Differences in Sustained Attention Capacity as a Function of Aerobic Fitness

ANTONIO LUQUE-CASADO[1,2,3], PANDELIS PERAKAKIS[1,4], CHARLES H. HILLMAN[5], SHIH-CHUN KAO[5], FRANCESC LLORENS[6,7], PEDRO GUERRA[1,4], and DANIEL SANABRIA[1,2]

[1]*Brain, Mind, and Behavior Research Center, University of Granada, Granada, SPAIN;* [2]*Department of Experimental Psychology, University of Granada, Granada, SPAIN;* [3]*Department of Physical Education & Sport, University of Granada, Granada, SPAIN;* [4]*Department of Personality, Evaluation & Psychological Treatment, University of Granada, Granada, SPAIN;* [5]*Department of Kinesiology & Community Health, University of Illinois at Urbana-Champaign, Champaign, IL;* [6]*Department of Physical Activity & Sport Sciences, Catholic University of Valencia, Valencia, SPAIN; and* [7]*Universidad Internacional Valenciana (VIU), Valencia, SPAIN*

ABSTRACT

LUQUE-CASADO, A., P. PERAKAKIS, C. H. HILLMAN, S.-C. KAO, F. LLORENS, P. GUERRA, and D. SANABRIA. Differences in Sustained Attention Capacity as a Function of Aerobic Fitness. *Med. Sci. Sports Exerc.*, Vol. 48, No. 5, pp. 887–895, 2016. **Purpose**: We investigated the relationship between aerobic fitness and sustained attention capacity by comparing task performance and brain function, by means of event-related potentials (ERP), in high- and low-fit young adults. **Methods**: Two groups of participants (22 higher-fit and 20 lower-fit) completed a 60-min version of the Psychomotor Vigilance Task (PVT). Behavioral (i.e., reaction time) and electrophysiological (ERP) (i.e., contingent negative variation and P3) were obtained and analyzed as a function of time-on-task. A submaximal cardiorespiratory fitness test confirmed the between-groups difference in terms of aerobic fitness. **Results**: The results revealed shorter reaction time in higher-fit than in lower-fit participants in the first 36 min of the task. This was accompanied by larger contingent negative variation amplitude in the same period of the task in higher-fit than in lower-fit group. Crucially, higher-fit participants maintained larger P3 amplitude throughout the task compared to lower-fit, who showed a reduction in the P3 magnitude over time. **Conclusions**: Higher fitness was related to neuroelectric activity suggestive of better overall sustained attention demonstrating a better ability to allocate attentional resources over time. Moreover, higher fitness was related to enhanced response preparation in the first part of the task. Taken together, the current data set demonstrated a positive association between aerobic fitness, sustained attention, and response preparation. **Key Words:** VIGILANCE, ERP, PHYSICAL ACTIVITY, EXERCISE, COGNITION, REACTION TIME

Over the past decades, growing evidence from various experimental approaches has shown that aerobic fitness and cognitive-behavioral performance are positively related (16). A major component of this research has revealed aerobic fitness-related improvements in a variety of tasks involving different cognitive functions, that is, from processing speed to higher-order cognitive control or memory (34). Despite the progress on this topic, relatively little is known about an inherent cognitive process in the majority of these cognitive tasks that is necessary for optimal performance, that is, sustained or vigilance attention. Here, we aimed at filling this gap by providing novel evidence of the positive relationship between aerobic fitness and the capacity to sustain attention (or to be vigilant) over time during task performance. To achieve this, we compared a higher-fit and a lower-fit group of young adults in terms of reaction time (RT) performance and brain function (by means of event-related potentials [ERP]) in a 60-min long attentional task.

Sustained or vigilant attention is a higher-order cognitive function that determines the readiness to respond to relevant stimuli and the capacity to effectively allocate attentional resources over time. This cognitive function represents a fundamental component of the general cognitive capacities of humans because a reduced ability to monitor significant sources of information directly affects all cognitive abilities (i.e., slow responses and/or failures to respond to target stimuli [33]). In effect, the capacity to sustain attention is highly important both in specific laboratory contexts and in the completion of many everyday or professional activities that usually occur over long periods, such as attending to academic lessons at school, driving, sports, surgery, or air traffic control (22). Crucially, our ability to sustain attention is far from stable and an extended period of attentional demands on a single task leads to a decrement in performance over time, which is known as time-on-task effect or vigilance decrement (8). Therefore, investigation into variables that might contribute against vigilance-related decrements in attention and performance over time is highly relevant.

Address for correspondence: Antonio Luque-Casado, M.S., Centro de Investigación Mente, Cerebro y Comportamiento (CIMCYC), Campus Universitario de Cartuja (s/n), 18071, Granada, Spain; E-mail: antonioluque@ugr.es.

Submitted for publication September 2015.
Accepted for publication December 2015.

0195-9131/16/4805-0887/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000000857

Previous research has examined the relationship between aerobic fitness and attentional mechanisms (30), but a relatively scant literature to date has addressed the association between aerobic fitness and sustained attention in a direct manner like in the present study. For example, Bunce (6) evaluated the influence of physical fitness on age differences in vigilance as a function of the time course of a task and the level of task complexity, showing an attenuated vigilance decrement in higher-fit older adults in comparison with their lower-fit counterpart. Crucially, no group differences were found in young adults. The results of the few related studies testing children also point to a positive relationship between aerobic fitness and sustained attention. For instance, Pontifex et al. (31) concluded that poor aerobic fitness was related to impaired vigilance on the basis of an observed increase in error of omissions and more sequences of omissions in lower-fit relative to higher-fit preadolescent participants during a flanker task. Chaddock et al. (7) investigated the time course of behavioral performance and brain functioning during a flanker task in preadolescents participants. They showed a decline in performance over time on incongruent trials, but only for lower-fit participants, who demonstrated a bilateral increase in activation in frontal and parietal brain regions from early to late blocks of trials. Higher-fit participants, in contrast to their lower-fit peers, showed decreased activity as a function of time-on-task, but greater activity was shown in early blocks with respect to lower-fit participants. Meanwhile, Ballester et al. (2) showed a positive relationship between fitness and vigilance during adolescence, with higher-fit participants showing overall shorter RT than lower-fit participants in the Psychomotor Vigilance Task (PVT).

Despite a growing literature in children and some studies with older adults, the potential significant relationship between aerobic fitness and sustained attention in young adults remains poorly understood. Although cognitive health peaks during young adulthood (32), which could act by reducing the room for exercise-related improvement in cognitive function in this age group, research consistently demonstrates the importance of physical activity in keeping, and potentially improving, cognitive function throughout life (14). Additionally, the study of the relationship between sustained attention and aerobic fitness in this age range is highly relevant because of the disproportionate decline in physical activity from adolescence to early adulthood (21). To the best of our knowledge, the results reported by Luque-Casado et al. (27) represent the sole evidence of a selective association between aerobic fitness and sustained attention in young adults. This study showed better vigilance performance in higher-fit as compared to lower-fit participants, indexed by shorter overall RT in a 10 min version of the PVT, whereas no differences where shown in an endogenous temporal orienting task and in a duration discrimination task. These results were taken as evidence suggesting superior sustained attention capacity in young higher-fit relative to lower-fit participants. Note, though, that Luque-Casado et al. reported group differences in overall RT but not in terms of the RT vigilance decrement.

Thus, convergent evidence suggests the important role of aerobic fitness on sustained attentional capacity, but research is scarce, and several important questions remain open. For example, the few studies to date assessing one of the factors that have been shown to tax-sustained attention (i.e., the duration of the task [8]), as a function of aerobic fitness, have reported inconsistent results. A vigilance decrement of greater magnitude has been shown in lower-fit individuals relative to their higher-fit peers both in preadolescents and in older adults (6,31), whereas no differences were found in young adults (6,27). Importantly, previous studies have shown that prolonged sustained attention demands (i.e., 20 to 30 min) are needed to elicit a significant deterioration in sustained attention performance in young adults (13). Therefore, given that all the aforementioned studies used experimental tasks that typically last for only a few minutes (i.e., 10 min at the most), the use of a task with extended sustained attentional demands (i.e., exceeding 30 min of duration) may increase the likelihood of observing a between-groups difference in the magnitude of the time-on-task effect in young adults.

Additionally, the underlying neural basis of the aerobic fitness-related improvements in vigilance performance is another important issue that remains unknown. Two main ERP components of interest with regard to fitness and sustained attention are the P3 and the contingent negative variation (CNV). On the one hand, the P3 potential is commonly thought to reflect the amount of attentional resources directed toward task-relevant information in the stimulus environment (29). It has been one of the main indexes of interest in the study of sustained attention, elucidating a relationship between P3 amplitude and task performance over time (i.e., with RT increasing and P3 amplitude decreasing [20]). Crucially, aerobic fitness has also been related to differences in P3 amplitude, with greater fitness related to larger P3 amplitude (15); thus, fitness may serve as a buffer against vigilance-related decrements in attention and performance over time. On the other hand, the CNV is a slow negative wave occurring during the preparatory interval between a warning signal and an impending stimulus that requires a response, which appears to reflect sensory, cognitive, and motor preparation processes (37). Importantly, studies have reported a positive relationship between aerobic fitness and the magnitude of the CNV, leading to improved cognitive performance in aerobically fit individuals compared with their lesser-fit counterparts across several cognitive tasks assessing working memory (19), cognitive control (35), or processing speed (1). However, although the magnitude of the CNV has been shown to depend on sustained attention (4), the association between aerobic fitness and the magnitude of the CNV has not been investigated on the basis of sustained attentional performance.

Thus, as noted above, the present study stands to provide novel evidence of the relationship between aerobic fitness, behavioral performance, and brain function of young adults in a prolonged sustained attention task during the prestimulus response preparation (i.e., CNV) and poststimulus periods (i.e., P3). Based on previous evidence (1,15,19,35), we expected the higher-fit group to have larger CNV and P3 amplitude values than the lower-fit group, which would also be related to higher overall performance in the vigilance task. Further, we predicted that both CNV and P3 amplitudes would gradually deteriorate as a result of the time-on-task effect, but with the higher-fit group showing an attenuated vigilance decrement and maintaining larger overall values during the course of the task.

METHOD

Participants. An *a priori* power analysis was conducted to determine the minimum sample size required for a power level of 0.80. This analysis was based on data from the previous study by Luque-Casado et al. (27) where they compared performance in the PVT of a group of young cyclists and triathletes (higher-fit) to that of a group of young adults with sedentary lifestyle (lower-fit). This analysis gave an outcome of 22 participants per group.

We recruited 50 young male adults to participate in the present study, 25 undergraduate students from the University of Granada (Spain) to be included in the lower-fit group and 25 young adults (15 members from triathlon local clubs and 10 from the Faculty of Physical Activity and Sport Sciences, University of Granada, Spain) to be included in the higher-fit group. The participants in the higher- and lower-fit groups met the inclusion criteria of reporting at least 8 h of training per week or less than 2 h, respectively. Eight of the 50 participants (three higher-fit and five lower-fit) were subsequently excluded from the analyses (see data reduction section). Thus, only data from the remaining 42 participants are reported (see Table 1).

The experiment reported herein was conducted according to the ethical requirements of the local committee and complied with the ethical standards laid down in the 1964 Declaration of Helsinki. All participants gave informed consent before their inclusion in the study, had normal or corrected-to-normal vision, and no history of neuropsychological impairment. They were required to maintain a regular sleep–wake cycle for at least 1 d before the study and to avoid caffeine and vigorous physical activity before the laboratory visit. All participants' data were analyzed and reported anonymously.

TABLE 1. Mean and 95% CI of descriptive and fitness data for the higher-fit and lower-fit groups.

	Higher-Fit	Lower-Fit
Anthropometrical characteristics		
Sample size[a]	22	20
Age (yr)	22 [21, 24]	23 [22, 24]
Height (cm)	1.76 [1.74, 1.78]	1.78 [1.75, 1.81]
Weight (kg)	69.6 [67.1, 72.1]	76.9 [69.0, 85.6]
Body Mass Index ($kg \cdot m^{-2}$)	22.4 [21.7, 23.1]	24.1 [22.1, 26.2]
Incremental test parameters		
Time to VAT (s)	1285 [1180.1, 1386.6]	494 [421.5, 566.5]
$\dot{V}O_2$ ($mL \cdot min^{-1} \cdot kg^{-1}$) at VAT	43.7 [40.4, 47.4]	19.5 [17.2, 21.8]
Relative power output at VAT ($W \cdot kg^{-1}$)	3.42 [3.13, 3.73]	1.39 [1.21, 1.58]

[a] Only data of the participants included in the analyses are reported.
VAT, ventilatory anaerobic threshold.

Procedure. Upon arrival to the laboratory, participants were seated in front of a computer in a dimly illuminated, sound-attenuated room with a Faraday cage. First, participants signed the informed consent and were prepared for electrophysiological measurement. Participants then received verbal and written instructions regarding the PVT and practiced the task for 1 min. The experiment consisted of a single 60-min block. Once they completed the PVT, all participants performed a submaximal incremental cycle ergometer test to evaluate their fitness level. The experimental session was administered during daylight hours, with approximately half the participants participating in the morning (i.e., 11 higher-fit athletes, 11 lower-fit nonathletes) and the other half in the afternoon (i.e., 11 athletes, nine nonathletes). The entire experimental session lasted 2 h approximately.

Incremental effort test. A brief preliminary anthropometric study of each participant was performed to measure height, weight, and body mass index (see Table 1). We used a ViaSprint 150 P cycle ergometer (Ergoline GmbH, Germany) to induce physical effort and to obtain power values and a JAEGER Master Screen gas analyzer (CareFusion GmbH, Germany) to provide a measure of gas exchange during the effort test. Before the start of the test, participants were fitted with a Polar RS800 CX monitor (Polar Electro Öy, Kempele, Finland) to record their HR during the incremental exercise test and the cycle ergometer was set to the individual anthropometric characteristics.

We used a modified version of the incremental effort test from the previous study by Luque-Casado et al. (27). The incremental effort test started with a 3-min warm-up at 30 W, with the power output increasing 10 W every minute. The test began at 60 W and was followed by an incremental protocol with the power load increasing 30 W every 3 min. Workload increased progressively during the third minute of each step (5 W every 10 s); therefore, each step of the incremental protocol consisted of 2 min of stabilized load and 1 min of progressive load increase. Each participant set his preferred cadence (60–90 rpm) during the warm-up. They were asked to maintain this cadence throughout the protocol. The ergometer software was programmed to increase the load automatically.

Determination of the ventilatory anaerobic threshold (VAT) was based on RER [RER = CO_2 production/O_2 consumption]. More specifically, VAT was defined as the $\dot{V}O_2$ at the time when RER exceeded the cutoff value of 1.0 (9,40). The researcher knew that the participant had reached his VAT when the RER was equal to 1.00 and did not drop below that level during the 2-min constant load period or during the next load step, never reaching the 1.1 RER. The submaximal incremental test ended once the VAT was reached. The oxygen uptake ($\dot{V}O_2$, $mL \cdot min^{-1} \cdot kg^{-1}$), RER, relative load ($W \cdot kg^{-1}$), HR (bpm), and time of the test (s) were continuously recorded during the entire incremental test. The fitness level of the participants was determined from the data set obtained during the incremental physical test (see Table 1).

The PVT. We used a PC with a 19-inch monitor and E-Prime software (Psychology Software Tools, Pittsburgh, PA) to control the stimulus presentation, response collection, and to generate and send triggers indicating the condition of each trial for offline sorting, reduction, and analysis of electroencephalogram (EEG) and behavioral data. The center of the PC screen was situated approximately 60 cm from the participant's head and at eye level. The device used to collect responses was a PC keyboard.

The procedure of the PVT was based on the original version (39). This task was designed to measure vigilance by recording participants' RT to visual stimuli that occur at random interstimulus intervals (3,39). Each trial began with the presentation of a blank screen in a black background for 2000 ms, and subsequently, an empty red circumference (6.68° × 7.82°) appeared in a black background. Later, in a random time interval (between 2000 and 10,000 ms), the circumference was filled all at once in a red color. Participants were instructed to respond as fast as they could once they had detected the presentation of the filled circle. The filled circle was presented for 500 ms, and the participants had a maximum of 1500 ms to respond. They had to respond with their dominant hand by pressing the space bar on the keyboard. An RT visual feedback message was displayed for 300 ms after response, except in case of an anticipated response ("wait for the target") or if no response was made within 1000 ms after target offset ("you did not answer"). After the feedback message, the next trial began. Response anticipations were considered errors. The task comprised a single block of 60 min of total duration, and the mean number of trials per participant was 402 ± 8.9.

EEG recordings. Continuous EEG data were recorded using a BioSemi Active Two system (Biosemi, Amsterdam, Netherlands) and were digitized at a sample rate of 1024 Hz with 24-bit A/D conversion. The 64 active scalp Ag/AgCl electrodes were arranged according to the international standard 10–20 system for electrode placement using a nylon head cap. The common mode sense and driven right leg electrodes served as the ground, and all scalp electrodes were referenced to the common mode sense during recording. The cap was adapted to the individual's head size, and each electrode was filled with Signa Electro-Gel (Parker Laboratories, Fairfield, NJ) to optimize signal transduction. Participants were instructed to avoid eye movements, blinking and body movements as much as possible, and to keep their gaze on the center of the screen during task performance.

Data reduction. The behavioral data analyses were performed on the overall participants' mean RT. Trials with RT below 100 ms (0.03%), anticipations (i.e., responses prior to the target presentation; 1.49%), and omissions (if no response was made within 1000 ms after target offset; 0.24%) were discarded from the analysis (3).

We used a combination of bespoke Matlab scripts (Matlab 2013a, Mathworks Inc.), EEGLAB toolbox (version 13.2.2b, [10]) and ERPLAB toolbox (version 4.0.2.3, [23]) for processing and analyzing ERP data. Continuous data were downsampled to 256 Hz, merged offline with behavioral data, and rereferenced to the average of all electrodes (average common reference). Noisy scalp electrodes were identified via visual inspection (only in three of the participants) and were replaced by an average of the voltages recorded at other neighbor scalp electrodes (three electrodes on average were replaced in these subjects). We applied independent component analysis (ICA) (10) to correct eye blink artifacts (17). In order to remove baseline drifts, data were high-pass filtered (0.1 Hz; 12 dB per octave) before running ICA. Prototypical ICA components representing eye movements and blinks were assessed on the raw EEG data before being excluded to corroborate their consistency and temporal match with the ocular artifacts. The ocular ICA components were removed in a systematic way for all participants to avoid any bias across the groups. On average, one independent component was removed per participant.

Once the ocular artifacts were corrected, separate epochs were constructed for cues (between −200 and 2000 ms relative to cue onset) and targets (between −200 and 1000 ms relative to target onset). The protocol typically used to elicit the CNV is a two-stimulus (S1-S2) paradigm in which changes in amplitude between warning (S1) and imperative stimuli (S2) are measured. Note that 2000 ms is the minimum duration of the random interval between the cue and the target in the PVT paradigm and therefore, the point of maximal uncertainty. There is previous evidence showing a reliable CNV potential even under conditions of high uncertainty about the onset of S2 (36). Then, the PVT paradigm whereby participants have to respond to a target stimulus (S2) that appears in a random interval between 2 and 10 s after the presentation of a cue stimulus (S1) allows the measurement of the CNV. The 200-ms prestimulus period was used for baseline correction both in cues and targets epochs. Subsequently, data were filtered with a 30-Hz low-pass cutoff (24 dB per octave). Remaining artifacts (EMG, noisy electrodes, etc.) exceeding ± 100 μV in amplitude were detected, and the epochs including those artifacts were excluded from further analysis. To ensure a sufficient signal-to-noise ratio and to reduce the possibility that the type I error rate was inflated by *post hoc* exclusion of subjects, we set an *a priori* criteria of excluding participants for whom more than 25% of trials were rejected (23,26). This resulted in the exclusion of three higher-fit and five lower-fit participants. A minimum of 68 trials per condition was maintained. Separate grand average waveforms were constructed across all participants according to both cues and targets categories.

Data measure and electrodes selection. For cue and target analyses, amplitude was calculated as the mean voltage in a specified temporal window and electrodes site. The temporal windows were chosen on the basis of visual inspection of the grand average waveforms. The electrodes selection for both cue-locked and target-locked analyses was a two-stage process. First, several electrodes were selected for each potential of interest based on the topographical distribution of the scalp activity (see Figs. 1 and 2). Next, electrodes for statistical analyses were chosen by their maximal positive or negative voltage value from each cluster, respectively. Thus, each potential was represented by an average of the selected electrodes. Specifically, the CNV potential was represented at frontal and central sites as the maximal negative mean amplitude between 1500 and 2000 ms after cue onset at electrode Fz, FCz, Cz, and CPz. The P3 potential was represented at posterior sites as the maximal mean amplitude between 240 and 440 ms after target onset at Pz and POz.

Design and statistical analysis. Three sets of dependent variables were evaluated in this study: 1) Participants' descriptive and fitness data (i.e., anthropometrical and incremental exercise test parameters), 2) behavioral data (i.e., overall mean RT), and 3) ERP data (i.e., CNV and P3 mean amplitude values). For the behavioral and ERP data, five temporal blocks of 12 min were considered for the analysis to measure the time-on-task effect.

Nonparametric permutation tests were used to analyze the data. Importantly, these tests are exact, unbiased, and assumption-free in terms of the underlying distribution of the data (11,28). We followed a general label exchange procedure for within-participants factorial designs (12) using a Monte Carlo approach.

The participants' descriptive and fitness data were analyzed using one-way between-groups design. For the behavioral and ERP data, we had a factorial design with the between-groups variable of group (higher-fit and lower-fit) and the within-groups variable of time-on-task (block 1, block 2, block 3, block 4, and block 5). Significant main effects and interactions were further explored by using *post hoc*, pairwise comparisons,

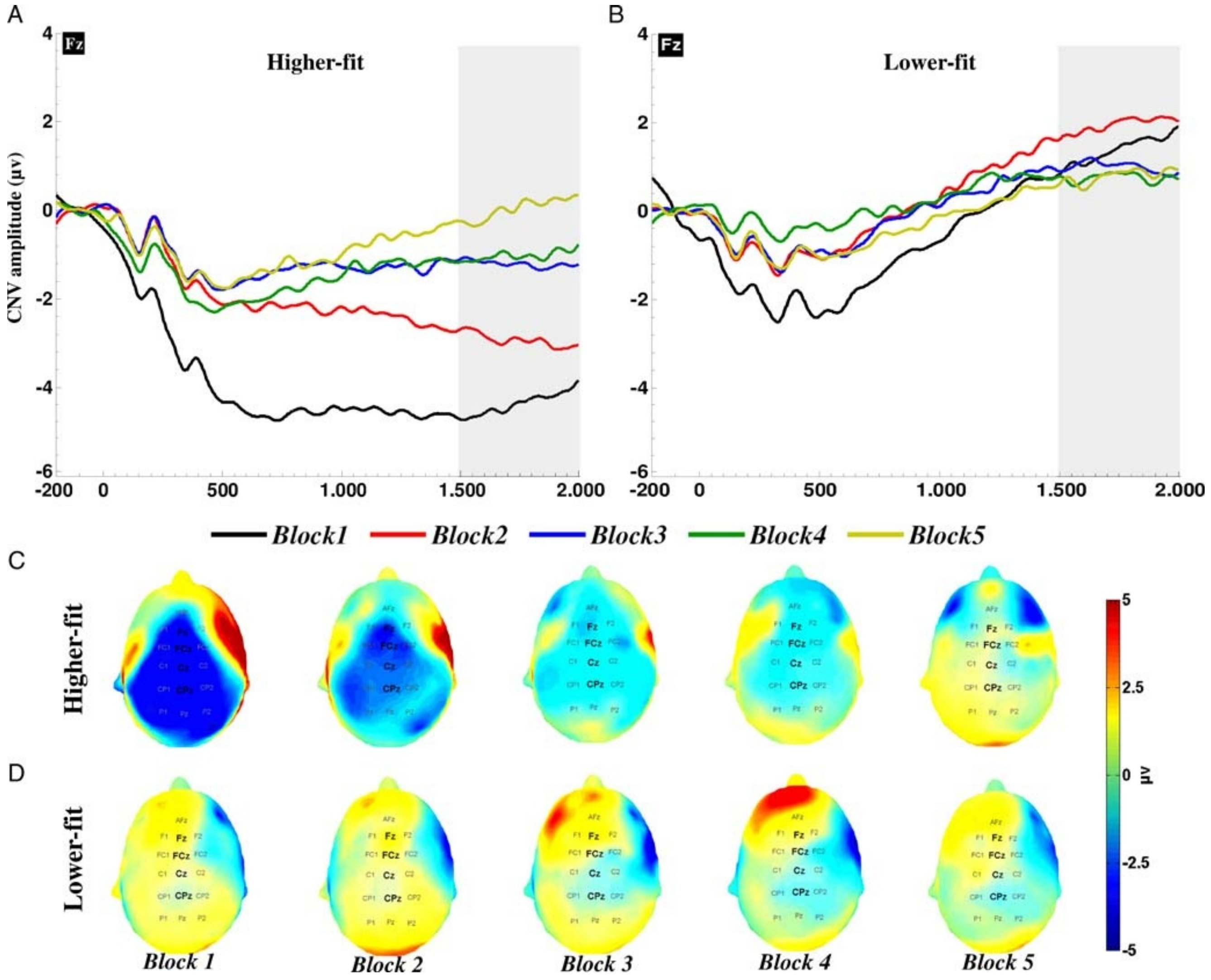

FIGURE 1—Grand average waveforms and topographic scalp distribution of the CNV as a function of group and block. Grand average waveforms are presented at Fz electrode. Time zero represents the cue stimulus appearance. Separate graphs for higher-fit (A) and lower-fit (B) are shown for clarity. Color lines are used to represent the waveforms as a function of block. Gray marks show the time windows analyzed (i.e., 1500–2000 ms). Topographic scalp distribution of CNV amplitude (spectrum scale: blue to red) is illustrated for the higher-fit group (C) and lower-fit group (D) as a function of block. The electrode sites included in the analyses are highlighted in bold in the topographic plots.

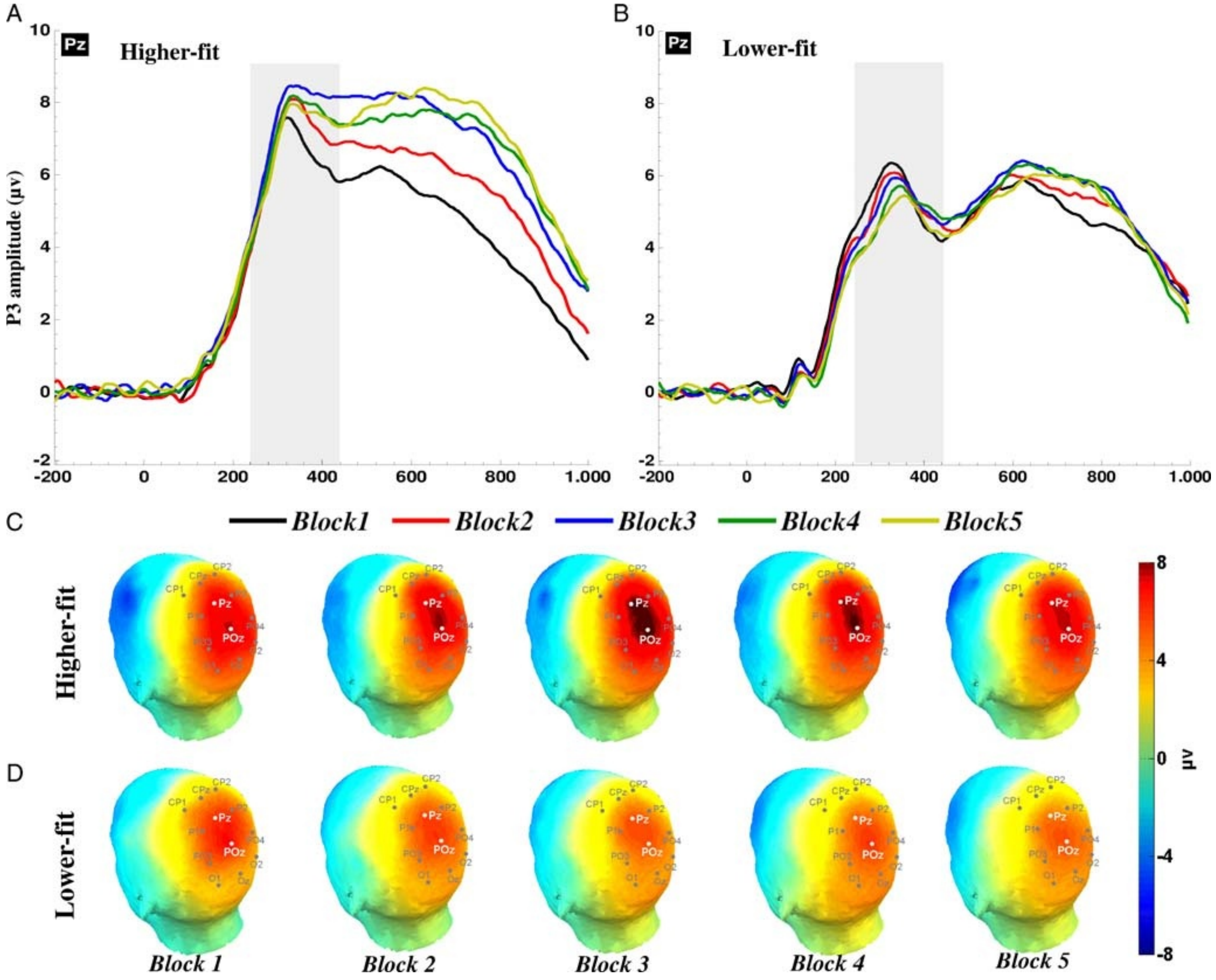

FIGURE 2—Grand average waveforms and topographic scalp distribution of the P3 amplitude as a function of group and block. Grand average waveforms are presented at Pz electrode. Time zero represents the target stimulus appearance. Separate graphs for higher-fit (A) and lower-fit (B) are shown for clarity. Color lines are used to represent the waveforms as a function of block. Gray marks show the time windows analyzed (i.e., 240–440 ms). Topographic scalp distribution of P3 amplitude (spectrum scale: blue to red) is illustrated for the higher-fit group (C) and lower-fit group (D) as a function of block. The electrode sites included in the analyses are highlighted in white in the topographic plots.

and separate main effects analyses when appropriate. Multiple comparisons correction was accounted for by applying the false discovery rate (FDR) approach. 95% confidence intervals (CI) and probability threshold values are reported.

RESULTS

Descriptive and Fitness Data

The permutations tests for independent samples revealed significant differences between groups in all the incremental test parameters (i.e., time to VAT (s), relative power output ($W \cdot kg^{-1}$) at VAT and $\dot{V}O_2$ ($mL \cdot min^{-1} \cdot kg^{-1}$) at VAT) (all P's < 0.01). All data showed evidence of the difference in fitness level between groups (see Table 1). There were no statistically significant differences between groups in any of the anthropometrical parameters (all P's ≥ 0.11).

Behavioral Results

Participants' mean RT results showed significant main effects of group ($P < 0.01$) and time-on-task ($P < 0.01$). Crucially, both main effects were better qualified by the significant interaction between group and time-on-task ($P < 0.01$; see Fig. 3). Pairwise comparisons (FDR corrected; P-threshold = 0.005) were performed between the higher-fit and lower-fit group within each temporal block. The comparisons showed significant differences between groups at blocks 1, 2, and 3 (all P's ≤ 0.005) with higher-fit being faster than lower-fit group (see Fig. 3). There were no significant differences when comparing both groups in the remaining blocks (all P's ≥ 0.78).

Electrophysiological Results

Cue-locked ERP. The CNV mean amplitude analyses revealed significant main effects of group ($P < 0.01$) and

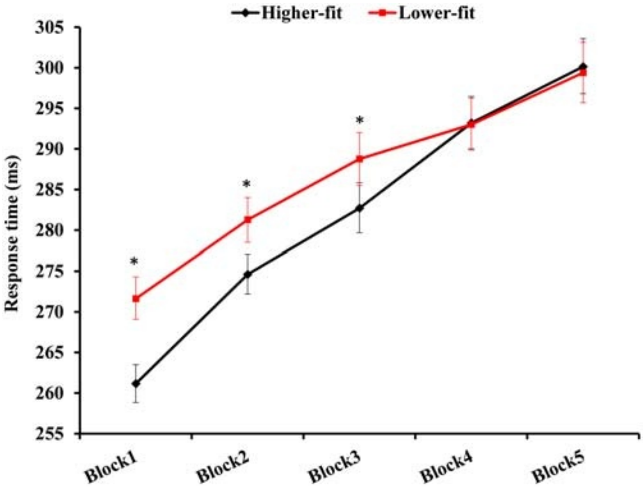

FIGURE 3—Mean and 95% CI of the response time (ms) as a function of group and block. *Significant differences between groups within each block ($P \leq 0.005$).

time-on-task ($P < 0.01$) that were better qualified by the significant interaction between group and time-on-task ($P < 0.01$; see Figs. 1 and 4). Further analyses showed a statistically significant main effect of time-on-task in the higher-fit group ($P < 0.01$), with the amplitude of the CNV becoming less negative as time went on. However, this same analysis was not significant for the lower-fit group ($P = 0.19$). Furthermore, pairwise comparisons (FDR corrected; P threshold = 0.029) showed significant differences between groups at block 1 ($P < 0.01$), block 2 ($P < 0.01$), and block 3 ($P = 0.029$). In all cases, the higher-fit group showed greater CNV negativity than lower-fit group (see Fig. 4). There were no significant differences when comparing groups in blocks 4 and 5 (both $Ps \geq 0.08$).

Target-locked ERP. The P3 mean amplitude results showed significant main effects of group ($P < 0.01$) and time-on-task ($P < 0.01$). Again, the interaction between group and time-on-task reached statistical significance ($P < 0.01$; see Figs. 2 and 5). Separate main effect analyses of time-on-task reached significance both for the higher-fit and lower-fit group (both P's < 0.01). In order to explain this interaction further, we performed *post hoc* comparisons (FDR corrected; P-threshold = 0.003). For the higher-fit group, P3 amplitude values peaked in block 3. There were statistically significant differences when comparing block 3 with respect to blocks 1, 2, and 5 (all P's ≤ 0.003). Additionally, the comparison between blocks 1 and 4 also showed significant differences ($P < 0.001$). There were no significant differences when comparing the remaining blocks (all P's ≥ 0.06; see Fig. 5). In the case of the lower-fit group, the comparisons showed significant differences only between blocks 1 and 5 ($P = 0.003$), with decreasing amplitude over time. None of the remaining comparisons between blocks reached statistically significant differences (all P's ≥ 0.02; see Fig. 5). Additionally, pairwise comparisons (FDR-corrected; P threshold = 0.0001) showed significant differences between groups in all blocks (all P's ≤ 0.0001), with the higher-fit group showing greater P3 mean amplitude than the lower-fit group (see Fig. 5).

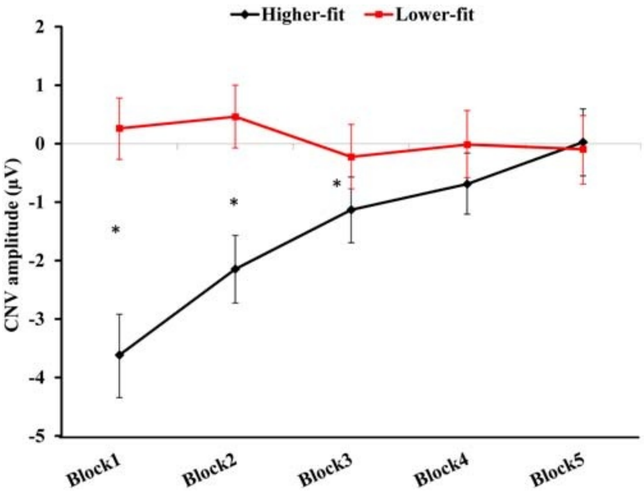

FIGURE 4—Mean amplitude and 95% CI of the CNV as a function of group and block. *Significant differences between groups within each block ($P \leq 0.03$).

DISCUSSION

In the present study, we tested the positive relation between aerobic fitness and sustained attention capacity by comparing RT performance, the CNV and the P3 amplitude, in a 60-min attention demanding task of two groups of participants: higher- and lower-fit young adults.

The results showed that higher-fit participants responded faster than lower-fit participants during the first three blocks of the task (i.e., 36 min). This was accompanied by larger CNV amplitude in the same blocks in higher-fit than in lower-fit adults; however, this difference disappeared in the later blocks. Crucially, higher-fit participants maintained larger P3 amplitude throughout the task compared with lower-fit participants,

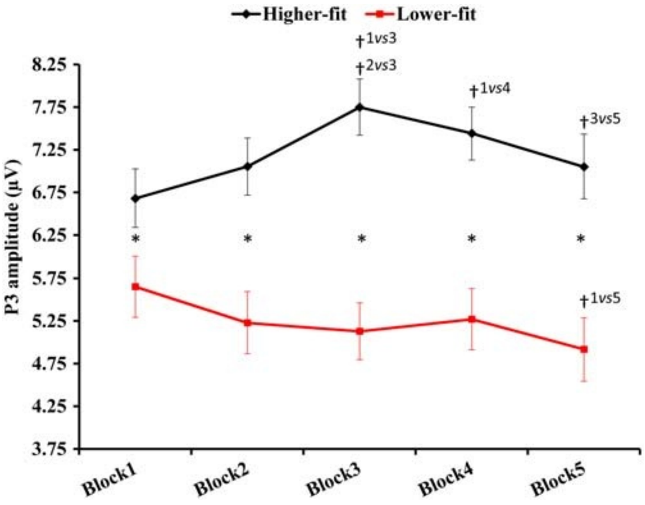

FIGURE 5—Mean amplitude and 95% CI of the P3 as a function of group and block. *Significant differences between groups within each block ($P \leq 0.0001$). †Significant differences between blocks within each group ($P \leq 0.003$).

who showed a reduction in the P3 magnitude as a function of the time-on-task.

Concerning performance in the PVT, the results in the first part of the task are in accordance with the previous study by Luque-Casado et al. (27), suggesting better vigilance capacity in higher-fit young adults relative to their lower-fit counterparts. However, a greater vigilance decrement was shown in higher-fit than in lower-fit participants. The ERP data provided crucial information in order to understand these apparently contradictory results. The CNV and RT patterns were closely related, such that the higher-fit group showed larger CNV amplitude in the first half of the task (blocks 1 to 3) compared with the lower-fit group, but, again, these differences disappeared in the later blocks. It is known that temporal preparation substantially enhances performance by reducing response times to an imminent signal in simple RT tasks, (18) and in fact, the magnitude of the CNV has been shown to depend on sustained attention (4). Thus, the improved performance in higher-fit participants indexed by shorter RT in the early blocks of the task might be the result of better cue facilitation despite the high temporal uncertainty of the task, suggesting an enhanced top-down processing in terms of endogenous preparation in this group. This supports previous evidence showing that higher-fit participants are better at the stage of preparation before target onset and the behavioral response (19,35) as well as activating and adapting neural processes involved in cognitive control to meet and maintain task goals (7). However, important here is that the response preparation benefit could not be maintained throughout the task by higher-fit participants and disappeared over time, leading in turn to the loss of group differences in RT.

Maintaining attention for long periods requires hard mental work leading to a mental fatigue state (38), which has been evidenced in our study by the vigilance decrement over time in both groups. Additionally, it is known that mental fatigue results in a reduction of top-down attentional capacity (5). Therefore, even though both groups were affected by mental fatigue, in the case of higher-fit participants, it appeared to impact on the enhanced endogenous preparation as a function of the time-on-task, thus leading to the disappearance of the improved behavioral performance. Indeed, this would agree with previous studies showing greater difficulties in maintaining the state of endogenous preparation in mentally fatigued participants (25) evidenced by the significant attenuation of brain activity elicited by cue information (i.e., CNV) as a function of time-on-task (24).

In general terms, the P3 potential is thought to reflect the amount of attentional resources directed to task-relevant information in the stimulus environment (29), and accordingly, the P3 should be taken as the relevant index of sustained attention in our study. In accordance with previous research (15), we observed larger P3 amplitude for the high-fit participants suggesting an enhanced ability to allocate attentional resources relative to their lower-fit counterparts. Novel to these previous accounts is the fact that, first, we measured directly and specifically the ability to maintain attention, unlike previous studies whose interest was focused mainly on investigating the relationship of fitness with cognitive control; and second, the time-on-task effect differentially affected P3 amplitude in higher-fit and lower-fit participants showing a depletion in the allocation of attentional resources from the beginning of the task only in the latter group.

Interestingly, higher-fit participants maintained larger P3 amplitude relative to lower-fit participants and demonstrated maximum amplitude in the third temporal block. The amplitude significantly decreased through the end of the task following the third block, although, importantly, never reaching lower values than in the first block. This apparent depletion in attentional resources allocation coincided in time with the disappearance of their improved temporal preparation (indexed by the CNV), which could have led indirectly to an increase in demands for maintaining the task goal in the absence of cue facilitation, causing added mental fatigue and leading to the observed decrease in P3 amplitude from the peak reached in block 3. In any case, it is noteworthy that the higher-fit group always showed greater amplitude of P3 relative to the lower-fit group throughout the task, and crucially, only the lower-fit group showed a significant reduction of the P3 amplitude from the beginning of the task. All in all, and according to previous evidence (20), these results can be taken as an index of enhanced ability to maintain the allocation of attentional resources over time in higher-fit participants with respect to lower-fit participants.

In conclusion, higher fitness was related to neuroelectric activity suggestive of better overall sustained attention and a better response preparation (although only in the first part of the task). Taken together, the current data set replicates and extends this area of research by demonstrating an association between higher amounts of aerobic fitness and sustained attention. However, it is important to consider that sport training context is a stimulating environment where both cardiovascular fitness and perceptual-cognitive skills are enhanced, which might in turn influence cognitive function. Consequently, other factors in addition to fitness might also account for (at least part) of the group differences reported here. Hence, future research would benefit from study designs that include specific sport groups and account for the potential influence of the perceptual-cognitive skills involved in sport training context to clarify the specific, rather than combined, effect both of the cardiovascular fitness and the sport training context on vigilance performance. Finally, because sustaining attention is a basic requirement for information processing and, consequently, a fundamental component of the general cognitive capacities of humans, our findings provide additional evidence of the broad relevance for public health of a physically active lifestyle aimed at improving aerobic fitness. In effect, this should be considered in environments, such as education (i.e., in integrated educational development plans), or many other aspects of everyday life and professional activities (e.g., driving, surgery, military and border surveillance, lifeguarding or air traffic control) because this might lead to a reduction of the likelihood of attentional failures in prolonged high-demand environments.

This research was supported by a predoctoral grant from the Spanish Ministerio de Educación, Cultura y Deporte (FPU-AP2010-3630) to the first author, and research grants from the Ministerio de Economía y Competitividad (PSI2013-46385-P) and the Junta de Andalucía (SEJ-6414) to Daniel Sanabria. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. We thank to Enrique Molina for providing his knowledge and assistance in the statistical data analyses, and to all the participants who took part in the experiment. We also thank to Human Psychophysiology and Health Research Group (University of Granada) for allowing us to use their facilities and assessment instruments. No conflicting financial, consultant, institutional, or other interests exist. Results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Arito H, Oguri M. Contingent negative variation and reaction time of physically-trained subjects in simple and discriminative tasks. *Ind Health*. 1990;28(2):97–106.
2. Ballester R, Huertas F, Yuste FJ, Llorens F, Sanabria D. The relationship between regular sports participation and vigilance in male and female adolescents. *PLoS One*. 2015;10(4):e0123898.
3. Basner M, Dinges DF. Maximizing sensitivity of the psychomotor vigilance test (PVT) to sleep loss. *Sleep*. 2011;34(5):581–91.
4. Bickel S, Dias EC, Epstein ML, Javitt DC. Expectancy-related modulations of neural oscillations in continuous performance tasks. *Neuroimage*. 2012;62(3):1867–76.
5. Boksem MA, Meijman TF, Lorist MM. Effects of mental fatigue on attention: an ERP study. *Cogn Brain Res*. 2005;25(1):107–16.
6. Bunce D. Age differences in vigilance as a function of health-related physical fitness and task demands. *Neuropsychologia*. 2001;39(8):787–97.
7. Chaddock L, Erickson KI, Prakash RS, et al. A functional MRI investigation of the association between childhood aerobic fitness and neurocognitive control. *Biol Psychol*. 2012;89(1):260–8.
8. Davies DR, Parasuraman R. *The Psychology of Vigilance*. Academic Press; 1982. p. 306.
9. Davis JA, Vodak P, Wilmore JH, Vodak J, Kurtz P. Anaerobic threshold and maximal aerobic power for three modes of exercise. *J Appl Physiol*. 1976;41(4):544–50.
10. Delorme A, Makeig S. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J Neurosci Methods*. 2004;134(1):9–21.
11. Ernst MD. Permutation methods: a basis for exact inference. *Statist Sci*. 2004;19(4):676–85.
12. Good PI. *Permutation, Parametric, and Bootstrap Tests of Hypotheses*. Springer Science & Business Media; 2006. p. 331.
13. Grier RA, Warm JS, Dember WN, Matthews G, Galinsky TL, Parasuraman R. The vigilance decrement reflects limitations in effortful attention, not mindlessness. *Hum Factors*. 2003;45(3):349–59.
14. Guiney H, Machado L. Benefits of regular aerobic exercise for executive functioning in healthy populations. *Psychon Bull Rev*. 2013;20(1):73–86.
15. Hillman CH, Buck SM, Themanson JR, Pontifex MB, Castelli DM. Aerobic fitness and cognitive development: event-related brain potential and task performance indices of executive control in preadolescent children. *Dev Psychol*. 2009;45(1):114–29.
16. Hillman CH, Erickson KI, Kramer AF. Be smart, exercise your heart: exercise effects on brain and cognition. *Nat Rev Neurosci*. 2008;9(1):58–65.
17. Hoffmann S, Falkenstein M. The correction of eye blink artefacts in the EEG: a comparison of two prominent methods. *PLoS One*. 2008;3(8):e3004.
18. Jennings JR, van der Molen MW. Preparation for speeded action as a psychophysiological concept. *Psychol Bull*. 2005;131(3):434–59.
19. Kamijo K, Pontifex MB, O'Leary KC, et al. The effects of an afterschool physical activity program on working memory in preadolescent children. *Dev Sci*. 2011;14(5):1046–58.
20. Koelega HS, Verbaten MN, van Leeuwen TH, Kenemans JL, Kemner C, Sjouw W. Time effects on event-related brain potentials and vigilance performance. *Biol Psychol*. 1992;34(1):59–86.
21. Kwan MY, Cairney J, Faulkner GE, Pullenayegum EE. Physical activity and other health-risk behaviors during the transition into early adulthood: a longitudinal cohort study. *Am J Prev Med*. 2012;42(1):14–20.
22. Larue GS, Rakotonirainy A, Pettitt AN. Driving performance impairments due to hypovigilance on monotonous roads. *Accid Anal Prev*. 2011;43(6):2037–46.
23. Lopez-Calderon J, Luck SJ. ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Front Hum Neurosci [Internet] 2014* [cited 2015 Sep 16]; 8 (213). Available from: http://journal.frontiersin.org/article/10.3389/fnhum.2014.00213/full. doi:10.3389/fnhum.2014.00213.
24. Lorist MM. Impact of top-down control during mental fatigue. *Brain Res*. 2008;1232:113–23.
25. Lorist MM, Klein M, Nieuwenhuis S, De Jong R, Mulder G, Meijman TF. Mental fatigue and task control: planning and preparation. *Psychophysiology*. 2000;37(5):614–25.
26. Luck SJ. *An Introduction to the Event-Related Potential Technique*. Cambridge, Mass: The MIT Press; 2005. p. 376.
27. Luque-Casado A, Zabala M, Morales E, Mateo-March M, Sanabria D. Cognitive performance and heart rate variability: the influence of fitness level. *PLoS One*. 2013;8(2):e56935.
28. Pesarin F, Salmaso L. The permutation testing approach: a review. *Statistica*. 2010;70(4):481–509.
29. Polich J, Kok A. Cognitive and biological determinants of P300: an integrative review. *Biol Psychol*. 1995;41(2):103–46.
30. Pontifex MB, Hillman CH, Polich J. Age, physical fitness, and attention: P3a and P3b. *Psychophysiology*. 2009;46(2):379–87.
31. Pontifex MB, Scudder MR, Drollette ES, Hillman CH. Fit and vigilant: the relationship between poorer aerobic fitness and failures in sustained attention during preadolescence. *Neuropsychology*. 2012;26(4):407–13.
32. Salthouse TA, Davis HP. Organization of cognitive abilities and neuropsychological variables across the lifespan. *Dev Rev*. 2006;26(1):31–54.
33. Sarter M, Givens B, Bruno JP. The cognitive neuroscience of sustained attention: where top-down meets bottom-up. *Brain Res Brain Res Rev*. 2001;35(2):146–60.
34. Smith PJ, Blumenthal JA, Hoffman BM. Aerobic exercise and neurocognitive performance: a meta-analytic review of randomized controlled trials. *Psychosom Med*. 2010;72(3):239–52.
35. Stroth S, Kubesch S, Dieterle K, Ruchsow M, Heim R, Kiefer M. Physical fitness, but not acute exercise modulates event-related potential indices for executive control in healthy adolescents. *Brain Res*. 2009;1269:114–24.
36. Trillenberg P, Verleger R, Wascher E, Wauschkuhn B, Wessel K. CNV and temporal uncertainty with "ageing" and "non-ageing" S1–S2 intervals. *Clin Neurophysiol*. 2000;111(7):1216–26.
37. Walter WG, Cooper R, Aldridge VJ, McCallum WC, Winter AL. Contingent negative variation: an electric sign of sensorimotor association and expectancy in the human brain. *Nature*. 1964;203:380–4.
38. Warm JS, Parasuraman R, Matthews G. Vigilance requires hard mental work and is stressful. *Hum Factors*. 2008;50(3):433–41.
39. Wilkinson RT, Houghton D. Field test of arousal: a portable reaction timer with data storage. *Hum Factors*. 1982;24(4):487–93.
40. Yeh MP, Gardner RM, Adams TD, Yanowitz FG, Crapo RO. "Anaerobic threshold": problems of determination and validation. *J Appl Physiol Respir Environ Exerc Physiol*. 1983;55(4):1178–86.