



Predicting affective responses to exercise using resting EEG frontal asymmetry: Does intensity matter?

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ABSTRACT

Affective responses to exercise may be important for improving adherence to regular programs of exercise. The present study sought to determine whether resting frontal EEG asymmetry, an individual difference measure of affective style, is predictive of affective responses to exercise performed at distinct intensities standardized relative to a metabolic landmark (i.e., the ventilatory threshold, VT). Resting EEG was collected from 30 participants and used to predict affective responses following treadmill running at three exercise intensities: below-VT, at-VT, and above-VT. Affect was assessed [via Activation-Deactivation Adjective Check List, yielding measures of Energetic Arousal (EA) and Tense Arousal (TA)] before, immediately following exercise, after 5 min cool down, and 10 and 20 min post-cool down. Resting mid-frontal asymmetry (F4–F3) significantly predicted EA immediately following below-VT exercise; resting lateral frontal asymmetry (F8–F7) predicted EA at 20 min post-cool down. Resting mid-frontal asymmetry predicted in EA immediately following and following cool down in above-VT exercise. As a whole, frontal asymmetry was predictive of affective responses following exercise, namely greater relative left frontal activity predicting lower EA. This was opposite to the predictions of the valenced motivation model, but may provide some support for the motivation direction model. This is based on the fact that low EA could be indicative of approach motivation, especially at higher exercise intensities.

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1. Introduction

Despite the numerous physical and mental health benefits that occur with regular physical activity participation, physical activity rates in the United States are low (Centers for Disease Control and Prevention, 2007; United States Department of Health and Human Services, 1996). One problem faced in increasing physical activity participation is the maintenance of an exercise program once it has been adopted. Approximately 50% of those individuals who begin an exercise program dropout within the first 3–6 months (Dishman and Buckworth, 1996). The affective responses that occur during a bout of exercise have been hypothesized to influence adherence to exercise (Ekkekakis et al., 2004; Williams, 2008). Research by Williams et al. (2008) found that affect experienced during an acute bout of moderate-intensity exercise was predictive of physical activity participation 6 and 12 months later. This evidence suggests a better understanding of the factors that influence affective responses resulting from exercise may be

important with respect to exercise adherence, and ultimately public health.

One variable that has been related to affective responses to exercise is frontal EEG asymmetry (Petruzzello et al., 2006). Petruzzello and colleagues (Hall et al., 2000, 2007; Petruzzello et al., 2001; Petruzzello and Landers, 1994; Petruzzello and Tate, 1997; Van Landuyt, 1999; see Petruzzello et al., 2006 for a review) have primarily utilized what has come to be referred to as the valenced motivation model (Harmon-Jones, 2004, 2007) to examine whether resting EEG activity can be useful in predicting affective responses to acute bouts of exercise. Overall, these studies suggest that the intensity of exercise may influence the relationship between resting frontal asymmetry and affective responses to that exercise. At low exercise intensities [walking at a self-selected pace (Hall et al., 2000); cycling at 55% VO_{2max} (Petruzzello and Tate, 1997); or cycling at 60% predicted VO_{2max} (Van Landuyt, 1999)], frontal EEG asymmetry has not predicted affective responses following exercise. However, at higher intensities [cycling at 70% VO_{2max} (Petruzzello and Tate, 1997); running at 70% VO_{2max} (Petruzzello and Landers, 1994); running at 75% VO_{2max} (Petruzzello et al., 2001); running to volitional exhaustion (Hall et al., 2007)], frontal EEG asymmetry has been predictive of affective responses.

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Davidson (1998a, 2000a,b, 2004; see also Allen and Kline, 2004) coined the term “affective style” to discuss individual differences in affective responsivity and hypothesized that regional brain activity (i.e., frontal EEG asymmetry) may account for differences in affective responses. Specifically, Davidson’s valenced motivation model (Harmon-Jones, 2004, 2007) hypothesizes that greater left anterior cortical activity, relative to the homologous right anterior region, is associated with an approach motivational system and positive affect whereas greater right anterior cortical activity, relative to left, is associated with an avoidance/withdrawal motivational system and negative affect. Davidson and his colleagues have provided support for this model, demonstrating that anterior asymmetry was predictive of affective responses to emotionally valenced film clips (Davidson et al., 1990; Tomarken et al., 1990; Wheeler et al., 1993).

Harmon-Jones (2004, 2007) proposed an alternative model utilizing frontal EEG asymmetry called the motivation direction model. In this model, the left frontal brain region is associated with the expression of approach-related emotions while the right frontal region is associated with the expression of withdrawal-related emotions. Support for the motivation direction model comes from work by Harmon-Jones that has shown anger to be associated with the left frontal brain region (Harmon-Jones, 2004, 2007; Harmon-Jones and Allen, 1997; Harmon-Jones et al., 2003). Anger is a negatively valenced emotion, but because it is also an approach-related emotion, such results are not consistent with the valenced motivation model.

The exercise studies cited earlier have shown some support for the valenced motivational model, with the left frontal region being associated with, and predictive of, positive affect. However, in a more recent study by Hall et al. (2007), greater relative left frontal activity predicted tiredness (and calmness) following strenuous exercise (e.g., maximal graded exercise test). This finding may be viewed as providing support for the motivation direction model because this ‘calm-tiredness’ may be viewed as a very pleasant state (Thayer, 1989, 2001) and possibly an approach-related emotion due to the intensity of exercise. Work by Hall et al. (2000) further supports the motivation direction model, wherein frontal EEG asymmetry predicted self-selected walking speed (i.e., those with greater relative left-sided activation chose faster walking speeds).

The apparent dose–response relationship in the prior frontal asymmetry, affect and exercise research is consistent with Davidson’s (1998a) suggestion that there may be a dose–response relationship in frontal asymmetry and affect. Exercise is an ideal setting within which to study dose–response characteristics because the intensity can be reliably and readily manipulated. Ekkekakis and colleagues (Ekkekakis et al., 2005b; Ekkekakis and Petruzzello, 1999; Hall et al., 2002) have explored the dose–response relationship for the influence of exercise intensity on self-reported affective responses, calling for exercise intensity to be standardized relative to important metabolic landmarks such as the ventilatory threshold (VT). The oft-used prescription of intensity relative to an arbitrary percentage of maximal aerobic capacity (e.g., VO_{2max} or maximal amount of oxygen consumed) has been shown to be limited because of individual differences in metabolic demands caused by these intensities. For example, although exercise performed at 70% of VO_{2max} may involve primarily aerobic metabolism in one individual, the same relative intensity may result in a significant degree of anaerobic metabolism in another person (Ekkekakis and Petruzzello, 1999). The VT has particular significance as a threshold for affective responses to exercise. Specifically, exercise below the VT relies predominantly on aerobic metabolism, with little accumulation of lactic acid and a predominantly pleasant affective profile. Exercise at, and exercise above, the VT is predominantly characterized by the accumulation

of lactic acid and the accompanying physiological challenges to maintaining the exercise intensity that such accumulation presents (e.g., increased ventilatory drive, increased recruitment of muscle fibers, increased catecholamine concentration; Ekkekakis et al., 2005b); the resultant affective profiles tend to become increasingly less pleasant/more unpleasant as intensities increase beyond the VT. Previous studies examining frontal EEG asymmetry and affect have primarily taken the approach of standardizing exercise intensities utilizing percentages of VO_{2max} rather than standardizing intensity based on VT, which may be a reason for the differences in results related to intensity.

Thus, the purpose of the present study was to clarify the exercise intensity–affect relationship by more effectively controlling the level of exercise intensity. Having a more standardized method of establishing exercise intensity, we can then better determine whether frontal EEG asymmetry, an individual difference measure of affective style, is predictive of affective responses following exercise performed at intensities relative to the VT. It was hypothesized that subjects having greater relative left-sided anterior brain activity at rest would have a more pleasant (i.e., increased energy or calmness) and/or less unpleasant (i.e., decreased tension or tiredness) affective response following exercise compared to those with greater relative right-sided activity. Additionally, based on previous studies it was hypothesized that EEG frontal asymmetry would be related to affective responses only at the highest exercise intensities, namely those intensities requiring a significant anaerobic component (i.e., $>VT$). Secondarily, we sought to determine which model of frontal asymmetry is most appropriate in explaining these results.

2. Methods

2.1. Participants

Thirty physically fit college students (14 females, M age = 21.2 ± 2.0 years, M height = 167.4 ± 9.1 cm, M weight = 60.5 ± 6.6 kg, M VO_{2max} = 47.7 ± 7.6 ml $kg^{-1} min^{-1}$; 16 males, M age = 21.5 ± 2.5 years, M height = 182.1 ± 5.0 cm, M weight = 78.3 ± 9.2 kg, M VO_{2max} = 56.6 ± 7.3 ml $kg^{-1} min^{-1}$) volunteered to participate in this study. All participants signed waivers claiming a physical examination within the past year and completed a statement of informed consent approved by the university’s Human Subjects Institutional Review Board. All participants were paid \$50 for their participation in the study.

2.2. Measures

2.2.1. Affect

The Activation–Deactivation Adjective Checklist (AD ACL) is a 20-item self-report measure of the bipolar affective dimensions of Energetic Arousal (EA) and Tense Arousal (TA), as described by Thayer (1989). The dimensions of Energetic Arousal and Tense Arousal (represented by 10 items each) are thought to possess positive and negative affective tone, respectively (Thayer, 1989). Responses to each item are made using a 4-point Likert-type scale (ranging from ‘definitely feel’ to ‘definitely do not feel’). Psychometric information has been published by Thayer (1978, 1986). The AD ACL has been shown to be a valid and reliable measure of affect and useful in exercise studies (see Ekkekakis et al., 2005a).

2.2.2. Brain activity

Resting EEG activity has been shown to be a reliable index of regional brain activity (Tomarken et al., 1992). Resting brain activity (i.e., EEG) was recorded from eight scalp locations. These included left and right recordings from the lateral frontal (F7, F8), mid-frontal (F3, F4), temporal (T5, T6), and parietal (P3, P4) regions. Raw EEG data were subjected to spectral analysis to decompose the complex EEG waveform into its component sine wave frequencies. The alpha frequency (8–13 Hz) was of interest because it is the primary basis of the Davidson valenced motivation model. Activity in this bandwidth is thought to be negatively related to the activity of the underlying cortex, such that greater alpha spectral power is related to less cortical activity, while less alpha spectral power is associated with greater activity (Oakes et al., 2004). Within Davidson’s framework, alpha activity in the frontal regions is used to calculate an asymmetry index (F4–F3; F8–F7) to determine relative left versus right activity. A similar asymmetry index was calculated based on alpha activity from the temporal regions (T6–T5) and parietal regions (P4–P3) to determine the regional specificity of any effects.

2.3. EEG recording

A stretchable lycra electrode cap (Electro-Cap, Inc.) was fitted on the participant's head for electrode application and assessment of regional brain activation (i.e., EEG). Placement of the cap utilized anatomical landmarks on the participant's head (i.e., theinion and nasion) to insure proper location. Using this procedure, electrode placements have been shown to deviate negligibly from the International 10–20 System locations (Blom and Anneveldt, 1982). EEG activity was recorded from the mid-frontal (F3, F4), lateral frontal (F7, F8), temporal (T5, T6), and parietal (P3, P4) regions. To avoid the problem of different resistances at differential reference sites, all leads were referenced to A1 (left ear) and a separate channel recorded A2 (right ear)–A1. To achieve an effective linked reference, the A2–A1 channel was subtracted from the channel of the site of interest. For example, given F3–A1 and A2–A1 channels, one can compute $(F3-A1) - (A2-A1)/2 = F3 - (A1 + A2)/2$. This would have been obtained if A1 and A2 were linked as a single reference (Miller et al., 1991). All electrode impedances were below 5 k Ω as measured by a Grass electrode impedance meter (Model EZM-4). Impedances for homologous (e.g., F3, F4) sites were within 500 Ω of each other. To reduce potential bias introduced by polygraph channels, each EEG site was randomly assigned to a polygraph channel for each participant. Ocular artifact (e.g., eye movements, eyeblinks) was assessed by electro-oculogram (EOG) recording from electrodes placed laterally to both eyes as well as above and below one eye. Each participant was connected to a ground on the Grass Model 12 system by an electrode in the lycra cap located on the forehead (Pivik et al., 1993).

EEG data were acquired using a Grass Model 12 Neurodata acquisition system equipped with Model 12A5 amplifiers. EEG was amplified 20,000 \times , EOG was amplified at 10,000 \times , and high and low pass filters were set at 1 and 100 Hz, respectively (rolloff = 6 dB/octave; 60 Hz notch filter in). The amplified and filtered signal was digitized at 256 samples per second and stored on a Gateway 486/DX2 computer for later analysis using EEGSYS software (Version 5.5, Friends Medical Science Research Center, Baltimore, MD).

2.4. Procedures

All participants visited the laboratory five times. The first visit began with each participant reading and signing an informed consent document that was approved by the University's Institutional Review Board. During that same initial visit, the participant then performed a graded exercise test to determine maximal aerobic capacity (VO_{2max}) and ventilatory threshold (VT). Prior to the participant's arrival at the laboratory, the oxygen and carbon dioxide analyzers of the AEI Technologies Oxygen Uptake System Model OCM-2 were calibrated with gases of known oxygen and carbon dioxide concentration and room air. When the participant arrived, s/he was fitted with a (a) Hans Rudolph nasal and mouth breathing facemask to collect expired gases and (b) Polar Vantage Model XL heart rate monitor to record heart rate during the test.

The graded exercise test began on the treadmill with a 5 min warm-up, walking at 4.84 km h⁻¹. Treadmill speed was then increased to 8 km h⁻¹ with the grade remaining at 0%. Workload was increased every 1 min thereafter, with the first change in workload being an increase in speed (0.81 km h⁻¹) followed by an increase in grade (1%) and alternating speed and gradation increases until volitional exhaustion. Throughout the test, breath-by-breath sampling of expired gases was recorded and averaged over 30-s intervals by a Physio-dyne Respiratory Response Data Acquisition System. Following the completion of the test, the participant cooled down on the treadmill for 5 min by walking at 4.84 km h⁻¹. They were then seated in a chair for 10 min.

Acceptance of VO_{2max} was based on satisfying one or more of the following criteria: (a) reaching a peak or plateau in oxygen consumption rate (changes ± 2 ml kg⁻¹ min⁻¹) followed immediately by a decrease in oxygen consumption with increasing workloads; (b) a respiratory exchange ratio ≥ 1.10 ; or (c) exceeding age-predicted maximal heart rate (i.e., 220 – age).

VT was graphically determined by plotting the ventilatory equivalents for oxygen (V_E/VO_2) and carbon dioxide (V_E/VCO_2) across work rates and identifying the point at which there was a systematic increase in V_E/VO_2 without a corresponding increase in V_E/VCO_2 (Davis et al., 1979). The point of divergence between the two lines was identified visually and agreed upon by two raters. Based on the determination of VT, the three intensities were determined for each participant for the second session.

Session 2 was used as a manipulation check to determine the three intensities that the participant would be running at during the following three sessions. The three intensities utilized in this study, based on the results of the graded exercise test, were 20% below the ventilatory threshold (below-VT), at the VT (at-VT), and 10% of VO_{2max} above the VT (above-VT). Based on pilot testing, the above-VT intensity was set at 10% above-VT to limit the slope of the slow component of O_2 uptake and ensure that all participants would be able to complete the session despite the expected absence of a physiological steady-state at this intensity.

For Session 2 participants were once again fitted with a Hans Rudolph nasal and mouth facemask to collect expired gases and a Polar Vantage Model XL heart rate monitor to record heart rate during the session. The session began with a 5-min warm-up of walking 4.84 km h⁻¹ followed by a 5-min run at the intensity corresponding to below-VT intensity. During the 5-min run, VO_2 and heart rate

were monitored to confirm the desired intensity, with minor adjustments made in either speed or grade as needed to ensure the proper intensity. In all cases, the grade never exceeded 2%. Following the 5-min run at below-VT, a short break was taken to allow heart rate to return to near resting levels. The same procedures were then followed for both the at-VT and above-VT intensities.

Sessions 3 through 5 were submaximal exercise sessions. All participants exercised at each of the three exercise intensities; however, the order of the exercise intensities was randomly assigned and counterbalanced. The same procedures were followed for each of these sessions. Each session began by preparing the participant for EEG recording (see above) while seated in a comfortable chair. After signal integrity was confirmed and impedance checks recorded, the subject was asked to sit quietly while baseline measures of EEG were collected. Resting EEG measures were obtained with the eyes closed for eight, 60-s baseline periods. Eight baseline periods was chosen because of the high degree of test–retest reliability that has been shown for eight relative to fewer baseline recordings (Tomarken et al., 1992; Hagemann et al., 1998). EEG was collected with eyes closed because EEG alpha asymmetry from the mid-frontal sites (F3, F4) has been shown to be more stable when the eyes are closed compared to when the eyes are open (Tomarken et al., 1992). During the recording of these baselines, the participant was instructed to be as “restful” as possible. After completion of EEG recording, the participant was fitted with a heart rate monitor and the self-report measure of affect (AD ACL) was completed. Participants ran on a motorized treadmill at the assigned intensity for 15 min. Immediately following completion of the exercise bout, participants completed the AD ACL while standing on the treadmill, then walked on the treadmill at 4.84 km h⁻¹ for a 5 min cool down. Following the cool down, the AD ACL was once again completed and participants sat in a comfortable seat. At 10 and 20 min post-cool down, the AD ACL was completed.

2.5. Data reduction and analysis

Off-line, EEG waveforms were visually inspected for artifact by comparing activity at the scalp leads with the EOG to detect artifact via eye movements. EEG containing artifact was marked and excluded from each EEG trial prior to further analysis of the data. All artifact-free data that was at least 2.0 s in duration was subjected to a Fast Fourier Transform (FFT) with a Hanning window to avoid error due to discontinuities at the beginning and end of each epoch (the Hanning windowing filter employs a cosine-bell function to taper the first and last 10% of the epoch to zero). The FFT produces estimates of absolute spectral power (in μV^2) for the alpha frequency band (8–13 Hz). Power density values (in $\mu V^2/Hz$) for each 60 s trial were computed by dividing spectral power by the number of Hz estimates within the band, providing an index of the mean power density within the alpha frequency range. A natural log transformation (ln) was applied to all power density values to normalize the distribution (Gasser et al., 1982). All participants had a minimum of 20 artifact-free epochs (or s) for each given baseline (Gasser et al., 1985; Mocks and Gasser, 1984).

An EEG asymmetry index was derived (Pivik et al., 1993), which reflects the log alpha power density difference in corresponding regions of the two hemispheres (i.e., $\ln R - \ln L$ alpha power). Thus, higher asymmetry scores represent lower amounts of alpha activity and relatively greater activity in the left hemisphere for a particular region. This asymmetry score has been shown to have acceptable psychometric properties (Tomarken et al., 1992). However, previous researchers have discussed the possibility that state variability may influence the trait stability of the frontal EEG asymmetry measure and have suggested that multiple measures of asymmetry may help produce conclusive findings (Davidson, 1998b; Hagemann, 2004; Hagemann et al., 2002). In the present study frontal EEG asymmetry was measured prior to each of the three sessions before exercise. As such, an average of the three baseline asymmetry readings was used in the present analyses.¹

Regression analyses were used to examine the predictive power of asymmetry scores on post-exercise affect (i.e., EA and TA) after partitioning out pre-exercise affect and VO_{2max} (fitness levels).² Regressions were conducted for mid-frontal (F4–F3), lateral frontal (F8–F7), temporal (T6–T5), and parietal (P4–P3) EEG asymmetry.

3. Results

Initial analyses were performed to examine whether there was any influence of gender. No significant main effects or interactions with gender were found, nor did gender affect results in any consistent fashion with respect to moderating any effects on affect or EEG. As such, gender is not considered further in the analyses presented.

¹ The correlations between conditions ranged from 0.73 to 0.83 and 0.73 to 0.79 for mid-frontal and lateral frontal asymmetry, respectively.

² Fitness levels were partialled out because previous work has shown fitness levels to influence the predictive ability of regional brain activity on affective responsivity (Petruzzello et al., 2001). Additionally, in the present study, fitness levels as measured by VO_{2max} were correlated with lateral frontal ($r = 0.40$, $p = 0.014$) and parietal ($r = -0.39$, $p = 0.017$) asymmetry scores.

Table 1
Means and standard deviations ($M \pm SD$) and effect sizes for Energetic and Tense Arousal by Condition.

Variable	Time	Below-VT	ES	At-VT	ES	Above-VT	ES
Energetic Arousal	Pre-exercise	22.9 \pm 8.5		22.1 \pm 9.1		23.5 \pm 8.1	
	Post-exercise	34.0 \pm 4.3	1.73	33.7 \pm 4.9	1.66	33.4 \pm 6.1	1.41
	Post-cool down	31.1 \pm 5.5	1.17	30.3 \pm 6.5	1.05	30.6 \pm 6.3	0.99
	Post-10 min	25.9 \pm 7.6	0.37	26.5 \pm 8.0	0.51	26.7 \pm 7.0	0.42
	Post-20 min	24.9 \pm 7.7	0.25	25.9 \pm 7.5	0.46	25.7 \pm 6.6	0.30
Tense Arousal	Pre-exercise	17.3 \pm 5.8		16.8 \pm 4.6		18.0 \pm 5.4	
	Post-exercise	21.6 \pm 5.1	-0.79	22.4 \pm 5.4	-1.12	24.3 \pm 4.3	-1.33
	Post-cool down	18.3 \pm 4.4	-0.20	18.1 \pm 4.6	-0.28	20.1 \pm 4.0	-0.45
	Post-10 min	15.1 \pm 3.3	0.48	15.6 \pm 4.8	0.26	17.1 \pm 4.4	0.20
	Post-20 min	14.9 \pm 3.2	0.53	15.8 \pm 5.5	0.20	16.4 \pm 4.9	0.31

Note: Effect sizes were calculated as $(M_{\text{post}} - M_{\text{pre}})/SD_{\text{pooled}}$ for EA and $(M_{\text{pre}} - M_{\text{post}})/SD_{\text{pooled}}$ for TA, thus positive effect sizes reflect either increased EA or decreased TA post-exercise.

3.1. Affective responses to exercise

The first set of analyses examined changes in affect from pre- to post-exercise at four time points (immediately following, post-cool down, 10 min post-cool down, 20 min post-cool down) during three exercise intensity conditions. The purpose of this analysis was to determine if exercise intensity differentially influenced self-reported affective responses. Means and standard deviations, along with effect sizes (Cohen's d), for energetic and Tense Arousal at each condition can be seen in Table 1. A repeated measures general linear model [(Cond (3) \times Time (5))] on Energetic Arousal (EA) and Tense Arousal (TA) showed a significant main effect of time [$F(8, 22) = 19.62, p < 0.001$], but not a significant condition [$F(4, 26) = 1.91, p = 0.138$] or condition \times time interaction [$F(16, 14) = 0.49, p = 0.912$]. The significant time main effect was attributable to changes in both EA [$F(4, 116) = 40.01, p < 0.001, \text{Huynh-Feldt } \epsilon = 0.73, \eta_p^2 = 0.58$] and TA [$F(4, 116) = 31.0, p < 0.001, \text{Huynh-Feldt } \epsilon = 0.61, \eta_p^2 = 0.52$]. Immediately after the exercise bout, there was an increase in both EA and TA compared to baseline. EA remained elevated post-cool down, then decreased to a level slightly above pre-exercise levels at both 10 and 20 min post-exercise. TA gradually declined following the increase immediately after exercise, with the post-cool down, post-10 min, and post-20 min values all being essentially equivalent to pre-exercise levels. While not significant, the effect sizes indicated that the increase in EA post-exercise (immediately, post-cool down) was greatest in the below-VT condition (1.73, 1.17), less so in the at-VT condition (1.66, 1.05), and smallest in the above-VT condition (1.41, 0.99). Likewise, TA increased the most (immediately, post-cool down) in the above-VT condition (1.33, 0.45), somewhat less in the at-VT condition (1.12, 0.28), and least in the below-VT condition (0.79, 0.20).

3.2. Resting EEG asymmetry predicting post-exercise affect

For the below-VT condition, resting mid-frontal asymmetry (F4–F3) accounted for significant variance (12.6%, $\beta = -0.36, p = 0.030$) in EA immediately following exercise after partialling out pre-exercise EA and $\text{VO}_{2\text{max}}$. Resting lateral frontal asymmetry (F8–F7) accounted for significant variance (15.8%, $\beta = -0.44, p = 0.018$) in EA at 20 min post-cool down. Neither temporal nor parietal asymmetry predicted EA responses at any post-exercise time point; EEG asymmetry was also not predictive of TA at any post-exercise time points, regardless of scalp derivation.

In the at-VT exercise condition, resting lateral frontal asymmetry (F8–F7) was the only asymmetry metric to account for any sizable variance in EA (7.8%, $\beta = -0.31, p = 0.066$), albeit not significantly and only at 20 min post-cool down. Once again, none of the EEG asymmetry metrics predicted TA at any post-exercise time points.

In the above-VT condition, resting mid-frontal asymmetry accounted for significant variance (15.7%, $\beta = -0.40, p = 0.025$) in EA both immediately following exercise and following the cool down (13.7%, $\beta = -0.37, p = 0.035$). None of the other asymmetries predicted significant variance in affective responses following exercise above-VT.

4. Discussion

The purpose of the present study was to examine the utility of frontal EEG asymmetry in predicting affective responses to three metabolically different intensities of exercise. In addition, the valenced motivation and the motivation direction models were examined to determine which best fit the results related to exercise. Previous studies in the context of exercise had suggested that the intensity of exercise might be a critical factor in determining whether or not resting frontal asymmetry could predict post-exercise affective states, showing significant relationships when the intensity was higher, but no relationship when the intensity was lower (Petruzzello et al., 2001, 2006; Hall et al., 2007). The present study was designed to extend this line of inquiry by more systematically examining the intensity parameter, utilizing the ventilatory threshold (VT) to help standardize intensity as opposed to an arbitrary percentage of aerobic capacity.

Although the intensity manipulation did not result in a significant influence on self-reported affect, the Energetic (EA) and Tense Arousal (TA) responses were in the direction expected. Specifically, examination of the means and effect sizes indicated that EA (i.e., activated pleasant affect) increased the most immediately post-exercise in the below-VT intensity condition ($d = 1.73$), increased the least in the above-VT intensity condition ($d = 1.41$), with the at-VT condition resulting in an increase between these ($d = 1.66$). TA responses were similar: greatest increase in TA immediately following the above-VT condition ($d = -1.33$), smallest increase following the below-VT condition ($d = -0.79$) and the increase falling between these two for the at-VT condition ($d = -1.12$). While the analyses may have been underpowered, it is also likely that the expected intensity differences in affect may have occurred during exercise and reversed themselves during the post-exercise period, the so-called rebound phenomenon (Ekkekakis et al., 2005b; Hall et al., 2002). This further highlights the importance of examining "in-task" affect (i.e., affect during exercise).

In the current study, mid-frontal EEG asymmetry predicted significant variance in EA immediately following and following cool down from exercise in the above-VT condition. However, in the below-VT condition, mid-frontal asymmetry predicted significant variance in EA immediately following exercise and lateral frontal asymmetry predicted significant variance in EA at 20 min post-exercise. It should be noted that the results, as indicated by

the beta weights, were in a direction opposite to that hypothesized by the valenced motivation model. Based on the valenced motivation model, individuals with greater left-relative to-right frontal activity would have been expected to exhibit a diathesis (predisposition) to respond to the eliciting stimulus (i.e., exercise) with predominantly greater positive affect/lesser negative affect. However, the present findings are in partial agreement with those from Hall et al. (2007) where found that greater relative left frontal activity, as measured by mid-frontal EEG asymmetry, predicted tiredness following strenuous exercise (a maximal graded exercise test ended by volitional exhaustion).

The results of the present study, as well as those from Hall et al. (2007), appear to provide additional support for the motivation direction model. It is possible that left frontal activity was predicting tiredness (low EA) or “calm-tiredness” (Thayer, 1989, 2001) resulting from the rather intense physical exertion of the above-VT condition. This could be viewed as approach motivation and may be predictive of a sense of success or accomplishment resulting from completing the more difficult exercise condition. A recent study by Kline et al. (2007) provided evidence to support the motivation direction model by examining frontal EEG asymmetry within the context of the opponent process theory (Solomon, 1980). Kline et al. proposed that greater relative left frontal activity may be indicative of an ability to modulate stress responses and emotional reactions. They found that those with greater relative left frontal activity at baseline showed greater relative left frontal activity following the viewing of aversive slides, suggesting that relatively greater left frontal activity may be reflective of more effective coping with stressful stimuli. With these results in mind, it may be that in the current study, resting asymmetry represents a regulatory process whereby relatively greater left-sided activation reflects a motivation to remain engaged in approach-related behavior in spite of experiencing aversive stimulation and/or to experience a “calm-tiredness” as a result of that engagement.

Although the present results are inconsistent with both the valenced motivation model and previous EEG-exercise work, such inconsistencies between frontal EEG asymmetry and affect have also been found by others (Hagemann et al., 1998; Reid et al., 1998). Hagemann et al. (2002) reviewed the relationship between resting EEG and affect in 33 independent samples. In this review, Hagemann et al. found that 14 of the 33 samples showed an association between relative right-sided activity and negative affect/withdrawal tendency. In 12 of the 33 samples where positive affect was examined, only 4 showed relationships between relative left-sided activity and positive affect/approach tendency.

Another explanation could come from the fact that affective responses to the three bouts of exercise were similar despite the fact that they occurred at three metabolically distinct exercise intensities. Despite these distinct intensities, there was not a significant condition or condition by time interaction in affective responses, demonstrating similar affective responses to all intensities of exercise. This could be due to the fact that the sample was a highly active and fit group of college students. The fact that they reported increases in Energetic Arousal immediately following exercise may have been a result of something inherent to them (e.g., preference for or tolerance of intense exercise) or that had developed over time and experience with exercise. This is consistent with Damasio's (1994, 1995, 1996) somatic marker hypothesis which proposes that prefrontal cortices, specifically the ventromedial prefrontal cortex (Bechera et al., 2000), establish “linkages between the disposition for a certain aspect of a situation (for instance, the long-term outcome for a response option), and the disposition for the type of emotion that in past experience has been associated with the situation.” (pp. 296–297). It may be that the participants in this study had acquired, over many exercise

sessions, a disposition that linked exercise, regardless of intensity, with a positive affective state when the exercise was completed. It is worth reiterating the fact that lateral frontal asymmetry was correlated with aerobic fitness ($r = 0.40$, $p = 0.014$), indicating that participants who were more fit had greater relative left frontal activity. Therefore, even when exercising at high intensities, the acquired disposition for positive affect may become activated and despite other, perhaps conflicting, information that the person is receiving from the body (e.g., increase in blood lactate, shortness of breath, increased heart rate), positive affect is reported. This is also consistent with the increasingly seen finding of post-exercise positive affect, often within the first minute after exercise stops, even when the affect reported during exercise is less positive or even negative (Backhouse et al., 2007).

Future research should continue to examine the moderating role of exercise intensity on the relationship between frontal EEG asymmetry and affective responses following exercise. Additionally, future investigations may want to begin examining the relationship between frontal EEG asymmetry, affective responses during exercise, and exercise intensity. Previous research has found that the greatest variability in affective responses occurs during exercise as compared to following exercise (Ekkekakis et al., 2005b; Hall et al., 2002; Van Landuyt et al., 2000). Davidson (1998a, 2000a) has identified several issues, such as affective chronometry, resilience and threshold for reactivity, which may be important in examining affective responses during exercise. It is worth noting that a recent study conducted by Lochbaum (2006) found resting EEG asymmetry to predict affective responses during exercise, particularly in the more active participants, but not following exercise. The examination of frontal EEG asymmetry and affective responses during exercise fits nicely with the capability model of individual differences proposed by Coan et al. (2006). This model proposes that the ideal time to measure individual differences in frontal EEG asymmetry would be *during* different emotional states. Therefore, if frontal EEG asymmetry is measured during exercise at various intensities of exercise, it might be able to explain the differences in affective responses to these manipulations of exercise intensity better than relying on resting frontal EEG asymmetry to predict affective responses following exercise.

In conclusion, the present study showed EEG frontal asymmetry was predictive of affective responses following exercise, albeit in a direction opposite of that hypothesized. There was also no systematic influence of exercise intensity in this investigation. Future research should continue to examine these dose–response relationships and begin examining the influence of frontal EEG asymmetry to account for affective responses during exercise.

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