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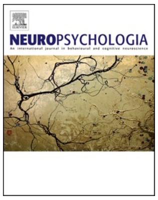

# Electrocortical correlates of the association between cardiorespiratory fitness and sustained attention in young adults

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## ABSTRACT

Cardiorespiratory fitness is thought to be positively related to sustained attention. However, the underlying mechanisms of this relationship have yet to be fully elucidated. The objective of this study was to i) explore the relationship between cardiorespiratory fitness and sustained attention in 72 young adults (18–37 years old) and ii) provide insight on the electrocortical dynamics supporting sustained attention performance in individuals differing in cardiorespiratory fitness by means of EEG topographic analyses and source localization. Behaviorally, cardiorespiratory fitness was related to faster response times and higher accuracy in the psychomotor vigilance task even when adjusting the model with confounding variables such as age, body mass index and chronic physical activity. However, there was no relationship between cardiorespiratory fitness and the classic vigilance decrement observed in the sustained attention task. At the electrocortical level, higher cardiorespiratory fitness was related to increased global field power (310–333 ms poststimulus) localized in the posterior cingulate cortex (BA 30) followed by changes in scalp topographies around the P3b ERP component (413–501 ms poststimulus), which corresponded to earlier activation of the supplementary motor areas (BA 6). This is the first study using high-density EEG, which harnesses the whole spatiotemporal dynamics of the relationship between cardiorespiratory fitness and sustained attention in young adults.

## 1. Introduction

Attention is defined as a dynamic cognitive functioning mode allowing for the detection, selection and use of relevant stimuli to adjust behavior to an ongoing situation (Hommel et al., 2019). Among the different types of attention, sustained attention refers to the ability to maintain attentional resources over time from minutes to hours (Esterman and Rothlein, 2019; Fortenbaugh et al., 2017). This cognitive function is usually conceptualized as a limited resource that can be depleted by factors such as cognitive effort or boredom (for review, see Smallwood and Schooler, 2006; Warm et al., 2008). Anyone who has attempted to stay focused on a difficult or dull task would know that an inevitable fluctuation and decrease in performance occur after a few minutes. The moment-to-moment performance fluctuation is thought to be due to a perturbation of the information processing while the decrease of performance over time is attributed to the vigilance decrement leading the response time and errors to increase (Clayton et al., 2015; Esterman and Rothlein, 2019; Fortenbaugh et al., 2017; Parasuraman, 2000).

Traditionally, sustained attention performances are measured using mean reponse time, response time standard deviation and accuracy (omission and/or commission errors). However, it has been shown that response time distributions are not Gaussian but rather similar to an ex-Gaussian distribution that is a combination of a Gaussian and an exponential distribution characterized by a positively skewed distribution (Luce, 1986). In this case, the analysis of the mean response time only, could mask some details if the effect appears in very fast or very slow response times (Whelan, 2017). One possibility to address this issue is to analyse the whole response times distribution using quantile analyses. This may reveal results that would not have been discovered by analyzing central tendency parameters only (Balota and Yap, 2011; Hervey et al., 2007; Whelan, 2017).

At the brain level, cognitive functional process models assume that endogenous control of attention relates to executive functions assisting active goal maintenance. Indeed, some studies suggest that the act of focusing on monotonous activity for long periods of time relies on the activation of a frontoparietal network to maintain endogenous attentional processes (Fortenbaugh et al., 2017; Langner and Eickhoff, 2013;

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Lawrence et al., 2003). However, the factors modulating the activation of this network to effectively maintain attentional performance remain to be clarified.

Interestingly, cardiorespiratory fitness (CRF) is thought to be related to sustained attention capacity. This factor represents the physiological capacity of the cardiorespiratory system to deliver oxygen to the working muscles during sustained physical activity (Caspersen et al., 1985; Wang et al., 2010). CRF is modulated not only by genetic and environmental factors but also by chronic physical activity (CPA) (Zeiher et al., 2019). Accordingly, multiple studies in young adults concluded that increased CRF by means of CPA has a positive impact on individual capacity to maintain attention over time (Ciria et al., 2017; Luque-Casado et al., 2013; Luque-Casado et al., 2016). These studies reveal better sustained attention performance (faster response time and higher accuracy) in individuals with higher CRF than in those with lower CRF. The mechanisms behind the relationship between physical activity and cognitive functions in general seem to rely on multiple interconnected levels in the brain (from cellular and molecular levels to structural and functional mechanisms), with potential cascade effects from one level to another (Stillman et al., 2016; Voss et al., 2013). However, few studies have examined the brain correlates underlying the relationship between CRF and sustained attention specifically.

To fill this gap, electroencephalography (EEG) and its millisecond temporal resolution is an adequate tool to highlight the electrocortical dynamics underlying attentional processing. Previous studies have shown that individuals of all ages with high CRF/CPA have generally larger P3b amplitudes and shorter P3b latencies in tasks requiring cognitive control compared to individuals with lower CRF/CPA (Hillman, Kamijo and Pontifex, 2012b; Kao et al., 2019). The P3b ERP component is a subcomponent of the P300 (peaking between 300 and 700 ms post-stimulus), which has a positive scalp potential distribution over centroparietal regions (Huang et al., 2015; Kappenman and Luck, 2012; Linden, 2005). Interestingly, the P3b ERP component is thought to be elicited during target processing and has been associated with changes in the attentional resources devoted to a task (Polich, 2007). In addition, larger amplitude of the Contingent Negative Variation (CNV) ERP component has been related to higher CRF in various cognitive tasks (Arito and Oguri, 1990; Hillman et al., 2012b; Stroth et al., 2009). The CNV is a negative component with a scalp potential over anterior regions that is thought to reflect the efficiency of the response preparation (Kappenman and Luck, 2012; Walter et al., 1964).

Concerning sustained attention, to the best of our knowledge, the study of Luque-Casado et al. (2016b) is the only one that investigated the electrocortical brain dynamics characterizing groups of young adults differing in their CRF in a sustained attention task. Their results revealed that high-fit participants were characterized by a greater P3 amplitude (with a maximal amplitude after approximately 30 min of a 60-min task) over centroparietal regions throughout the task compared to low-fit participants. In addition, the authors also found a larger CNV amplitude over centro-frontal regions in the first 36 min of the task. These results show a link between the level of CRF and electrocortical brain responses in a sustained attention task. However, the analysis used in this study does not fully exploit the amount of spatiotemporal information contained in EEG recordings. Indeed, their ERP analysis was performed within a priori selected electrode sites, thereby limiting the ability to characterize the dynamics of underlying brain networks of sustained attention.

At a behavioral level, the objective of the present study is to investigate the relationship between CRF and sustained attention in young adults using analyses on the traditional measures of performance (mean response times and accuracy), vigilance decrement, as well as complementary exploratory analyses on the whole response times distribution. At a brain level, the objective is to fully exploit whole-brain electrical activity to investigate the electrocortical dynamics involved in sustained attention among individuals differing in their level of CRF. More specifically, we investigated electrocortical activity by analysing ERPs as a sequence of electrical potential field topographic maps (topographical ANCOVA) (Michel et al., 2009; Murray et al., 2008). This approach is relevant because it allows disentangling differences due to intracerebral source strength from changes in the spatial orientation and/or location of the active sources, as well as localizing the source generators of the scalp topographies (Michel et al., 2009). Based on previous results, at a behavioral level, we expected that individuals with higher CRF would exhibit faster response times and fewer errors throughout the sustained attention task (Ciria et al., 2017; Fernandes M. de Sousa et al., 2018; Luque-Casado et al., 2013; Luque-Casado et al., 2016). In addition, we expected that complementary analyses on the whole response times distribution would confirm the results obtained in traditional analyses. At an electrocortical level, we hypothesized that sustained attention performance according to the CRF level would be linked to topographic maps in a time period corresponding to the P3b ERP component (Hillman et al., 2012b; Kao et al., 2019; Luque-Casado et al., 2016). Specifically, we expected modulations in subregions of the frontoparietal network according to the CRF level (Fortenbaugh et al., 2017; Langner and Eickhoff, 2013; Lawrence et al., 2003). To test these hypotheses, the CRF of participants was measured with an incremental effort test on a motor-driven treadmill. The CPA of participants was also evaluated with the Baecke questionnaire to take into account the global physical activity level of participants (Baecke et al., 1982). Sustained attention performance and continuous EEG were measured during the performance of a psychomotor vigilance task (PVT) ((Dinges and Powell, 1985).

## 2. Method

### 2.1. Participants

A power analysis was conducted to estimate the minimum sample size required for a power level of 0.80 and a medium effect size (f = 0.15). This analysis indicated a minimum sample size of 68 participants. Based on the power analysis and taking into account the possible dropout of a number of participants, seventy-two right-handed young adults, with normal or corrected-to-normal vision and no history of neuropsychiatric disorders were selected based on a self-screening questionnaire (PAR-Q, Physical Activity Readiness Questionnaire) that controlled their capacity to perform an intensive physical activity without risk to their health (Adams, 1999). Seven participants were excluded from the analyses because of the poor quality of EEG signals. The remaining sample consisted of 72 participants (26 males; mean age = 22.3, SD = 4.2, range 18–37 years old) for the behavioral analyses and 65 participants (20 males; mean age = 21.9, SD = 3.6, range 18–37 years old) for the EEG analysis. The whole sample of participants involved in this study provided informed consent and the study was approved by the Cantonal Ethics Committee for Human Research (Vaud, Switzerland; protocol N°2018–02107).

### 2.2. Study design

The investigation was carried out through two independent sessions. The two sessions were separated by at least one week and at most three weeks. The first session was dedicated to the measurement of the maximal rate of oxygen consumption (VO2 max) through an incremental effort test. The second session assessed individual habitual physical activity through a self-screening questionnaire (Baecke et al., 1982) and recorded continuous EEG during a psychomotor vigilance task (PVT) (Dinges and Powell, 1985).

### 2.3. Experimental procedure

#### 2.3.1. $VO_2$ max assessment (CRF)

Participants performed an incremental effort test on a motor-driven treadmill following the Roecker protocol (Roecker et al., 2002). The test began with a resting state period of 3 min allowing measuring baseline heart rate (HR) of participants through a Polar HR monitor (Model M400, Polar Electro, Finland), followed by a warm-up. After a period of familiarization with the treadmill, the speed of the warm-up was set at 4, 6 or 8 km/h with 2% slope for 5-min according to the preference of the participants. The 2% slope was chosen to simulate external conditions. After the 5-min warm-up, the treadmill speed increased by 2 km/h every 3 min until volitional exhaustion. Throughout the entire duration of the test, breath-by-breath pulmonary gas-exchanges ($O_2/CO_2$) were measured with the Ergocard Professional system (Medisoft, Sorinnes, Belgium) to evaluate the $VO_2max$. In addition, the rating of perceived exertion (RPE) was assessed after each step of the test using the Borg scale (Borg, 1970).

The $VO_2$ (expressed in ml/kg/min) was considered maximal when three of the following four criteria were met: (i) a plateau in oxygen consumption was reached despite the increase of the speed, corresponding to an increase of less than 2 ml/kg/min; (ii) an HR above 90% of the theoretical maximum HR (220-age) at the end of the test; (iii) respiratory exchange ratio greater than 1.1; (iv) RPE equal or greater than 17. Finally, the $VO_2$max was computed by averaging the $VO_2$ breath-by-breath measurements recorded during the last 30 s of the test (Robergs et al., 2010).

To account for the existing physiological $VO_2$max differences between women and men, the data were transformed - separately for each sex - in z-score values according to the reference standards for cardiorespiratory fitness of the Fitness Registry and the Importance of Exercise National Database (FRIEND) (Kaminsky et al., 2015; Pate and Kriska, 1984).

### 2.3.2. Chronic physical activity (CPA)

The Baecke questionnaire gives a rate between 1 (low activity) and 5 (high activity) for each physical activity domain (work, leisure and sport). The sample of participant was characterized by a global score ranging from 3 (lowest possible score) to 15 (highest possible score) calculated from each physical activity domain (Baecke et al., 1982).

### 2.3.3. Psychomotor vigilance task (PVT)

The PVT was developed as a sustained attention measure and is interpreted as the arousal state of an individual (Drummond et al., 2005). The reliability of the PVT-related behavioral and EEG measures has been evaluated in the study of McEvoy et al. (2000). This study showed that between session task-related mean response times ($r$ = 0.52), accuracy ($r$ = 0.63) as well as task-related EEG power spectral density ($r$-values ranging from 0.83 to 0.94 for theta and alpha power) are reliable (McEvoy et al., 2000).

The Psychopy software was used to display the PVT (adapted from, Dinges and Powell, 1985), record responses, and send markers to the EEG recording device (Peirce et al., 2019). During the PVT, participants were seated in a quiet room sheltered from electromagnetic disturbances (Faraday cage). They faced a monitor placed at 60 cm from their eyes and their head was placed on a chin rest to limit EEG artifacts due to head movements. In this version of the PVT, each trial began with a black screen for a random period of time (2–10 s), followed by a red dot stimulus appearing at the center of the screen for 500 ms, prompting the participant to press the space bar of the keyboard as fast as possible in a 1-s time window. If no response was given within 1 s (omission) or if a response was given before stimulus onset (commission), the trial was considered as an error. Importantly, to obtain a faster decrease in performance, no feedback was given after each trial. The task lasted 30 min and consisted of 240 trials. No breaks were included in the task design.

As several factors like sleep/wake balance, arousal, motivation and stress are known to influence the performance of sustained attention (Oken et al., 2006), participants were asked to spend a “normal” night’s sleep the day before the experiment. Also, they were asked to avoid all types of energy drinks and unusual amounts of nicotine or coffee just before the experiment. There was no financial compensation or rewards for the participants.

## 2.4. Behavioral data analysis

Data were analyzed using the Jamovi software (The jamovi project (2020), Version 1.2). To measure the performance decrement over time, the PVT was divided into four 60-trial blocks (for an approximate block’s duration of 7 min). The internal consistency reliability of response times was confirmed by a permutation-based splithalf approach (Parsons, 2021). Using 5000 random splits, the spearman-brown corrected reliability estimate was $r_{SB} = 0.92$, CI [0.90, 0.94]. To control for potential cofounding factors in further analyses, we firstly investigated whether CRF ($VO_2$max) was associated with age, sex, body mass index (BMI) and CPA (Baecke total score). The significance threshold was set at 0.05.

### 2.4.1. Performance decrement

To investigate the performance decrement over time among participants, response times and accuracy (commission + omission errors) were subjected to a repeated measures ANOVA with time-on-task (Blocks 1, 2, 3 and 4) as within-subject factor. In addition, in order to quantify the performance decrement, we computed the response times and accuracy delta changes (%) between the first and the last block of trials using the following formula:

$$\frac{Block\ 4\ -\ Block\ 1}{Block\ 1}\ \times\ 100$$

### 2.4.2. Cardiorespiratory fitness and psychomotor vigilance task

As the CRF was significantly correlated with age ($r$ = 0.331; $p$ = .005), BMI ($r$ = −0.267; $p$ = .023) and CPA ($r$ = 0.495; $p$ < .001) (see Table 1), further analyses were computed by taking into account these confounding factors.

To investigate if the CRF could predict response times in the PVT, a multiple linear regression was used with $VO_2$max, age, BMI and the Baecke total score as predictors and response times as the dependent variable. In the same way, to investigate if the CRF could predict accuracy (commission and omission errors) in the PVT, a multiple linear regression was used with $VO_2$max, age, BMI and the Baecke total score as predictors and errors as the dependent variable.

To investigate if the CRF could predict the response times changes over time in the PVT, a multiple regression was used with $VO_2$max, age, BMI and the Baecke total score as predictors and the response times changes as the dependent variable. In the same way, to investigate if CRF could predict the accuracy changes overt time in the PVT, a multiple regression was used with $VO_2$max, age, BMI and the Baecke total score as predictors and the accuracy changes as the dependent variable.

### 2.4.3. Cardiorespiratory fitness and psychomotor vigilance task: whole response times distribution analysis

To distinguish whether the relationship between response times and the CRF was due to faster response times and/or reduced attentional lapses (extremely slow response times), we analyzed the whole response times distribution. In that vein, we rank orders the response times of the participants and bin them into quintiles (Balota and Yap, 2011). Then, to investigate if the CRF could predict the response times in each quintile, multiple linear regressions were applied with $VO_2$max, age, BMI and the Baecke total score as predictors and response times in each quintile as the dependent variables.

## 2.5. EEG recording and ERP analysis

Continuous EEG was recorded during performance on the PVT from 64 electrodes (Biosemi ActiveTwo system) placed following the international 10–20 system location. Two additional electrodes were used as reference and ground (active CMS: common mode sense and passive

**Table 1**

Descriptive statistics and intercorrelations between variables. * Significant correlation ($p < .05$).

| Descriptive characteristics | *M* | *SD* | Min | Max | Age | BMI (kg/m$^2$) | VO$_2$max (ml/kg/min) | Baecke total (score) |
|---|---|---|---|---|---|---|---|---|
| N = 72 (26 males) | | | | | | | | |
| Age | 22.33 | 4.18 | 18 | 37 | – | | | |
| BMI (kg/m$^2$) | 22.30 | 3.48 | 17.30 | 34.30 | 0.15 | – | | |
| VO$_2$max (ml/kg/min) | 43.80 | 9.81 | 24.10 | 77.30 | 0.33* | −0.27* | – | |
| Baecke total (score) | 7.85 | 1.61 | 4.25 | 11.30 | 0.21 | −0.10 | 0.50* | – |

DRL: driven right leg) to constitute a feedback loop for amplifier reference. Data were recorded at a sampling rate of 1024 Hz with 24-bit A/D conversion.

One of the most important assumptions in ERP analyses is to have a similar timing of the signal within trials to obtain a sufficiently good quality of ERP components and avoid a latency jitter that could lead to a misinterpretation of the results (Luck, 2012). As in our case the response times vary considerably between the first block (M = 371 ms) and the last block (M = 405 ms), we decided to perform the EEG analyses on the second half of the task (the last 120 trials) in which response times were similar (Block3: M = 404 ms, Block 4: M = 405 ms, see Fig. 1A) to avoid any latency jitter. In addition, the second half of the task coincided with a period in which participants have significantly decreased their performance and are therefore struggling to maintain their attention.

Offline analyses were performed with Brain Vision Analyzer (version 2.1.2.327; Brain Products GmbH). Raw signals were filtered between 0.1 and 40 Hz using a zero-phase shift second order butterworth filter and then downsampled to 512 Hz. Next, eye blinks and saccades were corrected using an independent component analysis (ICA) (Cardoso, 1998). Bad electrodes were interpolated using linear splines interpolation of adjacent electrodes (Perrin et al., 1987). For ERP computation, data were segmented into epochs of 1200 ms (200 ms pre-stimulus to 1000 ms post-stimulus). Epochs containing electrical potential values exceeding ±80 μV were excluded from ERP averaging. In addition to the semi-automatic artifact rejection, signals were manually screened for residual artifacts. Data were then re-calculated to an average reference. After the preprocessing, the mean number of remaining trials (for the second half of the task, 120 trials) was 101.1 ± 14.8. No baseline correction was applied.

ERP analyses were performed with non-parametric randomization statistical tests implemented in the open-source software RAGU (Randomization Graphical User interfaces) implemented on Matlab (http://www.mathworks.com/) (Habermann et al., 2018; Koenig et al., 2011). A topographic consistency test (TCT) analysis, a topographic analysis of covariance (TANCOVA) and a global field power (GFP) were applied. All analyses were computed with 5′000 randomization runs and a *p* threshold fixed at 0.05 (Koenig et al., 2011).

### 2.5.1. *Consistency test, topographical analysis of covariance and GFP analysis*

The topographic consistency test (TCT) was applied to the ERPs to identify time periods of consistent pattern of active sources (i.e., stable topographies) across participants. This test allowed ensuring that the stimulus presentation activated common neuronal sources across subjects over time and prevented the risk of making false conclusions about any type of analysis performed on the ERPs (Habermann et al., 2018). The time periods showing consistent pattern of neuronal sources activations were then used for the TANCOVA analysis.

A TANCOVA was computed to highlight significant covariations between ERP topographies during the PVT and the VO$_2$max of participants (Koenig et al., 2008). The objective was to identify time periods where ERP topographies were significantly related to the CRF. In addition, the same analysis was computed to investigate covariations between ERP topographies and the response times of participants. The randomization test implemented in the TANCOVA was based on the GFP which is a well-accepted measure of the scalp field strength at a given period of time (Koenig et al., 2011). In the case of the TANCOVA, this value corresponds to the standard deviation of the signal at each electrode (Murray et al., 2008) of the covariance map computed from the covariation between ERP topographies and external variables of interest (VO$_2$max). The GFP was herein used as a global measure of the effect size of the covariance map to statistically test the association between ERP topographies and the CRF. An additional GFP analysis was performed to assess the relationship between the strength of all active

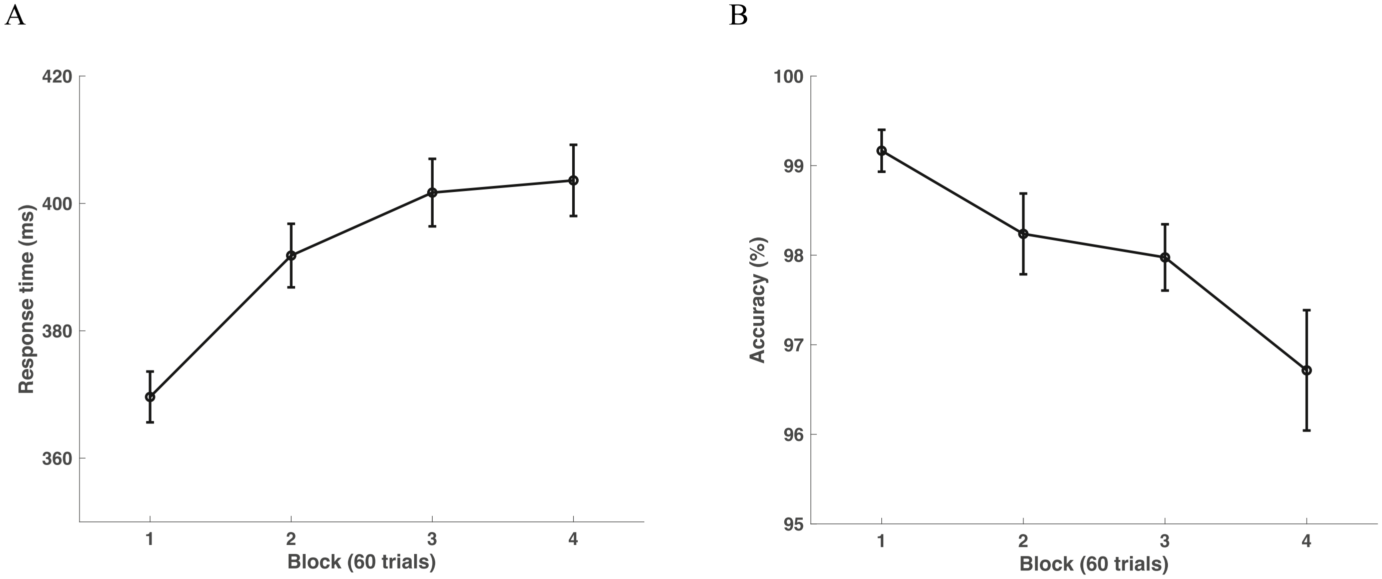

**Fig. 1.** Behavioral results of the PVT. (A) Mean response times (ms) in the PVT by block. (B) Accuracy (%) in the PVT by block. Error bars indicate the standard error of the mean (SEM). Significant differences between blocks are indicated in the text.

neural sources and the VO$_2$max as well as the response times of participants. As our analyses are based on the GFP, the internal consistency reliability of the GFP was confirmed by a permutation-based splithalf approach (Parsons, 2021). Using 5000 random splits, the spearman-brown corrected reliability estimate was $r_{SB} = 0.90$, CI [0.86, 0.93].

### 2.5.2. *Source localization*

A standardized low-resolution electromagnetic tomography method (sLORETA; (Pascual-Marqui, 2002) was used to identify the activation pattern of the neural generators at the origin of the observed relationship between the ERP topographies and the VO$_2$max. The sLORETA method allows for computing neuroelectrical images based on scalp potential measures by standardizing a minimal norm inverse solution by source variance and measurement noise (Pascual-Marqui, 2002). The solution space is restricted to grey matter of cortical and hippocampus region according to the digitized atlas of the Montreal Neurological Institute (MNI) and corresponds to 6239 voxels at 55 mm spatial resolution. As the covariance map represents the neural generators activity, the sources underlying the periods of significant covariation between ERP topographies, and VO$_2$max can be directly estimated (Koenig et al., 2008).

## 3. Results

### 3.1. *Psychomotor vigilance task*

To confirm that the PVT affected sustained attention of participants, mean correct response times and accuracy were separately subjected to a repeated measures ANOVA with time-on-task (Blocks 1, 2, 3 and 4) as within-subject factor. The mean response time increased over time (Block 1: M = 371 ms, SEM = 4 ms; Block 2: M = 393 ms, SEM = 5 ms; Block 3: M = 404 ms, SEM = 5 ms; Block 4: M = 405 ms, SEM = 6 ms; $F(3,213) = 71.4$, $p < .001$, $\eta_p^2 = .50$) (Fig. 1A) and differed significantly between the blocks 1–2 ($p < .001$), 1–3 ($p < .001$), 1–4 ($p < .001$), 2–3 ($p < .001$) and 2–4 ($p < .001$). In the same way, the accuracy rate decreased over time (Block 1: M = 99.2%, SEM = 0.23%; Block 2: M = 98.0%, SEM = 0.47%; Block 3: M = 97.4%, SEM = 0.54%; Block 4: M = 96.2%, SEM = 0.77%; $F(3,213) = 10.4$, $p < .001$, $\eta_p^2 = .13$) (Fig. 1B) and differed significantly between the blocks 1–3 ($p = .008$), 1–4 ($p < .001$) and 2–4 ($p = .020$).

### 3.2. *Cardiorespiratory fitness and psychomotor vigilance task*

Multiple linear regressions were computed to predict response times and accuracy based on VO$_2$max, age, BMI, and CPA scores. The model predicted the response times in the PVT ($F(4,67) = 3.03$; $p = .023$) with a $R^2$ of 15.30%. In this model, the VO$_2$max significantly predicted the participant's response times ($t = -2.51$; $\beta = -0.35$; 95% CI [−0.64, −0.07]; $p = .015$). Age, BMI, and CPA scores did not predict response times significantly (Table 2). Thus, higher VO$_2$max was related to faster response times in the PVT. The model also predicted the accuracy in the PVT ($F(4,67) = 3.09$; $p = .022$) with a $R^2$ of 15.60%. In this model, the VO$_2$max significantly predicted the participant's accuracy ($t = 2.73$; $\beta = 0.39$; 95% CI [0.10, 0.67]; $p = .008$). Age, BMI, and CPA scores did not predict the accuracy significantly (Table 2). Thus, higher VO$_2$max was related to fewer errors in the PVT.

Multiple linear regressions were also computed to predict response times and accuracy changes over time based on VO$_2$max, age, BMI, and CPA scores. The model did not predict significantly the response times changes ($F$ (4,67) 0.45; $p > .05$) and the accuracy changes over time ($F$ (4,67) = 1.75; $p > .05$) (Table 2).

Complementary multiple linear regressions were computed to predict the response times in each quintile based on VO$_2$max, age, BMI, and CPA scores. For each quintile, the VO$_2$max significantly predicted the response times in the PVT (all $p$-values < .05) while age, BMI and CPA did not.

**Table 2**

Multiple linear regressions table. Prediction of the response times, accuracy, response times and accuracy delta changes (Δ %) between the block 1 and 4, based on VO$_2$max, age, BMI and CPA scores. * Significant prediction (p < .05).

| Predictors | β | *SE* | *t* | *p* |
|---|---|---|---|---|
| Response times | | | | |
| VO$_2$max (ml/kg/min) | −0.355 | 0.007 | −2.507 | 0.015* |
| Age | 0.017 | 0.001 | 0.144 | 0.886 |
| BMI (kg/m$^2$) | −0.149 | 0.001 | −1.233 | 0.222 |
| Baecke total (score) | −0.093 | 0.003 | −0.722 | 0.473 |
| Accuracy | | | | |
| VO$_2$max (ml/kg/min) | 0.385 | 0.631 | 2.725 | 0.008* |
| Age | −0.200 | 0.104 | −1.616 | 0.111 |
| BMI (kg/m$^2$) | −0.032 | 0.123 | −0.267 | 0.790 |
| Baecke total (score) | 0.026 | 0.283 | 0.203 | 0.840 |
| Response times (Δ %) | | | | |
| VO$_2$max (ml/kg/min) | −0.106 | 1.378 | −0.704 | 0.484 |
| Age | −0.071 | 0.228 | −0.538 | 0.593 |
| BMI (kg/m$^2$) | −0.002 | 0.268 | −0.015 | 0.988 |
| Baecke total (score) | −0.027 | 0.619 | −0.200 | 0.842 |
| Accuracy (Δ %) | | | | |
| VO$_2$max (ml/kg/min) | 0.246 | 1.209 | 1.679 | 0.098 |
| Age | −0.085 | 0.200 | −0.664 | 0.509 |
| BMI (kg/m$^2$) | −0.133 | 0.235 | −1.060 | 0.293 |
| Baecke total (score) | 0.009 | 0.543 | 0.069 | 0.945 |

### 3.3. *TCT, TANCOVA and GFP analyses*

Exemplar ERP waveforms (Cz electrodes) between the mean of five high-fit and five low-fit participants (according to the Fitness Registry and the Importance of Exercise National Database (FRIEND)) are shown in the Fig. 2A.

The TCT revealed significant consistent topographies ($p < .05$) across participants over the entire time period of interest between −200 and 1000 ms. The TANCOVA was thus computed within this period to investigate the relationship of ERP topographies with the VO$_2$max. The analysis revealed three significant ERP topographic covariances ($p < .05$) in the time periods from 281 to 290 ms, from 413 to 429 ms and from 468 to 501 ms (Fig. 2B). The first covariance difference was not considered for further analyses because of its very short time period duration. Given the temporal proximity of the second and third time periods, we decided to run an additional TANCOVA on the average potential between 413 (onset time of the second period) and 501 (offset time of the third period) ms to justify the possibility to merge these two periods as one. The TANCOVA confirmed the relationship with the VO$_2$max in this whole time period (413–501 ms, $p < .05$). The topography of the covariance map revealed positive potential at central sites and diffused negative potential at fronto-temporo-parieto-occipital sites (Fig. 2C). A TANCOVA was also computed to investigate the relationship of ERP topographies with the response times. The analysis revealed three significant ERP topographic covariance ($p < .05$) in the time periods from 259 to 273 ms, from 392 to 484 ms and from 560 to 579 ms. The first and the last covariance differences were not considered for further analyses because of their very short time period duration. The topography of the covariance map revealed a negative potential at central sites and a diffused positive potential at fronto-temporo-parieto-occipital sites.

To assess the relationship between the strength of all active neural sources and the VO$_2$max of participants, a GFP analysis was computed. This analysis revealed a significant positive association of the GFP with the VO$_2$max in a time period from 310 to 333 ms ($p < .05$) (Fig. 3A). Thus, higher GFP was associated with higher VO$_2$max (Fig. 3B). In addition, the same analysis was computed with the response times. This analysis revealed a significant negative association of the GFP with the response times in a time period from 181 to 202 ms and from 253 to 370 ms ($p < .05$). Thus, higher GFP was associated with lower reponse times.

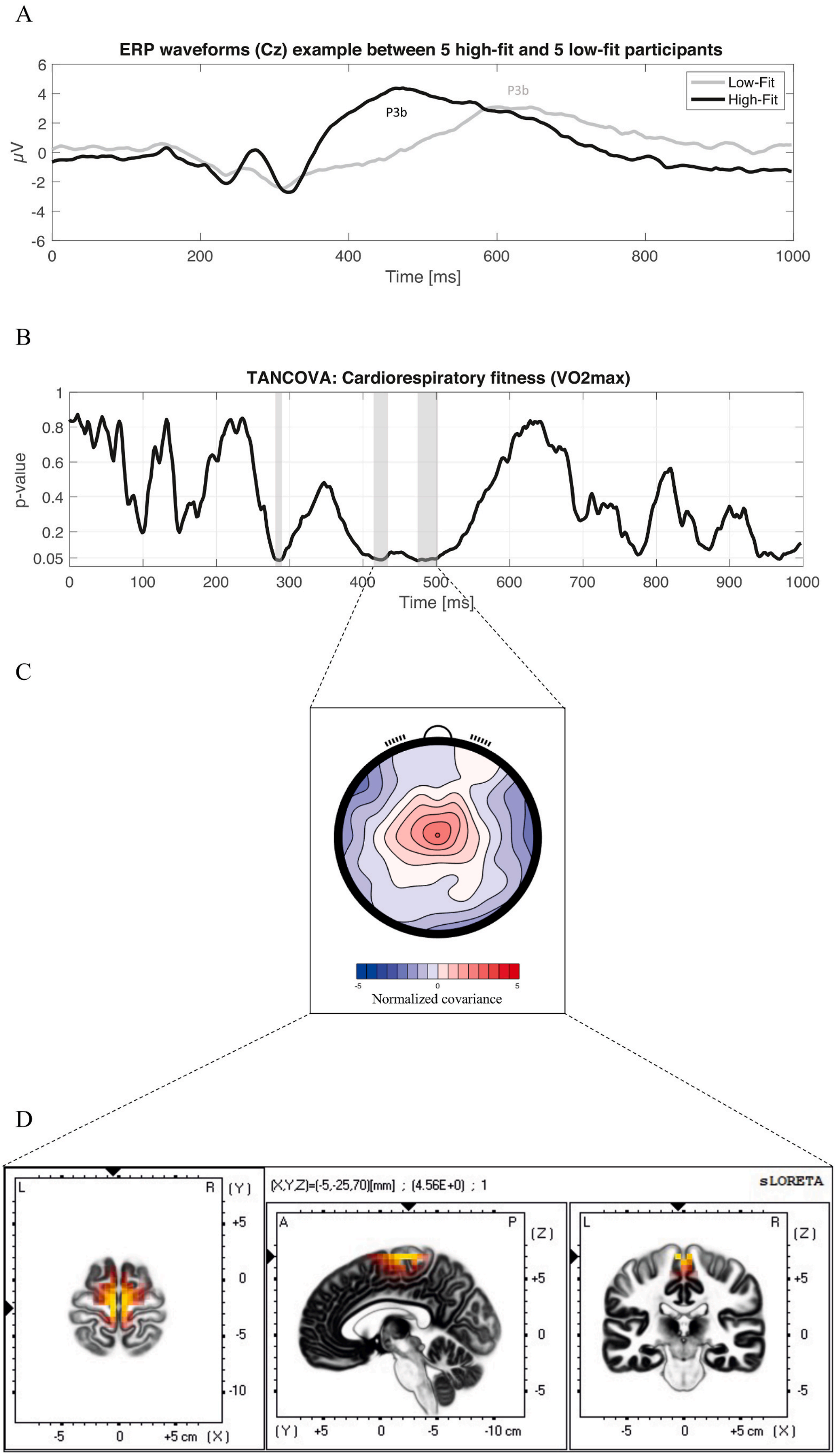

**Fig. 2.** Results of the TANCOVA and sLORETA analyses computed using the ERPs during the PVT and the CRF ($VO_2$max). (A) An example of the ERP waveforms (Cz electrode) of 5 high-fit and 5 low-fit participants (according to the Fitness Registry and the Importance of Exercise National Database (FRIEND)). These waveforms confirm the presence of the P3b component. (B) The p value of the TANCOVA is plotted as a function of time. The grey shadowed areas highlight the time periods of significant covariation of ERP topographies and $VO_2$max. (C) The covariance map observed from 413 to 501 ms is illustrated. (D) sLORETA visualization of the underlying sources of the covariance map showing activation in the supplementary motor areas (BA 6).

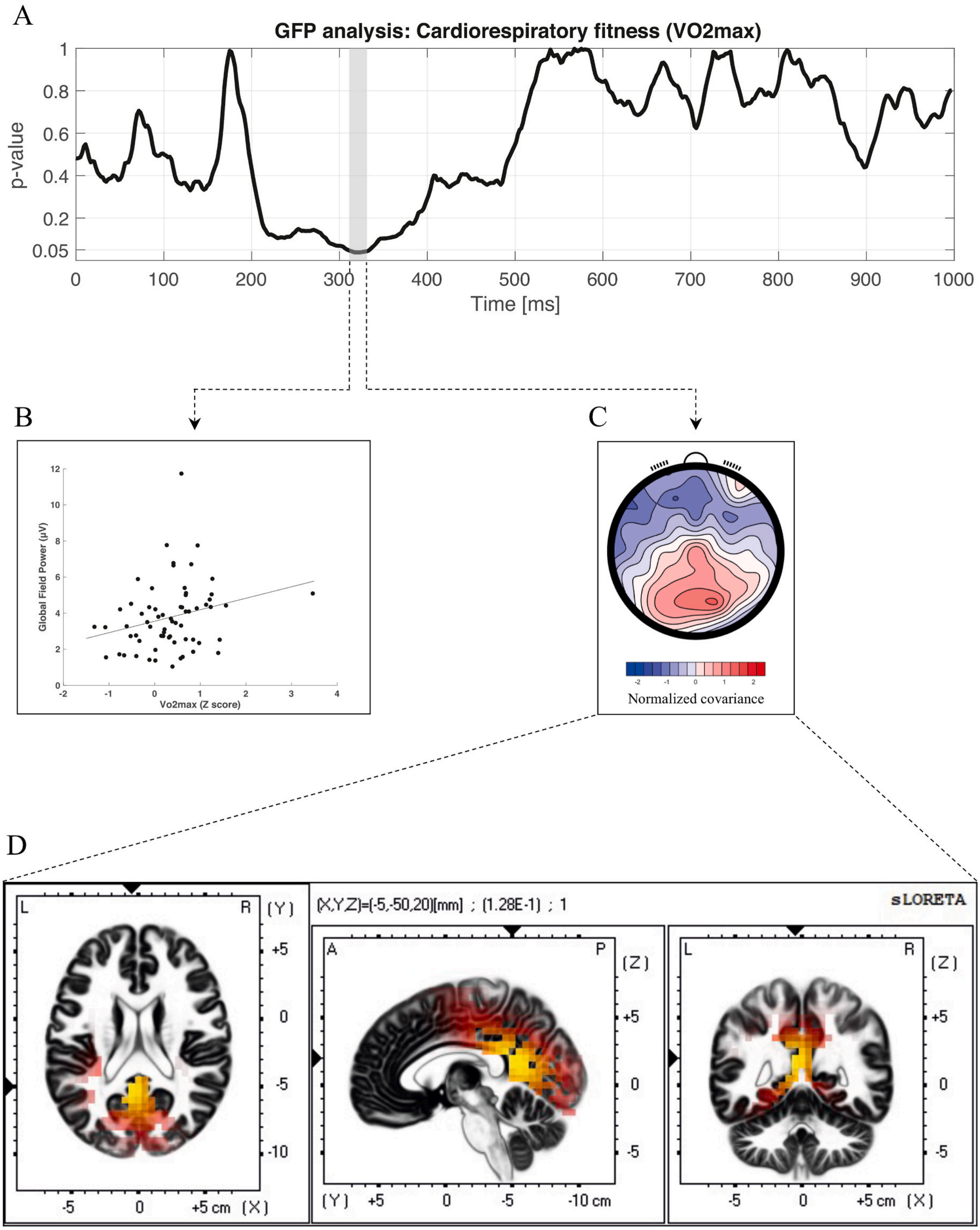

**Fig. 3.** Results of the GFP and sLORETA analyses computed using the ERPs during the PVT and the CRF ($VO_2$max). (A) The p value of the GFP analysis is plotted as a function of time. The grey shadowed area highlight the time period (310–333 ms) of significant covariation of GFP and $VO_2$max. (B) Scatterplot showing the positive relationship between the GFP and the $VO_2$max. Higher GFP values are associated with higher $VO_2$max. (C) The covariance map of the GFP result observed from 310 to 333 ms is illustrated. (D) sLORETA visualization of the underlying sources of the covariance map showing activation in the posterior cingulate cortex (BA 30).

### *3.4. Source localization*

To identify brain regions responsible for the covariation of ERP topographies with $VO_2$max, the covariance map (413–501 ms) was localized with sLORETA (Fig. 2D). The sources underlying the covariance map indicated the implication of the supplementary motor areas (SMA) (BA 6) with highest activation at MNI coordinates $X = -5$, $Y = -25$, $Z = 70$. In the same way, the covariance map (Fig. 3C) associated with the GFP effect (310–333 ms) suggested the implication of the posterior cingulate cortex (PCC) (BA 30) with highest activation at MNI coordinates $X = -5$, $Y = -50$, $Z = 20$.

## 4. Discussion

The first objective of the present study was to investigate the relationships between CRF and sustained attention performance assessed in a PVT. The second objective was to examine the electrocortical dynamics underlying sustained attention performance in individuals differing in CRF. At the behavioral level, we hypothesized that individuals with higher CRF would exhibit shorter response times and fewer errors throughout the task. In addition, we expected that complementary analyses on the whole response times distribution would confirm the results obtained in traditional analyses. At the electrocortical level, we hypothesized that sustained attention performance according to the CRF level would be linked to topographic maps in a time period corresponding to the P3b ERP component. Specifically, we expected modulations in subregions of the frontoparietal network according to the CRF level.

We found that in a large sample of young healthy adults, the CRF was related to sustained attention performance (response time and accuracy) but not to the performance decrement over time. At an electrocortical level, the analyses revealed that the CRF was associated with GFP (310–333 ms) and scalp topography changes (413–501 ms). The source localization analyses indicated increased activity within the PCC (BA 30) followed by earlier participation of the SMA (BA6) in the participants with higher physical fitness.

As expected, participants showed an increase in response times and a decrease in accuracy over time, suggesting that prolonged time on the PVT might have affected sustained attention in our group of young adults. CRF levels were associated with faster average response times and lower average accuracy. In addition, complementary analyses on the whole response times distribution indicated that CRF levels were associated with each quintile of the response times' distribution. This suggest that high-fit individuals have faster response times as well as less attentional lapses compared to low-fit ones. These results are consistent with previous studies suggesting better sustained attention performance in high-fit participants than in low-fit participants (Ciria et al., 2017; Luque-Casado et al., 2013; Luque-Casado et al., 2016; Sanabria et al., 2019). Moreover, the relationship between CRF and PVT performance was maintained even when adjusting the model with confounding variables such as age, BMI and CPA, reinforcing evidence in support of a role of CRF in PVT performance. However, the CRF was not related to the performance decrement over time (response times and accuracy), suggesting that higher CRF levels do not protect against the vigilance decrement. It is important to mention that we made the choice to examine the general performance and the performance decrement of sustained attention. Moment-to-moment fluctuations of performance, which is another way to evaluate sustained attention could be deeper scrutinized in future studies (for example, see Esterman et al., 2013). Taken together, our behavioral results suggest that CRF is related to the ability to allocate attention more quickly to an infrequent stimulus but not to a higher capacity to resist the vigilance decrement when attention is required over a long period of time.

At the electrocortical level, our data analysis approach enabled a more detailed understanding of the electrocortical dynamics by examining differential changes in the strength of the same active sources (GFP differences) or in the spatial distribution of the active sources within the brain (topographic differences) (Habermann et al., 2018).

First, we found that GFP and CRF significantly covaried between 310 and 333 ms. The topography identified in this time period looks similar to that found in the study of Luque-Casado et al. (2016b), which found higher P3 amplitudes in high-fit participants than in low-fit participants. Interestingly, the GFP and response time covaried significantly in a similar time window between 253 and 370 ms corroborating our behavioral result in which higher CRF is related to faster response times.

In addition, electrocortical localization of the generators of our topography indicated activation within the PCC (BA 30), meaning that between 310 and 333 ms, a higher CRF was associated with higher activation in this region. This finding is consistent with studies indicating that participation in physical activity and CRF are associated with increased activation of cerebral regions involved in cognitive control (Chaddock-Heyman et al., 2013; Colcombe et al., 2004). The higher activation of the PCC may seem counterintuitive given that the PCC is known to be a major node of the DMN that is generally involved in internally directed thought and thus associated with poorer cognitive performance (Buckner et al., 2008; Leech et al., 2012; Raichle et al., 2001). However, recent studies proposed a more complex role of the DMN in attention (Esterman et al., 2013; Hahn et al., 2007; Kucyi et al., 2016). Indeed, these studies showed an association between higher DMN activity and greater cognitive performance (faster response times and lower response times variability). More specifically, the PCC seems to play a role in attentional control by supporting behavioral responses to unpredictable events, allowing efficient reaction to environmental changes (Hahn et al., 2007; Leech et al., 2012; Leech and Sharp, 2014). The activation of the PCC appears congruent here, as the target occurrences were unpredictable in the PVT. Moreover, the literature has pointed out the involvement of the PCC in arousal regulation. Indeed, some studies have shown that the level of arousal is positively associated with activation of the PCC whereas low level of arousal is associated with low activation and a decreased functional connectivity of the PCC as observed in general anaesthesia, coma, and locked-in state (Fiset et al., 1999; Laureys et al., 2004; Song et al., 2017). As performing a sustained attention task requires a high level of arousal, our finding is in accordance with the hypothesis stating that the PCC is actively involved in arousal upregulation. Taken together, we can hypothesize that faster response times in the PVT by people with higher CRF are related to greater brain capacity to rapidly capture the visual target (via an increased arousal state) as compared to people with lower CRF.

Second, we found a significant scalp topographic covariance with the CRF in a time window between 413 and 501 ms. The covariance map was characterized by a central distribution classically associated with the P3b ERP component (Kappenman and Luck, 2012). This result is in accordance with a large number of studies that reported that CRF was related to larger P3b amplitudes and shorter P3b latencies with topographies characterized by centroparietal distributions during cognitive tasks (Kao et al., 2019). Moreover, we found a topographic covariance with the response time in a similar time window between 392 and 484 ms. The covariance map is characterized by a negative central distribution indicating that slow responders exhibit a lower central activity than fast responders. This result is in accordance with the relationship found between CRF, response times and the P3b component. In addition, since the TANCOVA analysis was normalized by the GFP, we can assume that the significant covariation with the CRF is due to a difference in the spatial distribution of the underlying active brain sources (Habermann et al., 2018). This topographic difference is likely to be explained by the fact that the P3b component appears earlier in high-fit participants than in low-fit participants (see Fig. 2A). Therefore, it can be suggested that greater CRF might speed up the occurrence of the P3b ERP component, which could explain why response times are faster.

Electrocortical localization of the generators of the covariance map indicated specific activation in the SMA in this time window. Interestingly, these regions are part of the frontoparietal network involved in sustained attention (Langner and Eickhoff, 2013). More specifically, it has been reported that the activation of the pre-SMA allows the cognitive maintenance of a motor plan to respond adaptively to a stimulus (Cunnington et al., 2002; Jennings and Van Der Molen, 2005). In this way, the SMA appears to play a role in the speed of response times by keeping the motor plan of the finger movement activated during the task. Consistent with our results, a previous study using a vigilance task with unpredictable stimuli showed that greater activation of the SMA before and after stimulus presentation was associated with faster response times (Hinds et al., 2013). Hence, it can be suggested that the earlier activation of the SMA in individuals with higher CRF is associated with a faster initiation of a motor response to a stimulus.

## 5. Limitations

This study has a certain number of limitations. First, we decided to use a very simple sustained attention task that is rather different than real life situations in which sustained attention is required. In future studies, it would be interesting to characterize these brain dynamics in a more ecological sustained attention task mixing targets and distractors to deeper understand the role of the PCC and SMA. Second, as our task design ended trials after 1000 ms, we cannot exclude different behavioral results in the last portion of the response times distribution (slower response times) if the task design allowed for longer response times. Finally, it is worth mentioning that, in addition to CRF, gait speed has also been found to be predictive of sustained attention capacity (Lo et al., 2017; Park et al., 2021). However, this relationship has been observed in elderly only. Instead of VO2max measurement, gait speed could serve as a proxy of the functional capacity that could be used in future studies investigating the association between physical fitness and sustained attention in young adults.

## 6. Conclusion

In conclusion, this work demonstrates that in young adults, sustained attention performance is actually related to CRF. However, higher CRF seems to not protect against the vigilance decrement classically observed in sustained attention tasks. At the EEG level, we confirmed the relationship between CRF and the P3b ERP component in young adults. Moreover, by using analyses sensitive to more complete spatiotemporal information of EEG recordings, we suggest that the higher level of CRF is primarily related to a stronger activation of the PCC followed by an earlier peak of the P3b component whose brain's sources have been localized within the SMA. These two brain regions are associated with the target capture, arousal and motor plan retrieval processes. Taken together, the results of the current study provide a further understanding of the brain mechanisms underlying CRF and sustained attention in young adults.

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## CRediT authorship contribution statement

**Francesco Di Muccio:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Paolo Ruggeri:** Software, Formal analysis, Writing – review & editing. **Catherine Brandner:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration. **Jérôme Barral:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration.

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## References

Adams, R., 1999. Revised physical activity readiness questionnaire. Canad. Family Phys. Médecin de Famille Canadien 45, 992.

Arito, H., Oguri, M., 1990. Contingent negative variation and reaction time of physically-trained subjects in simple and discriminative tasks. Ind. Health 28 (2), 97–106. https://doi.org/10.2486/INDHEALTH.28.97.

Baecke, J.A.H., Burema, J., Frijters, J.E.R., 1982. A short questionnaire for the measurement of habitual physical activity in epidemiological studies. Am. J. Clin. Nutr. 36 (5), 936–942. https://doi.org/10.1093/ajcn/36.5.936.

Balota, D.A., Yap, M.J., 2011. Moving beyond the mean in studies of mental chronometry: the power of response time distributional analyses. Https://Doi.Org/10.1177/0963721411408885. https://doi.org/10.1177/0963721411408885, 166, 20, 3, 160.

Borg, G., 1970. Perceived exertion as an indicator of somatic stress. Scand. J. Rehabil. Med. 2 (2), 92–98.

Buckner, R.L., Andrews-Hanna, J.R., Schacter, D.L., 2008. The brain's default network: anatomy, function, and relevance to disease. Ann. N. Y. Acad. Sci. 1124 (Issue 1), 1–38. https://doi.org/10.1196/annals.1440.011. John Wiley & Sons, Ltd.

Cardoso, J.F., 1998. Blind signal separation: statistical principles. Proc. IEEE 86 (10), 2009–2025. https://doi.org/10.1109/5.720250.

Caspersen, C.J., Powell, K.E., Christenson, G.M., 1985. Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research. Publ. Health Rep. 100 (2), 126–131.

Chaddock-Heyman, L., Erickson, K.I., Voss, M.W., Knecht, A.M., Pontifex, M.B., Castelli, D.M., Hillman, C.H., Kramer, A.F., 2013. The effects of physical activity on functional MRI activation associated with cognitive control in children: a randomized controlled intervention. Front. Hum. Neurosci. 7 (FEB), 72. https://doi.org/10.3389/fnhum.2013.00072.

Ciria, L.F., Perakakis, P., Luque-Casado, A., Morato, C., Sanabria, D., 2017. The relationship between sustained attention and aerobic fitness in a group of young adults. PeerJ 5, e3831. https://doi.org/10.7717/peerj.3831.

Clayton, M.S., Yeung, N., Cohen Kadosh, R., 2015. The roles of cortical oscillations in sustained attention. Trends Cognit. Sci. 19 (4), 188–195. https://doi.org/10.1016/j.tics.2015.02.004.

Colcombe, S.J., Kramer, A.F., Erickson, K.I., Scalf, P., McAuley, E., Cohen, N.J., Webb, A., Jerome, G.J., Marquez, D.X., Elavsky, S., 2004. Cardiovascular fitness, cortical plasticity, and aging. Proc. Natl. Acad. Sci. U.S.A. 101 (9), 3316–3321. https://doi.org/10.1073/pnas.0400266101.

Cunnington, R., Windischberger, C., Deecke, L., Moser, E., 2002. The preparation and execution of self-initiated and externally-triggered movement: a study of event-related fMRI. Neuroimage 15 (2), 373–385. https://doi.org/10.1006/nimg.2001.0976.

Dinges, D.F., Powell, J.W., 1985. Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. Behav. Res. Methods Instrum. Comput. 17 (6), 652–655. https://doi.org/10.3758/BF03200977.

Drummond, S.P.A., Bischoff-Grethe, A., Dinges, D.F., Ayalon, L., Mednick, S.C., Meloy, M.J., 2005. The neural basis of the psychomotor vigilance task. Sleep 28 (9), 1059–1068. https://doi.org/10.1093/sleep/28.9.1059.

Esterman, M., Noonan, S.K., Rosenberg, M., Degutis, J., 2013. In the zone or zoning out? Tracking behavioral and neural fluctuations during sustained attention. Cerebr. Cortex 23 (11), 2712–2723. https://doi.org/10.1093/cercor/bhs261.

Esterman, M., Rothlein, D., 2019. Models of sustained attention. Curr. Opin. Psychol. 29, 174–180. https://doi.org/10.1016/J.COPSYC.2019.03.005.

Fernandes, M., de Sousa, A., Medeiros, A.R., Del Rosso, S., Stults-Kolehmainen, M., Boullosa, D.A., 2018. The influence of exercise and physical fitness status on attention: a systematic review. Int. Rev. Sport Exerc. Psychol. 1–33. https://doi.org/10.1080/1750984X.2018.1455889.

Fiset, P., Paus, T., Daloze, T., Plourde, G., Meuret, P., Bonhomme, V., Hajj-Ali, N., Backman, S.B., Evans, A.C., 1999. Brain mechanisms of propofol-induced loss of consciousness in humans: a positron emission tomographic study. J. Neurosci. 19 (13), 5506–5513. https://doi.org/10.1523/JNEUROSCI.19-13-05506.1999.

Fortenbaugh, F.C., Degutis, J., Esterman, M., 2017. Recent theoretical, neural, and clinical advances in sustained attention research. Ann. N. Y. Acad. Sci. 1396, 70–91. https://doi.org/10.1111/nyas.13318.

Habermann, M., Weusmann, D., Stein, M., Koenig, T., 2018. A student's guide to randomization statistics for multichannel event-related potentials using Ragu. Front. Neurosci. 12 (JUN), 355. https://doi.org/10.3389/fnins.2018.00355.

Hahn, B., Ross, T.J., Stein, E.A., 2007. Cingulate activation increases dynamically with response speed under stimulus unpredictability. Cerebr. Cortex 17 (7), 1664–1671. https://doi.org/10.1093/cercor/bhl075.

Hervey, A.S., Epstein, J.N., Curry, J.F., Tonev, S., Eugene Arnold, L., Keith Conners, C., Hinshaw, S.P., Swanson, J.M., Hechtman, L., 2007. Reaction time distribution analysis of neuropsychological performance in an ADHD sample. Https://Doi.Org/10.1080/09297040500499081. https://doi.org/10.1080/09297040500499081, 12, 2, 125, 140.

Hillman, C.H., Kamijo, K., Pontifex, M.B., 2012b. The relation of erp indices of exercise to brain health and cognition. In: Functional Neuroimaging in Exercise and Sport Sciences. Springer, New York, pp. 419–446. https://doi.org/10.1007/978-1-4614-3293-7_18.

Hinds, O., Thompson, T.W., Ghosh, S., Yoo, J.J., Whitfield-Gabrieli, S., Triantafyllou, C., Gabrieli, J.D.E., 2013. Roles of default-mode network and supplementary motor area in human vigilance performance: evidence from real-time fMRI. J. Neurophysiol. 109 (5), 1250–1258. https://doi.org/10.1152/jn.00533.2011.

Hommel, B., Chapman, C.S., Cisek, P., Neyedli, H.F., Song, J.-H., Welsh, T.N., 2019. No one knows what attention is. Atten. Percept. Psychophys. 81 (7), 2288–2303. https://doi.org/10.3758/s13414-019-01846-w.

Huang, W.J., Chen, W.W., Zhang, X., 2015. The neurophysiology of P 300 - an integrated review. Eur. Rev. Med. Pharmacol. Sci. 19 (8), 1480–1488 https://doi.org/8813 [pii].

Jennings, J.R., Van Der Molen, M.W., 2005. Preparation for speeded action as a psychophysiological concept. Psychol. Bull. 131 (3), 434–459. https://doi.org/10.1037/0033-2909.131.3.434.

Kaminsky, L.A., Arena, R., Myers, J., 2015. Reference standards for cardiorespiratory fitness measured with cardiopulmonary exercise testing. Mayo Clin. Proc. 90 (11), 1515–1523. https://doi.org/10.1016/j.mayocp.2015.07.026.

Kao, S.-C., Cadenas-Sanchez, C., Shigeta, T.T., Walk, A.M., Chang, Y.-K., Pontifex, M.B., Hillman, C.H., 2019. A systematic review of physical activity and cardiorespiratory fitness on P3b. Psychophysiology, e13425. https://doi.org/10.1111/psyp.13425.

Kappenman, E.S., Luck, S.J., 2012. The oxford handbook of event-related potential components. In: The Oxford Handbook of Event-Related Potential Components. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780195374148.001.0001.

Koenig, T., Kottlow, M., Stein, M., Melie-García, L., 2011. Ragu: a free tool for the analysis of EEG and MEG event-related scalp field data using global randomization statistics. Comput. Intell. Neurosci. 14 https://doi.org/10.1155/2011/938925, 2011.

Koenig, T., Melie-García, L., Stein, M., Strik, W., Lehmann, C., 2008. Establishing correlations of scalp field maps with other experimental variables using covariance analysis and resampling methods. Clin. Neurophysiol. 119 (6), 1262–1270. https://doi.org/10.1016/j.clinph.2007.12.023.

Kucyi, A., Hove, M.J., Esterman, M., Hutchison, R.M., Valera, E.M., 2016. Dynamic brain network correlates of spontaneous fluctuations in attention. Cerebr. Cortex 27 (3), bhw029. https://doi.org/10.1093/cercor/bhw029.

Langner, R., Eickhoff, S.B., 2013. Sustaining attention to simple tasks: a meta-analytic review of the neural mechanisms of vigilant attention. Psychol. Bull. 139 (4), 870–900. https://doi.org/10.1037/a0030694.

Laureys, S., Owen, A.M., Schiff, N.D., 2004. Brain function in coma, vegetative state, and related disorders. Lancet Neurol. 3 (9), 537–546. https://doi.org/10.1016/S1474-4422(04)00852-X.

Lawrence, N.S., Ross, T.J., Hoffmann, R., Garavan, H., Stein, E.A., 2003. Multiple neuronal networks mediate sustained attention. J. Cognit. Neurosci. 15 (7), 1028–1038. https://doi.org/10.1162/089892903770007416.

Leech, R., Braga, R., Sharp, D.J., 2012. Echoes of the brain within the posterior cingulate cortex. J. Neurosci. 32 (1), 215–222. https://doi.org/10.1523/JNEUROSCI.3689-11.2012.

Leech, R., Sharp, D.J., 2014. The role of the posterior cingulate cortex in cognition and disease. Brain 137 (1), 12–32. https://doi.org/10.1093/brain/awt162. Oxford University Press.

Linden, D.E.J., 2005. The p300: where in the brain is it produced and what does it tell us? Neuroscientist : A Rev. J. Bring. Neurobiol. Neurol. Psychiatr. 11 (6), 563–576. https://doi.org/10.1177/1073858405280524.

Lo, O.Y., Halko, M.A., Zhou, J., Harrison, R., Lipsitz, L.A., Manor, B., 2017. Gait speed and gait variability are associated with different functional brain networks. Front. Aging Neurosci. 9 (NOV), 390. https://doi.org/10.3389/FNAGI.2017.00390/BIBTEX.

Luce, R.D., 1986. Response times: their role in inferring elementary mental organization. *Response Times: Their Role in Inferring Elementary Mental Organization*. https://doi.org/10.1093/ACPROF:OSO/9780195070019.001.0001, 1–562.

Luck, S.J., 2012. Event-related potentials. APA handbook of research methods in psychology, vol 1. Found. Plann. Measur. Psychometr. 1, 523–546. https://doi.org/10.1037/13619-028.

Luque-Casado, A., Perakakis, P., Ciria, L.F., Sanabria, D., 2016a. Transient autonomic responses during sustained attention in high and low fit young adults. Sci. Rep. 6, 1–6. https://doi.org/10.1038/srep27556.

Luque-Casado, A., Perakakis, P., Hillman, C.H., Kao, S.C., Llorens, F., Guerra, P., Sanabria, D., 2016b. Differences in sustained attention capacity as a function of aerobic fitness. Med. Sci. Sports Exerc. 48 (5), 887–895. https://doi.org/10.1249/MSS.0000000000000857.

Luque-Casado, A., Zabala, M., Morales, E., Mateo-March, M., Sanabria, D., 2013. Cognitive performance and heart rate variability: the influence of fitness level. PLoS One 8 (2). https://doi.org/10.1371/journal.pone.0056935.

McEvoy, L.K., Smith, M.E., Gevins, A., 2000. Test–retest reliability of cognitive EEG. Clin. Neurophysiol. 111 (3), 457–463. https://doi.org/10.1016/S1388-2457(99)00258-8.

Michel, C.M., Koenig, T., Brandeis, D., Gianotti, L.R.R., Wackermann, J., 2009. Electrical neuroimaging. In: Electrical Neuroimaging. https://doi.org/10.1017/CBO9780511596889.

Murray, M.M., Brunet, D., Michel, C.M., 2008. Topographic ERP analyses: a step-by-step tutorial review. Brain Topogr. 20 (4), 249–264. https://doi.org/10.1007/s10548-008-0054-5.

Oken, B.S., Salinsky, M.C., Elsas, S.M., 2006. Vigilance, alertness, or sustained attention: physiological basis and measurement. Clin. Neurophysiol. 117 (9), 1885–1901. https://doi.org/10.1016/j.clinph.2006.01.017.

Parasuraman, R., 2000. The Attentive Brain.

Park, H., Aul, C., DeGutis, J., Lo, O.Y., Poole, V.N., McGlinchey, R., Bean, J.F., Leritz, E., Esterman, M., 2021. Evidence for a specific association between sustained attention and gait speed in middle-to-older-aged adults. Front. Aging Neurosci. 13, 326. https://doi.org/10.3389/FNAGI.2021.703434/BIBTEX.

Parsons, S., 2021. splithalf: robust estimates of split half reliability. J. Open Sour. Softw. 6 (60), 3041. https://doi.org/10.21105/joss.03041.

Pascual-Marqui, R.D., 2002. Standardized low-resolution brain electromagnetic tomography (sLORETA): technical details. Methods Find. Exp. Clin. Pharmacol. 24 (Suppl. D), 5–12.

Pate, R.R., Kriska, A., 1984. Physiological basis of the sex difference in cardiorespiratory endurance. Sports Med.: An International Journal of Applied Med. Sci. Sport Exerc. 1 (2), 87–89. https://doi.org/10.2165/00007256-198401020-00001.

Peirce, J., Gray, J.R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., Lindeløv, J.K., 2019. PsychoPy2: experiments in behavior made easy. Behav. Res. Methods 51 (1), 195–203. https://doi.org/10.3758/s13428-018-01193-y.

Perrin, F., Pernier, J., Bertnard, O., Giard, M.H., Echallier, J.F., 1987. Mapping of scalp potentials by surface spline interpolation. Electroencephalogr. Clin. Neurophysiol. 66 (1), 75–81. https://doi.org/10.1016/0013-4694(87)90141-6.

Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. Clin. Neurophysiol. 118 (10), 2128–2148. https://doi.org/10.1016/J.CLINPH.2007.04.019.

Raichle, M.E., MacLeod, A.M., Snyder, A.Z., Powers, W.J., Gusnard, D.A., Shulman, G.L., 2001. A default mode of brain function. Proc. Natl. Acad. Sci. U.S.A. 98 (2), 676–682. https://doi.org/10.1073/pnas.98.2.676.

Robergs, R.A., Dwyer, D., Astorino, T., 2010. Recommendations for improved data processing from expired gas analysis indirect calorimetry. Sports Med. 40 (2), 95–111. https://doi.org/10.2165/11319670-000000000-00000.

Roecker, K., Niess, A.M., Horstmann, T., Striegel, H., Mayer, F., Dickhuth, H.H., 2002. Heart rate prescriptions from performance and anthropometrical characteristics. Med. Sci. Sports Exerc. 34 (5), 881–887. https://doi.org/10.1097/00005768-200205000-00024.

Sanabria, D., Luque-Casado, A., Perales, J.C., Ballester, R., Ciria, L.F., Huertas, F., Perakakis, P., 2019. The relationship between vigilance capacity and physical exercise: a mixed-effects multistudy analysis. PeerJ (6), e7118. https://doi.org/10.7717/peerj.7118, 2019.

Smallwood, J., Schooler, J.W., 2006. The restless mind. Psychol. Bull. 132 (6), 946–958. https://doi.org/10.1037/0033-2909.132.6.946.

Song, A.H., Kucyi, A., Napadow, V., Brown, E.N., Loggia, M.L., Akeju, O., 2017. Pharmacological modulation of noradrenergic arousal circuitry disrupts functional connectivity of the locus ceruleus in humans. J. Neurosci. 37 (29), 6938–6945. https://doi.org/10.1523/JNEUROSCI.0446-17.2017.

Stillman, C.M., Cohen, J., Lehman, M.E., Erickson, K.I., 2016. Mediators of physical activity on neurocognitive function: a review at multiple levels of analysis. Front. Hum. Neurosci. 10, 626. https://doi.org/10.3389/fnhum.2016.00626.

Stroth, S., Kubesch, S., Dieterle, K., Ruchsow, M., Heim, R., Kiefer, M., 2009. Physical fitness, but not acute exercise modulates event-related potential indices for executive control in healthy adolescents. Brain Res. 1269, 114–124. https://doi.org/10.1016/J.BRAINRES.2009.02.073.

Voss, M.W., Vivar, C., Kramer, A.F., van Praag, H., 2013. Bridging animal and human models of exercise-induced brain plasticity. Trends Cognit. Sci. 17 (10), 525–544. https://doi.org/10.1016/j.tics.2013.08.001.

Walter, W.G., Cooper, R., Aldridge, V.J., McCallum, W.C., Winter, A.L., 1964. Contingent negative variation : an electric sign of sensori-motor association and expectancy in the human brain. Nature 203 (4943), 380–384. https://doi.org/10.1038/203380a0, 1964 203:4943.

Wang, C.-Y., Haskell, W.L., Farrell, S.W., LaMonte, M.J., Blair, S.N., Curtin, L.R., Hughes, J.P., Burt, V.L., 2010. Cardiorespiratory fitness levels among US adults 20-49 Years of age: findings from the 1999-2004 national health and nutrition examination survey. Am. J. Epidemiol. 171 (4), 426–435. https://doi.org/10.1093/aje/kwp412.

Warm, J.S., Parasuraman, R., Matthews, G., 2008. Vigilance requires hard mental work and is stressful. Hum. Factors 50 (3), 433–441. https://doi.org/10.1518/001872008X312152. SAGE PublicationsSage CA: Los Angeles, CA.

Whelan, R., 2017. Effective analysis of reaction time data. Psychol. Record 58 (3), 475–482. https://doi.org/10.1007/BF03395630, 2008 58:3.

Zeiher, J., Ombrellaro, K.J., Perumal, N., Keil, T., Mensink, G.B.M., Finger, J.D., 2019. Correlates and determinants of cardiorespiratory fitness in adults: a systematic review. Sports Med. - Open 5 (1), 39. https://doi.org/10.1186/s40798-019-0211-2.