

# The relationship between aerobic fitness and neural oscillations during visuo-spatial attention in young adults

Chun-Hao Wang · Wei-Kuang Liang · Philip Tseng ·  
Neil G. Muggleton · Chi-Hung Juan · Chia-Liang Tsai

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**Abstract** While the cognitive benefits of aerobic fitness have been widely investigated, current findings in young adults remain unclear. Specifically, little is known about how these effects are reflected in the time–frequency domain. This study thus assessed the relationship between aerobic fitness and neural oscillations during visuo-spatial attention. A between-subjects design that included 20 participants with higher aerobic fitness (age =  $21.95 \pm 2.24$  years;  $VO_{2max} = 58.98 \pm 6.94$  ml/kg/min) and 20 age- and gender-matched lower aerobic fitness participants (age =  $23.25 \pm 2.07$  years;  $VO_{2max} = 35.87 \pm 3.41$  ml/kg/min) was used to examine the fitness-related differences in performance and neuroelectric indexes during a Posner visuo-spatial attention paradigm. The results demonstrated that high-fitness participants, in comparison with their low-fitness counterparts, showed faster reaction times as well as greater modulation of oscillatory theta and beta power during target processing, regardless of cue types. Moreover, the

neurocognitive correlation showed that higher theta power was related to better task performance. Collectively, these findings suggest that aerobic fitness is associated with general enhanced attentional control in relation to visuo-spatial processing, as evidenced through greater motor preparation and in particular the up-regulation of attentional processing in healthy young adults. The present study may contribute to current knowledge by revealing the relationship between aerobic fitness and modulation of brain oscillations.

**Keywords** Cardiorespiratory fitness · Time–frequency analysis · Oscillatory brain rhythms · Attentional processing

## Introduction

The association between aerobic exercise and cognitive benefits has been widely demonstrated (Kramer and Erickson 2007; Hillman et al. 2008; Voss et al. 2013), with a majority of studies focusing on populations during developmental (Pontifex et al. 2011; Chaddock et al. 2012; Raine et al. 2013) or aging trajectories (Erickson et al. 2009, 2011; Voss et al. 2012) undergoing cognitive changes. There is thus a lack of studies that focus on young adults, possibly because there is little room for exercise-related improvements in cognitive peaks for this age group. Despite both this and the inconclusive results in the literature (Scisco et al. 2008; Guiney and Machado 2013; Verburch et al. 2013), there have been a small number of studies of young adults showing fitness-related beneficial effects on cognitive processes and brain functioning (Themanson et al. 2008; Åberg et al. 2009; Kamijo et al. 2010). Obviously, these inconsistent findings result in uncertainty in the association between fitness and cognition in young populations.

C.-H. Wang · C.-L. Tsai (✉)

Lab of Cognitive Neurophysiology, Institute of Physical Education, Health and Leisure Studies, National Cheng Kung University, No. 1, University Road, Tainan City 701, Taiwan, ROC  
e-mail: andytsai@mail.ncku.edu.tw

W.-K. Liang · N. G. Muggleton · C.-H. Juan  
Institute of Cognitive Neuroscience, National Central University, Zhongli 320, Taiwan, ROC

P. Tseng  
Brain and Consciousness Research Center, Taipei Medical University-Shuang Ho Hospital, 250 Wuxing Street, Taipei City 110, Taiwan

N. G. Muggleton  
Department of Psychology, Goldsmiths, University of London, New Cross, London, UK

Previous studies have indicated that certain cognitive functions (i.e., executive control) are strongly related to the effects of physical activity or aerobic fitness (Kramer et al. 1999; Colcombe and Kramer 2003; Pontifex et al. 2011). However, studies on young adults are not so clear (Scisco et al. 2008; Themanson et al. 2008; Kamijo et al. 2010; Kamijo and Takeda 2010). For instance, in studies investigating task switching, Kamijo and Takeda (2010) found that physically active young adults had a lower switching cost compared to sedentary controls, whereas Scisco et al. (2008) observed no such effect between young adults with different levels of aerobic fitness. The differences in task design may help explain this discrepancy (Guiney and Machado 2013); that is, the switching set was predictable in Kamijo and Takeda (2010), but not in Scisco et al. (2008). This interpretation leads to the possibility that the cognitive benefits of fitness may occur in the anticipatory state of attention rather than the switching processes (Guiney and Machado 2013), and this argument is supported by prior studies showing the positive relationship of aerobic fitness to efficiency in motor preparation (Hillman et al. 2002; Kamijo et al. 2010). Despite this, it remains unclear whether aerobic fitness is related to the processing of anticipatory information (e.g., spatial cues) that modulates the levels of attention processing and motor preparation.

Individuals are better at the processing of a stimulus when they are informed in advance about its critical feature(s) (Corbetta and Shulman 2002). The deployment of attention toward an upcoming extrapersonal visual space without eye movements requires visuo-spatial attention (Posner 1980; Posner et al. 2007; Raine et al. 2013). The task devised by Posner (1980) can provide a suitable psychophysical assessment of the voluntary aspect of visuo-spatial attention. In this task, each trial begins with a cue that indicates the possible location of an impending target. Further, the directional cue may either validly or invalidly indicates the target location. As a consequence of enhanced levels of attention or motor preparation, faster reaction times (RTs) can be observed following valid predictions (benefits) relative to invalid ones (costs), with the difference between the two being representative of the attentional cueing effect (Posner 1980; Corbetta et al. 2000; Tsai et al. 2009).

A spatially central cue in a typical visuo-spatial attention task (Posner 1980) requires goal-directed, endogenous (top-down) attention processes that involve the dorsal fronto-parietal network (Hopfinger et al. 2000; Corbetta and Shulman 2002). In functional imaging studies (Corbetta et al. 2000; Hopfinger et al. 2000), the frontal and parietal cortices were shown to activate when participants attended the cued location, indicating that the recruited brain regions were involved in the control of visuo-spatial attention. Interestingly, when compared to an aerobically

untrained person, better attentional performance, along with higher task-related activation in the fronto-parietal network, was observed for the aerobically trained participants (Colcombe et al. 2004; Hillman et al. 2008). Therefore, it seems plausible that the enhanced neural circuitry (e.g., fronto-parietal network) related to higher aerobic fitness might lead to benefits on cognitive functions that share common or at least overlapping neural networks (e.g., visuo-spatial attention).

Despite a variety of studies revealing the underlying mechanisms supporting the relationship between cognition and aerobic fitness (or physical activity) in young adults by utilizing functional neuroelectric techniques such as event-related potentials (ERPs) (Hillman et al. 2002, 2006; Scisco et al. 2008; Themanson et al. 2008; Kamijo et al. 2010), which provides useful information with high temporal resolution in milliseconds (ms), less is known regarding effects in the frequency domain. A time–frequency analysis of electroencephalography (EEG) can provide important information related to frequency-specific activity time-locked to events of interest (Roach and Mathalon 2008; Lo et al. 2013). Additionally, it decomposes event-related EEG signals into magnitude and phase information for each frequency band (Roach and Mathalon 2008), thereby allowing the examination of more refined and detailed information about neural oscillations in task-related cognitive processes (Uhlhass et al. 2010). For example, previous studies have shown that oscillations in the theta and alpha frequency bands can be seen for factors associated with visuo-spatial processing (Capotosto et al. 2009b; Fan et al. 2007), while beta power is considered to be associated with levels of motor preparation (Tzagarakis et al. 2010; Zhang et al. 2008). Given that greater aerobic fitness has been suggested to be associated with better cognitive functioning, such effects on task-related neural oscillations may also be observed. In support of this assumption, physically active young adults have been reported to have greater synchrony of neural oscillations at 22–34 Hz between brain regions compared to individuals who were physically inactive, indicating that physical activity is associated with better regulation of top-down cognitive control (Kamijo et al. 2011; Kamijo and Takeda 2013). These findings suggest that time–frequency EEG may be a suitable approach with regard to probing the neural mechanisms underneath the relationship between aerobic fitness and cognitive functioning.

In this study, we attempted to further understand the relationship between aerobic fitness and cognition in young adults by examining the effects of aerobic fitness on visuo-spatial attention. Specifically, the aim of this study was to determine the effects of fitness on oscillatory neural dynamics in the fronto-parietal network. To achieve this, we conducted an event-related EEG study

in young adults using the modified endogenous Posner central cue paradigm (Posner 1980; Tsai et al. 2009), which allows for the measurement of visuo-spatial attention and motor preparation (Hung et al. 2004). Based on the previous findings, it was expected that high-fitness participants would show better endogenous visuo-spatial attention processing than low-fitness ones given the task-dependent involvement (Corbetta and Shulman 2002) and exercise-related modulation (Colcombe et al. 2004) of the fronto-parietal circuit. In addition, because attentional processing is not related to a single frequency band (Fan et al. 2007), we tested oscillatory theta (4–7 Hz), alpha (8–14 Hz), and beta (15–35 Hz) activities due to their close relationship to visuo-spatial attention (Capotosto et al. 2009a; Mishra et al. 2012) and motor preparation (Tzagarakis et al. 2010), as this may help reveal novel insights into the understanding of role of aerobic fitness in modulating brain functioning in relation to oscillatory neural activity.

## Materials and methods

### Participants

Fifty-seven male undergraduate and graduate students, aged from 19 to 27 years, were recruited for this study. Only participants with aerobic fitness above the 75th percentile ( $VO_{2max} = 49.2$  ml/kg/min) or below the 45th percentile ( $VO_{2max} = 43.1$  ml/kg/min) according to the American College of Sports Medicine (ACSM) guidelines (ACSM 2009) were included, and they were assigned into high-fitness ( $n = 20$ ; aged  $21.45 \pm 2.24$  years) and low-fitness groups ( $n = 20$ ; aged  $23.25 \pm 2.07$  years). In addition, in order to reduce any possible risks during the cardiorespiratory endurance ( $VO_{2max}$ ) assessment, we excluded those who experienced overall energy expenditure below 600 metabolic equivalents per week (MET-min/week) according to the International Physical Activity Questionnaire (IPAQ) (Table 1). All participants had normal or

corrected-to-normal visual acuity and were right-handed. No individuals reported having a history of neurological problems or cardiovascular diseases, nor taking any medications that affect cognitive functions. All participants gave informed consent prior to participating, and the study was approved by the Institutional Review Board of National Cheng Kung University.

### Procedure

The experimental procedure consisted of two steps carried out on separate occasions and completed in <3 days. For the first step, the experimenter explained the experimental procedure and asked the participants to complete an informed consent form, a medical history and demographics questionnaire, a handedness inventory, and a short-form IPAQ. The height and weight of the subjects were measured to estimate their BMI values. They were then fitted with a Polar heart rate (HR) monitor (RX800CX, Finland) and subjected to a continuous graded maximal exercise test, which examined the  $VO_{2max}$  values so that they could be assigned into the high-fitness ( $VO_{2max} > 49.2$  ml/kg/min) or low-fitness group ( $VO_{2max} < 43.1$  ml/kg/min).

Only eligible participants who passed the criteria with regard to the questionnaires and  $VO_{2max}$  test went on to perform the cognitive task in the second step. For this, participants were seated comfortably in a dimly lit and sound-proof room in front of a screen positioned at eye level at a distance of approximately 75 cm. Before the formal test, the experimenter explained the procedure and ensured the participants understood the task, and they then undertook a practice block of 30 trials. Additionally, the participants were instructed to avoid saccades with regard to the laterally presented stimuli. After being familiarized with the whole procedure, participants then performed the task while behavioral and EEG data were recorded. The duration of the cognitive task and EEG recording was approximately 1 h.

### Measures

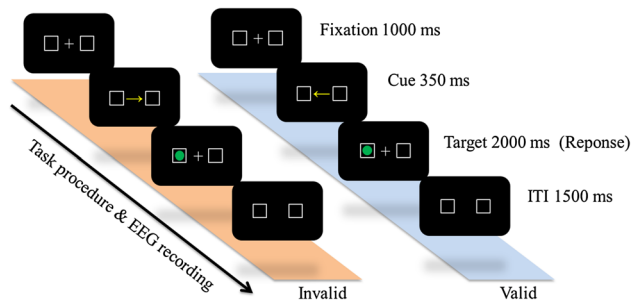
#### Cardiorespiratory endurance test

We measured the participants' maximal cardiorespiratory endurance by using a modified Bruce Protocol treadmill test on a Medtrack ST55 Control Treadmill (Quinton Instrument Company, USA). This protocol involved running on a treadmill, with both the speed and slope increasing every 3 min (Kalyani et al. 2008), until volitional exhaustion occurred or other criteria were met, as explained in detail below. After they were familiar with the exercise equipment, each participant was then fitted with head gear and a mouthpiece to collect expired gases using semicomputerized open-circuit spirometry with the logic pathway on a  $V_{max}$  system ( $V_{max}$

**Table 1** Demographics of participants in each group

Group	High fitness ( $n = 20$ )	Low fitness ( $n = 20$ )
Age (year)	$M = 21.95$ , SD = 2.24	$M = 23.25$ , SD = 2.07
BMI (kg/m <sup>2</sup> )	$M = 22.35$ , SD = 2.26	$M = 24.42$ , SD = 4.52
$VO_{2max}$ (ml/kg/min)	$M = 58.98$ , SD = 6.94	$M = 35.87$ , SD = 3.41***
IPAQ (Kcal/week)	$M = 6,538.31$ , SD = 2,478.03	$M = 1,380.18$ , SD = 627.97***

\*\*\* Significant differences between groups at  $p < .001$



**Fig. 1** Illustration of the Posner visuo-spatial cueing paradigm. Two different conditions were presented using this paradigm: (1) a valid condition, where the *cue* correctly indicated the location of target presentation, and (2) an invalid condition, where the *cue* incorrectly indicated the location of target presentation

Spectra Series Model 29, VIASYS Respiratory Care Inc., USA), which is required for the measurement of the following respiratory parameters: oxygen uptake ( $\text{VO}_2$ ), minute ventilation ( $V_E$ ), carbon dioxide output ( $\text{VCO}_2$ ), and respiratory exchange ratio ( $\text{RER}$ ,  $\text{VO}_2/\text{VCO}_2$ ), with a sampling interval of 20 s to determine the maximal oxygen uptake during the graded exercise test (GXT). Throughout the GXT, we monitored the HR and rhythm via electrocardiography (Yorba Linda, VIASYS Respiratory Care Inc., California) and a Polar heart rate monitor. Each test section included a 3-min warm up, cool down, and a GXT on a motor-driven treadmill. During the  $\text{VO}_{2\text{max}}$  test, we verbally encouraged the participants to continue exercising until exhausted, and the test was terminated according to the following four criteria: (1) indication of maximal exhaustion; (2) peak HR reaching more than 90 % of the theoretic age-predicted maximum ( $220 - \text{age}$ ); (3) a plateau in oxygen consumption corresponding to an increase of  $<150$  mL in  $\text{VO}_2$  values, despite an increase in exercise workload; or (4) an RPE  $>1.15$  (Medicine 2000).

#### *Posner endogenous visuo-spatial attention paradigm*

The current study employed a modified central cue Posner paradigm (Posner 1980; Tsai et al. 2009), which allows the investigation of endogenous visuo-spatial attention (Posner 1980; Tsai et al. 2009).

The paradigm was programmed using Stim2 software (Neuroscan Ltd, El Paso, TX, USA). All stimuli were presented on a 21-inch cathode-ray tube display against a black background. Figure 1 shows the procedure of the paradigm. The central fixation point ( $.5^\circ \times .5^\circ$ ) positioned midway between two empty white squares ( $2 \text{ cm} \times 2 \text{ cm}$ ) on the same horizontal plane indicated the start of each trial. The two empty squares were 1 cm apart from the fixation point and served as potential positions of the target.

Following the offset of fixation (1,000 ms duration), a yellow arrow (1.5 cm) cue appeared, which indicated the possible position of the upcoming target, and was then followed by the target presentation. The target was a green circle (with a diameter of 1.6 cm) which was presented in the center of one of the white squares. The interval (i.e., stimulus onset asynchrony, SOA) between cue and target was 350 ms, and the inter-trial interval (ITI) was 1,500 ms. The participant's task was to pay attention covertly to the target location indicated by the cue and make a key-response as quickly as possible with the fingers of the dominant hand corresponding to the target location (i.e., the *N* key with the index finger for left and the *M* key with the for middle finger for right). The paradigm comprised three blocks (90 trials for each) with a 3-min break in between each of these. In addition, three types of conditions were embedded randomly within one block: (1) a valid condition (54 trials), where the target was presented in the cued location; (2) an invalid condition (27 trials), where the target was presented in the uncued location; and (3) a neutral condition (nine trials), where no cue information was provided.

#### EEG recording

The EEG recording procedure was similar to that used in previous studies (Tsai et al. 2012a, b, 2014a, b; Wang et al. 2014). EEG activity was recorded using a Syn-Amps EEG amplifier and the Scan 4.3 package (Neuroscan Inc., El Paso, TX, USA) with 32 electrodes mounted in an elastic cap (Quik-Cap; Compumedics, Neuroscan Inc.) designed for the International 10–20 System. A reference electrode was placed on the mastoid and a ground electrode on the mid-forehead on the Quik-Cap. Horizontal and vertical electro-oculograms were recorded bipolarly from the superolateral right canthus, and below and lateral to the left eye connected to the system reference to monitor eye movements. Electrode impedances were kept below 5 k $\Omega$ . Electroencephalography data were acquired with an analog–digital rate of 500 Hz per channel, filtered with a Butterworth bandpass filter (.1–50 Hz), a 60-Hz notch filter, and was written continuously to hard disk for offline analysis.

#### Data processing and analysis

##### *Behavioral data*

The behavioral performance, including accuracy and reaction times (in ms), was recorded and calculated by Neuroscan Stim2 software. The following data were not included in the analysis: (1) non-response trials, (2) trials with wrong responses, and (3) anticipatory or delay errors (responses outside the range from 150 to 2,000 ms after target presentation).

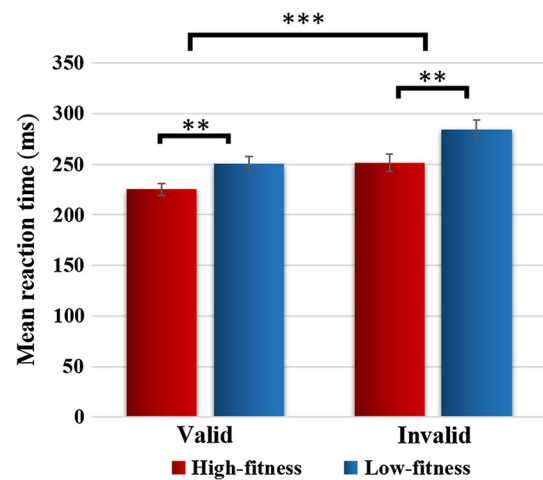
### Time–frequency analysis

This analysis was performed using SPM8 for MEG/EEG (Wellcome Department of Cognitive Neurology, London, UK; [www.fil.ion.ucl.ac.uk/spm/](http://www.fil.ion.ucl.ac.uk/spm/)) and custom MATLAB (MathWorks) scripts (Lo et al. 2013; Wang et al. 2015). Midline frontal to posterior region (Fz, FCz, Cz, CPz, and Pz) was clustered for the time–frequency analysis, due to the involvement of fronto-parietal network in visuo-spatial attention (Hopfinger et al. 2000; Corbetta and Shulman 2002; Vidyasagar and Pammer 2010). The continuous EEG data were locked to the cue onset and were segmented into epochs from  $-1,000$  to  $1,000$  ms relative to this. Trials containing artifacts exceeding  $\pm 150$   $\mu$ V were discarded. Power estimates were computed by a continuous Morlet wavelet transform (Morlet wavelet factor = 6) of single-trial data for the frequency band ranging from 2 to 50 Hz (Roach and Mathalon 2008). Oscillatory power, defined as the square of the modulus of the resulting complex number, was then averaged across trials. The averaged oscillatory power of each condition for each participant was rescaled by the baseline value from 200 to 0 ms before the cue onset and taking the log<sub>10</sub> transform of this quotient (dB). A mixed ANOVA was conducted to test whether power changes as a function of trial type (valid and invalid) or fitness level (high and low fitness). There was one within-subjects factor of trial type and one between-subjects factor of group. After the main effect test, a paired  $t$  test or a two-sample  $t$  test was conducted to examine the differences in power oscillations between conditions or groups. In addition, a one-sample  $t$  test was conducted for each group to see whether the rescaled power was significantly different relative to baseline. Correlations between mean RT and oscillatory EEG power were tested to gain insights into the possible neural mechanisms most associated with task performance. Values for all time points, frequencies, and conditions were used in the ANOVA analyses, with either the criterion of  $p < .01$  (uncorrected) or  $p < .05$  with a false discovery rate (FDR) correction for multiple comparisons (corrected). The adoption of the criterion of  $p < .01$  (uncorrected) was due to the fact that FDR correction may be too conservative for the results of interest (Knyazev et al. 2008; Sun et al. 2012).

## Results

### Participant demographics

The participants' demographic data are shown in Table 1. Demographic variables including age,  $t(38) = 1.91$ ,  $p = .064$ , and BMI,  $t(38) = 1.84$ ,  $p = .074$ , did not differ between groups. There was a significant group difference



**Fig. 2** Mean of the reaction times and standard errors (in ms) for valid and invalid conditions. \*\*\*  $p < .001$ ; \*\*  $p < .01$

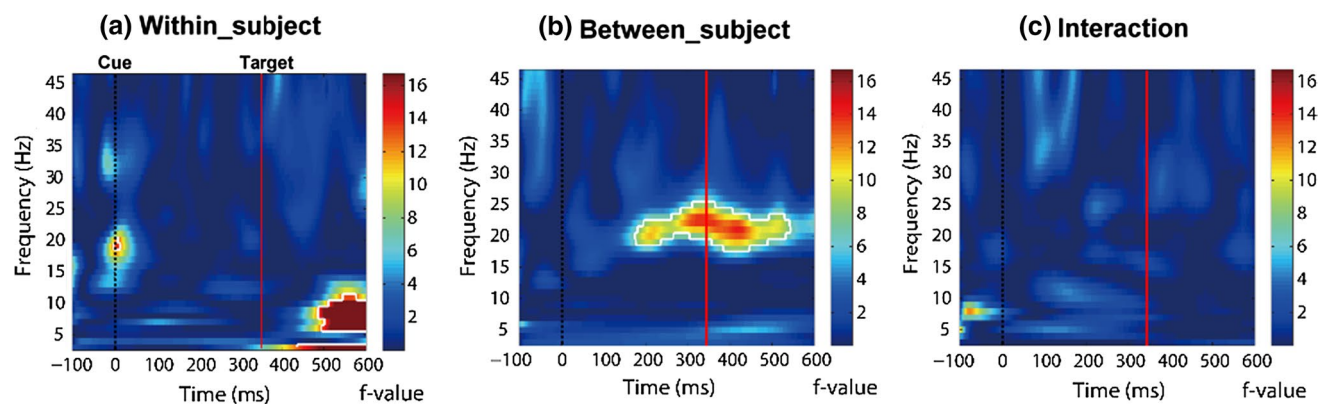
for the levels of  $VO_{2max}$ ,  $t(38) = -13.37$ ,  $p < .001$  and physical activity (IPAQ),  $t(38) = -9.02$ ,  $p < .001$ .

### Behavioral performance

Figure 2 shows the mean RTs across groups and conditions. Because we found a ceiling effect for the accuracy in both groups ( $99.26 \pm .01$  % for the high-fitness group and  $99.23 \pm .01$  % for the low-fitness one), no further analysis was conducted to test the group or condition effects on this measure. In terms of RTs, a significant main effect was observed between conditions,  $F(1,38) = 86.76$ ,  $p < .001$ ,  $\eta_p^2 = .70$ , with shorter RTs for the valid condition and longer RTs for the invalid one, showing the traditional cuing effect (Posner 1980). We also found a main effect for group,  $F(1,38) = 7.98$ ,  $p = .007$ ,  $\eta_p^2 = .17$  with the RTs of the high-fitness participants were much faster compared to those of the low-fitness participants. Notably, there was no significant condition  $\times$  group interaction,  $F(1,38) = 1.28$ ,  $p = .264$ ,  $\eta_p^2 = .03$ , indicating that there were no group differences in terms of attention benefit or cost.

### Time–frequency decompositions with Morlet wavelets

A mixed-effects ANOVA was used to test the changes in spectral power with respect to baseline in the fronto-parietal region between valid and invalid trials (condition factor), and between high- and low-fitness participants (group factor). As shown in Fig. 3a, the event-related spectral power modulations between conditions were significant with regard to the alpha power (8–11 Hz) approximately 150–250 ms after the target onset ( $p < .05$ , FDR corrected). The paired  $t$  test across participants revealed that this alpha activity was lower in the valid trials than in the invalid ones



**Fig. 3** Time–frequency analysis of the mixed ANOVA test in the midline region (Fz, FCz, Cz, CPz, and Pz). **a** The main effect of the within-subject factor (valid vs. invalid) was significant ( $p < .05$ , FDR corrected) in the alpha band (8–11 Hz) from 150 to 250 ms following the target onset. **b** The main effect of the between-subject factor (high fitness vs. low fitness) was significant ( $p < .01$ , uncorrected) in

( $p < .05$ , FDR corrected). There was also a main effect of group in the beta band (17–26 Hz), ranging from 150 to 200 ms following the cue onset ( $p < .01$ , uncorrected) (Fig. 3b). However, the interaction between condition and group was not significant (Fig. 3c), which was in line with the behavioral data (Fig. 2), suggesting that the effects of fitness are not condition dependent.

Figure 4 shows the power changes relative to baseline for each group, as well as the contrast between groups. During the Posner visuo-spatial attention paradigm, both high-fitness ( $p < .05$ , FDR corrected) and low-fitness groups ( $p < .05$ , FDR corrected) showed decreased beta power (15–30 Hz), with a greater decrease being found for the high-fitness group. This was confirmed by the group comparison, showing that the high-fitness group had relatively lower beta activity (17–26 Hz) than the low-fitness one ( $p < .01$ , uncorrected) during cue and target processing. Moreover, increased theta activity (4–7 Hz) relative to baseline was observed for both groups ( $p < .05$ , FDR corrected) after the target onset, whereas only the high-fitness group showed a significant increase in theta power during cue processing ( $p < .05$ , FDR corrected). The contrast between groups indicated that the high-fitness group had relatively higher theta synchronization than the low-fitness one during target processing ( $p < .01$ , uncorrected).

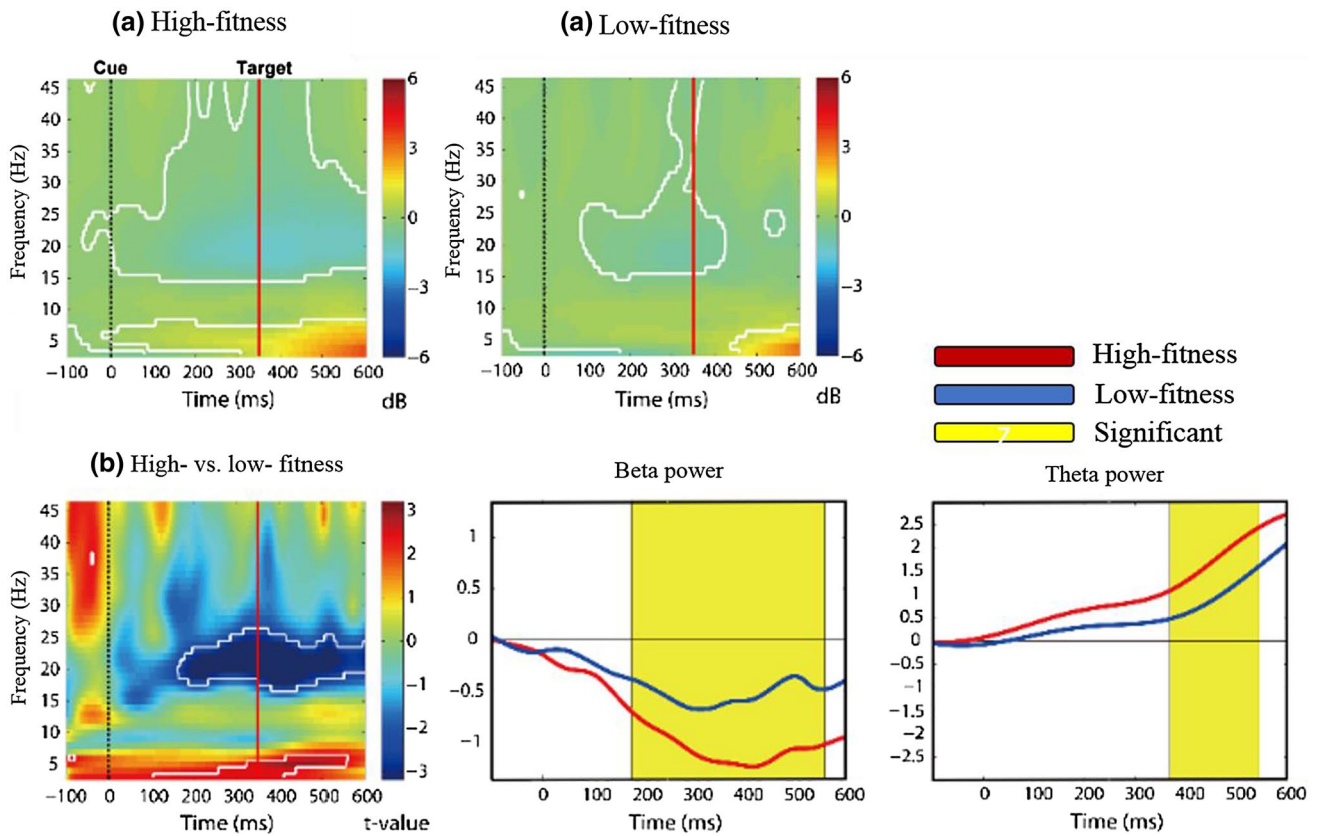
To test the relationship between oscillatory EEG activity and behavioral performance, Pearson correlation analysis was performed across participants. As shown in Fig. 5, there was a negative correlation between theta power (4–7 Hz) and mean RT ( $p < .01$ , uncorrected) from approximately 10 to 250 ms following target onset. Stronger theta synchronization is thus associated with better visuo-spatial attention performance.

the beta band (17–26 Hz) from 150 ms following the target onset to 200 ms following the target onset. **c** The interaction between group and condition was not significant. The *black dotted line* denotes the cue onset (ms = 0 ms), while the *red line* denotes the target onset (ms = 350 ms)

## Discussion

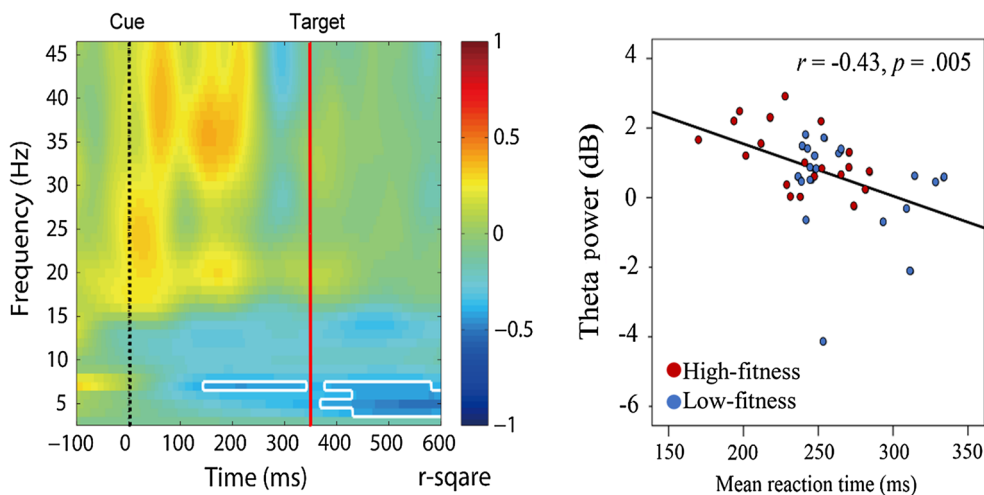
The present study used time–frequency analysis of EEG data to explore the effects of aerobic fitness on neural oscillations when healthy young adults were performing the Posner visuo-spatial attention task. Behaviorally, we found that both high- and low-fitness groups showed an attentional cueing effect, as revealed by the RT data, suggesting that participants used the cue to voluntarily orient their spatial attention. The overall processing speed, however, was much faster in the high-fitness group relative to the low-fitness one, suggesting that individuals with higher levels of aerobic fitness exhibited more rapid reaction to visuo-spatial information, regardless of the type of spatial cue used. Furthermore, as compared to the low-fitness participants, we found that the high-fitness ones showed relatively lower beta but higher theta activity during the processing of visuo-spatial attention. These results may be indicative of the effects that aerobic fitness has on oscillatory EEG activity. Importantly, the changes in theta power were negatively correlated with the overall mean RTs; in other words, those participants who showed higher theta activity may perform better with regard to visuo-spatial attention. To the best of the authors' knowledge, the present study is the first to investigate the relationship between aerobic fitness and dynamic neural rhythms in young adults.

Comparing the behavioral performance and EEG oscillations between valid and invalid trials, endogenous spatial expectation had a clear effect on the results. All participants had slower responses for the invalidly cued targets, with higher alpha (8–11 Hz) activity around 200 ms after target presentation. This enhancement in alpha power has been suggested to play an important role in functional



**Fig. 4** Time–frequency representation in the midline cluster (Fz, FCz, Cz, CPz, and Pz) across trials across conditions: **a** The enclosed areas denote the power significantly changes relative to baseline in the high-fitness group (in dB,  $p < .05$ , FDR corrected) and in the low-fitness group (in dB,  $p < .05$ , FDR corrected); **b** the enclosed areas denote the contrast between high- and low-fitness groups in beta

( $t$  values,  $p < .01$  uncorrected) and theta power ( $t$  values,  $p < .01$  uncorrected). For the *middle* and *right panels* of beta and theta band tests, the *yellow* regions denote a significant effect between groups. The *black dotted line* denotes the cue onset (ms = 0 ms), while the *red line* denotes the target onset (ms = 350 ms)



**Fig. 5** Left panel shows the behavior–EEG correlation in the midline cluster (Fz, FCz, Cz, CPz, and Pz) across conditions. The area enclosed by *white lines* denotes the area of theta power (4–7 Hz) from 10 to 250 ms following target onset reached statistical significance ( $t$  values,  $p < .01$ ) and is shown in the correlation coefficient

plot on the *right panel*. The *black dotted line* denotes the cue onset, while the *red line* denotes the target onset. The *red dots* represent the value for the high-fitness group, while the *blue dots* represent values for the low-fitness one

disengagement of brain activities unrelated to the focal task (Klimesch et al. 2007; Jensen and Mazaheri 2010). The increased alpha in the invalid trials may thus be related to top-down inhibition of incorrect responses that is established during the preparatory period (Digiacoia et al. 2008). However, fitness levels did not modulate this effect.

While the current study revealed group differences on overall performance of a visuo-spatial attention task, this should be interpreted with caution. A general rather than selective beneficial effect of aerobic fitness leads to unexpected findings that there is a lack of differential attentional cuing effect between groups. However, this failure to observe any relationship between aerobic fitness and attentional benefit or cost is in line with a previous study investigating the athlete–non-athlete differences in attentional flexibility (Hung et al. 2004). In this study, although table tennis players exhibited general faster RTs than non-athletic controls across trial types, no differences between groups in either the magnitude of attentional benefit or cost were found. The authors interpreted this finding as indicating that while both groups seemed to comparably utilize the cue information to prepare their speeded responses, the superior reaction in players to all trial types may imply a higher efficiency in response execution without suffering an increase in attentional cost or a reduction in attentional benefit. According to this claim, the high-fitness participants in the present study may be able to maintain greater celerity than the low-fitness ones when responding to a target regardless of the cue type, indicating that fitness may be associated with general benefits to cognitive processing in the Posner cueing task during young adulthood.

Examination of psychophysiological measures may aid the understanding of the underlying mechanism behind the behavioral outcomes. By employing a time–frequency EEG approach, the present study found that participants with higher aerobic fitness, in comparison with their low-fitness counterparts, showed greater desynchronized beta (15–35 Hz) during the preparatory period and greater synchronized theta (4–7 Hz) during target processing, demonstrating the relation of aerobic fitness to oscillatory neural synchrony/asynchrony during visuo-spatial attention.

Oscillatory beta rhythm can be an index for the state of dynamic motor preparation (Tzagarakis et al. 2010). For example, Tzagarakis et al. (2010), adopting an instructed-delay task, observed that the higher the directional uncertainty, the lower the beta asynchrony. This led the authors to suggest that the level of motor preparation for the forthcoming events modulates changes in beta power. In the present study, similar to previous human (Tzagarakis et al. 2010) and monkey (Zhang et al. 2008) studies, both groups exhibited decreased beta power after cue onset, and this desynchronization extended to target onset. This pattern of beta fluctuation may be related to motor preparation and

incorporation of visual information into the motor system (Tzagarakis et al. 2010). According to this, the relatively lower beta power in the high-fitness group is presumably related to higher efficiency in motor preparation and visuo-motor integration. The present findings may thus complement previous ERP data which showed better motor preparation in young adults with higher aerobic fitness (Hillman et al. 2002; Kamijo et al. 2010).

In contrast, theta power is considered to be associated with visuo-spatial attention processing (Mishra et al. 2012). Mishra et al. (2012) found that theta power increased when a spatial location was attended in comparison with when it was not, indicating enhanced strength of attended spatial representations. The higher theta activity found in the high-fitness group may thus represent an up-regulation of attentional resources during spatial stimuli processing in order to maintain optimal task performance (i.e., faster RTs). In line with this, previous ERP studies in children have demonstrated that high-fitness individuals showed a larger P3 amplitude accompanied with better executive functioning relative to their low-fitness counterparts (Pontifex et al. 2011), suggesting that higher aerobic fitness may contribute to an increase in attentional resource allocation during cognitive processing.

More importantly, the neurocognitive correlation across participants revealed that theta rather than beta oscillation was negatively related to mean RTs. This selective relation of behavioral to neuroelectric indices suggests that the better task performance in the high-fitness group may be more attributed to the enhancement in attentional processing instead of better motor preparation. This is interesting, because previous studies, employing contingent negative variation (CNV), found that although there was no effect of aerobic fitness on behavioral performance (e.g., RTs and accuracy), the CNV amplitude for high-fitness individuals was much smaller compared to low-fitness ones. It is thus suggested that this CNV difference might be because fewer neural resources were allocated to task execution for the aerobically fit participants, reflecting increased efficiency in their motor preparation (Hillman et al. 2002; Kamijo et al. 2010). Based on these findings, it can be inferred that the beneficial effect of aerobic fitness on motor preparation may be less observable at the behavioral level. On the other hand, we observed that the oscillatory theta power correlated with processing speed involving visuo-spatial attention, which supports prior studies, using visuo-spatial tasks, showing a positive relationship between theta power and task performance (Rugg and Dickens 1982) or intelligence scores (Capotosto et al. 2009b). Consequently, the greater activation of theta power in the individuals with higher levels of aerobic fitness in the present study may be related to enhanced visuo-spatial attention processing.



## Conclusions

The present study aimed to uncover some of the neural correlates behind the association between higher aerobic fitness and increased neurocognitive functioning, given the lack of such studies on healthy young populations (Guiney and Machado 2013). Our data not only agreed with previous research that indicated the beneficial effects of aerobic fitness on individuals during their cognitive peak (Themanson et al. 2008; Åberg et al. 2009; Kamijo et al. 2010), but also provided further evidence by revealing this effect in terms of fronto-parietal neural oscillations in relation to visuo-spatial attention. Furthermore, although aerobic fitness may be positively related to a person's visuo-spatial attention capacity through modulating preparatory and attentional processes, the enhanced task performance may be mostly related to increasing attentional resource allocation. The results of this work suggest that oscillatory brain rhythms may serve as a useful electrophysiological approach for examining fitness-related effects on cognitive functioning. It would thus be fruitful for future studies to apply long-term aerobic training interventions to test for causality between cognitive enhancement and changes in oscillatory power.

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