



# The relation of aerobic fitness to cognitive control and heart rate variability: A neurovisceral integration study

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## ABSTRACT

This aim of the present study was to investigate relationships between aerobic fitness, sympathetic and parasympathetic cardiac control using pre-ejection period (PEP) and high frequency heart rate variability (HF HRV), and performance on a task requiring variable amounts of cognitive control. Fifty-six participants completed a modified-version of the Eriksen flanker task while PEP and HF HRV were collected. A graded maximal exercise test was subsequently used to measure aerobic fitness by assessing maximal oxygen uptake. Results indicated a significant relation of fitness to reaction time performance. Although no fitness differences were observed in resting state PEP or HF HRV, higher fit adults exhibited greater task-induced parasympathetic cardiac control. However, no significant mediation was found for HF HRV on the fitness–cognitive control relationship, suggesting other mediators may be important. These findings highlight the role of aerobic fitness in enhancing integrated autonomic and neurocognitive health.

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## 1. Introduction

Although increasing research attention has been devoted to investigating the neurobiological mechanisms involved in the cognitive-enhancing benefits of exercise and cardiorespiratory fitness (Hillman, Erickson, & Kramer, 2008; Voss, Nagamatsu, Liu-Ambrose, & Kramer, 2011), the precise mechanisms involved remain elusive. One mechanism that has been proposed to aid in the understanding of efficient and adaptive behavioral responding in general, and higher order cognitive functioning in particular, is activity in the cardiovascular system (Thayer, Hansen, Saus-Rose, & Johnsen, 2009; Thayer & Lane, 2000). The normal, healthy cardiovascular system is characterized by complex and variable biosignals (e.g., heart rhythm) associated with the dynamic interplay of sympathetic and parasympathetic (or vagal) neural control (Saul, 1990). Heart rate variability (HRV), or the variability in consecutive beat-to-beat intervals of the electrocardiogram, provides an index of this dynamic balance and captures synergy between brain and cardiovascular control systems in modulating flexible responses to rapidly changing environmental demands (Bates et al., 2011). Although exercise and enhanced cardiorespiratory fitness have been shown to elicit favorable influences on HRV (Aubert,

Seps, & Beckers, 2003) as well as promote beneficial changes in brain structure and function and consequently, enhance cognitive performance (Erickson et al., 2011; Hillman et al., 2008; Voss et al., 2011), relatively few studies to date have examined relationships between aerobic fitness, HRV, and cognition within the same study (Luque-Casado, Zabala, Morales, Mateo-March, & Sanabria, 2013).

Luque-Casado and colleagues (2013) investigated the relationship between cognitive task performance and HRV as a function of physical fitness among 26 men, half of whom were considered sedentary and unfit. HRV was assessed at rest and during the performance of three cognitive tasks involving variable amounts of cognitive control. Cognitive control refers to a subset of goal-directed, self-regulatory operations involved in efficiently selecting, scheduling, and coordinating computational processes underlying perception, memory, and action (Gomez-Pinilla & Hillman, 2013; Miller, 2000). Core cognitive processes that are collectively termed “cognitive control” include those involved in working memory, selective and sustained attention, behavioral inhibition, and general cognitive flexibility. Although the high fit group in the Luque-Casado et al. study demonstrated greater HRV both at rest and during cognitive task performance, the beneficial relation of fitness to cognitive performance was limited to a task of sustained attention. Since aerobic fitness training studies have been shown to have selectively larger effects for cognitive tasks requiring greater amounts of cognitive control (Colcombe & Kramer, 2003) and significant reductions in HRV have been found for cognitive control-based tasks (Luft, Takase, & Darby, 2009), the authors

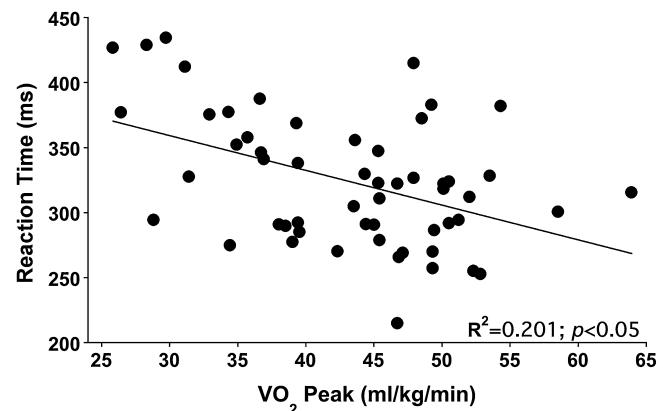
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noted that the level of cognitive control elicited by the cognitive tasks may not have been sufficient to differentiate performance between the two groups of participants. Hansen, Johnsen, and Thayer (2003) reported that individuals expressing greater baseline HRV performed better on cognitive tasks that require greater amounts of cognitive control whereas no differences were found for tasks requiring lesser amounts of cognitive control. Further, using an experimental manipulation of aerobic exercise detraining, performance on cognitive control tasks deteriorated concomitantly with reductions in HRV (Hansen, Johnsen, Sollers, Stenvik, & Thayer, 2004). More recently, Albinet, Boucard, Bouquet, and Audiffren (2010) randomly assigned 24 sedentary men and women aged 65–78 years to an aerobic exercise program or a stretching program three times a week for 12 weeks. The aerobic training group demonstrated greater vagally mediated HRV and improved performance on the Wisconsin card sorting test, a task involving cognitive control, from pre- to post-intervention. Collectively, these findings suggest important functional links between HRV and cognition and demonstrate the amenability of these variables to change dynamically through aerobic exercise and enhanced cardiorespiratory fitness.

Thayer and colleagues (2009) have proposed a model of neurovisceral integration that highlights efficient and adaptive responding to complex environments and includes both direct and indirect connections between the brain and the heart. They have demonstrated in several pharmacological and neuroimaging studies that individual differences in resting state or task-induced HRV are related to activity in a network of brain regions including the prefrontal cortices (Ahern et al., 2001; Lane, Reiman, Ahern, & Thayer, 2001; Lane et al., 2009) and performance on tasks requiring greater amounts of cognitive control (Hansen et al., 2003). In their model of neurovisceral integration, the central autonomic network (CAN) was identified as an important functional network involved in brain–heart communication. The CAN includes the anterior cingulate; insular, orbitofrontal, and ventromedial prefrontal cortices; the central nucleus of the amygdala (CeA); the paraventricular and related nuclei of the hypothalamus; the periaqueductal gray matter; the parabrachial nucleus; the nucleus of the solitary tract (NTS); the nucleus ambiguus (NA); the ventrolateral medulla; the ventromedial medulla; and the medullary tegmental field (Benarroch, 1997). These brain regions have also been implicated in select aspects of cognitive control including conflict monitoring, response inhibition, and interference resolution (Aron, 2007; Blasi et al., 2006; Botvinick, Cohen, & Carter, 2004; Miller, 2000). Important to the current study, the CAN has also demonstrated neuroplasticity following exercise and fitness interventions. Indeed, a number of recent electrophysiological and neuroimaging studies have provided evidence that cardiorespiratory fitness elicits better functioning of brain, particularly among these CAN brain regions associated with cognitive and cardiovascular control (Gomez-Pinilla & Hillman, 2013).

Although a large number of studies have examined the beneficial effects of exercise and aerobic fitness on cognition in younger and older populations, comparatively fewer studies have examined this relationship in young adult (18–35 years) populations, likely due to the relative stability and peak cognitive performance that characterizes this age group (Voss et al., 2011). However, it is important to examine behavioral approaches to enhance cognition, even in young adulthood, since it has been postulated that brain networks can not only be maintained but may be enhanced throughout life, thereby attenuating age-related decline or disease pathology, a process otherwise known as cognitive reserve (Stern, 2002). Moreover, although HRV has shown promise as a possible endophenotype for adaptive regulation across a variety of biobehavioral states (Thayer & Lane, 2009), including cognitive control, the mediating role of HRV in the physical fitness and



**Fig. 1.** Scatter plot of the relationship between aerobic fitness and total reaction time.

cognitive performance relationship has received little attention. Therefore, the purpose of this investigation was to examine the relationship between cognitive performance and HRV, and whether this relationship is associated with cardiorespiratory fitness, while participants completed a modified computerized-version of the Eriksen flanker task (Eriksen & Eriksen, 1974). The Eriksen flanker task has been frequently and successfully used as a measure of interference control, an important component of cognitive control. Variable amounts of interference control are required based on task demands, with congruent conditions of the task (e.g., «<; all arrows pointing in the same direction) resulting in faster and more accurate responses than incongruent task conditions («>; central arrow flanked by arrows pointing in the opposing direction), due to greater response competition in the incongruent task condition (Pontifex & Hillman, 2007). Additionally, Etnier (2008) has recommended using appropriate statistical analyses to test for potential mediators in order to advance our understanding of the aerobic fitness and cognitive performance relationship. Thus, we performed a mediation analysis (Baron & Kenny, 1986; MacKinnon, 2008) to test the role of HRV as a potential mediator of the relationship between aerobic fitness and cognitive control. Based on the reviewed evidence, it was hypothesized that (1) higher fit individuals would perform more rapidly and accurately on the Eriksen flanker task; (2) higher fit individuals would evidence greater HRV at rest and throughout the cognitive performance task relative to their less fit counterparts; and (3) HRV would partially mediate the relationship between aerobic fitness and cognitive control.

## 2. Methods

### 2.1. Participants

Fifty-six healthy normotensive undergraduate students between the ages of 18–25 (27 females; 21.0 ± 1.2 years) were recruited from Rutgers University through the use of campus flyers and advertisements. Participants were required to meet the following inclusion criteria: (1) no presence or history of cardiovascular, neurological, or musculoskeletal problems that would impact exercise ability or cardiovascular function, (2) no past or present history of psychological disorders (including attention deficit hyperactivity disorder (ADHD), clinical depression or anxiety, or alcohol or drug abuse), and (3) no use of medications that are known to influence cognition or cardiovascular responses. Qualifying and participating participants received monetary compensation for their participation. All participants provided written informed consent that was approved by a university institutional review board. Following a maximal graded exercise test on a treadmill, participants were classified as either higher or lower fit according to age- and gender-referenced maximal oxygen consumption (VO<sub>2</sub> peak) norms (American College of Sports Medicine, 2010; Kamijo, O'Leary, Pontifex, Themanson, & Hillman, 2010). Due to the fitness split by gender, one extra male and one extra female were grouped into the lower fit category, resulting in 27 higher fit and 29 lower fit participants in the analysis. Higher fit participants expressed greater VO<sub>2</sub>peak values than their lower fit counterparts, F(1,54) = 25.2, p < .001, see Fig. 1. Fitness groups did not differ in relation to age, F(1,54) = .21, p = .65, years of education, F(1,54) = .59,

**Table 1**Participant characteristics ( $M \pm SD$ ) overall and by fitness.

Measure	Higher fit	Lower fit	Total
n	27	29	56
Age (years)	$21.1 \pm 1.2$	$20.9 \pm 1.1$	$21.0 \pm 1.2$
Gender (male/female)	14/13	15/14	29/27
Height (cm)	$169.8 \pm 11.2$	$167.3 \pm 11.3$	$168.5 \pm 11.2$
Weight (kg)	$65.8 \pm 13.2$	$67.2 \pm 18.2$	$66.5 \pm 15.8$
BMI ( $\text{kg}/\text{m}^2$ )	$22.7 \pm 2.8$	$23.8 \pm 5.4$	$23.3 \pm 4.3$
$\text{VO}_2$ Peak ( $\text{mL kg}^{-1} \text{min}^{-1}$ ) <sup>a</sup>	$48.0 \pm 6.5$	$38.6 \pm 7.3$	$43.1 \pm 8.3$
IPAQ (MET-minutes/week)	$3256.6 \pm 1484.6$	$2401.9 \pm 1785.5$	$2813.4 \pm 1688.1$

Note:  $\text{VO}_2$  peak norms are available in the American College of Sports Medicine (2010) Guidelines for Exercise Testing and Prescription (8th ed.).<sup>a</sup> Significant difference, unpaired Student's *t* test between higher fit and lower fit individuals,  $p < .05$ .

$p = .45$ , body mass index,  $F(1,54) = 1.01$ ,  $p = .32$ , gender,  $\chi^2 = 0.01$ ,  $p = .99$ , or depressive symptoms assessed through the Beck Depression Inventory 2nd ed. – BDI II (Beck, Steer, & Brown, 1996),  $F(1,54) = .12$ ,  $p = .73$ . Although fit participants reported spending more minutes/week engaging in physical activity based on the International Physical Activity Questionnaire (Craig et al., 2003), this difference did not reach significance,  $F(1,54) = 3.63$ ,  $p = .06$ . Table 1 shows participants' demographic and fitness information according to their fitness grouping.

## 2.2. Eriksen flanker task

A modified version of the Eriksen flanker task (Eriksen & Eriksen, 1974) was used to manipulate interference control, an important component of cognitive control. During the task participants were instructed to focus on a centrally presented target stimulus amid an array of flanking stimuli. A set of instructions preceded the first trial that explained which button press would be used to indicate the direction of the central or target arrow. Participants performed a button press with their left thumb when the target arrow, or 3rd arrow from the left, pointed to the left (<) and a button press with their right thumb when the target arrow pointed to the right (>). Participants were instructed to respond as quickly and accurately as possible for each trial. Each block consisted of congruent and incongruent stimuli presented in random order. The congruent trials consisted of the target arrow being flanked by arrows facing the same direction (i.e., presented as «< or »>) while incongruent trials involved the target arrow being flanked by arrows facing the opposite direction (i.e., presented as «>< or »><). The stimuli were 7.6 cm tall black arrows centered focally on a white background for 100 ms (Themanson et al., 2008) with a response window of 1500 ms. This brief stimulus duration was chosen in an attempt to increase task difficulty. A random inter-stimulus time interval of 1100, 1300, or 1500 ms was also used between each 50 ms visual fixation (+) and the stimulus in order to increase task difficulty. After a practice block of 30 trials, two blocks of 120 trials were presented, each separated by 30-s.

## 2.3. Cardiovascular autonomic measures

Pre-ejection period (PEP) and high frequency (HF; 0.15–0.4 Hz) HRV were assessed as the primary cardiovascular measures of sympathetic and parasympathetic cardiac control, respectively. Electrocardiograph (ECG) and impedance cardiograph (ICG) signals were collected to derive HF HRV and PEP using standard lead II and tetrapolar electrode configurations and procedures outlined by Sherwood, Turner, Light, and Blumenthal (1990). The ECG and thoracic impedance biosignals were acquired and filtered through BioPac MP150 and MindWare Impedance Cardiograph equipment, and digitized at 1000 Hz. Custom software (Mindware, Gahanna, OH) was used to analyze the dZ/dt and ECG waveforms to obtain PEP and HF HRV. From the ECG and ICG signals, ensemble averages were created for each minute to produce estimates of PEP and HF HRV.

PEP, a commonly assessed measure of sympathetic cardiac control (Berntson et al., 1994; Cacioppo, Uchino, & Berntson, 1994; Sherwood et al., 1990), was quantified as the time interval (in milliseconds) from the start of ventricular depolarization marked by the onset of the Q wave in the ECG to the opening of the aortic valve and simultaneous onset of left ventricular ejection marked by the B point of the ICG dZ/dt wave (Berntson, Norman, Hawley, & Cacioppo, 2008; Lozano et al., 2007). Minute-by-minute means were then averaged over the baseline and cognitive assessment periods. Measures of PEP have previously been shown to exhibit good long-term temporal consistency (Burleson et al., 2003) and reliability (Berntson et al., 2008). Further, individual differences in PEP have been shown to be highly predictive of sympathetic cardiac control in pharmacological blockade studies (Cacioppo et al., 1994).

HF HRV, a relatively pure index of parasympathetic or vagal cardiac control, was derived by spectral analysis of the interbeat interval (R-R) series derived from the ECG (Mindware impedance cardiography system, Gahanna, OH), following procedures specified by Berntson et al. (1997). The R-R interbeat interval series were converted into time series data with a 4 Hz resolution (with interpolation), linearly detrended and end tapered, and submitted to a fast Fourier transformation. Power spectral density values over the respiratory frequency band (0.15–0.4 Hz) were used to calculate HF HRV. This measure of autonomic function has demonstrated good

long-term temporal consistency (Burleson et al., 2003) and reliability (Berntson et al., 2008). Moreover, HF HRV has been linked to vagal cardiac control in studies using pharmacological blockade (Grossman & Kollai, 1993; Hayano et al., 1991).

Given the number of studies that continue to present low frequency (LF) HRV as an index of cardiac sympathetic tone and the LF:HF ratio as a measure of sympathovagal balance (Malliani, 2005; Malliani, Pagani, Montano, & Mela, 1998), we have also provided this information here. However, it should be noted that this metric has been challenged on conceptual and neurophysiological grounds (Berntson et al., 1997; Eckberg, 1997; Goldstein, Bentho, Park, & Sharabi, 2011).

## 2.4. Cardiorespiratory fitness

$\text{VO}_2$  peak was assessed by a maximal oxygen consumption test using a motor-driven treadmill and a modified Bruce protocol (American College of Sports Medicine, 2010), which involved increasing the speed and grade of the treadmill every 2 min until volitional exhaustion or  $\text{VO}_2$  peak criteria were met. A Polar heart rate (HR) monitor (Polar Electro, Finland) was used to measure HR throughout the test.  $\text{VO}_2$  peak ( $\text{mL kg}^{-1} \text{min}^{-1}$ ) was determined from direct expired gas exchange data from the metabolic system and was established as the maximal average oxygen consumption when at least two of the following criteria were met: (1) a plateau in  $\text{VO}_2$  values despite a progressive increase in workload, (2) maximal heart rate (HR) within 10 beats per minute (bpm) of age-predicted maximal values (220 bpm minus age in years), or (3) a respiratory exchange ratio greater than 1.10. Oxygen consumption was measured through indirect calorimetry using a Parvo Medics TrueOne 2400 Metabolic Measurement Cart (ParvoMedics, Inc., Sandy, UT) averaged over 15-s intervals. A 3–5 min cool-down was then performed at 2.5 mph and 0% grade to ensure participants returned to near baseline cardiovascular values.

## 2.5. Procedures

Participants entered the laboratory and were given a general description of the study, provided written informed consent, and completed a health history and demographics questionnaire and a physical activity readiness questionnaire (PAR-Q) to ensure safety for the cardiorespiratory fitness assessment. Participants also completed the Beck Depression Inventory II (Beck et al., 1996) to limit the possibility of including mildly depressed individuals in the study. Participants were asked to avoid exercise for 24–48 h prior and to avoid any caffeine or other stimulants (e.g., energy drinks) for 3–4 h prior to testing. Participants who met all inclusion criteria had their height and weight measured for the calculation of BMI and were then escorted to a sound attenuated testing room for cognitive and electrophysiological testing. Participants were fitted with disposable ECG snap electrodes for electrocardiographic (ECG) and impedance cardiographic (ICG) recordings and were subsequently asked to relax in a seated position for 15 min. Participants were encouraged to remain as relaxed as possible during this procedure. Following this resting period, the Flanker task was presented on a 17" IBM laptop using E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA). The center of the laptop screen was situated approximately 60 cm from the participants' head at eye level. Verbal and written instructions were given to the participant prior to the start of the cognitive assessment. Cardiovascular responses were assessed continuously during a baseline period (i.e., during the last 5 min of the seated rest condition), and throughout the cognitive assessment. Following completion of this phase of the study, participants were accompanied to an exercise testing area for maximal aerobic fitness testing. After completion of the fitness assessment, all electrodes were removed and participants were provided a 5–10 min cool down period and briefed on the purpose of the experiment.

## 2.6. Data analysis

Descriptive statistics were first performed on participant demographic and fitness data. The cardiovascular indices (PEP, HF HRV, and LF HRV) used in this study were not normally distributed in our sample and thus were natural log transformed prior to statistical analysis. Reaction time (RT) data were prescreened and omitted from the analysis if the response went undetected or was incorrect, less than 150 ms, or greater than three standard deviations from the mean for a block of

**Table 2**  
Intercorrelations among study variables.

Variable	1	2	3	4	5	6	7	8
1. VO <sub>2</sub> peak	1							
2. BMI	-.11	1						
3. Congruent accuracy	.35**	-.38**	1					
4. Incongruent accuracy	.11	-.26	.61**	1				
5. Congruent RT	-.43**	.08	-.26	.08	1			
6. Incongruent RT	-.44**	.04	-.13	.08	.89**	1		
7. In-task PEP	.08	-.20	.21	-.01	-.22	-.18	1	
8. In-task HF HRV	.29*	-.10	.22	.13	-.34*	-.35*	.03	1

Note: VO<sub>2</sub> peak, maximal oxygen uptake ( $\text{mL kg}^{-1} \text{min}^{-1}$ ); BMI, body mass index; RT, reaction time (ms); PEP, pre-ejection period; HF HRV, high frequency heart rate variability.

\*  $p < .05$ .

\*\*  $p < .01$ .

trials. Pearson product-moment correlation coefficients were used to describe the relationships among key study variables. Cognitive performance data (i.e., reaction time (RT) and response accuracy) were submitted to a 2 (Fitness: higher fit, lower fit)  $\times$  2 (Task Congruency: Congruent, Incongruent) ANOVA with repeated measures. Because raw RT data can be difficult to interpret in studies investigating between group differences (Salthouse & Hedden, 2002), in addition to comparing raw RT data we also created a composite index by converting raw values of RT and accuracy data to z scores and computing the average of the two (Salthouse & Hedden, 2002). Similar 2 (fitness)  $\times$  2 (Task Congruency) ANOVAs were conducted on median scores and z-score transformations for RT. Differences between the two fitness groups for BMI and VO<sub>2</sub> peak by fitness grouping and gender were investigated by a one-way ANOVA. Resting state and in-task PEP and HF HRV values (i.e., averaged across the flanker task performance) were analyzed by a 2 (Fitness: higher fit, lower fit)  $\times$  2 (Time: Baseline, In-task) ANOVA with repeated measures to determine differences by fitness level. We chose to use ANOVA with repeated measures since preliminary analyses revealed that PEP and HF HRV values did not differ at baseline by fitness groupings. Partial eta squared ( $\eta_p^2$ ) values are reported to demonstrate the magnitude of effect sizes, with .01–.059 representing a small effect, .06–.139 a medium effect, and >.14 a large effect (Cohen, 1973). Post hoc comparisons were conducted using univariate ANOVAs and Bonferroni corrected *t* tests. Finally, to test the third hypothesis (i.e., mediating role of HRV in the fitness and cognitive control relationship) we conducted two separate mediation analyses using RT on congruent and incongruent trial conditions as the dependent variables and HF HRV as the mediator variable. Mediation was performed using the bootstrap method of Preacher and Hayes (2004). This method compares coefficients for path a (significant prediction of IV on mediator), path b (significant prediction of mediator on the DV controlling for the IV), path c (significant prediction of IV on the DV), and path c' (a non-significant direct prediction of the IV on DV when adjusted for the mediator) pathways (Baron & Kenny, 1986; Judd & Kenny, 1981). Mediation occurs if paths a-c are significant and if c' becomes non-significant after controlling for the mediator. If c' is reduced relative to c, but still statistically significant, partial mediation is present. RT and HF HRV were selected as dependent and mediator variables based on previous literature and the established significance from the correlation analyses (see Table 2). A critical alpha level of  $p < .05$  was adopted for all significance tests.

### 3. Results

Preliminary analyses revealed no gender effects on behavioral task performance variables (RT and accuracy) or HF HRV and PEP values, and as expected males expressed higher VO<sub>2</sub> peak values ( $48.6 \pm 5.2 \text{ mL kg}^{-1} \text{ min}^{-1}$ ) relative to females ( $37.2 \pm 6.9 \text{ mL kg}^{-1} \text{ min}^{-1}$ ). No significant differences in BMI or baseline resting state values of PEP or HF HRV were observed as a function of fitness. A significant relation was observed between aerobic fitness and RT on both congruent ( $r = -.43$ ,  $p < .01$ ) and incongruent ( $r = -.44$ ,  $p < .01$ ) versions of the flanker task. Fitness was also correlated with accuracy on the congruent condition of the flanker task ( $r = .35$ ,  $p < .01$ ) but not on the incongruent condition ( $r = .11$ ,  $p > .05$ ). HF HRV was significantly associated with VO<sub>2</sub> peak ( $r = .29$ ,  $p < .05$ ) and RT on congruent ( $r = -.34$ ,  $p < .05$ ) and incongruent ( $r = -.35$ ,  $p < .05$ ) task conditions.

RT analysis revealed main effects for Congruency,  $F(1,53) = 445.7$ ,  $p < .001$ ,  $\eta_p^2 = .89$ , with shorter RT latency during the congruent compared to incongruent task condition, and Fitness,  $F(1,53) = 5.79$ ,  $p < .05$ ,  $\eta_p^2 = .10$ , with faster RT for higher fit relative to lower fit participants, (Figs. 1 and 2). No significant Fitness by Congruency interaction was observed on RT,  $F(1,53) = .03$ ,

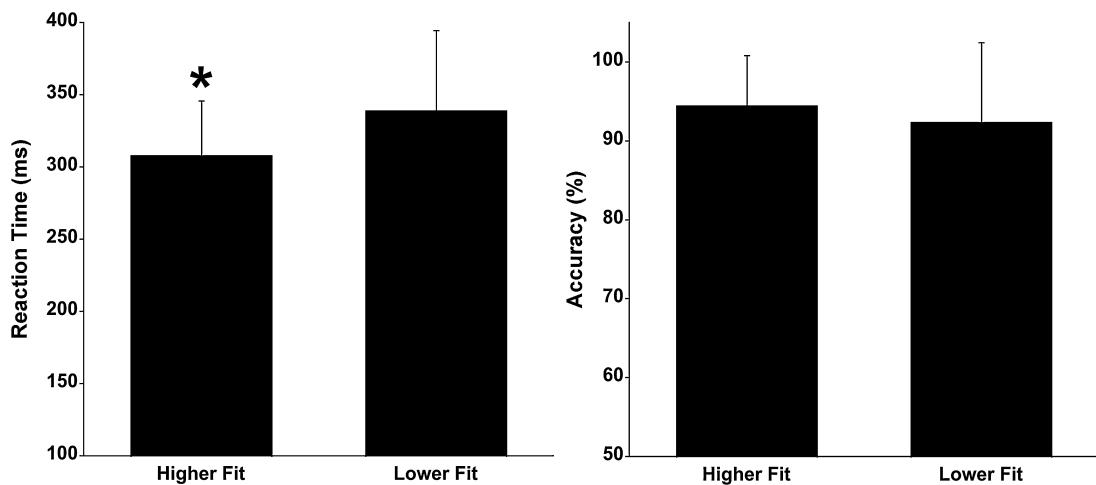
$p > .05$ . The results of separate statistical analyses on median values and z-score transformed data did not differ substantively from statistical outcomes for the raw RT data, with the exception of the Congruency main effect for the z-score transformations. When attempting to control for a speed-accuracy tradeoff through z scores, a Fitness main effect was found,  $F(1,53) = 5.68$ ,  $p < .05$ ,  $\eta_p^2 = .10$ , but the Congruency main effect was no longer significant,  $F(1,53) = 0.01$ ,  $p > .05$ . Response accuracy analysis revealed a main effect for Congruency,  $F(1,53) = 34.6$ ,  $p < .001$ ,  $\eta_p^2 = .40$ , with greater response accuracy during the congruent compared to incongruent task condition. No significant Fitness effect or Fitness  $\times$  Congruency interaction was observed on response accuracy.

Table 3 illustrates the values of autonomic parameters for higher and lower fit individuals at rest and during cognitive task performance. No significant Time, Fitness, or Time  $\times$  Fitness interaction effects were found for the PEP analyses. HF HRV analyses revealed main effects for Time,  $F(1,53) = 5.01$ ,  $p < .05$ ,  $\eta_p^2 = .09$ , with greater HF HRV observed at rest relative to in-task cognitive performance, and Fitness,  $F(1,53) = 4.07$ ,  $p < .05$ ,  $\eta_p^2 = .08$ , with fit individuals demonstrating greater HF HRV than their lesser fit counterparts (Fig. 3). No significant Time  $\times$  Fitness interaction was found on HF HRV.

Multiple regression analyses were conducted to assess each pathway (i.e., a, b, c, and c') of the proposed mediation model. In line with our ANOVA results, aerobic fitness was positively associated with RT for congruent ( $B = -2.88$ ,  $t(53) = 3.59$ ,  $p < .001$ ) and incongruent ( $B = -2.94$ ,  $t(53) = 3.57$ ,  $p < .001$ ) task conditions (i.e., c path). Aerobic fitness was also positively associated with HF HRV,  $B = .01$ ,  $t(53) = 2.1$ ,  $p < .05$  (a path). However, the b-path was not found to be significant. That is, HF HRV was not associated with RT for congruent ( $B = -.66$ ,  $t(53) = 1.7$ ,  $p = .10$ ) or incongruent ( $B = -71.27$ ,  $t(53) = 1.76$ ,  $p = .09$ ) trials when controlling for aerobic fitness. Because a, b, and c pathways must all be met for mediation or partial mediation to occur, the relation between fitness and RT performance on the cognitive control tasks was not mediated by HF HRV.

### 4. Discussion

The primary purpose of this study was to examine the relationship between cognitive performance and HRV, and whether this relationship is associated with cardiorespiratory fitness, while participants completed a widely used cognitive task of inhibitory cognitive control (Eriksen & Eriksen, 1974). Examining the relationship between aerobic fitness and cognitive performance in young healthy men and women serves as a replication of previous work that has largely been focused on older adults and preadolescent children (Colcombe & Kramer, 2003; Etnier, Nowell, Landers, & Sibley, 2006; Hillman et al., 2008). Analyses revealed that participants responded more slowly and less accurately during the more challenging incongruent task condition. Moreover, the relationship



**Fig. 2.** Mean ( $\pm$ SE) behavioral task performance for total reaction time (ms) and response accuracy (%) for the flanker task in higher and lower fit individuals.

**Table 3**

Autonomic measures ( $M \pm SD$ ) at baseline and during the flanker task.

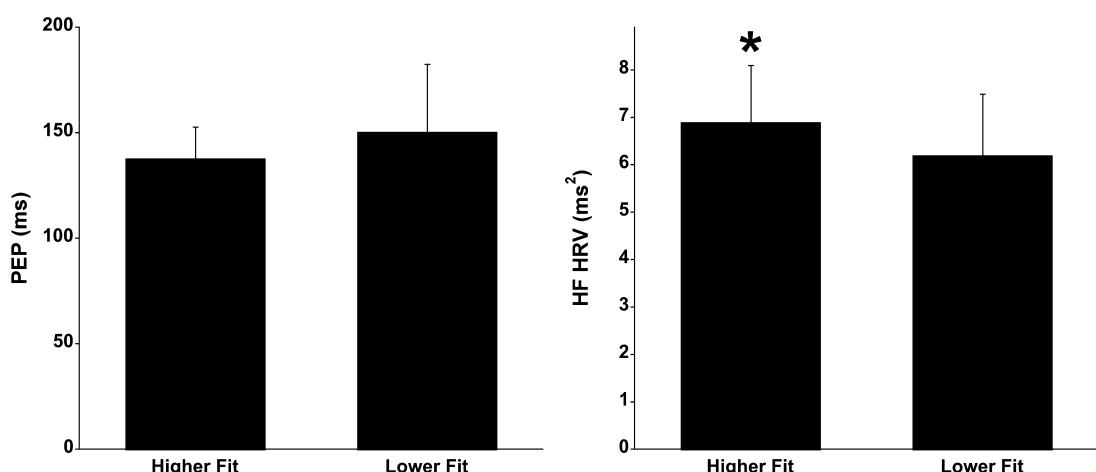
Measure	HR (bpm)	LF ( $ms^2$ )	HF ( $ms^2$ )	LF:HF	PEP (ms)
<i>Baseline</i>					
Lower fit	$77.26 \pm 10.81$	$6.83 \pm 1.18$	$6.69 \pm 1.25$	$1.91 \pm 2.09$	$148.82 \pm 26.07$
Higher fit	$68.74 \pm 9.90$	$7.36 \pm 0.69$	$7.11 \pm 0.53$	$1.39 \pm 0.58$	$145.68 \pm 31.28$
Overall	$72.99 \pm 11.12$	$7.09 \pm 0.99$	$6.90 \pm 0.97$	$1.65 \pm 1.54$	$147.25 \pm 28.54$
<i>In-task</i>					
Lower fit	$79.15 \pm 10.59$	$5.67 \pm 1.36$	$6.22 \pm 1.28$	$0.70 \pm 0.37$	$155.48 \pm 41.79$
Higher fit	$69.31 \pm 11.51$	$6.41 \pm 1.39$	$6.88 \pm 1.23$	$0.90 \pm 1.02$	$142.11 \pm 25.10$
Overall	$74.23 \pm 12.02$	$6.04 \pm 1.41$	$6.55 \pm 1.29$	$0.80 \pm 0.77$	$148.93 \pm 34.94$

Note: HR, heart rate; LF, low frequency heart rate variability; HF, high frequency heart rate variability; LF:HF, the ratio of low frequency power to high frequency power; PEP, pre-ejection period. Low frequency and high frequency spectral power estimates are presented as log-transformed units.

between aerobic fitness and RT was significant, such that higher fit individuals responded more rapidly during the cognitive task, without a concomitant reduction in accuracy (i.e., no speed-accuracy tradeoff). In fact, the correlation analysis revealed a relationship between fitness and response accuracy, but this correlation was only significant for the congruent flanker task condition. In turn, greater HF HRV was observed across conditions and higher fit individuals expressed greater *in-task* HF HRV (i.e., during cognitive task performance). However, when tested using mediation analyses and RT performance (not accuracy), HRV was not found to mediate the fitness and cognitive control relationship. These findings add to the extant literature and provide further support for the position that

aerobic fitness is beneficial for cognitive and brain health. Although HRV may index a group of neurophysiological systems involved in self-regulation and adaptability, and which are associated with physical fitness, future research investigating this possibility using similar recommended statistical techniques are warranted.

A growing body of evidence supports the influence of exercise and fitness on the function and vitality of the central nervous system and in promoting resistance against neurological disease (Gomez-Pinilla & Hillman, 2013). Previous narrative and meta-analytic reviews have outlined the beneficial effects of exercise across a range of cognitive abilities and information processing, including intelligence, perceptual, cognitive, and motor skills,



**Fig. 3.** Mean ( $\pm$ SE) parasympathetic (HF HRV,  $ms^2$ ) and sympathetic (PEP, ms) cardiac control during flanker task performance in higher and lower fit individuals.

and academic achievement (Etnier et al., 1997; Sibley & Etnier, 2003; Tomporowski, Davis, Miller, & Naglieri, 2008). In a meta-analytic review of randomized fitness intervention trials conducted between 1966 and 2001 among men and women aged 55–80 years, Colcombe and Kramer (2003) reported a general and selective benefit of fitness training on cognition, with a more robust effect for tasks requiring greater amounts of cognitive control relative to tasks requiring lesser amounts of cognitive control. However, it should be noted that several more recent reviews (Angevaren, Aufdemkampe, Verhaar, Aleman, & Vanhees, 2008; Etnier et al., 2006) have reported less impressive relations and suggest that factors beyond aerobic fitness per se may be responsible for the cognitive-enhancing benefits of exercise. This has led investigators to study the neurobiological mechanisms involved in order to advance our understanding of the benefits of exercise and physical fitness on cognitive function. Although a number of promising mechanisms ranging from the molecular to systems levels have been proposed and studied, the precise mechanisms underlying the beneficial effects of exercise and aerobic fitness remain unclear and controversial (Etnier et al., 2006; Gomez-Pinilla & Hillman, 2013). However, one promising approach for assessing the structural and functional organization of brain regions and neural circuits involved in regulating adaptive cognitive and cardiovascular control, may be through HRV (Thayer et al., 2009).

Individual differences in cardiac autonomic balance have long been linked to health and disease and there is growing evidence for the role of the autonomic nervous system (ANS) in cognitive functioning. Thayer and colleagues (2009) have conducted a series of studies examining the relationship of HRV to cognition and assert that vagally mediated HRV may serve to index the functional capacity of a set of brain structures or neural circuits that support adaptive and efficient cognitive performance, particularly among tasks requiring greater amounts of cognitive control. A large body of evidence also supports the influence of aerobic fitness on HRV and specifically on parasympathetic modulation of cardiac function in young and older adults (Albinet et al., 2010; Boutcher, Nugent, McLaren, & Weltman, 1998; Buchheit et al., 2005) and it has recently been proposed that a direct link between fitness, HRV, and cognition may exist (Albinet et al., 2010; Hansen et al., 2004). In fact, several fitness intervention studies have demonstrated an increase in vagal cardiac control concomitant with improvements on tasks of cognitive control following either eight (Hansen et al., 2004) or 12 weeks (Albinet et al., 2010) of aerobic exercise training. Moreover, after a short-term period of detraining, previously trained individuals who were deconditioned demonstrated lower HRV and performed more poorly on tasks of cognitive control relative to the trained group (Hansen et al., 2004). This training-induced benefit was only found for tasks requiring greater amounts of cognitive control, and was not significant for tasks requiring minimal cognitive control. Our current cross-sectional findings demonstrate relationships between aerobic fitness, HRV, and cognitive control. First, the parasympathetic components of cardiac control (i.e., HF HRV) were related to fitness and behavioral task performance. We also examined the role of PEP in the fitness–cognition relationship. Previous research has shown that PEP, derived from impedance cardiography, is a valid measure of sympathetic cardiac control (Berntson et al., 2008). However, no fitness or cognitive performance effects were found for this index of cardiac control. Importantly, when we employed recommended statistical techniques to assess the possible mediating role of HF HRV in the fitness and cognitive performance relationship, no significant mediation effect was found.

One of the more popular hypotheses regarding the exercise and cognition relationship has been that aerobic exercise improves cardiovascular fitness ( $\text{VO}_2 \text{ peak}$ ) which is thought to be associated with underlying neurobiological changes including cerebral blood

flow (Brown et al., 2010; Endres et al., 2003), cerebral structure and plasticity (Colcombe et al., 2003), and neurotrophic factors such as brain-derived neurotrophic factor (Cotman & Berchtold, 2002; Gomez-Pinilla & Hillman, 2013), which themselves have been associated with cognitive performance. However, the empirical literature has not shown consistent support for the cardiovascular fitness hypothesis (Etnier et al., 2006). Given the current findings along with previous research (Albinet et al., 2010; Hansen et al., 2004; Thayer et al., 2009), it is possible that HRV and cardiac vagal control could provide better indices of the improvements in cognitive control and prefrontal cortical activity than merely relying on improvements in aerobic capacity per se. Future studies examining the effects of different modes of exercise and optimal dose-response relationships between exercise and HRV, and whether the aerobic exercise-related changes in HRV also accompany improvements in other aspects of cognitive control are thus warranted.

Cognitive flexibility and the ability to inhibit prepotent but inappropriate responses are critical for health and optimal functioning. Many tasks important for survival in today's world involve these aspects of healthy cognition, including working memory, sustained attention, behavioral inhibition, and general mental flexibility. Deficits in cognition and impairments in inhibition have been associated with a wide variety of psychopathological conditions such as anxiety, depression, attention-deficit hyperactivity disorder, and schizophrenia. These deficits have also been implicated in healthy aging. In line with the neurovisceral integration hypothesis (Thayer et al., 2009), all of these conditions have been shown to be associated with reductions in HRV and cardiac vagal control. Conversely, exercise and fitness have been shown to robustly enhance cognitive and mental health across the lifespan, and evidence supporting its beneficial effects in each of these conditions exists. For instance, Hughes et al. (2010) found that the relationship between depression and HRV was attenuated after accounting for physical activity and aerobic fitness and concluded that fitness may help to explain altered cardiac autonomic balance that characterizes patients with cardiovascular disease or psychopathological conditions. Clearly, more research needs to be conducted on individuals with altered or dysregulated autonomic functioning.

Interestingly, in the current study we did not find fitness-related differences on baseline levels of HF HRV or PEP. Several previous investigations have shown that trained individuals have greater resting levels of HRV and cardiac vagal control than untrained individuals (De Meersman, 1993; Gutin et al., 2005; Rossy & Thayer, 1998) although not all studies are in agreement (Dishman et al., 2000). Many of the previous investigations of aerobic exercise and fitness-related differences in HRV have relied on the low frequency component of HRV as a measure of sympathetic cardiac control and as a ratio with HF HRV to derive a measure of relative autonomic balance. HF HRV, in the respiratory frequency band, is generally believed to provide a relatively pure index of parasympathetic cardiac control, whereas variability in the LF power range reflects a combination of both sympathetic and parasympathetic influences (Berntson, Cacioppo, & Quigley, 1993; Berntson et al., 2008; Malik, 1996). PEP, on the other hand, has been recently used as a measure of sympathetic influence and has been shown to be highly predictive of cardiac sympathetic control when indexed with the “gold standard” of pharmacological blockades (Cacioppo et al., 1994). Despite these differences in cardiac autonomic variables, it is possible that the lack of fitness differences in resting levels of PEP and HF HRV were due to our relatively homogeneous young and healthy sample. Moreover, although clear fitness differences based on metabolic assessments (i.e.,  $\text{VO}_2 \text{ peak}$ ) were found between the two groups, it is often difficult for researchers to recruit young healthy adult participants who score in the very low fitness range (Kamijo et al., 2010). This lack of variability among a healthy adult

sample may have also resulted in the lack of support found for our last hypothesis related to mediation. Although not all pathways in the mediation model were met, it is possible that differences in HRV may be more prevalent among older individuals or those who suffer from a condition that might dually impact both the cardiovascular and cognitive systems. Further investigation of these relationships in individuals at the extreme ends of the aerobic fitness spectrum, including those suffering from obesity, diabetes, or other pathological conditions that limit physical activity and impair aerobic capacity is warranted. It is also important for future studies to employ similar recommended statistical approaches to examine potential mediators of the relationship between fitness and cognitive performance (Etnier, 2008).

In summary, the results are consistent with the literature regarding the influence of aerobic fitness on cognition and HRV. Recent research examining exercise and fitness effects on cognition have largely focused on cognitive control (Gomez-Pinilla & Hillman, 2013), and our findings lend further support for the benefit of fitness on inhibitory cognitive control. These findings also suggest that HRV, particularly vagally mediated HRV, is associated with inhibitory cognitive control and may assist in better understanding the mechanisms underlying the benefits of aerobic exercise on brain structure and function. Given that our mediation analysis was not significant, it is possible that other important mediators are more influential in the fitness–cognition relationship. Future research combining neuroimaging approaches with neurophysiological assessments of HRV with other populations will be helpful to clarify that exact nature of the relationship between fitness, HRV, and cognitive function.

## Conflict of interest

The authors declare that they have no conflict of interest.

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