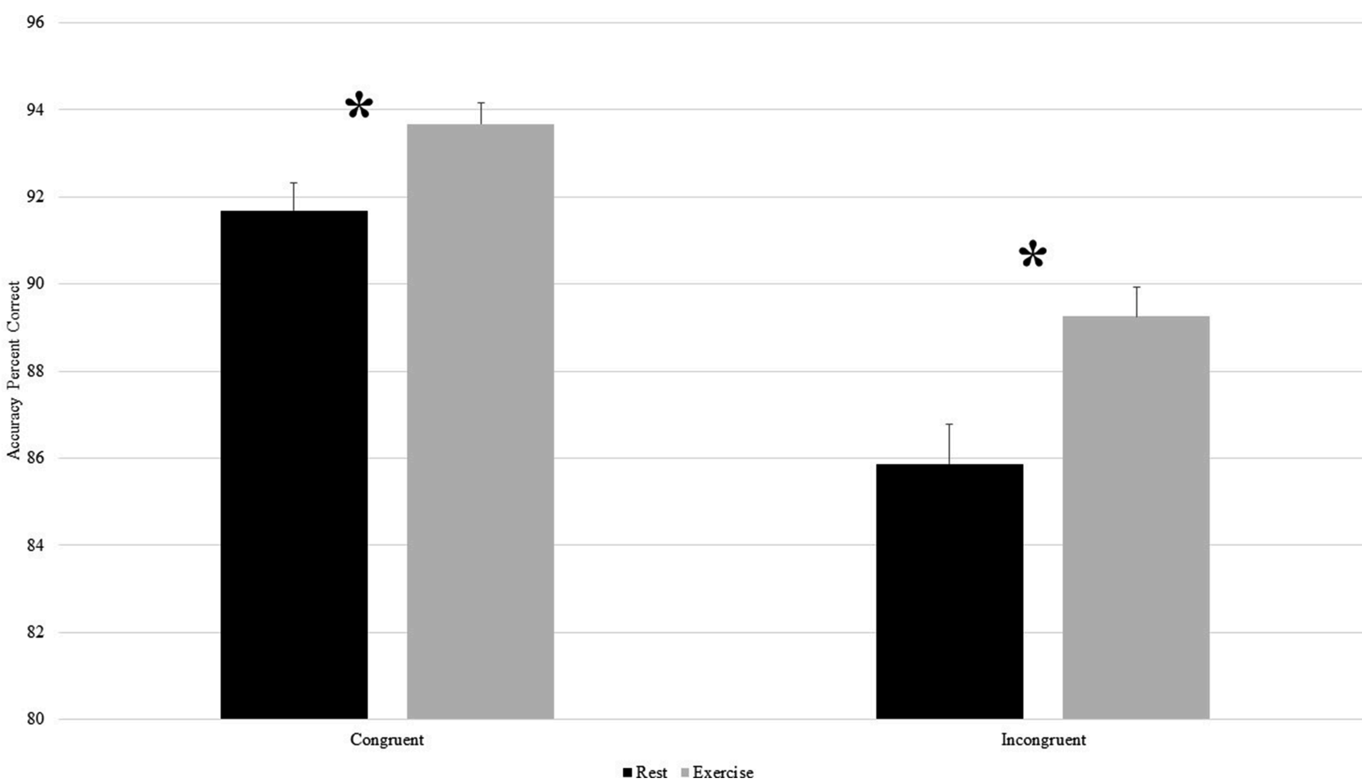



**Fig. 1.** Response accuracy (Mean ± SE) for congruent and incongruent trials by intervention.

incremental amount of variance in incongruent accuracy after exercise beyond associated demographic variables and $VO_2$ (see Table 4 and Fig. 3).

#### 3.2.6. *Post Exercise accuracy interference and BMI*

The Step 1 regression analysis which included SES for post exercise accuracy interference was significant, adjusted $R^2$=0.09, $F(1, 114)$= 12.69, $p$=0.001. While Step 2 was significant, $\Delta R^2$=0.03, $F(1, 113)$= 8.17, $p \leq 0.001$, $VO_2$ did not account for an incremental amount of variance in post exercise accuracy interference (β=-0.16, $t(113)$=-1.84, $p$=0.07). Step 3 was also significant, $\Delta R^2$=0.02, $F(1, 112)$=6.19, $p$=0.001, however BMI did not account for an incremental amount of variance in accuracy interference after exercise beyond associated descriptive variables, β=0.15, $t(112)$=1.44, $p$=0.15 (see Table 4).

#### 3.2.7. *Post Exercise congruent Mean RT and BMI*

The Step 1 regression analysis which included age for post exercise congruent MeanRT was significant, adjusted $R^2$=0.07, $F(1, 114)$=9.12, $p$=0.003. Step 2 was also significant, $\Delta R^2$=0.04, $F(1, 113)$=7.05, $p \leq 0.001$, with the addition of BMI accounting for an incremental amount of variance in congruent Mean RT after exercise beyond associated descriptive variables, β=-0.19, $t(113)$=-2.16, $p$=0.03. All other regressions involving Mean RT were nonsignificant (see Table 4).

## 4. Discussion

The results of this investigation are clinically relevant due to the nationwide increase in levels of OB [55] as well as declines in PA among children [56]. The current study compliments previous research within the field examining behavioral outcomes on an inhibitory control task following an acute bout of PA in a relatively larger sample of

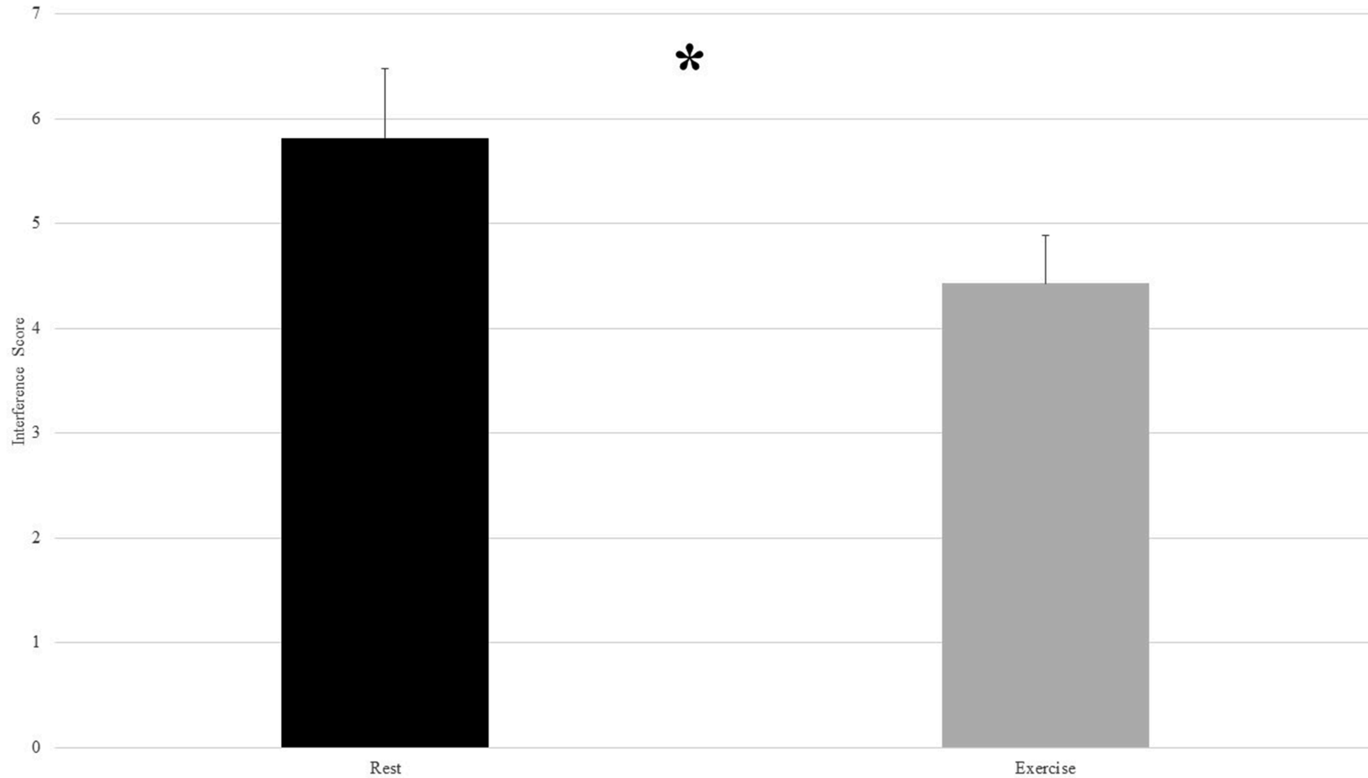



**Fig. 2.** Interference accuracy (Mean ± SE) by intervention.

**Table 4**
Summary of the final step of the hierarchical regression analysis for the relationship between BMI and flanker performance after controlling for the variance associated with descriptive variables following rest and exercise interventions.

| | B | SE B | Beta | t | *p* | $\Delta R^2$ | VIF |
|---|---|---|---|---|---|---|---|
| **Performance After Rest** | | | | | | | |
| Accuracy | | | | | | | |
| Congruent | -0.17 | 0.17 | -0.11 | -0.98 | 0.33 | 0.008 | 1.37 |
| Incongruent | -0.35 | 0.24 | -0.16 | -1.50 | 0.14 | 0.02 | 1.32 |
| Interference | -0.01 | 0.17 | -0.008 | -0.07 | -0.34 | 0.000 | 1.39 |
| MeanRT | | | | | | | |
| Congruent | 0.29 | 2.35 | 0.01 | 0.12 | 0.90 | 0.000 | 1.32 |
| Incongruent | -0.42 | 2.39 | -0.02 | -0.18 | 0.86 | 0.000 | 1.32 |
| Interference | 0.83 | 0.81 | 0.11 | 1.03 | 0.30 | 0.009 | 1.39 |
| **Performance After Exercise** | | | | | | | |
| Accuracy | | | | | | | |
| Congruent | -0.36 | 0.12 | -0.31 | -3.04 | 0.003* | 0.07 | 1.39 |
| Incongruent | -0.52 | 0.16 | -0.32 | -3.26 | 0.001** | 0.07 | 1.26 |
| Interference | 0.16 | 0.11 | 0.15 | 1.44 | 0.15 | 0.02 | 1.26 |
| MeanRT | | | | | | | |
| Congruent | -2.84 | 2.14 | -0.14 | -1.33 | 0.19 | 0.01 | 1.32 |
| Incongruent | -3.54 | 2.26 | -0.17 | -1.57 | 0.12 | 0.02 | 1.39 |
| Interference | -0.51 | 0.76 | -0.07 | -0.67 | 0.50 | 0.004 | 1.39 |

* Model is significant at the 0.05 level.
** Model is significant at the 0.01 level.

preadolescent children. These children came from several smaller, previously reported studies, in which we conducted re-analyses to 1) examine the main outcomes using a pooled sample to provide greater power for statistical analysis, and 2) investigate the differential role of BMI on task performance following PA and rest interventions; an important health factor that has been previously unreported within the context of acute exercise effects on cognition. Importantly, the results of this investigation corroborate previous work, suggesting that children are better able to manage inhibitory control demands following acute PA compared to following seated reading. The interference effect was also examined to better determine the general vs. selective nature of the effects of acute PA on inhibitory control. The findings revealed both a general and selective effect, such that following a single bout of PA, overall task performance was improved relative to rest. However, the interference control findings indicated a selective effect of acute PA during task conditions requiring greater amounts of inhibitory control. Stated differently, decreased conflict between target and flanking stimuli that require different action schemas was observed following the exercise intervention, suggesting that the benefits of acute PA are greatest for the task conditions that require the upregulation of inhibitory control. Such a finding indicates an increased ability to inhibit irrelevant stimuli following an acute bout of PA.

These results replicate and extend previous research suggesting that acute, moderate intensity PA improves behavioral correlates of

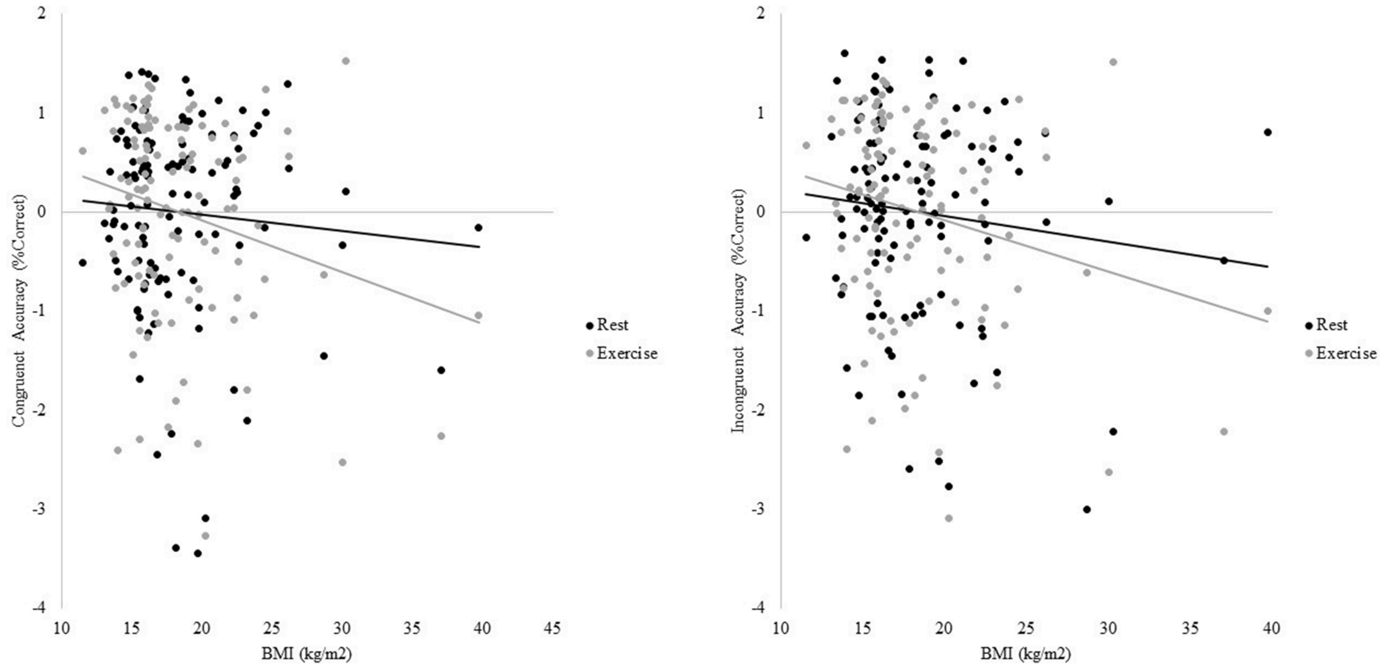



**Fig. 3.** Regression plots by congruency.

inhibition in preadolescent children [28–30]. Inhibitory control has been implicated in both reading [57,58] and mathematics [59,60]. Executive function, and inhibition in particular, provide the foundation for academic achievement as well as learning during childhood, such that children often have to inhibit irrelevant stimuli in their environment, and process and store diverse types of information during academic lessons. Clearly, effective learning is critical for successful academic achievement. Thus, if children have less optimal inhibitory control abilities, they may struggle to learn, and have lower academic achievement, which may have deleterious effects throughout development and across the lifespan. Thus, these findings are particularly relevant to the educational system as there are growing concerns from teachers regarding concentration and attention in children [61]. The findings from the present investigation provide compelling support that acute PA facilitates inhibitory control, and thus may benefit the classroom environment and the context of learning.

However, novel to the present investigation, and in contrast with our *a priori* hypothesis, performance following the cessation of the acute bout of PA was negatively related with BMI, suggesting that higher BMI blunts the benefits observed in inhibitory control performance following an acute bout of PA, and for those children with the highest BMI, may be detrimental. Rather than an acute bout of PA 'equalizing the cognitive playing field' for children with higher BMI, the findings herein suggest that it is less beneficial for higher BMI children. This negative relationship between BMI and inhibitory control occurred for both the congruent and incongruent conditions, suggesting that this blunting effect may be generalized. There are a number of interesting features to this finding, the first of which is that these effects occurred after accounting for important demographic characteristics (such as age and SES) as well as aerobic fitness. Furthermore, the negative relationship between BMI and performance only occurred following PA, such that there was no relationship between BMI and performance following the resting control condition. This suggests that while the acute bout of PA may be beneficial to improving inhibitory control, these benefits decrease as a child's BMI increases. This effect was surprising, as a variety of special populations derive the most benefit from an acute bout of PA [29–30]. While children with ADHD, autism, and lower performing executive "functioners" experience the greatest cognitive benefits following an acute bout of PA, these effects do not extend to increasing BMI. Instead, while children in general benefit from acute PA, the benefits appear reduced in children with higher BMI.

While the mechanisms linking acute PA effects to inhibitory control remain elusive, the extant literature suggests several possibilities. These include increased oxidative cerebral blood flow [62] that may lead to an increase in arousal [63] and an upregulation of neuronal proliferation and cell survival (such as brain derived neurotrophic factor and insulin like growth factor-1) [64–66], which may in turn positively influence the performance on cognitive tasks shortly after performing PA [67]. Acute bouts of exercise are also associated with an inflammatory response. Short term increases in inflammatory monocytes are seen after a single, acute bout of exercise with a rapid return to baseline during recovery [68]. Research suggests that each bout of exercise induces an anti-inflammatory environment [69–71], such that after an acute bout of exercise, pro- and anti-inflammatory cytokines are elevated. In children, 30 minutes of moderate to vigorous intensity exercise resulted in the release of cytokines and elevated inflammatory markers (specifically in terms of IL-6 and IL-8) [72–74]. However, children with OB display exaggerated pro-inflammatory responses following exercise [75–77]. In addition, children with OB exhibit chronic low grade inflammation [78–80], as evidenced by elevated levels of C-reactive protein (CRP), interleukin-6 (IL-6), and tumor necrosis factor (TNF) [81]. The inflammation that results from obesity has been implicated in the cognitive consequences of OB [82–84]. Thus, it is possible that chronic low-grade inflammation in addition to an exaggerated inflammatory response following exercise may be a possible mechanism linking blunted inhibitory control after exercise with increasing BMI.

Despite the fact that current estimates suggest that 124 million children worldwide are OB [55], the investigation of the effects of BMI on changes in inhibition following an acute bout of PA has received surprisingly little attention and remains largely unexplored. Given that obesity and physical inactivity are major public health concerns with a myriad of health consequences [85,86], this investigation provides critical evidence for the beneficial effects of PA on cognitive health in children; however, as BMI increases in children, cognitive performance after exercise decreases. These findings have implications for the educational environment and the context of learning. Critically, since OB children engage in less PA than their HW peers, moderate intensity walking may be a particularly beneficial means to promote PA among a population that has been found to be less physically active [87–89]. The present findings highlight the importance of using PA as a means to regulate attention in the classroom and create an environment that promotes learning.

## Declaration of Competing Interest

None

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### *Ethical Statement*

A statement in the manuscript is included that informed consent was obtained for experimentation with human subjects. The privacy rights of human subjects was always observed.

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