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## An Investigation of Associations Between Heart Rate Measures of Aerobic Fitness and Executive Functioning in Pre-Adolescent Children

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An Investigation of Associations Between Heart Rate Measures of Aerobic Fitness and  
Executive Functioning in Pre-Adolescent Children

Kimberly Anne Barnett

A thesis submitted to the faculty of  
Brigham Young University  
in partial fulfillment of the requirements for the degree of  
Master of Science

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## ABSTRACT

### An Investigation of Associations Between Heart Rate Measures of Aerobic Fitness and Executive Functioning in Pre-Adolescent Children

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The present study evaluated the associations between direct measures of aerobic fitness and executive functioning in pre-adolescent children aged 8 – 12 years. To evaluate these associations, the study employed a cross-sectional design and a series of three step hierarchical regressions were conducted. Results suggest that after controlling for age, sex, and BMI percentile, heart rate measures of aerobic fitness did not independently predict executive function. These findings provide preliminary evidence that contradicts a growing body of research within the adult literature demonstrating an association between aerobic fitness and executive function.

Keywords: aerobic fitness, executive function, heart rate measures

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## An Investigation of Associations Between Heart Rate Measures of Aerobic Fitness and Executive Functioning in Pre-Adolescent Children

Aerobic exercise is defined as any exercise that requires additional effort by the heart and lungs to meet the increased demand for oxygen. A growing consensus throughout the literature suggests that aerobic exercise produces significant improvements in overall mood and substantial reductions in symptoms of depression and anxiety, independent of age, gender, or medical condition. More specifically, individuals who regularly engage in aerobic exercise experience lower levels of depression, anxiety, insomnia, psychosocial stress, and fatigue, as well as higher levels of self-esteem and improved sleep quality (US Department of Health Human Services, 2008) compared to their less aerobically active peers. Further, across randomized controlled trials among individuals with mood and anxiety disorders, aerobic exercise is comparable to gold-standard pharmaceutical and psychological treatments in reducing mood and anxiety symptoms (Babyak et al., 2000; Blumenthal et al., 1999). In general, there is a large body of evidence to suggest that aerobic exercise has benefits that extend beyond physical fitness. However, it is unclear what underlying mechanisms account for these findings (Khan & Hillman, 2014).

One of the possible mechanisms of action that might explain the benefits of aerobic exercise is executive function. Within the adult literature research suggests that executive function is directly associated with aerobic fitness (S. Colcombe & Kramer, 2003; Hillman, Kramer, Belopolsky, & Smith, 2006). While this relationship is not as clearly established in children, there are several studies that highlight the relationship between executive function and aerobic fitness in child and adolescent populations (Castelli, Hillman, Hirsch, Hirsch, & Drollette, 2011; Chaddock et al., 2012; Chen, Yan, Yin, Pan, & Chang, 2014; Hillman, Buck,

Themanson, Pontifex, & Castelli, 2009; Hillman, Pontifex, et al., 2009; Verburch, Königs, Scherder, & Oosterlaan, 2014). The term executive function refers to the higher order cognitive abilities that allow an individual to adjust and control thoughts and behavior in order to achieve personal goals in the context of changing environmental demands. It includes the ability to monitor, shift, and inhibit prepotent responses in order to meet higher-order goals (Diamond, 2002, 2006; Eisenberg, Smith, & Spinard, 2011; Miyake et al., 2000). Executive function is predominately measured through examining attention and inhibitory control, and these abilities are generally associated with frontal lobe structure and function (Diamond, 2002). In a meta-analysis conducted by (Best, 2010), he found that children who engage in single bouts of aerobic exercise realized short term positive changes in executive function and that routine exercise participation induced more enduring improvements in executive function. These findings suggest that fitness influences the development of specific executive function abilities during preadolescence (Best, 2010).

Buck and colleagues (2008) illustrated this association in an initial cross-sectional study that explored the relationship of executive control with aerobic fitness in children (ages 7-12). In this study they hypothesized that increased fitness, as measured by the Progressive Aerobic Cardiovascular Endurance Run (PACER) (Welk & Meredith, 2010), would relate to improvements in test performance across the three conditions of the Stroop color word test (e.g., color condition, word condition, and color-incongruent condition). During the PACER test, participants are asked to run as long as possible, back and forth, across a 20-meter distance at a specified pace, which is incrementally increased each minute. A participant's score on the PACER test is used as an objective proxy of aerobic fitness and equal to the number of laps completed. In this study, they found that greater aerobic fitness was also associated with better

performance on each of the three Stroop conditions independent of demographic variables. These findings suggest that increased levels of fitness may be beneficial to cognition during preadolescent development (Buck et al., 2008).

However, much of the research examining the association between executive functioning and aerobic fitness use indirect measures of aerobic fitness rather than more direct measures, such as VO<sub>2</sub>Max or heart rate. Among the few studies that have utilized direct measures of cardiovascular fitness, there is good evidence linking heart rate with prefrontal neural functioning. Sub-maximal heart rate (HR<sub>Sub-max</sub>) is a non-invasive measure of aerobic capacity measured at one minute into an exercise protocol and is often used to distinguish fit from less aerobically fit individuals. Heart rate recovery (HRR) is closely related to an individual's level of aerobic capacity and provides a distinct indicator of aerobic fitness and is calculated by taking the absolute difference between the maximum heart rate during exercise and the heart rate at 1 minute post-exercise recovery (Buchheit, Papelier, Laursen, & Ahmaidi, 2007; Ohuchi et al., 2000). HRR is a widely used marker of physical fitness and good health and it is worth noting that recovery occurs more quickly on average in children than in adults (Baraldi, Cooper, Zanconato, & Armon, 1991). Although there is a relative paucity of research evaluating the predictive validity of these cardiovascular measurements in children, an extensive adult literature suggests that these indicators are valid measures of aerobic fitness in adults.

Given the lack of research investigating associations between direct measures of aerobic fitness and executive functioning in children, our primary aim is to determine whether cardiovascular measures (e.g., heart rate sub-max, and 1-minute post exercise recovery) reliably and independently predict executive functioning outcomes in adolescents 8-12 years old. Thus,



we hypothesize that increased aerobic fitness will predict greater executive performance, as measured by the Stroop test.

## **Method**

### **Procedures**

Data for this study were collected as part of a larger investigation, which examined associations between executive function, aerobic fitness, and emotion regulation. Participants ( $N = 278$ ) were recruited from schools within the Provo, Utah school district through a brief announcement and paper advertisement. Parents and children were determined to be eligible if they were between the ages of 8-12 ( $M_{\text{age}} = 9.73$ ,  $SD = .901$ ), had no serious health related concerns which precluded them from participation in a physically rigorous activity, had a parent/guardian willing to participate, and spoke English. All participants provided written informed consent/assent. Those parents who provided informed consent also provided demographic information, a brief child health history, and the Physical Activity Readiness Questionnaire (PAR-Q).

Each child completed measures in a standardized order in order to control for the acute effects of exercise on executive function. Each participant completed the Stroop test by a trained experimenter according to a standardized protocol in groups of two to five during the afternoon between the hours of 12-3 pm in order to minimize daytime differences. Prior to completing the PACER test each child's height and weight were measured and they were equipped with a Polar FT2 Heart Rate Monitor. According to a standardized protocol, participants listened to audio-recorded instructions for the PACER, and then completed at least one practice trial prior to examination. Heart rate measurements were collected while participants completed the PACER test in groups of two to five participants. Trained experimenters recorded the number of laps

completed and recorded sub-maximal heart rate at 1 minute into the exercise test. Maximum heart rate and heart rate at 1-minute post-exercise during passive recovery were recorded after each child failed to complete two laps at the required pace.

## Measures

**Aerobic fitness.** Physical Activity Readiness Questionnaire (PAR-Q; (Thomas, Reading, & Shephard, 1992)) is a 7-item measure completed by parents to assess whether participants were physically able to participate in a physically rigorous activity. Those children whose parents endorsed any of the items on the PAR-Q were determined ineligible and unable to participate.

Body Mass Index Percentile (BMI) for age and sex was calculated for each participant based on the child's height and weight using a standardized formula ( $BMI = [\text{weight (kg)}]/[\text{height (m)}]^2$ ; (Keys, Fidanza, Karvonen, Kimura, & Taylor, 1972)). BMI was then converted to an age-and sex-adjusted percentile score using the Center for Disease Control and Prevention (CDC) BMI percentile calculator (Center for Disease Control and Prevention, 2010). BMI percentile has been shown to be a moderately reliable indicator of body fat percentage (Mei et al., 2002).

Participants completed the Fitnessgram's Progressive Aerobic Cardiovascular Endurance Run (PACER) (Welk & Meredith, 2010) which is a standardized field measure of maximal oxygen consumption that consisted of a 20-meter shuttle run with one-minute incremental increases in speed until the participant failed to complete two consecutive laps at the required pace. This test was completed in order to collect heart rate measurements and has been shown to provide reliable and valid estimates of aerobic capacity for children and adolescents (Welk & Meredith, 2010). The PACER test has been shown to have high test-retest reliability ( $r = .84$  to

.90) in preadolescent children and moderate to high concurrent validity ( $r = .54$  to  $.90$ ) when compared to gold-standard treadmill test of  $VO_2\text{Max}$  (Welk & Meredith, 2010).

Heart rate measurements were recorded during the PACER, using the Polar FT2 portable electrocardiogram (ECG) based heart rate monitor, including sub-maximal heart rate ( $HR_{\text{Sub-max}}$ ) (Goran, Fields, Hunter, Herd, & Weinsier, 2000) and heart rate recovery (HRR) (Baraldi et al., 1991). Although reliability estimates have not yet been established,  $HR_{\text{Sub-max}}$  is a non-invasive measure used to distinguish aerobically fit individuals from less aerobically fit and is heart rate recorded at one minute into an exercise protocol (Goran et al., 2000; Jones & Carter, 2000; Spina, 1999). HRR is a non-invasive measure of cardiorespiratory adjustment following exercise, calculated by taking the absolute difference between maximum heart rate during exercise and at one minute post-exercise during passive recovery (Buchheit et al., 2007; Ohuchi et al., 2000; Shetler et al., 2001). HRR has been shown to have high test-retest reliability estimates ( $ICC = 0.70$ ,  $SEM = 10.1s$ ) (Buchheit et al., 2008).

**Executive control.** Prior to aerobic fitness testing, participants completed the Stroop Test (Golden, Freshwater, & Zarabeth, 2003), a well-established standardized behavioral measure of response inhibition and attentional control that consists of three 45-second conditions, Word-condition, Color condition, and Incongruent Color-Word condition (Strauss, Sherman, Spreen, & Spreen, 2006). In the Word-condition participants are presented with a sheet of 100 color words printed (i.e., red, green, blue) printed in black ink and required to read aloud the color words down each column as quickly as they can within the time limit. In the Color-condition participants are again presented with a sheet of 100 words printed in red, green, or blue ink and are required to name aloud the ink color of the word's down each column as quickly as they can within the time limit. Finally, in the Incongruent Color-Word condition

participants were presented with the sheet of 100 words from the first page, which are printed in incongruent colors from the second page (i.e., the word “red” printed in green ink or the word “blue” printed in red ink). The number of items answered correctly within the time limit is totaled to produce three subtest scores. Each subtest score was then combined to produce a composite interference score (Chafetz & Matthews, 2004). The Stroop Test measures an individual’s ability to resolve incongruences by inhibiting their prepotent responses to read the word, and instead activating a subdominant response to name the ink color. The measure has been shown to have modest correlations ( $r = .31$  to  $.56$ ) with other measures of attentional control and response inhibition, suggesting moderate concurrent validity, and test-retest reliability ( $r = .73$  to  $.86$ ) for the three different subtests (Strauss et al., 2006).

### **Data Analytic Procedure**

**A priori analyses.** A priori analyses were conducted to ensure the assumptions of the regression analysis were met, which included multicollinearity/singularity, outliers, normality, linearity, and homoscedasticity. It was determined that a sample size of 48 was necessary to be adequately powered to detect an effect of 0.35 at the .95 level.

**Hierarchical multiple regression analyses.** A series of three step hierarchical multiple regressions were conducted to evaluate whether heart rate measures could independently and reliably predict executive function using scores from the four sub-scales (Color, Word, Color-Word, and Interference) of the Stroop test in adolescents. This analysis allowed the independent variables to be entered into the equation in a specified order based on theoretical groups. The variables were entered in blocks to determine the unique variance attributable to each independent variable in its ability to predict the dependent variable, after controlling for previously entered variables. The overall model and the relative contribution of each block are

assessed in terms of its ability to predict the dependent measure (executive function). Previous research suggests that age and gender may be associated with the primary study variables (Diamond, 2006; Hackman & Farah, 2009), thus in order to control for these variables, Block 1 included the independent variables of BMI percentile, age and sex.  $HR_{\text{Sub-max}}$  and HRR were entered into Block 2 to evaluate whether  $HR_{\text{Sub-max}}$  and HRR independently predict executive function. In Block 3 an  $\text{Age} \times HR_{\text{Sub-max}}$  and an  $\text{Age} \times \text{HRR}$  interaction term (created using mean centered scores) were entered in order to determine whether cardiovascular fitness effects on performance were dependent upon age.

## Results

### Participants

Two hundred seventy-eight participants (52.2% female; 81.7% Caucasian) between the ages of 8 and 12 years old ( $M = 9.73$ ,  $SD = 0.90$ ) were included in the final analyses (see Table 1 for detailed demographic information).

Table 1 *Participant Demographic Information*

<i>N</i>	278	(133 Males)
Mean Age ( <i>SD</i> )	9.73	(0.90)
BMI percentile ( <i>SD</i> )	53.16	(29.11)
Race (% of Total)		
Caucasian	227	(81.7%)
Hispanic	23	(8.27%)
Pacific Islander	5	(1.80%)
Asian American	1	(0.36%)
Multiracial & Other	22	(7.91%)
Monthly Gross Income ( <i>SD</i> )	6.32	(3.12)

*Note.* Monthly Gross Income was measured in the following \$1,000 increments: 1 = \$0 – 999, 2 = \$1,000 – 1,999, 3 = \$2,000 – 2,999, 4 = \$3,000 – 3,999, 5 = \$4,000 – 4,999, 6 = \$5,000 – 5,999, 7 = \$6,000 – 6,999, 8 = \$7,000 – 7,999, 9 = \$8,000 – 8,999, 10 = \$9,000 – 9,999, 11 = \$10,000 +

## A Priori Analyses

A priori analyses indicated no violations of the assumptions of multicollinearity, normality, homoscedasticity, and independence of residuals.

## Full Group Hierarchical Multiple Regression Analysis

For the first hierarchical multiple analysis that looked at the number of items read in the word condition (WC) of the Stroop test we found a significant overall effect for the model,  $F(7, 213) = 3.96, p < .001$ , in which age was the only statistically significant measure ( $b = 4.53, SE_b = .91$ ). Step 1, significantly explained 10.9% of the variance in WC,  $\Delta R^2 = .109, \Delta F(3, 217) = 8.88, p < .001$ . However, the two measures of cardiovascular function, which were entered into Step 2, did not explain any additional variance in WC,  $\Delta R^2 = .000, \Delta F(2, 215) = .004, p = .996$ . Step 3 which included the two interactions (i.e., Age  $\times$  HRR, Age  $\times$  HR<sub>Sub-max</sub>) was also not significant,  $\Delta R^2 = .006, \Delta F(2, 213) = .690, p = .503$ , indicating that the interactions between age and cardiovascular measures did not add to the prediction of performance scores on the WC subscale (see Table 2).

The second hierarchical analysis which regressed the number of items read in the color condition (CC) demonstrated an overall significant effect for the model as a whole,  $F(7, 213) = 4.256, p < .001$ , in which age was the only statistically significant predictor ( $b = 3.50, SE_b = .69$ ). Step 1 was statistically significant and explained 11.7% of the variance in CC,  $\Delta R^2 = .117, \Delta F(3, 217) = 9.57, p < .001$ , while Block 2,  $\Delta R^2 = .002, \Delta F(2, 215) = .209, p = .811$ , and 3,  $\Delta R^2 = .004, \Delta F(2, 213) = .498, p = .609$ , were non-significant and together explained less than 1% of the variance in CC (see Table 2).

Results from the third hierarchical regression, which regressed the number of items read in the incongruent color-word condition (CWC) suggest that the model as a whole is statistically

significant,  $F(7, 213) = 3.527, p < .01$ , with age as the only significant predictor ( $b = 2.09, SE_b = .50$ ). Step 1 was statistically significant and explained 8.3% of the variance in CWC,  $\Delta R^2 = .083, \Delta F(3, 217) = 6.54, p < .01$ , while Blocks 2 and 3 were both non-significant and together explained an additional .4% and 1.7% respectively (see Table 2).

In the final model, the composite Stroop interference scores were regressed using identical steps from the previous three regression models. Results from this analysis demonstrated that the model as a whole was statistically significant,  $F(7, 213) = 2.05, p = .05$ . Blocks 1 and 2 were non-significant ( $\Delta R^2 = .018, \Delta F(3, 217) = 1.34, p = .262$ ;  $\Delta R^2 = .011, \Delta F(2, 215) = 1.25, p = .287$ , respectively). Block 3 explained an additional 3.4% of the variance in the composite Stroop interference scores,  $\Delta R^2 = .034, \Delta F(2, 213) = 3.82, p < .05$ . In the final model, the Age  $\times$  HR<sub>Sub-max</sub> interaction was statistically significant ( $b = -.087, SE_b = .034$ ) but the Age  $\times$  HRR interaction was not (see Table 2).

Table 2 Summary of Hierarchical Multiple Regression Analyses Predicting WC, CC, CWC, and Composite Scores of Interference

	b	SE <sub>b</sub>	$\beta$	p-value
Word Condition				
Block 1				
Age	4.538	.898	.325	.000
Sex	-.188	1.615	-.007	.908
BMI	-.026	.028	-.061	.344
Block 2				
HRR	.002	.057	.002	.972
HR <sub>Sub-max</sub>	-.006	.062	-.006	.926
Block 3				
Age $\times$ HRR	.067	.061	.074	.271
Age $\times$ HR <sub>Sub-max</sub>	.010	.076	.009	.898
Color Condition				
Block 1				
Age	3.470	.678	.328	.000
Sex	.181	1.219	.010	.882
BMI	-.030	.021	-.090	.158
Block 2				
HRR	.004	.043	.007	.918
HR <sub>Sub-max</sub>	.028	.047	.040	.549
Block 3				

Table 2 *Continued*

Age × HRR	.024	.046	.035	.604
Age × HR <sub>Sub-max</sub>	.040	.057	.047	.483
Color-Word Condition				
Block 1				
Age	2.105	.492	.279	.000
Sex	.654	.885	.048	.461
BMI	-.002	.015	-.010	.881
Block 2				
HRR	-.010	.031	-.022	.760
HR <sub>Sub-max</sub>	-.026	.034	-.053	.437
Block 3				
Age × HRR	.048	.033	.097	.150
Age × HR <sub>Sub-max</sub>	-.071	.041	-.118	.085
Interference Score				
Block 1				
Age	.632	.413	.103	.127
Sex	.697	.743	.063	.349
BMI	.009	.013	.045	.501
Block 2				
HRR	-.012	.026	-.033	.648
HR <sub>Sub-max</sub>	-.039	.028	-.097	.171
Block 3				
Age × HRR	.046	.027	.115	.097
Age × HR <sub>Sub-max</sub>	-.087	.034	-.177	.012

## Discussion

The purpose of the present study was to investigate whether cardiovascular measures of aerobic fitness predicted executive functioning outcomes on four subscales of the Stroop test in preadolescent children. Results from this cross-sectional study provide preliminary evidence that is incongruent with our original hypothesis and previous research suggesting that the superior heart rate measures of aerobic fitness would predict greater performance on the Stroop test. Specifically, results from a series of hierarchical regressions suggest that, after controlling for age, sex, and BMI percentile, neither HR<sub>Sub-max</sub> nor HRR independently predicted performance on either Stroop test subscales or Stroop Composite score. Moreover, the effect of HR<sub>Sub-max</sub> and HRR on Stroop test performance was not dependent upon age. Within the adult literature, there is a growing body of research demonstrating an association between aerobic fitness and



executive function. However, this relationship is not as well understood in children and typically involves indirect measures of aerobic fitness.

To examine our hypothesis, we conducted four separate regression analyses to evaluate whether direct measures of aerobic fitness were predictive of global executive functioning. Results from these analyses found that  $HR_{\text{Sub-max}}$  and HRR were not significant predictors of executive function in pre-adolescents after controlling for age, gender, and BMI percentile. These findings are inconsistent with those found by Buck and colleagues (2008) and contradict findings within the adult literature. Specifically Buck (2008) found that aerobic fitness, age, and IQ were related to better cognitive function in preadolescent children. Similarly, results from a meta-analytic review of randomized controlled trials within the adult literature found a significant relationship between aerobic exercise and attention, processing speed, executive function, and memory (Smith et al., 2010). A recent study that investigated the effects of acute exercise on cognitive functioning in older adults found that acute exercise led to improvements in executive function, particularly for those with a higher fitness level compared to those with a lower fitness level (Chu, Chen, Hung, Wang, & Chang, 2015). However, Etnier and colleagues demonstrate that the effect of exercise on cognitive process is largely dependent upon a number of factors including, the exercise protocol, rigor of research, characteristics of the participants, and the specific measures used to evaluate cognitive processes (Chang, Labban, Gapin, & Etnier, 2012; Etnier et al., 1997).

Consistent with previous literature (Buck et al., 2008) we conducted a series of secondary exploratory analyses to investigate whether an interaction between age and heart rate variables further predicted scores on subscales of the Stroop test and an overall interference score. Our results suggest that neither interaction,  $\text{Age} \times \text{HRR}$  or  $\text{Age} \times HR_{\text{Sub-max}}$ , significantly predicted

scores for any sub-scales of the Stroop test, including the Word Condition, Color Condition, and Color-Word Condition. In our final regression model that predicted interference scores, the only interaction that contributed significantly to the overall model was the  $\text{Age} \times \text{HR}_{\text{Sub-max}}$ . These results suggest that the effect of submaximal heart rate on interference scores was moderated by the participant's age.

Results from the current study stand in contrast to adult and child/adolescent studies that have found a significant association between executive functioning and aerobic fitness, such that higher fit individuals responded more rapidly during tasks of cognitive control, while sustaining accuracy. However, these studies largely utilize cardiovascular fitness measures including heart rate variability and  $\text{VO}_2\text{Max}$  (Alderman & Olson, 2014; Chaddock et al., 2010; Hillman, Pontifex, et al., 2009), or more indirect measures, such as the PACER (Buck et al., 2008). Two separate reviews (Hillman, Khan, & Kao, 2015; Khan & Hillman, 2014) summarizing findings from neuroscience research suggest that greater aerobic fitness is not only associated with greater performance on tasks measuring cognitive control but also greater structural integrity and volume in areas of the brain involved in attentional and cognitive control (Chaddock et al., 2010; Krafft et al., 2014). The majority of this literature comprises cross-sectional research, and there have been relatively few prospective studies addressing this question. However, consistent with findings in the adult literature (S. J. Colcombe et al., 2004) findings from a recent randomized controlled trial, which assessed the effectiveness of a physical activity intervention for improving executive control in pre-pubertal children, found that the 9-month intervention had significant effects on brain and behavioral indices of executive control (Hillman et al., 2014).

Although there *is* evidence to support the relationship between aerobic fitness and executive function in children and adolescents there is still a considerable amount of work to be

done in order to establish conclusive evidence. More specifically, much of the existing literature lacks consistency in how they measure aerobic fitness and executive control (Guiney & Machado, 2013). Further, much of the existing literature in children and adolescents is limited to cardiovascular fitness research and has yet to determine the implications of how acute exercise versus overall physical fitness could differentially impact findings (Guiney & Machado, 2013; Khan & Hillman, 2014). Lastly, the discrepancies between the adult and child literature might be explained by the lack of cardiovascular differences in children because development of impaired cardiovascular processes are insidious (Hasselstrom, Hansen, Froberg, & Andersen, 2002) and, unlike in adults, children may have less variability in their overall level of aerobic fitness (Amorim, Byrne, & Hills, 2009; Cadenas-Sanchez et al., 2014; DiPietro, Bornstein, Hahn, Costigan, & Achy-Brou, 2007; Gasior et al., 2015; Kemper, Hamilton, & Atkinson, 2007; Leicht & Allen, 2008; Martini et al., 2001; Nagai & Moritani, 2004; Silvetti, Drago, & Ragonese, 2001; Srinivasan, Sucharita, & Vaz, 2002). Guiney & Machado (2013), also theorizes that null findings in children may be best explained by their limited experience with word reading, making tasks of interference relatively less challenging.

### **Study Limitations**

Our study includes several limitations, largely due to the cross-sectional study design. Specifically, because our study was not experimental, we are unable to determine the causality and direction of influence. Future studies that include robust control conditions (e.g., experimental assignment to high or low exercise interventions) will help to evaluate the causal influence of aerobic fitness on executive function in adolescents. Although our sample was reasonably representative of children within the school district within which participants were recruited, it does not mirror the current distribution of BMI percentile norms within the US

population of children. Specifically, less than 30% of our sample was within the obese or overweight category. Therefore, it is important to consider the possibility that those who chose to participate were those children who were physically fit, limiting the generalizability of our study results.

Additionally, we utilized a single measure for each of the variables included in the study, which may have limited the comprehensiveness and construct validity of our assessment procedures. Future studies should consider collecting additional measures of the target variables in order to determine if there are differences in the expected outcome across measurement methods. Results may also be confounded by the fact that children were evaluated in front of their peers in groups of 2-5 participants. This design characteristic may have led anxious individuals to perform more poorly or better confounded the results and outcomes of the study's findings. It is also possible that executive functioning changes are contingent on the level of aerobic fitness (i.e., moderate aerobic fitness is predictive of executive functioning, but high-moderate aerobic fitness is not predictive of executive function). Future studies that examine the variability of heart rate measurements would provide insight about the level of aerobic fitness necessary to improve executive functioning. The experimenters who conducted the study were unblinded to hypotheses making it difficult to determine if the expectations of the experimenter lead to bias of the data obtained. Given the lack of reliability data for the  $HR_{Sub-max}$  variable we were unable to determine if the measure accurately registered true changes. Since a group mean is more stable than individual scores, follow-up research should consider using aggregated units as opposed to single units of measurement. For example,  $HR_{Sub-max}$ ,  $HRR$  and  $HR_{Max}$  could be combined in a higher order factor, which would reduce error variance in measurement, or record consider assessing heart rate variables for a longer duration (Durant et al., 1992). Future research

should also replicate findings in experimental settings in order to lower the variance associated with environmental variables. Lastly, due to the heterogeneity of our population it is possible that study results may be due to individual differences that were unaccounted for in our study; thus future research is needed in more homogenous populations.

### **Implications**

While we were unable to determine conclusively an association between cardiovascular measurements of aerobic fitness and executive function in children, it is difficult to determine their relative contribution to the existing literature given the limited amount of empirical support in this area. Overall results from the present study are inconsistent with findings from previous research in children that suggests an association between aerobic fitness and increased speed on executive function tasks. Moreover, these findings certainly suggest that measures of heart rate are an inadequate predictor of executive function in children; however future research is vital to better understand not only the relationship between direct measures of aerobic fitness (Esco & Williford, 2013) and executive functioning in children and adolescents, but also the potential underlying mechanisms that may elucidate discrepancies between the adult and adolescent literature. Future research should continue to investigate how different measures of aerobic fitness relate to executive function outcomes in both cross-sectional studies and randomized control trials.

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