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ORIGINAL ARTICLE

The effects of cardiorespiratory fitness on executive function and prefrontal oxygenation in older adults

Said Mekari · Olivier Dupuy · Ricardo Martins · Kailey Evans · Derek S. Kimmerly · Sarah Fraser · Heather F. Neyedli

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Abstract Reviews on cardiovascular fitness and cognition in older adults suggest that a higher level of cardiorespiratory fitness may protect the brain against the effects of aging. Although studies reveal positive effects of cardiorespiratory fitness on executive function, more research is needed to clarify the underlying mechanisms of these effects in older adults. The aim of the current study was to assess the association between cardiorespiratory fitness level, cerebral oxygenation, and cognitive performance in older adults (OAs). Seventy-four OAs (68 ± 6.3 years) gave their written, informed consent to participate in the study. Complete data was collected from 66 participants. All participants underwent a cycle ergometer maximal continuous graded exercise test in order to assess their peak power output (PPO) and a neuropsychological paper and pencil tests (Trail Making Test A and B) while changes in left prefrontal cortex oxygenation were measured with functional near-infrared spectroscopy (fNIRS). The results reveal increased cardiorespiratory fitness was associated with decreased response time (i.e., better performance) on the Trail Making Test (B) (standardized $\beta = -0.42$, $p < 0.05$). Cerebral oxygenation in higher fit older adults mediated the relationship with improved executive functioning (standardized $\beta = -0.08$, $p < 0.05$). Specifically, in older adults with higher cardiorespiratory fitness (based on a median split), cerebral oxygenation was related to executive functioning but no such relationship existed in lower fit adults.

Keywords Exercise physiology · Cognition · Fitness · Aging

Introduction

Studies have shown that the aging process is often accompanied by a decrease in numerous cognitive functions (Salthouse 2010; Wang et al. 2013). With age, the neural activity in the brain also becomes less utilized in some regions such as the prefrontal cortex, which is where most of the executive functions occur (Bishop et al. 2010). Cognitive impairment includes deficits in memory, attention, executive function, and psychomotor speed (Murman 2015) and has been related to loss of gray matter in various brain regions (Longstreth Jr. et al. 2005), cerebral atrophy (van der Veen et al. 2013), and low cerebral blood flow (Xing et al. 2017). Whether vascular or blood flow abnormalities mediate some or

S. Mekari (✉) · R. Martins · K. Evans
School of Kinesiology, Acadia University, 550 Main Street,
Wolfville, Nova Scotia B4P 2R6, Canada
e-mail: said.mekary@acadiau.ca

O. Dupuy
Laboratory MOVE (EA 6314), Faculty of Sport Sciences,
University of Poitiers, Poitiers, France

D. S. Kimmerly · H. F. Neyedli
Division of Kinesiology, School of Health and Human
Performance, Faculty of Health Halifax, Dalhousie University,
Halifax, Nova Scotia, Canada

S. Fraser
Interdisciplinary School of Health Sciences, University of Ottawa,
Ottawa, Ontario, Canada

all of these potential mechanisms remains a question of debate. Often, older adults exhibit lower (Dupuy et al. 2015) and different (Cabeza 2002) patterns of cerebral oxygenation during cognitive performance compared to younger adults. While there is evidence for decline in executive function with age, it is also well documented that these changes are heterogeneous and can be modulated by lifestyle factors (Kramer et al. 1999; McAuley et al. 2004; Kramer et al. 2004).

The American College of Sports Medicine (ACSM) recognizes that "exercise is medicine," suggesting that physical activity can be a potential treatment for many of the health problems that the aging population is currently facing (Bossers et al. 2015). Several studies have supported that a delay in cognitive decline is associated with individuals who are physically active (Angevaren et al. 2008). Cross-sectional and interventional studies that have compared age groups and/or provided aerobic training interventions have supported the importance of cardiorespiratory fitness to maintain or improve executive function (Boucard et al. 2012, Predovan et al. 2012, Dupuy et al. 2015, Freudenberger et al. 2016). In a recent paper, Freudenberger et al. (2016) reported that in 877 older adults, a higher physical fitness level is associated with better memory, executive function, and motor skills (Freudenberger et al. 2016). In their cross-sectional study, Dupuy et al. (2015) demonstrated that physical fitness was selectively associated with better performance in the executive condition of a computerized Stroop task.

The effect of fitness on both global cognition as well as on executive function suggests that better fitness may slow down the process of brain aging in general. Although these studies support the positive effects of physical activity on executive function, more research is needed to clarify the underlying mechanisms of these changes in older adults

Hypotheses proposed to account for the relationship between aerobic fitness and cognition include corresponding increases in vascularization of brain tissue (Dustman et al. 1990; Rogers et al. 1990). Also, evidence suggests that increasing physical activity can enhance synaptogenesis (i.e., formation of new neuronal synapses), and neurogenesis (i.e., generation of new neurons), via increased production of brain-derived neurotrophic factor, in addition to vascular plasticity (Stein et al. 2018; Tsai et al. 2015; Churchill et al. 2002). In older adults, recent findings using a voxel-based morphometric approach, which involves segmentation of high-resolution anatomical brain scans, found that better cardiorespiratory fitness (i.e., VO_{2max}) was associated with reduced grey and white matter loss in the frontal, prefrontal, and temporal regions (Colcombe, Kramer et al. 2004). A recent review summarizing the association between physical activity, fitness level, and dementia concludes that even modest physical activity can preserve its plasticity and can reduce the risk of dementia (Erickson et al. 2012). Studies also report a higher integrity of white matter in physically active individuals (Gons et al. 2013). The effect of fitness level on cognition lets us hypothesize that both cortical and subcortical structures are protected by exercise.

Human brain imaging studies have provided complementary evidence that highlights the benefit of aerobic fitness and possible mechanisms on the aging brain and cognitive functions. Of the research studies that have reported better cognitive functioning is associated with higher fitness levels; those that examined brain activity during cognitive performance have typically found that this is accompanied by an increased activation in the left side of the brain. For example, Colcombe et al. (2004) found a higher activation in different prefrontal regions during a cognitive task for higher fit older adults as compared to lower fit older adults (Colcombe et al. 2004). In addition to performance benefits on the Stroop Task, Dupuy et al. (2015) also found that higher fit older women had greater cerebral oxygenation than lower fit women, during an executive task (Dupuy et al. 2015).

One possible mechanism that could explain improvement of cognition in the prefrontal cortex with regular exercise could be cerebral oxygenation. Evidence suggests that cerebral oxygenation plays an important role in the regulation of cognitive processes in the prefrontal cortex. A near-infrared spectroscopy (NIRS) and exercise study by Mekari et al. (2015) demonstrates that the availability of oxygen in the brain seems to be positively linked with better executive task performance (Mekari et al. 2015). Another NIRS study by Dupuy et al. (2015) reported that older females with a higher cardiorespiratory fitness had higher cardiorespiratory fitness and also had greater cerebral oxygenation in the prefrontal cortex during the executive portions of the Stroop task. The authors, however, did not examine whether the change in oxygenation was linked to changes in Stroop performance making it unclear whether the change in oxygenation levels with fitness was actually linked to changes in performance.

All in all, existing evidence suggests that a there is a positive relationship between high level of cardiorespiratory fitness and executive function that may be related to cerebral oxygenation. However, no study has examined these three factors together in a heterogeneous sample of older adults. Therefore, the aim of the current study was to assess the association between cardiorespiratory fitness level, cerebral oxygenation, and cognitive performance in older adults. Based on the existing literature, we hypothesized that the cardiorespiratory level would selectively enhance executive functions. Secondly, we predicted that improved executive functioning in higher fit older adults would be mediated by correspondingly greater cerebral oxygenation changes.

Methods

Participants

Seventy-four (50 females) participants gave their written informed consent to participate in the study. Complete data was collected from 66 participants (44 females). Their participant data can be found in Table 1. All participants were right-handed, healthy, and had normal-to-corrected vision. None of the participants were smokers or had a history of neurological or psychiatric disorder, color blindness, surgery with general anesthesia in the past 6 months, involuntary tremors, epilepsy, or drug/alcohol problems. Three participants were on Synthroid for hypothyroidism. Four participants were prescribed medications to treat high blood pressure. Specifically, participants were taking Teveten® (angiotensin-receptor blocker), Adalat® (calcium channel blocker), Diuril® (diuretic), and Coversyl Plus® (angiotensin-converting enzyme inhibitor + diuretic). One person was asthmatic. During the study, participants were requested to continue taking all prescribed medications. Finally, a minimal score of 24 on the Mini Mental State Examination (MMSE) was required to be included in the study. All criteria were assessed during a telephone screening and the meeting at the research center. The protocol was reviewed and approved by the Institutional Research Ethics Board in the Health Sciences of Acadia University and was conducted in accordance with recognized ethical standards and national/international laws.

Experimental design

All the participants in this study completed a cardiorespiratory and a cognitive assessment during a 60-min session. Upon arrival to the lab, participants signed the consent form and completed questionnaires on their health and mental status followed by a clinical neuropsychological test (described below). Participants concluded the session with a continuous graded maximal cycling exercise test (see details below). Cerebral oxygenation was measured with functional near-infrared spectroscopy (fNIRS) (PortaLite, Artinis Medical Systems, Netherlands) during the cognitive assessments (see Fig. 1). In order to limit accumulated fatigue during the day, all tests were completed before noon each day. Participants were asked to refrain from vigorous exercise 24 h prior to their testing and were also asked to consume a normal breakfast on the morning of the test. No effort was made to control the nutrition of the participants.

Maximal continuous graded exercise test

This test was performed on cycle ergometer (Lode B.V., Groningen, Netherlands). Initial workload was set at 1 W/kg body mass. The workload was increased by 15 W every minute until voluntary exhaustion. Strong verbal encouragement was given throughout the test. The power of the last completed stage was considered as the peak power output (PPO, measured in W). PPO was used as a marker of cardiorespiratory fitness in this article. Oxygen uptake ($\dot{V}O_{2max}$, in ml/min/kg) was determined continuously on a 30-s basis using an automated cardiopulmonary exercise system (Parvo Medics TrueOne 2400, UT, USA). Gas analyzers were calibrated before each test using a gas mixture of known concentrations (15% O_2 and 5% CO_2). The turbine was calibrated before each test using a 3-l syringe at several flow rates. The primary criterion for the attainment of VO_{2max} was a plateau in VO_2 (change < 2.1 ml/min/kg) despite an increase in workload. In the absence of a plateau, attainment of VO_2peak was based upon a respiratory exchange ratio of ≥ 1.10 and the inability to maintain a pedaling cadence of 60 revolutions/min. Furthermore, VO_{2max} was considered to be the highest VO_2 value attained during the test if the following criteria were observed: (1) a respiratory exchange ratio ≥ 1.10 and (2) a peak heart rate $\geq 95\%$ age-predicted maximum (i.e., 220–age). Approximately 85% of the participants attained both criteria.

Electrocardiographhic activity was monitored continuously using a 12-lead ECG (Philips, Netherlands). All tests were administered by a Certified Exercise Physiologist.

Table 1 Descriptive statistics

Variable	Mean	Standard deviation	High Fit mean	Standard deviation	Low fit mean	Standard deviation
Age	68.1 years	6.35	66.50	7.41	69.6 years	4.68
Height	1.66 m	0.09	1.71 m*	0.09	1.61 m*	0.07
Body mass	74.3 kg	13.50	77.4 kg	13.00	71.3 kg	13.50
BMI	27.00	4.66	26.30	3.60	27.50	5.52
PPO	137 W	45.50	174 W*	33.30	100 W*	17.20
VO_2 peak	23.00	7.05	27.50	5.92	18.40	4.77
Trail A RT	24.8 s	7.13	23.6 s	6.28	25.90	7.83
Trail B RT	55.6 s	22.50	46.7 s*	16.40	64.50*	24.30
Trail A O2Hb	2.67	3.15	3.58	3.37	1.76	2.65
Trail B O2Hb	3.73	3.38	4.58	3.75	2.87	2.77

MMSE Mini Mental State Examination, *BMI* body mass index, *PPO* peak power output, *RT* reaction time, *O2Hb* oxyhemoglobin

*Significant difference between groups at $P < 0.001$

Cognitive assessment

Neurophysiological test

All participants completed the Trail Making Test Part A prior to completing the Trail Making Test Part B. The Trail Making Test Part A (Trail A) was used to measure an individuals' processing speed. Participants were given the following Trail Making Test instructions: "Please take the pencil and draw a line from one number to the next, in order. Start at 1 [point to the number], then go to 2 [point], then go to 3 [point], and so on. Please try not to lift the pen as you move from one number to the next. Work as quickly and accurately as you can". Participants were encouraged to correct their errors and this was included in the total time to complete. The speed at which all the numbers were connected was measured in seconds (s). Part B (Trail B) was used to measure cognitive flexibility or switching ability. In this portion of the test, participants were given the same instructions

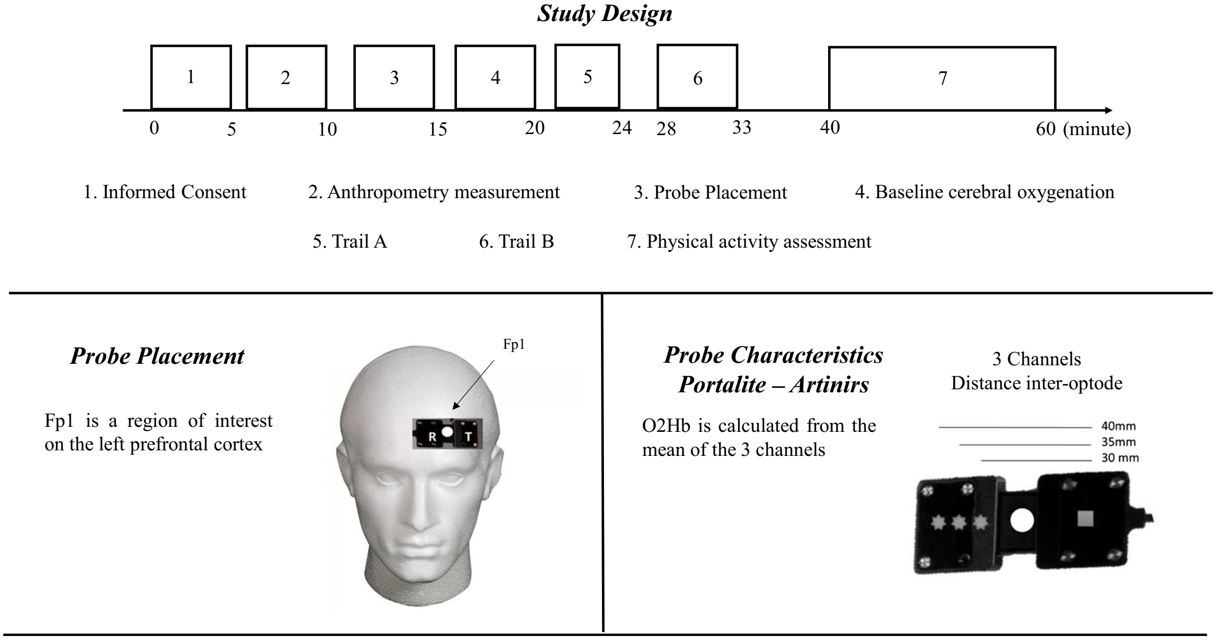

Fig. 1 Graphical representation of study design, probe placement, and probe characteristics

as Part A but had to alternate between numbers in ascending order and letters in alphabetical order (1-A-2-B-3-C, etc.). The time to complete Part B was also measured in seconds. Prior to the standard administration of this test, participants were given a short practice of each test before taking the test.

Cerebral oxygenation

A multi-channel device was used to measure relative changes in concentrations of oxygenated hemoglobin (O2Hb) in the brain, using continuous wave NIRS (PortaLite, Artinis Medical Systems, Netherlands). The small, non-invasive probe was placed on the participant's left forehead on the Fp1 prefrontal cortex region, using the 10/20 positioning system. A 2-wavelength continuous measurement system was used in accordance with the absorption characteristics of light, with standard wavelengths of 760 and 850 nm. Optode distances between the receiver and transmitters were 30, 35, and 40 mm. The absorption of which was measured, and concentration changes in O2Hb was calculated using the difference in absorbance based on the Beer-Lambert law. Because continuous-wave technology does not measure optical path lengths (Ekkekakis 2009), only changes in concentration of O2Hb relative to baseline (last minute of a 5-min resting period prior to the Trail Making Test) could be inferred assuming both a path length factor and partial volume.

The NIRS device was tightly secured with a black bandage wrapped around the participant's forehead to reduce the amount of interference from device movement or background light.

Continuous NIRS measurements were recorded during Trail test (Parts A and B), as well as throughout the cardiopulmonary assessment, with the average relative concentration of O2Hb recorded for each participant. "Events" were manually inserted into the test's time frame to indicate a change in condition (i.e., "event 1—begin non-executive practice 1"), to ensure that separation between test conditions was specified for proper data analysis. Cerebral oxygenation was recorded on the left side of the prefrontal cortex in accordance with existing literature showing sensitivity of the Trail Making Test to frontal regions in the left hemisphere (Zakzanis et al. 2005).

NIRS data was acquired at 10 Hz and filtered with a Savitzky-Golay smoothing algorithm before analysis. All data analyses were completed in the Oxysoft analysis software. Data was averaged over every task component (rest, Trail A, Trail B), and normalized to express the magnitudes of changes from a baseline period. The baseline period took place immediately before the cognitive assessment; participants sat quietly and were asked to close their eyes and eliminate extraneous thoughts to establish a 60-s baseline of NIRS data (last 60 s of a 5-min rest period).

Statistical analysis

Overall, a total of 66 participants were included in the final analysis for this study. Eight participants were initially excluded from the analysis due to incomplete data (5 participants could not complete the Maximal Continuous Graded Exercise Test and 3 participants had incomplete NIRS data due to the quality of the recording). All statistical analyses were done on SPSS v.25 for Mac.

Initial analysis consisted of constructing two separate linear regression models to predict Trail A time and Trail B time with age, PPO and task related O2Hb (i.e., Task A O2Hb was entered for the Trail A model) forced entered as predictors. Age was included in the model to account for established changes in cognitive performance with increased age (Colcombe et al. 2004). Standardized coefficients were used as measures of effect size. If there was a significant relationship between PPO and Trail time and there was either a significant relationship between O2Hb and/or Age and Trail time in the initial linear regression model, a mediation model was constructed with PPO entered as the predictor. Trail time was added as the outcome variable and either O2Hb or Age included as the mediator. If both O2Hb and Age were significantly related to Trail time, both variables were entered in parallel as mediators to test for the separate indirect (i.e., mediation) effects of age and O2HB on Trail time (Fig. 2). Bootstrap 95% confidence intervals (10,000 samples) were used to determine if the coefficient of the indirect effect(s) (i.e., the mediation effect) were significantly different from zero. The index of mediation—the fully standardized indirect effect—was used to indicate the mediation effect size.

Occasionally, inconsistent mediation can occur where the indirect and direct effects have opposite signs (i.e., one is positive and the other negative; see MacKinnon et al. 2000, for discussion of inconsistent mediation (MacKinnon et al. 2000)) and the inclusion of the mediator actually strengthens the direct effect.

Inconsistent mediation can indicate a complex relationship between the predictor, mediator, and dependent variable with opposing effects of the predictor and mediator on the outcome variable. In the case of inconsistent mediation, to investigate this complex series of relationships, post hoc, participants will be divided into two groups based on a median split of fitness levels and separate correlations will be run between the mediator and outcome variable for each group.

Results

Trail A time was significantly predicted by the regression model, $F(3,65) = 3.97$, $P = 0.012$, $R^2 = 0.16$, adj. $R^2 = 0.12$. However, only age had a significant relationship with Trail A time, $\beta = 0.44$, 95% CI [0.17, 0.71], $t(62) = 3.23$, $P = 0.002$, with longer Trail A completion time associated with increasing age. No other predictors were significant (Table 2).

Trail B time was also significantly predicted by the regression model, $F(3,65) = 10.5$, $P < 0.001$, $R^2 = 0.34$, adj. $R^2 = 0.31$, with more variance being explained in the Trail B model than the Trail A model (i.e., the Trail B model had a larger R^2 and adj. R^2 than the Trail A model). Further, all predictors were significantly associated with Trail B completion time (Table 3 for predictor statistics). Similar to Trail A, as age increased, Trail B completion time was longer. PPO had a negative relationship with completion time indicating that an increase in PPO lead to improved performance on Trail B. Finally, there was a positive relationship between Trail B O2Hb and Trail B completion time with poorer performance on Trail B associated with higher Trail B O2Hb, indicating that participants who found the task more challenging may have recruited additional resources to complete the task.

There was a significant indirect effect of PPO on Trail B time via Age, $\beta = -0.04$, 95% CI [-0.08, -0.004], standardized $\beta = -0.08$, 95% CI [-0.17, -0.01], indicating that age mediates the relationship between cardiovascular fitness and executive functioning.

There was a significant indirect effect of PPO on Trail B time through Trail B O2Hb, $\beta = 0.06$, 95% CI [0.01, 0.13], standardized $\beta = 0.12$, 95% CI [0.02, 0.26] indicating that cerebral oxygenation levels mediated the relationship between cardiovascular fitness and executive functioning. Critically, the indirect effect of Trail B O2Hb is positive while the direct and total effect of PPO on Trail B time is negative indicating inconsistency. To elaborate, in the current sample, it appears that higher fitness (predictor variable) is associated with an augmented ability to increase cerebral oxygen levels (mediator variable) (positive relationship *a*, Fig. 2) but increased cerebral oxygen levels is associated with worse Trail B performance through longer completion times (positive relationship *b*, Fig. 2). However, higher fitness (predictor variable) is also associated with decreased Trail B times (outcome variable) (negative relationship *c*).

Participants were divided based on a median split (128 W) into higher fit individuals (174 W ± 33) and lower fit individuals (mean PPO = 100 W ± 17). There was a significant relationship between O2Hb and response time in the higher fit group, $r = 0.48$, $P = 0.004$, but not in the lower fit group $r = 0.11$, $P = 0.51$ (Fig. 3). This finding indicates that only higher fit individuals can elevate their cerebral oxygenation in response to increased task demands but lower fit individuals cannot. Note that the higher fit individuals had significantly lower Trail B times than the lower fit group, $t(64) = 3.5$, $P = 0.001$ (also characterized by the significant total effect, relationship *c*, Fig. 1). This increase in O_2 with increased demands occurred only in higher fit individuals, who also performed better overall at the task.

Discussion

The aim of this study was to assess the association between cardiorespiratory fitness level, cerebral oxygenation, and cognitive performances in older adults. Based on the existing literature, we hypothesized that the cardiorespiratory level would selectively enhance executive functions in the Trail B task. Secondly, we hypothesized that the relationship between cardiorespiratory fitness level and performance on the Trail task would be mediated by cerebral oxygenation level availability and age. The findings support our first hypothesis, such that older adults with a higher cardiorespiratory fitness level performed better on the executive condition of the Trail Making Test (Trail B) than older adults with a lower cardiorespiratory fitness level. This effect was specific to the executive condition and did not emerge in the non-executive condition of the Trail Making Test (Trail A). For our second hypothesis, we found that cerebral oxygenation did mediate the relationship

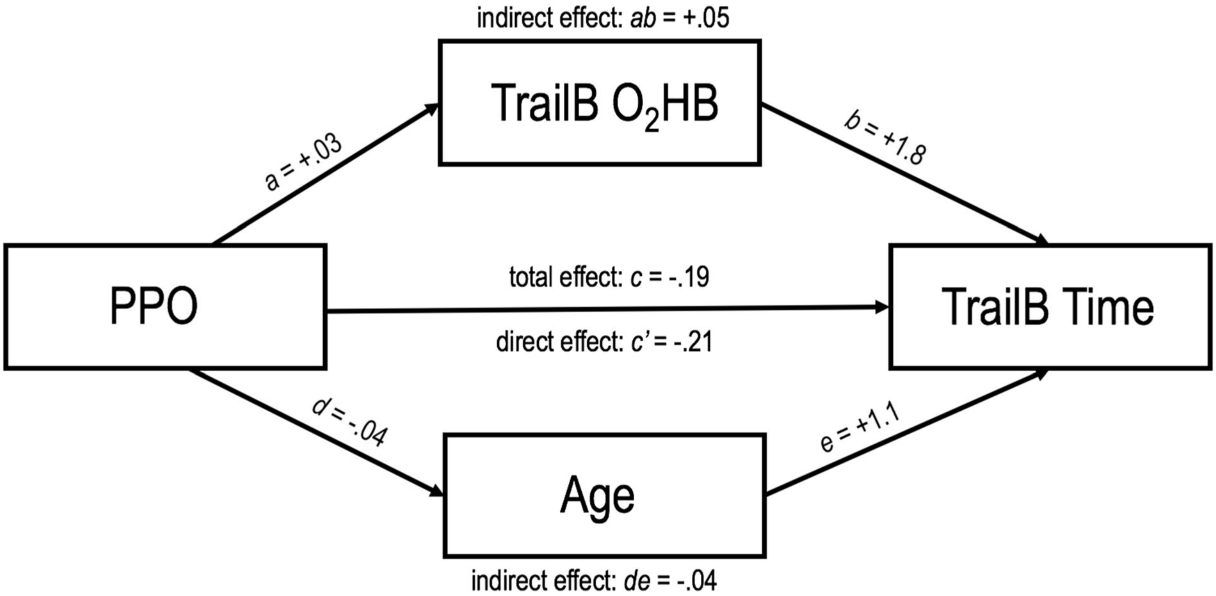

Fig. 2 Parallel mediation model relating PPO to Trial B completion time, mediated by Trial B O2Hb and age. Note that all weights are significant using 95% confidence intervals

between cardiorespiratory fitness and executive performance. More specifically, we found that there was an increase in cerebral oxygenation with longer completion time for Trail B but only for higher fit adults. This suggests that higher fit older adults can increase cerebral oxygenation availability to respond to increased task demands.

Regarding cognitive performances, a higher cardiorespiratory fitness level was significantly associated with Trail B completion time. Our findings are in accordance with a review (Bherer et al. 2013), a meta-analysis (Colcombe and Kramer 2003), and recent cross-sectional studies (Renaud and Halpern 2010; Boucard et al. 2012; Labelle et al. 2013; Dupuy et al. 2015) that have demonstrated that older adults with a higher fitness levels show specific physical training benefits in executive functioning. The results are also consistent with Renaud and Halpern (2010), who found in older adults a specific effect of cardiorespiratory fitness level in executive condition reaction time when compared to older adults who had a lower cardiorespiratory fitness level. Similarly, our results align with Dupuy et al. (2015) who found that regardless of age, individuals with a higher VO_{2max} performed better in the executive condition of the computerized Stroop task than individuals with a lower VO_{2max}. Additionally, Smiley-Oyen et al. (2008) found that aerobic training and resistance training can selectively improve executive function in older adults (Smiley-Oyen et al. 2008). Our findings support the proposal that higher cardiorespiratory fitness might improve functioning in the prefrontal areas of the brain, which are sensitive to age-related changes in executive functions.

Studies that have examined the relationship between brain activity and cognitive performances have also found that a higher fitness level was associated with greater brain oxygenation when the cognitive task demand increased, indicating that fitter older adults were able to increase cortical activation when the task

Table 2 Coefficients for Trail A completion time model

Predictor	*b*	95% CI	Standardized *b*	*t*
Constant	4.80	[− 25, 16]		− 0.47
Age	0.44	[0.17, 0.71]	0.40	3.23*
PPO	0.00	[− 0.04, 0.04]	− 0.03	− 0.19
Trail A O2Hb	0.05	[− 0.52, 0.62]	0.02	0.18

Table 3 Coefficients for Trail B completion time model

Predictor	*b*	95% CI	Standardized *b*	*t*
Constant	2.52	[− 55, 60]		0.09
Age	1.10	[0.32, 1.9]	0.31	2.83*
PPO	0.21	[− 0.32, − 0.09]	− 0.42	3.54*
Trail B O2Hb	1.84	[0.32, 3.37]	0.28	2.42*

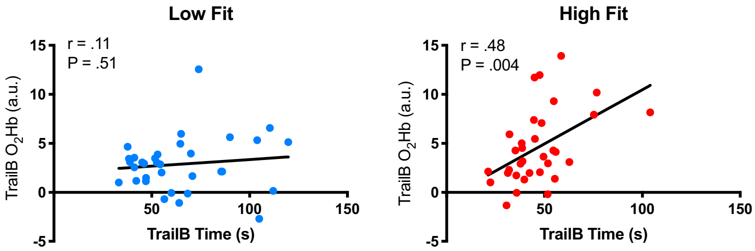

Fig. 3 To explore the mediating effect of HBO between PPO and Cognition, a median split was used to separate participants into high fit and low fit individuals. Within these two groups, Trail B time and Trail B O2Hb were correlated. Significant correlation between Trail B time and Trail B O2Hb only in high fit individuals. Note that overall Trail B times were significantly shorter in the high fit individuals indicating better executive functioning

difficulty increased. Colcombe et al. (2004) found a higher activation in the prefrontal region during the executive component of a Flanker Task in older adults with a higher cardiorespiratory fitness. In another cross-sectional study, Prakash et al. (2012) also found greater blood oxygen level dependent (BOLD) signaling in the prefrontal cortex during the executive component of the Stroop Task for older adults who demonstrated a higher VO_{2max} (Prakash et al. 2012). Dupuy et al. (2015) found that regardless of age, greater amplitude in the O2Hb NIRS signal for higher fit females in comparison to lower fit females, during the executive part of the Stroop Task. A recent study by Mekari et al. (2015) confirmed that a higher cerebral oxygenation availability in the prefrontal cortex was selectively associated with a faster reaction time in the executive condition of the Stroop Task only. Compared to previous work, by including measures of cardiorespiratory fitness, executive function, and cerebral oxygenation in one model, the results are able to more directly link increased cerebral oxygenation with increased fitness and variations in cognitive performance. Our results support that greater cardiorespiratory fitness is associated with greater cerebral oxygen availability in the prefrontal cortex to respond to task demands.

Multiple neurophysiological adaptations inherent to fitness level could explain these functional activation changes. Previous studies in the literature suggest that better cognitive performance in higher-fit individuals associated potential benefits to the size and structures of the brain (Colcombe and Kramer 2003, Erickson et al. 2009). In addition to an increase in white and gray matter volume, fitness-related changes in brain vascular health could also explain our results. Davenport et al. (2012) put forward the hypothesis that the cerebrovascular reserve could be the link between the fitness levels and cognition (Davenport et al. 2012). Using neuroimaging techniques, Bailey et al. (2013) and Murrell et al. (2013) found a higher cerebral blood flow at rest in higher-fit individuals (Bailey et al. 2013; Murrell et al. 2013). However, none of these studies evaluated the impact of improved vascular health on cognition. To support that greater cerebrovascular oxygenation is associated with improved cognitive function, Pereira et al. (2007) reported that three months of aerobic training with middle age adults led to an increase in cerebral blood volume in the dentate gyrus of the hippocampus and was associated with an improved VO_{2max} (Pereira et al. 2007). Recently, it has also been suggested that neurogenesis and enhanced survival of existing neurons have been implicated as potential mechanisms. For instance, it has been found that a number of neurotrophins such as brain-derived neurotrophic factors (BDNFs), vascular endothelial growth factor (VEGF), or insulin-like growth factors (IGF) are associated with higher levels of physical activity (Churchill et al. 2002). Also, it is well known that cardiorespiratory fitness improves vasoreactivity and improves endothelial function in older adults (O'Brien et al. 2018) that could lead to better perfusion and better brain functioning (Voelcker-Rehage and Niemann 2013). These data suggest that brain vascularity is highly plastic throughout the lifespan, and interventions that may increase brain vascularization may be effective strategies in reducing or delaying age-related cognitive impairments (Churchill et al. 2002). Our results are in accordance with all these previous findings and more specifically with recent research by Dupuy et al. (2015) that measured cerebral oxygenation with NIRS technique and found that higher-fit older adults (females) have a greater O2Hb response during an executive task and that this increase in cerebral activity was related to better executive performance. Furthermore, Zimmerman et al. (2014) put forward the hypothesis that lower-fit older adults may suffer from decreased cerebral capillary density. This is consistent with the notion that aerobic exercise leads to an increase in angiogenesis, and thus increased perfusion, and that can lead to improved executive function (Davenport et al. 2012).

A few limitations in this study warrant discussion. Firstly, we did not screen our older adults for depression. It has been shown that depression is linked with worse executive function in older adults (Pantzar et al. 2014). We measured O2Hb in the left prefrontal cortex. The frontal cortex is activated during a Trail task and is an area targeted for changes in executive functions (Shibuya-Tayoshi et al. 2007; Colcombe et al. 2004). Therefore, our interpretation of the cognitive data is limited to our choice of brain area and observing the contributions of additional areas involved in the Trail Making Test might extend the current findings. Compared with the other neuroimaging methods, NIRS has both some important strengths and some notable limitations. On the one hand, NIRS is a noninvasive and relatively low-cost optical technique that has become a widely used instrument for measuring changes in HbO_2 particularly during exercise and movement (Dupuy et al. 2015; Mekari et al. 2015). It can indirectly measure brain blood flow and provides good temporal resolution. On the other hand, NIRS does not have a good spatial resolution and the depth coverage is limited, so most NIRS investigations are limited by skull thickness, scalp flow or adipose tissue thickness (Ekkekakis 2009). Finally, the current results link increased cerebral oxygen levels to increased task demands through individual differences in performance. Future research should manipulate task demands within-subjects to further determine the link between cerebral oxygen availability and performance in higher fit and lower fit older adults. The results of this study could lead to a further understanding the mechanisms by which regular physical activity can influence cognitive function.

Conclusion

Although the relationship between physical activity and cognition requires further investigation, the current study took a step in assessing the cerebral mechanisms by which cardiorespiratory fitness can improve cognition. The results indicate that regardless of age, the higher-fit individuals performed better in the executive conditions than lower-fit individuals. These findings support previous work that executive functioning is most sensitive to fitness levels and that this relationship is likely mediated by neurophysiological changes in the prefrontal cortex.

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