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Authors
Schneider, Margaret
Graham, Dan
Grant, Arthur
et al.

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Regional brain activation and affective response to physical activity among healthy adolescents

Margaret Schneider[1], **Dan Graham**[1], **Arthur Grant**[2], **Pamela King**[1], and **Dan Cooper**[1]

[1] University of California at Irvine

[2] SUNY Downstate Medical Center

Abstract

Research has shown that frontal brain activation, assessed via electroencephalographic (EEG) asymmetry, predicts the post-exercise affective response to exercise among adults. Building on this evidence, the present study investigates the utility of resting cortical asymmetry for explaining variance in the affective response both during and after exercise at two different intensities among healthy adolescents. Resting EEG was obtained from 98 adolescents (55% male), who also completed two 30-minute exercise tasks on a cycle ergometer at a moderate and hard intensity. Affect (as measured by the Feeling Scale) was assessed prior to exercise, every 10 minutes during exercise, immediately post-exercise, and 10 minutes post-exercise. When moderate exercise was performed first, resting frontal cortical asymmetry was related to the affective response to moderate exercise, such that left-dominant adolescents reported more positive affect compared to right-dominant adolescents. When hard exercise was performed first, the association was not significant. The results are interpreted in light of current theory related to affect in response to exercise.

Keywords

Physical Activity; affect; electroencephalogram; exercise

Introduction

Recent epidemiologic data using an objective measure of physical activity indicate that fewer than 12% of male and 6% of female adolescents in the United States are engaging in sufficient physical activity to meet public health recommendations (Troiano et al., 2008). Data from studies around the world indicate that this problem is not confined to North America. Low rates of physical activity participation during childhood and adolescence have been described in locales as disparate as Hungary (Pali, Katona, Paragh, Zrinyi, & Fulesdi, 2005), the United Kingdom (Stratton et al., 2007), and Brazil (Hallal, Bertoldi, Goncalves, & Victora, 2006). Despite increased attention to this issue, efforts to reverse this trend have been minimally successful. Throughout the high school years (approximately ages 14–18 years), there is a precipitous decline in physical activity participation (Caspersen, Pereira, & Curran, 2000), and sedentary adolescents are at high risk for remaining sedentary into adulthood (Alfano, Klesges,

Corresponding Author: Margaret Schneider, 620 University Tower, 4199 Campus Drive, Irvine, CA, Tel (949) 824–8853, Fax (949) 824–8849.

Murray, Beech, & McClanahan, 2002; Azevedo, Araujo, Cozzensa da Silva, & Hallal, 2007). Many environmental and social influences have been identified that may contribute to this decline, including automobile-oriented community design (Anderson & Butcher, 2006), lack of neighborhood safety (Weir, Etelson, and Brand, 2006), and the increasing popularity of video gaming (Nelson, Gordon-Larsen, Adair, & Popkin, 2005).

Despite influences to the contrary, some adolescents do continue to engage in regular physical activity, yet the dynamics behind such behavioral resilience are poorly understood. Research into individual differences that may explain why some adolescents remain active and others do not has generally focused on traditional constructs derived from psychosocial models of health behavior, such as perceived benefits, perceived barriers, and self-efficacy. Few studies have attempted to identify individual differences in underlying psychophysiology that might contribute to adolescents’ likelihood of remaining active.

Davidson (1998) has suggested that individuals differ along a dimension termed “affective style” that refers to individual differences in emotional reactivity in response to stimuli. According to this theory, some individuals will be more likely than others to respond to an emotion-eliciting stimulus with positive affect. Research supports the assertion that individuals who score highly on assessments of extraversion are more likely to experience positive affect in response to emotion-eliciting stimuli (Carver & White, 1994; Gross, Sutton, & Ketelaar, 1998). Interestingly, it is this aspect of personality (i.e., extraversion) that has been most consistently associated with physical activity (Rhodes & Smith, 2006). Extraversion is characterized by a preference for social interaction and lively activity (Eysenck, 1970), and in contemporary personality theory it has been conceptualized as closely aligned with the approach or appetitive motivation that forms one of the two structural components of personality; the other being withdrawal or avoidance (Carver, Sutton, & Scheier, 2000). Thus, there is evidence to support the hypothesis that individuals with a more approach-oriented affective style will experience relatively greater positive affective responses to stimuli and that these individuals also are more likely to participate in regular physical activity.

In a compelling series of laboratory and clinical observations, Davidson and others have demonstrated both that individuals differ in their tendency to respond with positive versus negative affect when confronted with emotion-eliciting stimuli, and also that affective style is associated with electrophysiological measures of activation in the frontal cortex (Davidson, 2004; Harmon-Jones, 2003). In one study (Sutton and Davidson, 2000) greater left-sided frontal cortical activation relative to right, assessed using electroencephalogram (EEG), was associated with a bias toward selecting more positively valenced words in a forced-choice paradigm Similarly, greater left versus right frontal cortical activation predicted a more positive affective response to an emotion-eliciting film clip (Wheeler, Davidson, & Tomarken, 1993).

Further evidence that patterns of activation in the frontal cortex may be used to characterize affective style emerges from a number of studies that have demonstrated an association between frontal cortical activation and the behavioral activation system (BAS). The BAS is a neurophysiologically-based system that is sensitive to cues of impending reward (Gray, 1994), and high trait BAS activation is associated with a predilection to engage in goal-directed (i.e., approach) behavior concomitant with positive affect. Both Gray (1970) and Davidson (2004) have suggested that greater BAS sensitivity is related to frontal cortical asymmetry such that higher activation in the left versus the right frontal cortex at rest corresponds to a more highly activated BAS. A number of studies have supported this hypothesis (Amodio, Master, Yee, & Taylor, 2008; Coan & Allen, 2003; Harmon-Jones & Allen, 1997; Hewig, Hagemann, Seifert, Naumann, & Bartussek, 2004, 2006).

Based on the evidence that regional brain activation acts as a biological marker for affective style, a small group of studies has investigated the utility of frontal cortical asymmetry for predicting individuals' affective response to exercise. Essentially, these studies have employed exercise as the emotion-eliciting stimulus in a further extension of the inquiry into patterns of regional cortical activation and affective style. That exercise does function as an emotion-eliciting stimulus has been demonstrated (Ekkekakis, Hall, & Petruzzello, 2008; Reed & Ones, 2006). Moreover, that individuals differ in their magnitude of affective responding to exercise also has been shown (Welch, Hulley, Ferguson, & Beauchamp, 2007). Hence, the data support using acute exercise as an emotion-eliciting stimulus in a test of the association between cortical activation and affective style.

Among adults, there is some evidence that resting frontal cortical asymmetry predicts the affective response to a bout of exercise. A study of 20 highly fit young adults (Petruzzello & Tate, 1997) found that after exercising on a stationary cycle for 30 minutes at 70% VO2max, resting frontal EEG asymmetry accounted for significant variance in post-exercise positive affect. More specifically, greater left frontal activation at rest was predictive of greater increases in positive affect. In order to determine whether these findings would generalize to less-fit individuals, a subsequent study (Petruzzello, Hall, & Ekkekakis, 2001) investigated the dynamic with both highly- and moderately- fit adults. After exercising on a treadmill at 75% of VO2max for 30 minutes, the subjects with greater resting left frontal activation relative to right had significantly greater increases in positive affect, although this effect was found only in the high-fit group. In another follow-up study in adults, greater relative left frontal activation predicted a state of "calm tiredness" (an affective state that Thayer (2001) describes as "very pleasant (p. 211)" and as characteristic of the exhaustion that follows substantial physical demand) at 10 and 20 minutes following exercise to volitional exhaustion, after controlling for fitness (Hall, Ekkekakis, & Petruzzello, 2007). Overall, these findings support the hypothesis that, among adults, greater left frontal cortical activation predicts a more positive affective response to exercise.

The present study

The present study addresses limitations to prior work in this area in a number of ways. Notably, all of the published research on the association between cortical activation and the affective response to exercise has been conducted with adults. A number of studies have investigated frontal cortical asymmetry as a correlate of behavior among children with disorders such as Down syndrome (Conrad et al., 2007), autism (Sutton et al., 2005), or mood disorders (Rybak, Crayton, Young, Herba, & Konopka, 2006), yet there is a dearth of information relating cortical activation to affective style among healthy adolescents. In addition, the possible moderating role of exercise intensity on the relationship between cortical activation and affective response to exercise has yet to be adequately explored. Evidence shows that exercise above the ventilatory threshold (the intensity level at which there is an abrupt increase in blood lactate or a nonlinear increase in expired carbon dioxide relative to oxygen consumption) has a qualitatively different impact on affect as compared to exercise below the ventilatory threshold (Ekkekakis et al., 2008) and the association between cortical asymmetry and affective response to exercise may not emerge in response to lower-intensity exercise (Hall et al., 2007). Finally, evidence indicates that unique information can be obtained when data on affect are collected *during* the exercise bout, rather than just before and after (Bixby, Spalding, & Hatfield, 2001; Sheppard & Parfitt, 2008; Welch et al., 2007). Thus, this study extends prior work by focusing on healthy adolescents, investigating cortical activation relative to exercise both below and above the ventilatory threshold, and assessing affect before, during and after exercise.

The aim of the present study was to examine the association between resting frontal cortical asymmetry and affective response to exercise among healthy adolescents. We hypothesized that left versus right frontal cortical activation would be positively correlated with the affective response to an acute bout of exercise.

Methods

Participants

One hundred and one adolescents (55% male; 70% Caucasian, 9% Asian, 8% Latino, 13% other; mean (SD) age = 14.74 (.48) years, range = 14–16) were recruited from two public high schools in Southern California. In order to be eligible for the study, participants had to meet the following criteria: 1) no health problems that precluded participating in regular moderate to vigorous exercise; 2) right-handed (scoring as right-hand dominant on the Chapman scale (Chapman & Chapman, 1987)); 3) a self-report of no history of neurological disorders, stroke, or significant head trauma (i.e., head trauma associated with loss of consciousness for greater than 24 hours); 4) not clinically depressed (defined as ever having been diagnosed with clinical depression or scoring at least 20 on the Beck Depression Inventory (Beck, Steer, & Brown, 1996)).

Measures

Brain Activation—Resting EEG asymmetry has been characterized by good test-re-test reliability and internal consistency, suggesting that it can justifiably be used as a measure of individual differences (Tomarken, Davidson, Wheeler, & Doss, 1992). Moreover, EEG alpha activity has been found to be inversely related to cortical activation (Feige et al., 2005), meaning that as cortical activation decreases, alpha power increases. Therefore, lower values of the variables obtained through EEG procedures indicate higher cortical activation. In the present study, EEG signals from electrodes F3, F4, P3 and P4 (referenced to linked mastoids) were subjected to a fast Fourier transform (FFT) power spectral analysis in the alpha band (8 – 13Hz; Insight II software, Persyst Development Corp.). In keeping with the predominant tradition of research in this area (e.g., Hall et al., 2007; Petruzzello et al., 2001), the asymmetry between left and right frontal cortical activation was calculated as the difference between normalized alpha power at F4 and F3 (i.e., logF4–logF3). Similar computations were performed for EEG signals from electrodes P3 and P4 (parietal region) as a means of testing for the regional specificity of the association between cortical asymmetry and affective response to exercise.

Cardiovascular fitness—Each participant performed a progressive ramp-type cycle-ergometer exercise test to the limit of his or her exercise tolerance. Subjects were vigorously encouraged during the high-intensity phases of the exercise protocol. Gas exchange was measured breath-by-breath (Cooper, Weiler-Ravell, Whipp, & Wasserman, 1984) and the ventilatory threshold and peak VO_2 (oxygen consumption) were calculated using a Sensor Medics metabolic system (VIASYS, Yorba Linda, CA).

Affective Valence—The Feeling Scale (FS) is a single-item 11-point bipolar measure of pleasure-displeasure, which is used for the assessment of affective valence. The scale ranges from 5 (very bad) to +5 (very good). Originally developed by Hardy and Rejeski (1989), the FS has been shown to represent a broad measure of emotional expression, and to be only moderately related to ratings of perceived exertion, suggesting that the two constructs are distinct. Moreover, recent work has demonstrated that FS is sensitive to alterations in affect among adolescents during exercise (Sheppard & Parfitt, 2008).

Ratings of perceived exertion (RPE)—According to Borg and Kaijser (2006), perceived exertion can be regarded as a “Gestalt” made up of perceptions from cues that may be both physiological and psychological. Although RPE may vary between individuals at a given work rate, individual RPE typically increases with work rate. Borg's RPE scale was developed to provide a rating scale that permits the individual to report his or her overall level of perceived exertion based on his or her own physiological and psychological perceptions. In the present study, the RPE scale was employed as a manipulation check to verify that individuals perceived themselves to be working at different levels of exertion during the moderate and hard tasks. This scale ranges from 6 (no exertion at all) to 20 (maximal exertion). Participants were asked to provide a rating on the RPE scale every three minutes (excluding baseline) throughout the exercise tasks.

Heart Rate—Heart rate was recorded continuously using a Sensor Medic V-max system via Cardio System software using a three-lead ECG. Every three minutes during the exercise task an exercise technician recorded the current heart rate on an exercise data sheet.

Procedures

Participants were recruited using flyers distributed to all high school freshmen at two public schools. An initial telephone screening was followed by an orientation session during which potential participants completed consent forms and screening questionnaires. All participants provided written assent to participate, and written consent was also obtained from a parent or guardian. All study procedures were reviewed and approved by a University-based Institutional Review Board.

Assessments were conducted at a University-based General Clinical Research Center (GCRC). Study participants visited the GCRC three times, with each visit separated by approximately one week. During the first visit, participants underwent an EEG and a cardiovascular fitness test. The EEG was performed on resting, awake subjects in a quiet room, using clinical digital EEG equipment (Nihon-Kohden; Tokyo, Japan) at a sampling rate of 200Hz. Standard gold/silver-silver chloride 10 mm cup electrodes were placed according to the international 10–20 system under the guidance of a board-certified clinical neurophysiologist. Scalp electrode sites were prepared in the standard fashion with a mild abrasive, and electrodes were attached with Elefix electrode paste. All electrode impedances were maintained at less than 10 kOhm. EEG was recorded for eight consecutive minutes; four minutes with eyes open (EO) and four minutes with eyes closed (EC). Participants were instructed to remain quietly alert during the recording session. After completing the EEG, participants were prepared for the cardiovascular fitness assessment.

After the conclusion of the fitness test, each participant's ventilatory threshold was determined by the exercise technician, using the V-slope method. The work rate at the ventilatory threshold was used to calculate the target work rate for the moderate and hard exercise tasks as described below. The selection of the ventilatory threshold as a reference point for assigning exercise of different intensities was based on evidence that exercise above the ventilatory threshold is qualitatively different from exercise below the ventilatory threshold, and has been shown to have differential effects on affect (Ekkekakis et al., 2008; Welch et al., 2007).

During the second visit to the GCRC, participants completed a 30-minute exercise task on a cycle ergometer. Prior to initiating the task, participants self-reported their affective valence using the Feeling Scale (FS). Throughout the task and after a 10-minute recovery period, participants were asked to provide a rating of affect every 10 minutes. Ratings of perceived exertion also were obtained every 3 minutes throughout the exercise task (excluding baseline). The exercise task was repeated at a third visit to the clinic, with visits two and three randomly determined to be at either a moderate intensity (target work rate equivalent to 80% of the work rate at the participant's ventilatory threshold) or a hard intensity (target work rate equivalent to the work rate at the mid-way point between the individual's peak oxygen uptake during the fitness test (VO2peak) and the ventilatory threshold). Exercise technicians were instructed to be alert for signs of fatigue on the part of participants and to reduce the target work rate in increments of 5–10 watts after the first five minutes of exercising, as needed, to ensure that the participant would be able to complete the 30-minute task while pedaling at a rate of at least 60 rpm. Participants were not informed a priori as to the intensity level at which they would be exercising. Participants received $25 monetary compensation following each clinic visit.

Data Reduction and Analysis

A board-certified neurologist and electroencephalographer reviewed each EEG for clinical abnormalities. Whenever possible we chose for analysis a single continuous two-minute EEG segment within each four-minute sample of EO and EC. These segments were carefully chosen to contain as little artifact of all types as possible. However, unlike some other researchers, we did not routinely exclude all EEG segments containing eye blink or eye movement artifact, as these artifacts contain an insignificant amount of power in the 8–13 Hz band. This approach has at least two advantages. First, it uses a relatively large amount of EEG data and thus increases statistical power. Second, by minimizing the number of EEG segments we minimize unavoidable error in FFT analyses of non-infinite time series. In cases where the EEG showed considerable artifact or the participant appeared to be drowsy, we omitted these segments from the computation. Analyses were limited to those participants who had a minimum of 220 usable seconds of EEG data (N = 98). In most cases, we were able to obtain these data with a single two-minute continuous recording from each of the four-minute samples (i.e., 77% of EO and 75% of EC EEG). Among those participants for whom we were required to use multiple segments, we obtained 120 seconds of data using as few segments as possible (mean[SD] number of segments = 1.38 [SD = .84]). Power density values were computed independently for the EO and EC EEG and then the two values were averaged. For the FFT analyses, the high-pass filter was set at 70Hz, the time constant was 1 second, and the 60Hz notch filter was on. FFT parameters included: Hamming window, 1024 points per window, 50% window overlap. The alpha band power spectrum was then further analyzed to determine the total power within the band (μV^2/Hz). The power density was normalized using a log transformation and the transformed values were used to yield measures of frontal (logF4–logF3) and parietal region (logP4–logP3) cortical asymmetry. Higher asymmetry scores represent lower alpha power (i.e., relatively greater cortical activation) in the left hemisphere. For the purposes of statistical analysis, the frontal and parietal asymmetry variables were dichotomized into two groups: subjects with greater activity in the left hemisphere relative to right (left-dominant; asymmetry greater than 0), and subjects with greater activity in the right hemisphere relative to left (right-dominant; asymmetry less than 0). Because our interest was in those with left frontal dominance, participants with no asymmetry were placed in the right-dominant group.

Manipulation checks (repeated measures ANOVAs) were run to confirm that there was an effect of the exercise tasks on heart rate, RPE, and FS. The relationship between frontal cortical asymmetry and affective response to exercise was evaluated using repeated measures ANOVA, with time and intensity as within- subjects factors, and cortical asymmetry as a between-subjects factor. Because an initial analysis predicting affective response to exercise in a 2 (intensity: moderate and hard) X 5 (time: baseline, minutes 10, 20, 30, 40) X 2 (order of the task: moderate first and hard first) repeated-measures ANOVA revealed a significant three-way interaction between the order of the tasks, intensity, and time, analyses were conducted separately for participants who completed the moderate exercise task on their first visit (N = 52) and those who completed the vigorous exercise task on their first visit (N = 46). Baseline cardiovascular fitness (VO_2peak) was included as a covariate. An analogous analysis was run using parietal asymmetry as a predictor variable to establish the regional specificity of the association between cortical asymmetry and affective response to exercise. Initially, all analyses controlled for gender, but since there were no main or interactive effects for gender, this variable was removed from the analyses. When the assumption of sphericity was violated, multivariate tests were used. Probability values were assessed using Wilks Lambda (converted to F), and effect sizes were estimated using partial eta-squared (η^2).

Results

Descriptive Statistics

The dichotomous split on frontal cortical asymmetry yielded a group of 42 participants with right-dominant frontal asymmetry and a group of 56 participants with relatively left-dominant frontal asymmetry. The difference in frontal asymmetry between the two groups was statistically significant ($t = -8.75$, $p < .001$). Table 1 shows the means and standard deviations for cardiovascular fitness (VO_2peak), Body Mass Index (BMI), age-adjusted BMI percentile, and the EEG measures. There were no significant differences in these participant characteristics between participants with left-dominant and those with right-dominant frontal asymmetry. Moreover, there was no significant association between frontal asymmetry and parietal asymmetry. Boys had higher cardiovascular fitness compared to girls (data not shown); there were no other gender differences.

Exercise Task Work Rate

During the moderate exercise task, 96% of the study participants were able to maintain the target work rate throughout the 30-minute exercise task. Four participants exhibited signs of tiring during the task (i.e., they were unable to maintain a cadence of 60 rpm for a full minute), resulting in an average reduction in work rate of 18 watts per participant for these four individuals (range = 10–30 watts). During the hard exercise task, 79% of study participants exhibited signs of fatigue prior to the end of the 30-minute task, resulting in an average reduction in the target work rate of 32 watts per participant for these 78 individuals (range = 5–120 watts).

Effect of Exercise Intensity on Heart Rate and Rating of Perceived Exertion (RPE)

A 2 (exercise intensity: moderate and hard) X 11 (time points: baseline, minutes 3, 6, 9, 12, 15, 18, 21, 24, 27, 30) repeated measures ANOVA on the heart rate data showed a significant main effect of exercise intensity (F (1, 80) = 380.18, $p < .001$), a significant main effect of time (F(10, 71) = 265.59, $p < .001$), and a significant intensity by time interaction (F(10, 71) = 57.15, $p < .001$). Average heart rate increased over time in both exercise conditions, and the increase was greater during the hard exercise task.

A 2 (exercise intensity: moderate and hard) X 10 (time points: minutes 3, 6, 9, 12, 15, 18, 21, 24, 27, 30) repeated measures ANOVA on the RPE showed a significant main effect of exercise intensity (F (1, 88) = 357.43, $p < .001$), a significant main effect of time (F(9, 80) = 45.57, $p < .001$), and a significant intensity by time interaction (F(9, 80) = 5.31, $p < .001$). As with heart rate, RPE increased over time in both conditions, and the increase was greater in the hard exercise task. Thus, both the heart rate and RPE data indicated that the two exercise tasks were executed effectively and resulted in two experientially different intensities.

Effect of Exercise Intensity on Affect

A 2 (exercise intensity: moderate and hard) X 5 (time points: baseline, minutes 10, 20, 30, 40) repeated measures ANOVA on the Feeling Scale (FS) showed a significant main effect of exercise intensity (F (1, 97) = 112.02, $p < .001$), a significant main effect of time (F(4, 94) = 46.68, $p < .001$), and a significant intensity by time interaction (F(4, 94) = 17.95, $p < .001$). The mean FS reported by the participants during the moderate exercise task decreased compared to baseline during the task (at 10 and 20 minutes), returned to baseline at 30 minutes, and increased compared to baseline at 40 minutes. The mean FS reported by participants during the hard exercise task declined more substantially than during the moderate exercise task, and did not return to baseline levels until the final assessment, 10 minutes after the termination of the exercise bout.

Association of Frontal Cortical Activation and Affective Response to Exercise

Moderate task first—The association between frontal cortical asymmetry and affective response to the exercise tasks among those adolescents who completed the moderate-exercise task first was assessed in a 5 (time points: baseline, minutes 10, 20, 30, 40) X 2 (intensity: moderate and hard) X 2 (asymmetry: left-dominant and right-dominant) repeated measures ANCOVA with cardiovascular fitness as a covariate. The multivariate results showed a main effect of cardiovascular fitness ($F(1,49) = 4.91$, $p < .05$, $\eta^2 = .09$), a marginally significant main effect of time ($F(4,46) = 2.34$, $p = .06$, $\eta^2 = .17$), and a significant 3-way interaction between time, intensity, and cortical asymmetry, ($F(4, 46) = 2.64$, $p < .05$, $\eta^2 = .19$). Individual post-hoc repeated measures ANCOVAs examining the relationship between cortical asymmetry and affective response for moderate- and hard-intensity exercise, respectively, indicated that the relationship was significant for the moderate-intensity exercise task only (data not shown).

Hard task first—The association between frontal cortical asymmetry and affective response to the exercise tasks among those adolescents who completed the hard-intensity exercise task first was assessed in a 5 (time points: baseline, minutes 10, 20, 30, 40) X 2 (intensity: moderate and hard) X 2 (asymmetry: left-dominant and right-dominant) repeated measures ANCOVA with cardiovascular fitness as a covariate. The multivariate results showed a main effect of intensity ($F(1, 43) = 25.51$, $p < .001$, $\eta^2 = .37$) and a marginally significant main effect of time ($F(4,40) = 2.59$, $p = .05$, $\eta^2 = .20$). There were no main or interactive effects with cortical asymmetry.

Figure 1 illustrates the affective response to moderate exercise as a function of the order of the exercise tasks. When moderate exercise was performed first, participants with left-dominant frontal cortical asymmetry experienced a more positive affective response compared to participants with right-dominant frontal cortical asymmetry. When hard exercise was performed first, however, cortical asymmetry had no relationship to the affective response to moderate exercise.

Association of Parietal Cortical Activation and Affective Response to Exercise

The association between posterior cortical asymmetry and the affective response to exercise was assessed using analogous ANCOVAs to those described above. Both 5 (time points: baseline, minutes 10, 20, 30, 40) X 2 (intensity: moderate and hard) X 2 (asymmetry: left-dominant and right-dominant) repeated measures ANCOVAs controlled for cardiovascular fitness, and the results showed no main or interactive effects for parietal asymmetry.

Discussion

The present study was designed to test the hypothesis that adolescents with greater left than right frontal cortical activity at rest (i.e., higher activation in the left versus the right frontal cortex) would respond to an acute bout of exercise with more positive affect compared to adolescents with greater right frontal cortical activation. The results were consistent with this hypothesis for subjects randomly assigned to complete the moderate exercise task before the hard exercise task. In addition, the results were consistent with the dual-mode theory of the affective response to exercise in that the association between cortical asymmetry and affective response emerged during moderate, but not hard, exercise. Moreover, parietal alpha power asymmetry was not related to the affective response to exercise, thus supporting the regional specificity of the association between frontal cortical activation and affective response to exercise. In other ways, however, the results were unexpected and did not conform to our hypothesis.

An unexpected finding was the moderating effect of the order of the exercise tasks. Among those adolescents who were randomly assigned to perform the hard exercise task at the earlier clinic visit and the moderate-intensity task at a later visit, the association between frontal cortical asymmetry and affective response to exercise was not significant. Possible explanations for the moderating effect of the order of the tasks are speculative, and may point the way to further research into the nature of the relationship between frontal cortical asymmetry and the affective response to exercise.

When considering possible mechanisms underlying the effect of task order, it is important to clearly define what differed between the two conditions. Participants were never informed at what intensity they were expected to exercise during a visit. They were asked to maintain a pedaling cadence of approximately 60 rpm, and the exercise technician adjusted the work rate to correspond to the individuals' target intensity for that visit. There should, therefore, have been no systematic variation in participants' expectations regarding the first task. In contrast, participants who engaged in hard exercise on the first task could naturally be expected to anticipate that the second task would be of a similar intensity. Thus, it would appear that the major difference between the two order conditions was the expectation that participants brought with them to the second task.

Our findings indicate, therefore, that when adolescents with a left-dominant frontal cortical asymmetry encounter a moderate-exercise task about which they have no intensity expectations, they are likely to experience a more positive affective response than their right-dominant compatriots. That this difference in affective response disappears when adolescents encounter a moderate-intensity exercise task with the expectation that the task will be extremely physically challenging suggests that the mechanism by which frontal cortical asymmetry impacts affective response to exercise is more cognitive than physiological. After all, the physical demands of the moderate task were the same regardless of whether the task was completed first or second. Since frontal cortical asymmetry did not predict affective response when adolescents performed the moderate task with the expectation of a much harder task, their affective interpretation of the task differed depending on their expectations. Future research could further elucidate this mechanism by manipulating participants' expectations as part of the research design.

Our results extend the findings of earlier studies examining the relationship between cortical asymmetry and the affective response to exercise. In a study of EEG asymmetry and affect in response to exercise at 55% and 75% of VO_2max, Petruzzello and Tate (1997) found that resting frontal EEG asymmetry was unrelated to affect during or after exercise at the lower intensity, but was related to affect following the higher-intensity exercise. These analyses did not, however, control for the order in which the exercise tasks were completed. If, as in the present study, the order of the task presentation moderated the affective response to moderate exercise, this moderation may have obscured the latent association between resting EEG and affective response to exercise at 55% of VO_2max. A later study (Petruzzello et al., 2001) examined the association between resting EEG asymmetry and affective response to a single bout of exercise at 75% VO_2max. Results indicated that the relationship between resting EEG asymmetry and post-exercise affect emerged only among highly fit participants. This study did not, however, assess affect *during* exercise, and so would not have detected the influence of cortical asymmetry on the affective response during an exercise bout. Examination of our data suggests that the discrepancy in affective responding in relation to EEG asymmetry is most prominent during the exercise task, and so may not be detected in a pre-post design. In a test of the affective response to a single bout of exercise to exhaustion (Hall et al., 2007), resting EEG asymmetry was predictive of a post-exercise state of "calm tiredness," which the authors identify as a pleasant state associated with physical exhaustion. These prior studies provide support for the hypothesis that resting EEG asymmetry is related to the affective response to exercise, and the present study builds on these findings by extending the investigation to adolescents, by calibrating the intensity of the exercise tasks relative to individual ventilatory threshold, by assessing affect before, during and after exercise, and by examining the moderating effects of the order in which the exercise tasks were performed. The results provide a multi- dimensional picture of the way in which EEG asymmetry is associated with affect in response to exercise, and generate new hypotheses about the mechanisms that underlie the relationship.

This evidence that adolescents are not homogeneous in their affective responding to exercise may help to explain some of the individual variability in physical activity participation on a population level. Although adolescents may choose to engage in physical activity for many reasons, including the desire to compete, the influence of parental expectations, or the desire for the social interaction that often accompanies sports, our findings suggest that there may also be a biologically-based individual difference in affective response to exercise that contributes to this variability in behavior. According to some theorists in behavioral economics, individuals will base their behavioral decisions in part on whether they anticipate that a behavior will generate positive or negative affect, and they will use their past experiences to inform these decisions (Slovic, Finucane, Peters, & MacGregor, 2002). Our results suggest that adolescents with relatively greater left frontal cortical activation at rest experience greater positive affect in response to moderate exercise when they have no expectations about the intensity of the exercise. Consequently, they may be more likely to seek out opportunities to be physically active, and to maintain an active lifestyle.

This study is unique in that it demonstrated that frontal cortical asymmetry among adolescents is related to the affective response to exercise. The next step is to show that adolescents who do experience a more positive affective response to exercise will engage in a more active lifestyle. A recent study suggests that this may be the case, at least for adults (Williams et al., 2008). Among a group of healthy adults who volunteered to take part in a controlled physical activity promotion program, the affective response to a bout of exercise at baseline predicted physical activity participation 6 and 12 months later. Similarly, adolescents who report more positive affect during moderate-intensity exercise also engage in more moderate-to-vigorous activity (Schneider, Dunn, and Cooper, in press). This evidence highlights the relevance of affective style for the highly salient challenge now facing the United States regarding how best to promote physical activity to a generation of increasingly sedentary youth.

It should be noted that this study is correlational in design. The results show that among adolescents there is an association between cortical asymmetry at rest and the affective response to exercise. The study design, however, precludes any conclusions about the direction of causal influence. Although it may be that cortical asymmetry is a stable trait that influences an individual's likelihood of responding to a bout of exercise with positive affect, it is also possible that individuals who feel better while exercising bring about an increase in their resting cortical asymmetry by engaging in a more active lifestyle.

There are aspects of our study design that limit the generalizability of the findings. We assessed the affective response to a laboratory-based exercise task, which has limited ecological validity. In free-living situations, individuals' affective response to exercise may reflect the influence of numerous stimuli, including social interaction, competition, and achievement of personal goals. It is therefore uncertain whether the affective response to this highly structured exercise task will generalize to freely chosen and unstructured exercise. In addition, the adolescents who participated in this study represent a self-selected group who demonstrated considerable initiative simply in volunteering to participate. As such, they may not be representative of the larger population, within which there are no doubt numerous adolescents who would not consider joining a project that required them to travel multiple times to a University-based clinic and undergo a range of novel assessments.

In sum, this study upholds a link between frontal cortical asymmetry and affective responses to exercise. These findings suggest that adolescents may differ in their underlying physiology, in such a way that predisposes some to enjoy exercise more than others. Future work should examine whether different types of behavior change interventions would be more or less effective among adolescents with left- versus right- frontal cortical dominance.

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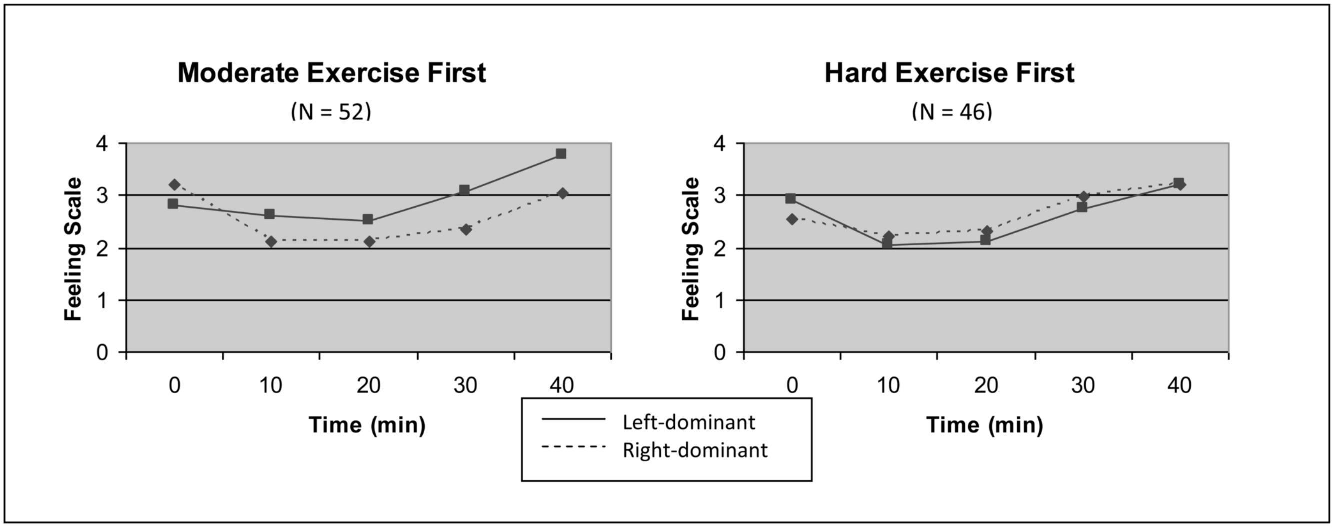

Figure 1.
Affective valence (Feeling Scale) during moderate-intensity exercise by frontal cortical asymmetry.

Table 1

Means and Standard Deviations of study variables *M*(*SD*).

	Left-dominant frontal asymmetry (*n* = 56)	Right-dominant frontal asymmetry (*n* = 42)	Full Sample (*n* = 98)
VO_2peak l/min	2.34 (.57)	2.56 (.67)	2.44 (.64)
VO_2peak ml/kg/min	38.64 (8.47)	39.11 (8.31)	39.09 (8.39)
Body Mass Index kg/m^2	21.42 (3.62)	22.61 (3.46)	21.71 (3.40)
Body Mass Index percentile	56.24 (26.26)	65.54 (29.19)	59.66 (27.31)
Anxiety-Moderate Task	32.76	32.04	32.45
Anxiety-Hard Task	32.48	32.34	32.42
Frontal Asymmetry* logF4–logF3	.02 (.01)	−.01 (.02)	.007 (.01)
Parietal Asymmetry logP4–logP3	.01 (.04)	.01 (.05)	.004 (.06)

Note: t-tests assessed differences between genders;

* $p < .001$