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EEG Responses to Incremental Self-paced Cycling Exercise in Young and Middle Aged Adults

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ABSTRACT

International Journal of Exercise Science 12(3): 800-810, 2019. Electroencephalography (EEG) is a non-invasive method of measuring electrical activity of the brain during exercise. There is conflicting evidence as to how neural activity changes in relation to incremental exercise testing (IET), or if age has any effect. The purpose of this study was to determine 1) how brain activity changes throughout an IET, and 2) if age affects this response. 13 younger (age: 24.9 ± 2.6 years, 9 males) and 10 middle-aged (49.1 ± 3.2 years, 3 males) recreationally active individuals volunteered for this study. A self-paced, perceptually regulated IET was performed, while subjects wore an EEG electrode strip. Power spectral density (PSD) was calculated; alpha (8-13 Hz) and beta (13-30 Hz) activity from the prefrontal and motor cortices was compared to baseline measures. A one-way repeated-measures ANOVA with age as a between-subjects factor was used to determine the effect of test stage and age on PSD. Relative PSD in both the alpha and beta frequency bands increased with exercise intensity. In the prefrontal and motor cortices there was a main effect of stage (both $p < .05$), and PSD increased markedly at the end of the test. There was no difference between age groups (all $p > .05$). The lack of a downregulation in neural activity in the final stage of the test is in contrast to some studies but corroborates others. A likely cause for the differences between studies is exercise modality preference. There was no age effect, which may be due to the subjects used (middle-aged regular exercisers).

KEY WORDS: Cortical brain activity, aerobic, GXT, SPV, VO_{2peak}

INTRODUCTION

Electroencephalography (EEG) is a non-invasive method of assessing and monitoring changes in the activity of the brain, and has become a commonly used tool in exercise-related research. Many studies have investigated changes in the brain's electrical activity before and after various types of exercise (16, 23, 28, 32), and a primary advantage of EEG is the high level of temporal resolution. It also has the ability to capture changes in brain activity with much less restraint on movement to obtain accurate data, and is relatively inexpensive, when compared to other brain monitoring technology such as magnetencephalography and functional magnetic resonance imaging (17).

Recent advances in technology have allowed for the ability to utilize EEG during exercise (1, 24, 26). The most commonly investigated frequency bands analyzed within exercise and sport research are alpha (8-13 Hz) and beta (13-20 Hz). Previous research has reliably shown that alpha wave power increases after exercise and is associated with improvement in mood and decreased anxiety (19). Additionally, beta wave power, which is linked to neural synchronization and improved motor planning and execution, has been shown to increase after fatigue and high intensity exercise (19). A study by Bailey et al. (1) showed a steady increase in both alpha and beta activity throughout an entire incremental exercise test (IET) to exhaustion. However, Robertson and Marino (26), who later performed a similar study, found that alpha and beta activity increased but only up to a certain time point, not the full duration of the study. After the RCP, activity in both the alpha and beta frequency bands decreased. Given disparities such as this, more research investigating brain activity during an IET is warranted. Additionally, variances in EEG activity surrounding exercise due to age have been shown (20), but most studies include young, healthy individuals, or the elderly; there is a need to further investigate any age-related changes that may exist in middle-aged subjects.

Information gained from the study of brain responses to brief, but intense bouts of incremental exercise, and how it is involved with termination of exercise has many implications. Multiple studies have shown differences in resting EEG activity between middle-aged and young-adult subjects (6,14), but it is unknown whether or not differences exist during an IET as well. EEG activity may differ as one ages, and this pattern may be intensity dependent. Therefore, the main purpose of this study was to investigate the changes in cortical brain activity during a short but intense bout of self-paced incremental exercise. We also sought to explore any age-related differences by including a group of younger individuals (18-30 years) and a middle-aged group (40-55 years). We hypothesized that there would be an increase in EEG power spectral density during the IET, and that a difference in magnitude would be present between age groups.

METHODS

Participants

The study included 13 younger (mean ± SD age: 24.9 ± 2.6 years, 9 males, 4 females) and 10 middle-aged (49.1 ± 3.2 years, 3 males, 7 females) healthy, recreationally active individuals (participated in endurance related activity a minimum of two days per week). The average body mass index of the younger subjects was 27.1 ± 3.9 $kg \cdot m^{-2}$ and for the middle-aged subjects 25.2 ± 4.0 $kg \cdot m^{-2}$. The study was approved by the university's Human Subjects Institutional Review Board. Additionally, this research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (22).

Protocol

Subjects were first asked to read and sign the informed consent document, and completed a Physical Activity Readiness Questionnaire (PAR-Q (23)). Exclusion criteria included > 2 cardiovascular disease risk factors. Height was measured with a wall-mounted stadiometer and mass was measured with a digital scale (AD2343, AND Weighing, Milpitas, CA). Then the subjects were fully familiarized with all of the laboratory equipment. The rating of perceived exertion [RPE; (3)] is a subjective rating scale that is primarily used to assess and quantify how hard subjects are working and perceiving their exertion during exercise. It ranges from 6 to 20 and includes verbal descriptors such as "very light," and "somewhat hard." It is often used, however, to prescribe or regulate the intensity of exercise. This chart was described in detail, and they were allowed to practice adjusting resistance on the cycle ergometer (Wattbike, Woodway USA, Waukesha, WI) in order to maintain various RPE levels. When subjects felt comfortable with the equipment, they were asked to sit in a chair so that the EEG electrode strip and battery pack could be placed on their heads. Subjects were then fitted with a heart rate monitor (Forerunner 620, Garmin, Olathe, KS)

Prior to the incremental exercise test, subjects were instructed to be seated in a comfortable, relaxed position in order to collect 3 minutes of eyes open (EO) baseline EEG measurements. Thereafter, subjects completed a self-paced VO_{2max} (SPV) test (18), which is a protocol that is exactly ten minutes in length, with five 2-minute stages. Rather than a set workload for each stage, the stages are perceptually regulated, using RPE values of 11, 13, 15, 17, and 20 (in that order). These correspond to the descriptors of "light," "somewhat hard," "hard," "very hard," and "maximal exertion." Subjects were blind to the ergometer control panel but were allowed to adjust their cadence and resistance to maintain each prescribed RPE for the duration of the test. This protocol has been validated in numerous studies and has shown to be accurate in measuring maximal oxygen consumption (10, 12, 27).

Figure 1. EEG data collection during a self-paced VO_{2max} (SPV) test.

Expired gases were collected during the SPV through use of a metabolic cart (True One 2400, ParvoMedics, Sandy, UT). Flow and gas calibrations were performed approximately 5-10 minutes before each test. Fifteen-breath rolling averages were calculated for each of the variables of interest [oxygen consumption (VO_2), carbon dioxide production (VCO_2), respiratory exchange ratio (RER) and ventilation (V_E)] as has been done previously (10). The average and maximal values were then taken for each of these variables.

A nine-channel wireless system was used for acquisition of EEG data (B-Alert X10, Advanced Brain Monitoring, Carlsbad, CA). A pre-assembled sensor strip was placed using the international 10-20 system (13). Vertical distance from the nasion to inion, and horizontal distance from left to right pre-auricular were measured to determine the placement of the Cz (center) electrode. By using this as a reference point, the remaining electrodes on the sensor strip were placed in the estimated locations. The electrodes used for analysis were from the prefrontal cortex (PFC; F3, Fz, & F4) and the motor cortex (MC; C3, Cz, & C4). Reference electrodes were placed on the right and left mastoids. An impedance check was performed after placement of all electrodes and was kept under 40 kΩ, which is suggested by the manufacturer for the hybrid active electrodes; data was collected at 256 Hz. It was made very clear to each subject that they must be as still as possible throughout the exercise test, to look straight ahead and prevent any side to side movement, as it would affect the EEG recording.

Statistical Analysis
The Wattbike has a sampling frequency of 100 Hz, and then provides data for each pedal stroke. These raw data were processed using custom MatLab software (MathWorks, Natick, MA). EEG data were processed using Acknowledge 4.4.2 software (Biopac, Inc., Goleta, CA). The data were first visually inspected and large artifacts were manually removed (eyeblink, muscular contractions, etc.). FzF3F4 and CzC3C4 values were averaged, then inputted into the software. The final 30s of each stage were used for analysis, and focus areas were created for these stages (EO, RPE11, 13, 15, 17 and 20). The 30s periods were then separated into 5s epochs for further analysis. The software uses a Welch periodogram for computation of average power spectral density (PSD, measured in $\mu V^2 \cdot Hz^{-1}$) of the signal between 8-13 Hz (alpha band) and 13-30 Hz (beta band). This method evaluates the power spectrum by splitting the time series into segments that overlap. The periodograms, or PSD estimates, for the individual segments are then averaged and the Welch periodogram can then be calculated (34). All values were then compared to the eyes open PSD baseline measures and are shown as percent change from EO, as previously done by other research groups (1, 26).

All analyses were performed with IBM SPSS Statistics for Windows (Version 25, Armonk, NY). One-way repeated measures ANOVAs were used to compare the five stages of the SPV test, with age group as a between-subjects factor. Greenhouse-Geisser corrections were used when the assumption of sphericity was violated. Independent samples t-tests were used to determine if there were any differences between groups on the Wattbike and metabolic variables. Significance was set *a priori* at $p < .05$.

RESULTS

Variables calculated from the Wattbike and from the metabolic cart during each stage are presented in Table 1. There was a significant difference ($p = .013$) in measured relative VO_{2max} between the younger (44.9 ± 5.6 $ml \cdot kg^{-1} \cdot min^{-1}$) and middle-aged ($37.6 \pm 7.2$ $ml \cdot kg^{-1} \cdot min^{-1}$) individuals. Figure 2 shows the trend in VO_2 for each stage in both groups.

Table 1. Maximal values for metabolic and Wattbike data.

Variable	Younger	Middle-Aged	*p*
VO_2 (ml · kg^{-1} · min^{-1})	44.9 ± 5.6	37.6 ± 7.2	.013
VCO_2 (L · min^{-1})	4.37 ± 1.00	3.07 ± .52	.001
HR (beats · min^{-1})	186.6 ± 8.4	161.0 ± 15.8	< .001
RER	1.22 ± .13	1.18 ± .08	.485
V_E (L · min^{-1})	151.6 ± 41.1	99.1 ± 17.2	.001
Power (W)	498.5 ± 186.2	291.4 ± 61.3	.003
Speed (km · hr^{-1})	51.2 ± 4.5	42.3 ± 2.3	.001
Torque (N · m)	45.7 ± 6.6	33.8 ± 3.0	.008

Note. Data presented as mean ± SD.

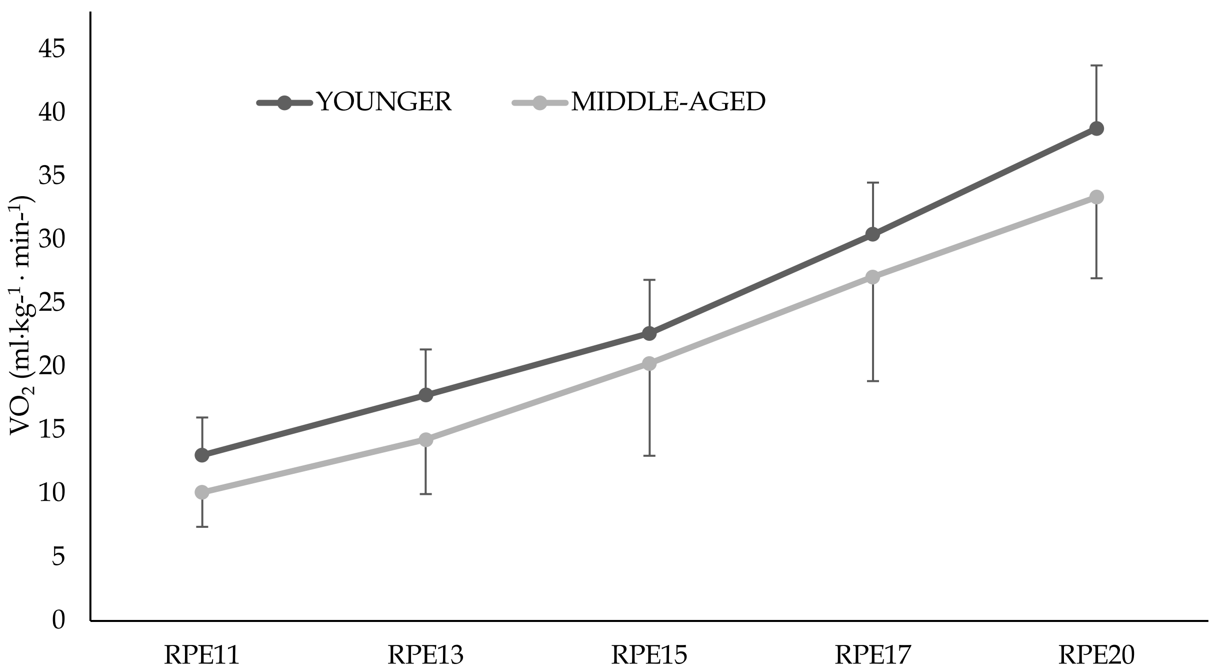

Figure 2. Mean oxygen consumption (VO_2) during each stage of the SPV; data presented as mean ± SE.

In both the alpha and beta frequency bands within the PFC, activity increased in the later stages (RPE 17 and RPE 20) of the SPV. There was a significant main effect of stage (alpha: $F(1.287, 27.036) = 8.598$; $p = .004$); beta ($F(1.054, 22.138) = 7.213$; $p = .012$). Independent of age group, the activity within the final two stages of the tests was relatively greater compared to the beginning of the test. There were no differences found between the age groups for the alpha or beta frequencies (*p* = .447 and .830, respectively). Figure 3 shows the alpha and beta PSD in both regions of the brain that were investigated.

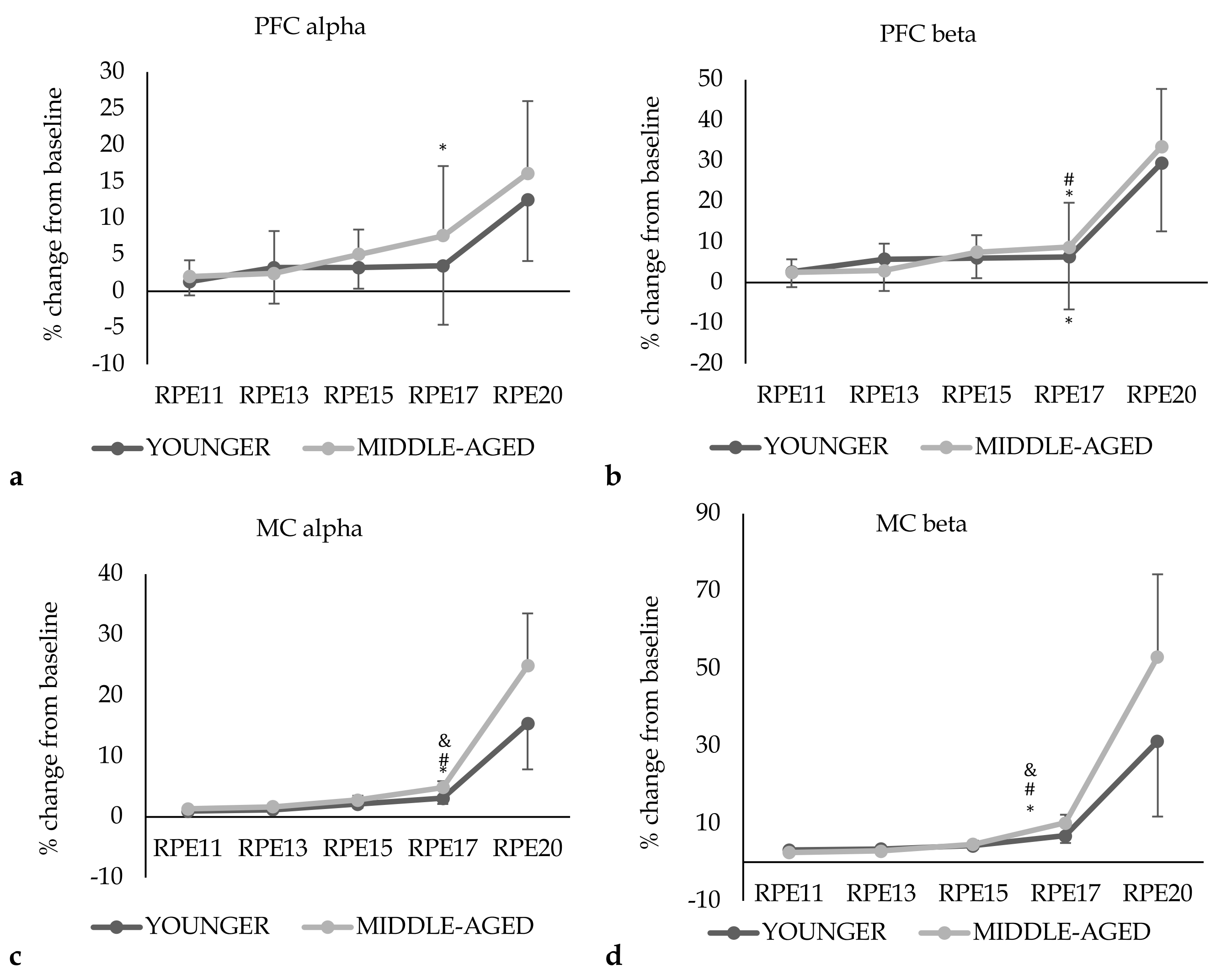

Figure 3. Alpha band power spectral density (PSD) in the prefrontal cortex (PFC) (a) and the motor cortex (MC) (b), and beta band PSD in the PFC (c) and MC (d). Data presented as mean ± SE. * indicates a significant ($p < .05$) difference from RPE11; # indicates a significant difference from RPE13; & indicates a significant difference from RPE15.

Similar to the PFC, alpha activity in the MC increased in the later stages of the testing session; beta activity had greater variability but some differences in this frequency range were present as well. There was a significant main effect of stage for both frequency bands that were examined (alpha: $F(1.008, 21.173) = 10.729$; $p = .004$); beta: ($F(1.007, 20.134) = 7.276$; $p = .014$). As seen in the PFC, there were no differences between age groups in either the alpha ($p = .359$) or beta ($p = .440$) frequency bands.

DISCUSSION

The primary purpose of this study was to compare the EEG responses to an incremental self-paced exercise test in both younger and middle-aged individuals. Analysis of the power spectral density in the alpha and beta frequency bands of the motor and prefrontal cortices showed that age did not significantly affect the response of the brain during exercise.

One of the key findings from this study is the rise in PSD in the final two stages of the exercise test. Four studies could be located that have investigated the effect of an IET on EEG responses (1, 5, 7, 26). Findings from the current study are in line with two of those previous studies that have shown a concomitant increase (1) or plateau (7) in EEG activity with increasing exercise intensity during the final stages of an IET. In the motor cortex, the finding of a greater rise in PSD within the beta frequency band compared the alpha band may be partially explained by the view that premotor and supplemental motor areas simply require an increase in their relative activity to facilitate movement of large muscle groups, especially at maximal intensities. Furthermore, there have been no studies showing a consistent effect of exercise on the alpha frequency band specifically; thus, the beta frequency band may be more important to interpret (21).

Greater synchronization of the neural signals and activity in the premotor and parietal cortices is thought to be crucial for motor planning and sensory integration (8). It follows that increased activity in these areas can engender greater top-down muscle activation during exercise. Subsequently, these neural circuits must be increasingly activated as an individual is challenged and may be manifested through increases in cortical activity. It has been shown that in the motor cortex, beta power is stronger as individuals plan and execute movements; it is likely that PSD within the beta band increases along with muscle fiber recruitment to meet the demands of an IET. Studies using EEG during small muscle contractions have shown synchronization between electromyography activity with EEG beta activity in the cerebral cortex (9, 19). Again, this may explain the large increase in prefrontal and motor EEG activity within the beta frequency band, as those areas of the brain are responsible for the planning and execution of movement, respectively (15, 31).

Our results do not corroborate those from Robertson & Marino (26) or Brümmer et al. (5), who both showed relative EEG activity decreased at the very end of an IET. These are not the only studies that have suggested an inhibitory role of the prefrontal cortex, when exercise intensity increases to a point past the ventilatory threshold, or the respiratory compensation point. For example, Thomas & Stephane (33) showed that cerebral oxygenation (COxy) decreased at the end of a VO_{2max} test. In a follow-up paper (25), it was stated that *"Studies failing to show a decline in prefrontal COxy or neural activity before exhaustion during incremental exercise have not used individual thresholds that might account for this discrepancy."* Results from the current study, along with those from Bailey et al. and Edwards et al. suggest otherwise and warrant future research in this area. Ultimately, the disparity among findings is likely not merely a perfusion issue and the complexity and integrated information processing capacity of the brain remains to be determined.

Studies investigating EEG activity between younger and middle-aged adults is scarce, and most involve measurements taken during sleep (7). To our knowledge, no studies have looked at EEG during exercise in these groups. Lack of between-group differences may be attributed to the fact that our older population was not considered "elderly" and they were also regular exercisers. It has been found that cognitive decline can begin as early 45 years (30) and a minimally invasive means to examine correlates of this process is through the use of EEG. The association between the aging brain and decreased executive and sensorimotor function is often identified through structural changes across the entire brain, but more specifically within the prefrontal cortex (2, 11). Exercise provides a prophylactic mechanism that may help to maintain structural integrity and neuroplasticity in middle-aged and older populations, though there is some disagreement about how cortical electrical activity is affected.

Findings from the current study suggest that age alone does not affect the neural response to exercise. This is somewhat surprising given the findings from other studies. For example, Moraes and colleagues (20) showed that a 20-minute acute bout of exercise was able to induce significant pre to post-exercise increases in alpha and beta wave power in a group of younger subjects (21-30 years of age) but not in a group of older individuals (60 + years). The authors suggest that lack of statistically significant changes in the older group may be the result of decreased release of dopamine (thought to be involved with movement execution, motivation and the reward system) and less production of brain derived neurotrophic factor (BDNF) that commonly occurs in the aging brain. Importantly, their older subjects were considered elderly whereas ours were middle-aged (70.4 ± 7.0 years vs. 49.1 ± 3.2 years); additionally, their measurements were taken after exercise, whereas our primary focus was the response during exercise.

Berchicci et al. (2) tested individuals within a wide age range, from 15-86 years. They were split into two groups, sedentary individuals and regular exercisers. It was found that in individuals under the age of 38, regular physical activity (PA) was not significantly correlated with cognitive function. However, after 38 years of age, the effect of regular PA was highly influential. Those that exercised regularly engaged their PFC less, and were faster than their less active counterparts. This shows the influence of regular PA, especially during middle-age years, as it has been shown to promote neurogenesis and synaptogenesis (2). In addition, volume may affect the relationship between age and PFC activity as well, and account for inter- and intra-study differences. Future work should continue to examine EEG activity during exercise across a spectrum of age groups and fitness levels.

It is possible that the findings from the current study may be largely due to the characteristics of the subjects. In the two studies that were mentioned that found a decrease in EEG activity at the end of an IET, one (26) used highly trained cyclists as subjects, and the other (5) used experienced, albeit not highly trained, cyclists. In the studies that found an increase or plateau in EEG activity at the end of an IET (the current study, along with Bailey et al. and Edwards et al.) the subjects were all recreationally trained individuals, likely with very little to no cycling experience. Although the peak power output obtained from our younger subjects was higher than the subjects in the Robertson & Marino study (498.5 ± 186.2 W vs. 411.7 ± 42.7 W), the absolute VO_{2peak} in our younger subjects was lower (3.7 ± 0.7 L · min^{-1} vs. 4.1 ± 0.7). The EEG differences between studies may be related to peak power or cardiorespiratory fitness level, but it is arguably more likely that either cycling experience, or the preference for cycling, affected the change in EEG activity during very intense exercise.

Schneider et al. (29) used three different testing modalities (arm crank, cycle ergometer, and treadmill) to show that exercise preference can affect EEG response post exercise. Brümmer et al. (4) also showed how exercise preference can influence brain activity. Their study included twelve (age 26.3 ± 3.8 years) recreational runners that exercised at 50 and 80% of their VO_{2max} on four different modalities (treadmill, bicycle, arm crank and isokinetic exercise). In the 80% VO_{2max} condition, they showed an increase in frontal beta wave activity compared to baseline, but only in the treadmill modality. The authors suggest that the automaticity that comes with training can affect activation of the brain. Perhaps when exercising in a familiar modality, less activation is needed for synchronization of brain activity. They also suggested that an unfamiliar modality may elicit feelings of insecurity, fear of physiological demands, and negative mood states, manifested as a decrease in frontal activation (or an increase in alpha EEG), which was found when the runners were asked to perform intense isokinetic exercise. Though neither of these studies collected EEG during exercise, they show that preference to an exercise modality influences brain activity in some fashion. Processing of emotions surrounding exercise, especially unfamiliar modalities or intensities, is likely an indicator of changes in cortical activity.

In the middle-aged group there was a higher percentage of females compared to the younger group, which is a potential limitation. Additionally, some of the subjects may have been more familiar with cycling than others. Future studies should further investigate the effect of either preference or experience on EEG activity. The IET protocol that was chosen for this study was the self-paced VO_{2max} test, or the SPV. The advantages of this protocol are that it has a set time, and it is self-paced, giving subjects much more autonomy than traditional IETs. The decision-making process that is involved with pacing strategy is complex, and may influence EEG activity. Therefore, future studies should compare this protocol with traditional IETs. Additionally, by better understanding cognitive implications, military personnel, as well as elite and nonprofessional athletes, could standardize and incorporate specific exercises into their training programs with the intent to maximize cognitive gains and maintain mental acuity during otherwise stressful or taxing circumstances.

This study showed that alpha and beta wave activity increased in both prefrontal and motor regions as exercise intensity increased; this pattern was similar in both younger and middle-aged individuals. These results suggest that in middle-aged individuals that regularly exercise, there is no difference in EEG response compared to younger individuals.

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