Effect of acute exercise and cardiovascular fitness on cognitive function: An event-related cortical desynchronization study

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Abstract
This study aimed to clarify the effects of acute exercise and cardiovascular fitness on cognitive function using the Stroop test and event-related desynchronization (ERD) in an aged population. Old adults (63.10 ± 2.89 years) were first assigned to either a high-fitness or a low-fitness group, and they were then subjected to an acute exercise treatment and a reading control treatment in a counterbalanced order. Alpha ERD was recorded during the Stroop test, which was administered after both treatments. Acute exercise improved cognitive performance regardless of the level of cognition, and old adults with higher fitness levels received greater benefits from acute exercise. Additionally, acute exercise, rather than overall fitness, elicited greater lower and upper alpha ERDs relative to the control condition. These findings indirectly suggest that the beneficial effects of acute exercise on cognitive performance may result from exercise-induced attentional control observed during frontal neural excitation.

Descriptors: Electroencephalography (EEG), Event-related synchronization (ERS), Executive function, Stroop test

Growing evidence has demonstrated the beneficial effects of acute exercise, also known as a single session of exercise, on cognition. These beneficial effects of acute exercise on cognitive performance have been found in research investigating diverse exercise modalities (Chang, Tsai, Huang, Wang, & Chu, 2014; Coles & Tomporowski, 2008), different aged populations (Audiffren, Tomporowski, & Zagrodnik, 2008; Netz, Argov, & Inbar, 2009; Pesce & Audiffren, 2011), and different levels of cognitive function (Audiffren, Tomporowski, & Zagrodnik, 2009; Chang, Tsai et al., 2014; Hung, Tsai, Chen, Wang, & Chang, 2013; Pesce & Audiffren, 2011). Recent meta-analyses have further concluded that acute exercise has a significant positive effect on cognitive function throughout the lifespan, including in children, young adults, and a population of all ages (Chang, Labban, Gapin, & Etnier, 2012; Lambourne & Tomporowski, 2010; McMorris, Sproule, Turner, & Hale, 2011; Verburgh, Königs, Scherder, & Oosterlaan, 2014), reflecting the essential role of acute exercise in improving cognitive function.

Evidence has suggested that the benefits of acute exercise on cognition are disproportionate, with a larger facilitative effect found in executive function-related tasks that require a higher amount of cognitive control. Executive function is described as a higher level of cognition that involves top-down processes to supervise and regulate complex goal-directed or nonautomatic behaviors, including inhibition, planning, scheduling, and switching (Jurado & Rosselli, 2007; Miyake et al., 2000). Executive function has been linked to the prefrontal cortex (Casey, Galvan, & Hare, 2005), and it is believed to be negatively associated with aging (Kennedy et al., 2009). Recent studies have revealed that acute exercise might have particular beneficial effects on executive control. For example, Chang, Tsai et al. (2014) investigated the effects of acute exercise on the Stroop test using multiple cognitive measurements (i.e., the Stroop congruent, word, square, neutral, and incongruent conditions) in middle-aged adults. The results revealed that, although acute exercise enhanced global cognitive performance, performance related to executive function (i.e., the Stroop incongruent condition) showed a higher facilitative effect than those related to the other four conditions of the Stroop test.

In addition to behavioral measurements, event-related potentials (ERP) are widely used to study the relationship between acute exercise and cognition. The ERP is elicited from scalp electroencephalography (EEG) and refers to a neuroelectric activation pattern that records a specific event or cognitive process (Hillman, Kamijo, & Scudder, 2011). ERPs involve high temporal resolution and separated components, which are allowed to investigate intrinsic and distinct cognitive processes in addition to underlying mechanisms beyond overt behavioral actions. For example, compared with low- and high-intensity exercise, a session of moderate exercise produced the largest contingent negative variation (CNV) amplitude of the ERP, suggesting that exercise induced appropriate attention and arousal for orienting responses and motor preparation (Kamijo et al., 2004). Additionally, acute exercise...
produced a larger P3 amplitude (Hillman et al., 2009; Hillman, Snook, & Jerome, 2003) and shorter P3 latency (Kamijo et al., 2009) compared with the control conditions, reflecting that acute exercise is associated with enhanced attentional resource allocation and faster stimulus classification and evaluation times while engaged in a given task (Polich, 2007). It should be noted, however, that the Ericksen flanker task and go/no-go task have been extensively employed to assess the executive function in research regarding exercise and ERP. Other tasks, such as classical neuropsychological assessments (e.g., the Wisconsin Card Sorting test, Stroop test, Trail Making test) that are frequently used to assess executive function and that can be modified for ERP techniques (e.g., Stroop test) are recommended for use in exercise-cognition research (Entier & Chang, 2009).

Although various ERPs have been used to explore the relationship between acute exercise and cognition and to elucidate the cognitive processes involving stimulus encoding and response execution, the examination of EEGs has been limited. Specifically, previous studies using EEGs emphasized the effect of acute exercise on the affect response, in which the electrocortical activity of the brain was recorded at a resting state rather than during the performance of a cognitive task (Crabbe & Dishman, 2004). To further evaluate the neural function underlying acute exercise and cognition, the present study employed EEG with a specific focus on event-related desynchronization (ERD). ERD and its associated index, event-related synchronization (ERS), refer to transient increases or decreases, respectively, in electrophysiological brain oscillation activity triggered by an event or stimulus at a specific frequency band (e.g., alpha, 8–13 Hz in frequency), at which these indices are thought to reflect the state of synchrony in a population of neurons (Klimesch, Sauseng, & Hanslmayr, 2007; Pfurtscheller, 1977, 1992). Similar to ERP, ERD provides a high temporal resolution within milliseconds of a stimulus; however, the underlying mechanisms for ERP and ERD are different. ERD is elicited based upon event-induced postsynaptic activity from pyramidal neurons, whereas ERD is believed to reflect a number of parameters that regulate oscillations in a neural network. Therefore, ERD could offer an alternative interpretation for cortical activity while conducting a cognitive task (Pfurtscheller & Lopes da Silva, 1999). Here, alpha ERD’s%, quantified by previously proposed ERD/ERS algorithms (Pfurtscheller, 1977), was emphasized because this index has been broadly used to explore cognitive processes (Chen, Bin, Daly, & Gao, 2013; Klimesch, Doppelmayr, & Hanslmayr, 2006; Klimesch, Doppelmayr, Puchinger, & Russegger, 1997; Peng, Hu, Zhang, & Hu, 2012).

The role of fitness in acute exercise and cognitive performance warrants further exploration. When considering fitness independently, and particularly cardiovascular fitness, meta-analyses have reported that aged adults who engage in aerobic exercise or are highly fit have superior cognitive functions (Angevaren, Auf dem Kampe, Verhaar, Aleman, & Vanhees, 2008; Colcombe & Kramer, 2003). Previous fitness-related studies using ERP measures also found similar patterns for acute exercise in neurocognitive function. Generally, larger P3 amplitudes or shorter P3 latencies in aged adults were associated with higher amounts of physical activity (Chang, Hu, & Hung, 2013), greater cardiovascular fitness (Polich & Lardon, 1997; Pontifex, Hillman, & Polich, 2009; Pontifex et al., 2011), or exercise on a regular basis (Dai, Chang, & Hung, 2013). Given the similarity regarding behavioral and neuroelectric indices found in both acute exercise and fitness studies, determining whether fitness influences the relationship between acute exercise and cognitive performance is important (Brisswalter, Collardeau, & Arcelin, 2002; Tomporowski, 2003). However, some recent studies have observed that aged adults with higher fitness levels receive increased benefits from exercise, suggesting that fitness moderates the relationship between exercise and cognition (Chang, Chi et al., 2014; Netz et al., 2009; Pesce, Cereatti, Forte, Crova, & Casella, 2011), whereas other studies have shown that only fitness level and not participation in acute exercise impacts cognition-related behavioral and ERP neuroelectric indices in younger adults and adolescents (Stroth et al., 2009; Themanson & Hillman, 2006). This discrepancy may result from the differences in the ages of the populations studied because the moderating role of fitness on acute exercise and cognition may be more prominent in old adults (Netz et al., 2009). Recently, Hogan et al. (2013) first examined this issue using EEG coherence analysis in preadolescents. The findings revealed an interaction of fitness and acute exercise in which the fit group showed improved cognitive performance and the unfit group had a higher error rate. In addition, a higher level of coherence in lower alpha, upper alpha, and beta was observed in the unfit group, suggesting that preadolescents with lower fitness require more neuronal resources for the cortical network and interaction for a given task. Nonetheless, the interactive effect of acute exercise and fitness on cognitive performance has not been investigated in aged adults using ERD analysis.

The aforementioned investigations have provided evidence of the facilitative effects of acute exercise and fitness on multiple aspects of cognitive function regarding behavioral and ERP approaches. Nevertheless, the interactive effects of acute exercise and fitness on cognitive function as measured by classical neuropsychological assessment and ERD analysis in old adults have not yet been explored. Therefore, the current study attempted to explore the effects of acute exercise and fitness simultaneously on the Stroop test using an ERD approach in old adults. Specifically, an acute bout of aerobic exercise of moderate intensity for 20 min plus warm-up and cool-down periods of 5 min each (Chang et al., 2011, 2014) and the Stroop test, comprised of the Stroop congruent and incongruent conditions (Chang, Tsai et al., 2014), were applied. In addition, we specifically focused on the lower alpha and upper alpha frequency bands of ERD’s% because these frequency bands have been demonstrated to be related to performance on the Stroop task (Hanslmayr et al., 2008). We expected that acute exercise would lead to improvements in the Stroop test performance and that old adults with higher fitness levels would attain increased benefits from acute exercise compared with those with lower fitness levels. With regard to ERD’s%, we hypothesized that acute exercise would increase the alpha ERD, with the higher-fitness group exhibiting a greater alpha ERD than the lower-fitness group following the cessation of acute exercise.

Method

Participants

Participants included 42 healthy male adults, aged 60 to 70 years, recruited from residential areas surrounding Taoyuan County, Taiwan. The participants were invited to the National Taiwan Sport University for the experiment. All participants were screened by the Physical Activity Readiness Questionnaire (PAR-Q) and Health Screeners Questionnaire (HSQ) to confirm their ability to safely engage in exercise, or they underwent a cardiovascular fitness test. Additional inclusion criteria were (a) right-handed, (b) free of neurological and psychiatric disorders, (c) not color blind and with
normal or corrected-to-normal vision, and (d) cognitively intact (i.e., Mini-Mental State Examination < 26). Eligible participants were then requested to complete the International Physical Activity Questionnaire (IPAQ; Bauman et al., 2009) and the Digit Span test of the Wechsler Adult Intelligence Scale—Third Edition (WAIS-III; Wechsler, 1997) to determine their level of physical activity and working memory aspect of the intelligence quotient, respectively. All participants received an explanation of the experimental processes before the study began and provided written informed consent. The study protocol involving human participants was approved by the Institutional Review Board of National Taiwan Sport University.

Eligible participants were assigned to either the higher-fitness group \( (n = 21) \) or lower-fitness group \( (n = 21) \) based on whether their peak oxygen consumption \( (VO_{2peak}) \) was above or below the 50% percentile of \( VO_{2peak} \) in standard, normal adults aged between 60 and 69 years (i.e., \( VO_{2peak} \) power analysis utilizing a 2 × 2 mixed design for detecting an acute exercise effect on Stroop test performance in middle-aged adults (Chang, Tsai et al., 2014) and an effect of cardiovascular fitness on cognition in old adults (Colcombe & Kramer, 2003).

Submaximal Fitness Test

Each participant was instructed individually and underwent a submaximal exercise test to determine their cardiovascular fitness level using the YMCA cycle ergometry protocol (Golding, 1989), an exercise test protocol that was appropriated for adults with Class A risk stratification (Fletcher et al., 2001). The YMCA protocol involves three consecutive stages. The participant started the test at a power and pedaling rate of 25 W and 50 rpm, respectively, for 3 min (150 kpm/min). The heart rate \( (HR) \), as assessed by a Polar heart rate monitor (Sport Tester PE 3000, Polar Electro Oy, Kempele, Finland), during the last minute of cycling determined the next two exercise stages. For example, at a heart rate of less than 80 bpm, the participant was instructed to exercise at 125 W for the second stage (750 kpm/min) and then at 150 W (900 kpm/min) for the third stage. Two heart rate values were recorded during the final 15 to 30 s of the second and third stages. These two heart rate values, along with the YMCA equations, the individual’s body weight, and age-predicted maximal heart rate (220—age), were used to calculate the estimated \( VO_{2peak} \) (American College of Sports Medicine, 2013).

Acute Exercise Intensity Manipulation Check

Heart rate. Participants were asked to wear the Polar heart rate monitor throughout the experimental procedure to determine the heart rate, which was recorded at 2-min intervals. Three HR indices, pre-HR, treatment-HR, and post-HR, were identified. Pre-HR represents the average HR assessed before the treatment intervention and Stroop test. Treatment-HR represents the average HR during the treatment intervention. Post-HR represents the average HR following the cessation of the treatment intervention and before the Stroop test.

Rating of perceived exertion. The rating of perceived exertion \( (RPE) \) was used to subjectively determine the exercise intensity level. The classical Borg RPE range from 6 to 20 was utilized, in which 11 to 15 represents categories of fairly light to hard (Borg, 1982) The RPE represents the average RPE assessed over 2 min during the exercise session.

Stroop Test

The Stroop test, originally developed by Stroop (1935), is a classical assessment that measures multiple aspects of cognitive function, including information processing speed, sustaining attention, interference, and inhibition. It is also a neuropsychological assessment that is recommended in research regarding exercise and cognition (Etnier & Chang, 2009).

The Stroop test was adapted to a computerized version and presented using Stim2 software (Neurosoft Labs, Inc., Sterling, VA) in the NeuroScan system. The Stroop test consisted of congruent and incongruent conditions. During the test, participants practiced with 20 stimuli and then completed blocks of two congruent and two incongruent conditions with a 2-min rest between each block. Stimuli in the congruent condition were three Chinese color words (i.e., “红” means red, “蓝” means blue, and “绿” means green) presented in the same color (e.g., the word Red printed in a red color). Stimuli in the incongruent condition were the color words presented in either of the two colors that did not match the color word (e.g., the word Red printed in a green color). Each condition block involved 60 congruent or 60 incongruent stimuli, and two blocks each resulted in a total of 120 congruent and 120 incongruent stimuli. A fixed cross was first presented, followed by the stimulus for 500 ms. The time between the fixed cross and stimulus presentation was approximately 500 ms, and the presentation of the stimuli was in a random order to minimize expectation. All stimuli had a size of 2 cm and appeared in the center of the computer monitor with a white background and vertical and horizontal visual angles of 2 degrees each.

During the Stroop test, the participants were instructed to respond to the color of the word stimulus, regardless of each condition, as quickly and accurately as possible by pressing one of three color buttons with their right thumb on a response box corresponding to the three possible colors. Responses with times less than 200 ms or more than 1,000 ms were recorded as incorrect responses. The reaction times were identified as the primary index for further analysis.

EEG Recording and Quantification

The participants underwent EEG in a sound-attenuated room. The EEG was recorded from an elastic cap with 30 Ag/AgCl electrodes (Neuroscan Quick-Cap, Neuroscan Inc., VA), according to the International 10–20 system. All electrodes were referenced to the average of the right and left mastoids and grounded to FPz. Throughout data collection, the impedance of the electrodes was maintained below 5 kΩ. Vertical and horizontal electrooculograms (EOG) were recorded by bipolar external electrodes for the offline correction of ocular artifacts. Amplified EEG data, assessed through a Neuroscan Synamps2 amplifier (Scan 4.3, Neurosoft Labs, Inc.), were digitally filtered by a band-pass from 0.1 to 30 Hz with a sampling rate of 500 Hz, in which 60 Hz was set as a notch filter.

The offline data reduction of EEG was started by correcting for the EOG activity. For the event-related EEG analysis, the lower alpha (8–10 Hz) and upper alpha (11–13 Hz) frequency bands were identified. The power spectrum was analyzed by fast Fourier transform (FFT) with the Welch technique and Hanning windowing. The EEG epoch was extracted from −800 ms to 1,000 ms relative to the target stimulus onset. Three time phases \( (T) \), including \( T_1 \) (0–200 ms), \( T_2 \) (200–400 ms), and \( T_3 \) (400–600 ms), were identified in posttarget processing to investigate whether the time phase was influenced by acute exercise and fitness. The length of the EEG...
epochs for each T employed as an input for FFT was 200 ms. The transformed epochs were averaged for each participant such that estimates of power spectral values (μV²) of the frequency bands (lower alpha or upper alpha) were derived for each time interval.

The primary ERD/ERS index of each frequency band was obtained using the equation proposed by Pfurtscheller and Lopes da Silva (1999): ERD% = (E-B)/B × 100, in which E denotes the power density at the events (T1, T2, and T3) (250 ms) of interest and B denotes the baseline. The baseline of the ERD/ERS was defined as the period from −500 to −300 ms before cue onset. Subsequently, two event-related frequency bands at the three sites of the prefrontal area (F3, Fz, and F4) were identified for further analysis. Note that a negative ERD value represents alpha desynchronization or alpha suppression, and a positive ERD value represents alpha synchronization or ERS.

**Experimental Procedures**

Participants were requested to visit the laboratory individually three times. The three visits were separated by at least 3 days but completed within 2 weeks. The first preliminary visit was used for inclusion criteria screening, assessment of physical activity and intelligence quotients, and measurement of estimated cardiovascular fitness. Eligible participants were labeled as having higher or lower fitness based upon their VO2peak being categorized as “above average” and “below average,” respectively.

The participants completed the next two treatment conditions in a counterbalanced order. During their second visit, EEG was recorded during the administration of the Stroop test. The participants performed a practice trial until an 85% correct rate for the Stroop test was achieved. Then, the participants in the acute exercise condition exercised. The exercise protocol involved warm-up and cool-down periods for 5 min each and a primary period that achieved 50% to 60% of the HR reserve (i.e., 110 to 125 beats/min) for 20 min. The participants were instructed to maintain their pedaling rate at 70 rpm. The workload started at 15 W and was then adjusted until the targeted HR zone was reached. The exercise protocol, modified based upon previous studies (Chang et al., 2011, Pesce & Audiffren, 2011), was sensitive to multiple cognitive functions. Cognitive function was assessed within 15 min after the cessation of exercise in which the EEG was recorded while the Stroop test was simultaneously performed. Similar experimental processes regarding cognitive tasks and EEG recordings were performed during the third visit, but only the reading treatment was involved. US$15 was provided as compensation for each visit, and a brief explanation of the research was provided at the last visit.

**Statistical Analysis**

An independent t test was performed initially to examine the mean of the differences between the two fitness groups to examine the appropriate group assignment. A two-way analysis of variance (ANOVA) was conducted separately to examine the effect of exercise on the HR response of the higher- and lower-fitness groups, with treatment condition (exercise vs. control) and time point (pre-HR, treatment-HR, and post-HR) as the within-subject factors.

A three-way ANOVA with repeated measures was used to analyze the reaction time in the Stroop test, in which the fitness group (higher vs. lower fitness) was considered the between-subject factor, whereas the treatment condition (exercise vs. control) and Stroop test condition (congruent vs. incongruent) were the within-subject factors. For the EEG recordings, the average value of the three electrodes (i.e., F3, Fz, and F4) was specifically chosen because executive function has been linked to the prefrontal cortex (Cohen & van Gaal, 2013; Hesse, Möller, Arnold, & Schack, 2003). A three-way repeated measures MANOVA was used to analyze the two EEG bands (i.e., lower alpha and upper alpha) at three time phases (200, 400, and 600 ms after stimulus onset) as the dependent variables, with the fitness groups representing the between-subject factors, whereas the treatment condition and Stroop test condition represented the within-subject factors. A follow-up separate three-way ANOVA was subsequently employed for the three specific time phases. The Greenhouse-Geisser method was used to adjust for the violation of the sphericity assumption, and multiple contrasts using t tests with Bonferroni adjustment were performed when appropriate. All alpha levels for significance were set as .05 prior to Bonferroni adjustment.

**Results**

**Participant Characteristics**

Descriptive data of the participant demographic characteristics are presented in Table 1. No significant differences were found for age, education, height, weight, or body mass index (ts > −.74, p > .05). Additionally, no significant differences were found for cognitive abilities assessed by digit span forward and digit span backward (ts > −.15, p > .05). These results indicate no differences in the participants’ demographic characteristics between the two groups.

Regarding fitness-related indices, both VO2peak and IPAQ were significantly different between the two groups, with participants in the higher fitness group having higher cardiovascular fitness and a higher amount of physical activity (ts < 8.00, p < .01). These findings suggested that the participants were appropriately assigned to the two groups.

**Exercise Intensity Check**

In the higher-fitness group, a mixed ANOVA revealed a significant main effect of the treatment and time points (F > 70.24, p < .001, η² = .84) and an interaction between treatment and time point (F = 153.28, p < .001, η² = .95). The follow-up analysis revealed that the acute exercise condition resulted in higher treatment-HR

<table>
<thead>
<tr>
<th>Table 1. Descriptive Data for Participants’ Demographic and Physical Characteristics Between Two Fitness Groups (Mean ± SD)</th>
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</thead>
<tbody>
<tr>
<td>Variable</td>
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<td>---</td>
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<tr>
<td>n</td>
</tr>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>Height (cm)</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
<tr>
<td>Education (years)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
</tr>
<tr>
<td>Digit span forward</td>
</tr>
<tr>
<td>Digit span backward</td>
</tr>
<tr>
<td>MMSE</td>
</tr>
<tr>
<td>VO2peak</td>
</tr>
<tr>
<td>IPAQ (MET)</td>
</tr>
</tbody>
</table>

Note. BMI = body mass index; MMSE = Mini-Mental State Exam; IPAQ = International Physical Activity Questionnaire; MET = metabolic equivalent. 

* p < .05.
(92.91 ± 1.51 beat/min) and post-HR (78.53 ± 8.4) than the control condition (67.94 ± 1.19). In addition, a higher treatment-HR (118.17 ± 6.64) and pre-HR (85.00 ± 7.73) in the exercise condition.

Similar patterns were also found in the lower-fitness group, with a significant main effect of the treatment and time point ($F_{s} > 89.78, p < .001, \eta^2_p > .88$) and an interaction between the condition and time point ($F = 173.48, p < .001, \eta^2_p > .95$). The follow-up analysis revealed that the acute exercise condition resulted in higher treatment-HR (93.18 ± 1.31) and post-HR (77.88 ± 1.01) than the control condition (69.48 ± 1.23). In addition, a higher treatment-HR (118.17 ± 7.75) was observed compared with post-HR (84.33 ± 7.75) and pre-HR (70.43 ± 10.12) in the exercise condition.

Acute exercise resulted in a 53% HR reserve and 14.3 ± 1.2 RPE in the higher-fitness group and a 36% HR reserve and 14.3 ± 1.39 RPE in the lower-fitness group, indicating that both groups experienced exercise at a moderate intensity, as designed in the protocol.

**Behavioral Data**

The descriptive data for the behavioral measures in the Stroop test are summarized in Table 2.

A three-way ANOVA revealed significant main effects of the treatment condition, in which the exercise condition had a shorter reaction time than the control condition (58.67 vs. 609.30; $F = 30.91, p < .001, \eta^2_p = .44$), and for the Stroop test condition, in which the Stroop congruent condition had a shorter RT than the Stroop incongruent condition (570.15 vs. 621.81 ms; $F = 91.40, p < .001, \eta^2_p = .70$). No significant effect was found in the fitness group ($F = .83, p > .05$). A significant three-way interaction was found among the treatment, Stroop test, and fitness ($F = 6.50, p = .015, \eta^2_p = .14$), and a two-way interaction was revealed between the treatment and fitness ($F = 5.10, p = .03, \eta^2_p = .11$). Analysis of the three-way interaction revealed a two-way interaction between treatment and fitness, with additional analysis revealing a significant difference between treatment in the high-fitness group (602.63 vs. 565.17, $p < .01$) and that in the low-fitness group (615.97 vs. 600.15, $p < .01$). In addition, the higher-fitness group had a shorter RT in the exercise condition but not in the control condition, in contrast to the lower-fitness group in the exercise condition ($p < .01$; Figure 1).

**Alpha ERD% Data**

Table 3 provides the statistical summary of the three-way MANOVA for the EEG frequency bands. Table 4 presents descriptive data for the alpha ERD% measures regarding the Stroop test.

**Lower Alpha.** Significant main effects of the treatment were revealed, in which the exercise condition produced a greater negative ERD value than the control condition ($−22.64 vs. −15.05$). However, no other significant main effects, interaction effects, or univariate effects were observed.

**Upper Alpha.** There was no significant main effect of the treatment, but the follow-up analyses showed a significant effect for T2, in which the exercise condition produced a greater negative ERD value than the control condition ($−32.18 vs. −34.65$). The analysis also revealed a significant main effect of the Stroop test ($F = 6.07, p = .02, \eta^2_p = .33$). The follow-up analysis showed significant effects of T1, T2, and T3, in which the Stroop incongruent condition led to a less negative ERD value than the Stroop congruent condition at all time points (T1: 2.32 vs. −22.35, T2: −27.45 vs.

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**Table 2. Behavioral Data for Stroop Test Congruent and Incongruent Condition as a Function of Exercise and Control Conditions Between Two Fitness Groups (Mean ± SD)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Higher fitness</th>
<th>Lower fitness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exercise</td>
<td>Control</td>
</tr>
<tr>
<td>Congruent (ms)</td>
<td>541.19 ± 81.85</td>
<td>569.10 ± 84.67</td>
</tr>
<tr>
<td>Incongruent (ms)</td>
<td>589.15 ± 85.45</td>
<td>636.17 ± 113.50</td>
</tr>
</tbody>
</table>

**Figure 1.** Illustration of interaction effect between treatment condition and fitness group. Y axis represents the reaction time of Stroop test performance. *Significant difference between treatment conditions, $p < .05$. #Significant difference between fitness groups, $p < .05$.  

**Table 3. EEG Frequency Band Statistical Summary Table for Three-Way MANOVA of Effect of Acute Exercise, Fitness, and Stroop Test Conditions on Time Phase**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Effect</th>
<th>df</th>
<th>$F$</th>
<th>$p$</th>
<th>$\eta^2_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower alpha</td>
<td>Treatment (exercise &gt; control)</td>
<td>3.38</td>
<td>7.07</td>
<td>&lt; .001</td>
<td>.36</td>
</tr>
<tr>
<td></td>
<td>Treatment</td>
<td>3.38</td>
<td>2.07</td>
<td>.12</td>
<td>.14</td>
</tr>
<tr>
<td>Upper alpha</td>
<td>Treatment (exercise &gt; control)</td>
<td>1.40</td>
<td>4.79</td>
<td>&lt; .02</td>
<td>.11</td>
</tr>
<tr>
<td></td>
<td>Stroop test (congruent &gt; incongruent)</td>
<td>3.38</td>
<td>6.07</td>
<td>&lt; .02</td>
<td>.33</td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>1.40</td>
<td>16.57</td>
<td>&lt; .001</td>
<td>.29</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>1.40</td>
<td>8.86</td>
<td>&lt; .01</td>
<td>.18</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>1.40</td>
<td>7.23</td>
<td>&lt; .01</td>
<td>.15</td>
</tr>
</tbody>
</table>
Event-related desynchronization study

Table 4. EEG Data for Stroop Test as a Function of Treatment Condition and Time Phase Between Two Fitness Groups (Mean ± SD)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Higher fitness</th>
<th>Lower fitness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exercise</td>
<td>Control</td>
</tr>
<tr>
<td>Congruent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>−26.62 ± 47.28</td>
<td>−33.65 ± 49.57</td>
</tr>
<tr>
<td>T2</td>
<td>−65.79 ± 142.49</td>
<td>−26.80 ± 51.3</td>
</tr>
<tr>
<td>T3</td>
<td>−41.21 ± 83.56</td>
<td>−38.33 ± 70.61</td>
</tr>
<tr>
<td>Incongruent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>−15.85 ± 44.87</td>
<td>−20.40 ± 42.24</td>
</tr>
<tr>
<td>T2</td>
<td>−5.76 ± 51.23</td>
<td>−14.21 ± 51.01</td>
</tr>
<tr>
<td>T3</td>
<td>−17.49 ± 60.18</td>
<td>−7.75 ± 43.76</td>
</tr>
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| Upper alpha |                |               |               |
|             | Exercise       | Control       |               |
| T1          | 3.43 ± 40.88  | 5.31 ± 37.81  | 5.29 ± 38.034 | −4.74 ± 59.93 |
| T2          | −40.54 ± 68.054| −15.97 ± 53.89| −34.89 ± 36.09| −18.43 ± 29.38 |
| T3          | −40.24 ± 77.31| −4.00 ± 49.92 | −34.38 ± 48.60| −37.56 ± 53.78 |

−59.38, and T3: −29.04 vs. −53.85 (Table 4). No other main effects or interaction effects were observed.

Discussion

Many studies have examined the effect of acute exercise on cognitive function using behavioral measurements and ERP approaches, but, to the best of our knowledge, a study of an older population using EEG has not been performed. The present study, therefore, evaluates the effects of acute exercise and fitness on multiple cognitive functions using ERD. The primary behavioral findings revealed that acute exercise enhances performance on the Stroop test regardless of the type of cognitive function. Furthermore, fitness was observed to moderate the effect of acute exercise on cognition, in which aged adults with higher fitness levels received a larger benefit from exercise. Regarding ERD, a similar main effect was found for acute exercise and cognition-related ERD, in which the acute exercise condition demonstrated a higher alpha desynchronization relative to the control condition. However, no alterations in lower and upper alpha ERDs were found in the relationship between fitness and cognitive performance.

Our findings in the Stroop test corroborate previous research that found a longer reaction time in the Stroop incongruent condition in aged adults (Ben-David & Schneider, 2009). The phenomenon is referred to as the “total Stroop effect”; that is, compared with the Stroop congruent condition that indexes basic information processes, the Stroop incongruent condition requires more cognitive processes, particularly inhibition of or interference with executive function, which leads to increased reaction time to process the conflict in the incongruent condition (Brown, 2011).

The present results showed that an acute session of aerobic exercise produced better performance in all of the Stroop conditions, and these results agree with those of several previous studies (Chang et al., 2014; Hogervorst, Riedel, Jeukendrup, & Jolles, 1996; Lichtman & Poser, 1983), suggesting general improvement in multiple cognitive functions. Additionally, the findings extend the present state of knowledge by showing that the improvement occurred regardless of the fitness level. Although somewhat inconsistent with studies that found a larger improvement in executive function following exercise, these previous studies observed both general and specific improvements assessed by the Stroop test following resistance exercise (Chang, Tsai et al., 2014), or only specific improvements assessed by other cognitive tasks such as the flanker task (Hillman et al., 2003). These differences in terms of exercise modality and cognitive task type may explain the discrepancies among previous studies and indicate the importance of our findings.

Exercise-induced arousal has been generally recognized as a potential mechanism underlying the acute exercise effect on cognition, in which the exercise induces appropriate physiological arousal temporally, which in turn benefits cognition (Chang & Etner, 2013; Tomporowski, 2003). Our findings that higher treatment-HR as well as post-HR relative to pre-HR prior to conducting the post-Stroop test support the arousal hypothesis. Additionally, based on Sander’s cognitive-energetic model, acute exercise influences decision making through three-dimensional effects on arousal, effort, and activation for stimulus extraction, response selection, and motor adjustment of information processing, respectively (Sanders, 1983). These changes with regard to arousal, effort, and activation attributed to acute exercise may be responsible for the general cognition improvements.

The present study is novel because event-related changes in alpha ERD values induced by the Stroop test may provide alternative thoughts on the relationship between acute exercise and cognition. Our results are in accord with previous studies that have observed greater alpha ERD values during the performance of cognitive tasks (Klimesch et al., 2007; Peng et al., 2012; Pfurtscheller & Lopes da Silva, 1999) and a higher alpha power for the Stroop incongruent condition (Hanslmayr et al., 2008). Furthermore, we also observed more negative ERD values for both the lower and upper alpha values on the Stroop test following the cessation of exercise. Alpha ERD refers to alpha oscillation suppression, in which a large portion of neurons related to the stimulus (e.g., thalamic nucleus) oscillate in desynchrony or excitation.
Given that alpha power is inversely correlated with cortical activation and is suppressed during the performance of a cognitively demanding task, ERD, which decreases alpha rhythm, is presumed to reflect active information processing (Klimesch et al., 2007). For example, using rapid serial visual presentation, a larger alpha ERD was observed in short lag trials (less than 500 ms after the first target) under high attentional blink magnitude (ABm) and in long lag trials under low ABm, suggesting that alpha ERD is positively associated with attentional investment for anticipation (MacLean & Arnell, 2011). In addition, a greater decrease in event-related alpha oscillations in addition to improved performance was observed in a memory task (Klimesch, 1999). These elevations in alpha ERD indicate greater information transfer within the thalamocortical reentrant network (Klimesch et al., 2007). Interestingly, alpha ERD can be observed in a dark room without any visual stimulation (Moosmann et al., 2003) and in the frontal cortex during performance of an executive function task (e.g., the Stroop test; Tang, Hu, & Chen, 2013), indicating that alpha ERD reflects a top-down process. Accordingly, along with better behavioral performance and larger alpha ERD values following acute exercise, the current alpha ERD-related findings suggest that acute exercise may provide neural resources for attentional investment and top-down processes to facilitate cognition. Moreover, because no difference was found in the enhanced alpha ERD value between the two fitness groups, these findings may imply that these exercise-dependent neural resources are not affected by fitness status. While the present study has provided initial evidence, it is possible that behavioral performance and ERD induced by acute exercise are influenced both reciprocally and independently. Future studies directly investigating the relationships among acute exercise, cognitive function, and ERD are encouraged to provide further clarification.

Our results also exhibited a discrepancy in exercise-related alpha ERD, in which lower alpha ERD was enhanced regardless of the time phase, but upper ERD exhibited greater elevation during the T2 phase. Klimesch (1999) has argued that alpha ERD is not a unitary phenomenon but encompasses distinct frequency bands that reflect discrete reactivity and topography. Lower alpha commonly exhibits widespread and unspecific topography across the entire scalp and is believed to reflect general attentional processes (e.g., arousal or vigilance), whereas upper alpha is found in more restricted brain locations and is thought to be related to specific cognitive processes (Klimesch, 1999; Ptčurtscheller & Lopes da Silva, 1999). Our findings of greater lower and upper alpha ERD values following acute exercise suggest that acute exercise may not only increase attentional demand in general during multiple task conditions but may also cause increased neural excitation at a region specific to the task-related condition, particularly during the 200 to 400 ms following the stimulus onset.

Along with the main effects of acute exercise and type of cognitive function, an interaction between acute exercise and fitness was observed. This interaction revealed that aged adults who were more fit obtained more benefits from exercise than their less fit peers, suggesting that fitness level moderated the relationship between acute exercise and cognition. These results are consistent with a recent meta-analysis (Chang et al., 2012) and contemporary empirical experience (Chang, Chi et al., 2014; Netz et al., 2009; Pesce et al., 2011). Increased benefits following acute exercise observed in old adults with high fitness levels may be contributed to by existing brain resources; old adults with higher fitness levels have been reported to possess a greater brain cortical functional connectivity related to cognitive function (Prakash et al., 2011; Voss et al., 2010). Additionally, the elevation of fitness presumably results from repeated exercise; therefore, acute exercise and fitness should be considered to be interactive rather than independent variables (Kesaniemi et al., 2001). According to Haskell (1994), the relationship between acute exercise and exercise training on health outcome can be interacted through four possible approaches: (1) positive effects could occur immediately after acute exercise, but these effects are only transient; (2) positive effects could also accumulate following acute exercise until a plateau is reached; (3) exercise training most likely results in greater effects; and (4) positive effects arise from continuous and intermittent acute exercise. The results obtained in the present study agree with the third view, in which old adults with higher fitness levels (suggesting that they participate in more exercise) demonstrate improved cognitive performance following an acute session of exercise.

A main effect of acute exercise on cognition was found in both the behavior and alpha ERD measurements; however, no interaction between acute exercise and fitness was observed in the alpha ERD indices. Previous studies have indicated that frontal alpha asymmetry is altered following the cessation of acute exercise, with greater left cortical activation (Hall, Ekkekakis, & Petruzzello, 2007). These findings have been extended to a moderating role of fitness in acute exercise and EEG, further indicating that fitness is positively associated with frontal cortical oscillations, suggesting that fit adults show more EEG asymmetry than their unfit peers (Hall, Ekkekakis, & Petruzzello, 2010; Petruzzello, Hall, & Ekkekakis, 2001). Nevertheless, these studies have addressed EEG in the resting state but not EEG induced by a cognitive task, which is the manner by which the ERD is analyzed. Therefore, ERD is speculated to be insufficient for explaining the manner by which fitness moderates the effect of acute exercise on cognitive performance, with other neural mechanisms potentially being responsible. For example, the effects of fitness on acute exercise and cognition have been studied using EEG with coherence analysis, in which acute exercise has been shown to induce the lower coherence of alpha and beta frequency bands in the fit group relative to the unfit group (Hogan et al., 2013). Brain density may provide another possibility: when compared with old adults with lower fitness, old adults with higher fitness levels have been found to have more gray and white matter in the prefrontal area (Colcombe et al., 2003) and greater hippocampal volume (Erickson et al., 2009).

The present study provides tentative evidence for the effect of both acute exercise and fitness on cognitive function, but some potential limitations should be considered when interpreting our findings. Although the present study applied a classical neuropsychological assessment recommended for use in exercise and cognition research, the task is believed to reflect the inhibition of executive function, which has been mainly investigated in previous acute exercise-cognition research (Pontifex, Hillman, Fernhall, Thompson, & Valentini, 2009). However, rather than a unitary construct, executive function encompasses several distinct subcomponents, including working memory, updating, switching, and planning (Alvarez & Emory, 2006; Miyake et al., 2000), and their responses to exercise may be specific (Etien & Chang, 2009). Therefore, the results from the present study cannot be generalized to global executive function, and examination of other specific subcomponents induced by acute exercise is recommended to offer a comprehensive map. Moreover, executive function has been strongly linked to the frontal cortex; thus, we only evaluated frontal electrode activity in this preliminary ERD study. Consequently, neural activity outside this brain region that may contribute to executive function processes was not evaluated. A few previous
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studies have utilized a larger number of electrodes to obtain the topography of the alpha ERD (Klimesch et al., 2006, 2007), and exploring the scalp topography of the ERD may be valuable. Furthermore, alpha frequency bands have been the primary focus in exercise and EEG research, leading to insufficient evidence regarding other brain oscillation responses to exercise (Crabbe & Dishman, 2004). Given that the alpha ERD has been extensively investigated, it is appropriate for the present study to use this specific brain electrocortical activity as a primary index. However, the examination of other frequency bands, including beta and theta ERDs may provide additional knowledge regarding cortical oscillation and cognitive processes (Braunstein et al., 2012; Pfurtscheller et al., 2013). Further examinations with these indices should be conducted to address the relationship among exercise, cognition, and EEG.

To the best of our knowledge, the present study is the first to examine the effects of acute exercise on cognitive function and the associated role of fitness by exploring ERD in old adults. In summary, acute exercise improved cognition, regardless of the level of cognitive function, but old adults with higher fitness levels benefited more from acute exercise. Additionally, we tentatively propose that the beneficial effects of acute exercise on cognitive performance may be associated with exercise-induced frontal neural oscillations related to attentional control; however, the neural activity-related mechanisms may be insufficient for explaining the moderating role of fitness in acute exercise and cognition. The present study suggests some important directions for future research, including investigating other subcomponents of executive functioning, exploring the topographical distribution of ERD, and examining other ERD frequency bands. We suggest that old adults should not only undergo a single session of exercise but also exercise on a regular basis to enhance their aerobic fitness levels, which may help to maximize the cognitive improvements attained with acute exercise.

References


