Received: 8 October 2019 | Revised: 26 May 2020 | Accepted: 9 June 2020

DOI: 10.1111/psyp.13633

ORIGINAL ARTICLE

PSYCHOPHYSIOLOGY SPR WILEY

Frontal asymmetry: A novel biomarker for physical activity and sedentary behavior

A. Hunter Threadgill[1] | **Ricardo A. Wilhelm**[2] | **Battogtokh Zagdsuren**[2] | **Hayley V. MacDonald**[2] | **Mark T. Richardson**[2] | **Philip A. Gable**[2,3]

[1]Department of Psychology & Biomedical Sciences, Florida State University, Tallahassee, FL, USA

[2]Department of Psychology, The University of Alabama, Tuscaloosa, AL, USA

[3]Department of Psychological & Brain Sciences, The University of Delaware, Newark, DE, USA

Correspondence

A. Hunter Threadgill, Department of Psychology & Biomedical Sciences, Florida State University, 1107 W. Call Street, Tallahassee, FL 32306-4301, USA.
Email: ahunterthreadgill@gmail.com

Ricardo A. Wilhelm, Department of Psychology, The University of Alabama, 505 Hackberry Lane, P.O. Box 870348, Tuscaloosa, AL 35487-0348, USA.
Email: rawilhelm@crimson.ua.edu

Abstract

Past research has demonstrated that regular physical activity provides a myriad of physical, mental, and emotional benefits. The decision of whether to partake in physical activity (PA) or remain sedentary appears to be partially influenced by motivational and emotional systems. Research suggests left frontal alpha asymmetry is a neural marker of approach motivation. However, studies have not explored whether habitual levels of PA and sedentary behavior relate to this neurophysiological signal. Across two studies, individuals completed measures of habitual PA and sedentary behavior using the International Physical Activity Questionnaire-Short Form. Then, resting electroencephalography activity was recorded. Results of Study 1 ($N = 32$, 72% women) indicated that more time spent sitting on both weekdays and weekend days were associated with less left frontal asymmetry ($r = -.45$, $p = .027$, and $r = -.55$, $p = .005$, respectively). Study 2 recruited a larger sample ($N = 96$, 31% women) and investigated moderators. Greater levels of moderate ($r = .27$) and total ($r = .29$) PA were associated with greater left frontal asymmetry ($ps < .05$), and the relationship between sedentary behavior and less left frontal asymmetry was moderated by sex (weekday: $\beta = .62$, $p = .011$; weekend day: $\beta = .41$, $p = .034$). Our results suggest that left frontal asymmetry may be a novel neurophysiological marker for PA and sedentary behavior.

KEYWORDS

approach motivation, EEG, frequency, frontal asymmetry, physical activity, sedentary behavior

1 | INTRODUCTION

Regular physical activity offers a broad array of well-established and accepted health benefits. There is extensive evidence supporting its role in chronic disease prevention (e.g., heart disease, diabetes, and several cancers), and more recently, brain health, by reducing the risk of clinical depression, the number and severity of depressive symptoms, and symptoms of anxiety (U.S. Department of Health & Human Services, 2018). In the United States, recent figures reported by the Centers for Disease Control and Prevention (CDC) suggest nearly 9% of deaths are associated with inadequate levels of physical activity (Carlson, Adams, Yang, & Fulton, 2018). From an economic standpoint, over 11% of overall healthcare expenses in the United States are associated with inadequate levels of physical activity (Carlson, Fulton, Pratt, Yang, & Adams, 2015).

A. Hunter Threadgill and Ricardo A. Wilhelm share co-first authorship. Author order for submission was determined by alphabetical order of last names.

Despite the wide-ranging benefits of physical activity, only 26% of men and 19% of women meet the public health guidelines for recommended levels of physical activity (U.S. Department of Health & Human Services, 2018). In addition to low levels of physical activity, high levels of sedentary behavior are associated with increased health risks. Due to the high prevalence of sedentary behavior and low levels of physical activity, the United States Department of Health and Human Services recommend both decreasing time spent sitting and increasing participation in moderate-to-vigorous physical activity (U.S. Department of Health & Human Services, 2018).

Sedentary behavior is a complex health-related behavior. More specifically, it involves a myriad of individual and environmental factors that interact synergistically to promote, condition, or prevent sedentary behavior (Chastin et al., 2016). Consistent with other human behaviors, sedentary behavior (i.e., any waking behavior characterized by an energy expenditure ≤1.5 metabolic equivalents [METs], while in a sitting, reclining or lying posture; Tremblay et al., 2017) appears to be modulated, at least in part, by emotional and motivational processes (Conroy, Maher, Elavsky, Hyde, & Doerksen, 2013; Hogan, Catalino, Mata, & Fredrickson, 2015).

Decades of research examining the relationship between emotion, motivation, and neural processes has found that approach and withdrawal motivation show different patterns of asymmetric frontal cortical activity (for review, see Harmon-Jones & Gable, 2018; Rutherford & Lindell, 2011). By examining the lateralized patterns of electrical activity over the frontal cortex, this method has been highly successful at detecting differences in motivation and emotion at the neurophysiological level (Allen, Keune, Schönenberg, & Nusslock, 2018). More specifically, research has found that greater relative left frontal alpha activity is associated with greater approach motivation (i.e., the drive to move toward some goal or object; Harmon-Jones & Allen, 1997; Harmon-Jones & Gable, 2018; Mechin, Gable, & Hicks, 2016; Neal & Gable, 2016; Sutton & Davidson, 1997). Conversely, greater relative right frontal alpha activity is associated with behavioral inhibition exhibited through withdrawal motivation (i.e., the drive to avoid some goal or an object; Shackman, McMenamin, Maxwell, Greischer, & Davidson, 2009; Sutton & Davidson, 1997) or motivational control (i.e., the detection and resolution of conflicts between approach and withdrawal motivation; Gable, Neal, & Threadgill, 2018; Neal & Gable, 2017, 2019).

Research has found that individuals with clinical disorders, such as bipolar disorder (Allen, Iacono, Depue, & Arbisi, 1993) and depression (Allen, Urry, Hitt, & Coan, 2004; Henriques & Davidson, 1991; Jacobs & Snyder, 1996; Schaffer, Davidson, & Saron, 1983; Thibodeau, Jorgensen, & Kim, 2006), demonstrate different patterns of resting asymmetric frontal cortical activity than healthy populations. For instance, greater left frontal activation is related to manic and hypomanic states (Harmon-Jones et al., 2002, 2008). Manic states are accompanied with high levels of activity and movement (Grande, Berk, Birmaher, & Vieta, 2016). In contrast, depressive states are associated with greater right frontal activity (Allen et al., 2018). These mood states are associated with deficits of approach motivation and often are accompanied by "a reduction in physical movement," "fatigue or loss of energy," and "diminished interest or pleasure in all … activities" (American Psychiatric Association, 2013). Thus, it seems likely that changes in relative left frontal activation might possibly relate to changes in propensity to engage in physical activity or sedentary behaviors.

There is some evidence to suggest that the decision, motivation, or intention to engage in physical activity and exercise (or not) is related to frontal cortical activity. For example, one study found that greater resting left frontal alpha asymmetry predicted self-selected walking speed (Hall, Ekkekakis, Van Landuyt, & Petruzzello, 2000). Indeed, the majority of existing research conducted to date has examined affective responses to varying types of exercise or physical activities, with some, but not all, studies observing that increased resting left frontal alpha asymmetry predicts post-exercise affective responses such as increased positive affect and decreased anxiety (Hall, Ekkekakis, & Petruzzello, 2007; Hall et al., 2000; Petruzzello & Landers, 1994; Woo, Kim, Kim, Petruzzello, & Hatfield, 2009). The effect of acute aerobic exercise on mood and frontal asymmetry has also been investigated, finding that a variety of exercise interventions can moderate the relationship between mood and frontal asymmetry (Lattari et al., 2014). Furthermore, some studies have begun to explore neurophysiological activity associated with the act of partaking in physical activity or sedentary behavior (Cheval, Boisgontier, Bacelar, Feiss, & Miller, 2019) or in response to imagery depicting physical activities or sedentary behaviors (Cheval et al., 2018). However, few studies, if any, have investigated whether frontal cortical activity is a potential neurobiological marker related to habitual sedentary or physically active behavior. Thus, the present studies seek to fill this important gap by examining the relationship between habitual levels of physical activity and sedentary behaviors and resting frontal asymmetry.

Reduced physical activity likely has neurophysiological substrates correlating with reduced approach motivation. Based on past work linking depression with less left frontal activity (Allen et al., 2018; Thibodeau et al., 2006) and more recent work examining the association of neurophysiological activity in response to physical activity or sedentary behavior stimuli (Cheval et al., 2018, 2019), we undertook a preliminary correlational study (Study 1) to explore whether lower levels of physical activity and higher levels of sedentary behavior would be related to reduced left frontal activity. To further explore the relationships between physical activity, sedentary behavior, and left frontal activity, we conducted a follow-up study with a considerably larger sample (Study 2). This larger, more diverse sample provided the opportunity to examine potential moderators and their influence on these relationships.

2 | METHOD

In both Study 1 and 2, participants underwent nearly identical experimental procedures. Specifically, they underwent the same baseline measures of habitual physical activity, habitual sedentary behavior, and resting frontal activity. As such, we report the combined methods for Study 1 and Study 2 below, only distinguishing between studies when differences occur.

2.1 | Participants and procedures

Study 1 had 45 right-handed undergraduate introductory psychology students, and Study 2 had 109 right-handed undergraduate introductory psychology students, all from the University of Alabama, participate in exchange for partial course credit. After removing participants who did not have both valid physical activity or sedentary behavior outcomes and measures of resting frontal activity, the final sample included 32 participants in Study 1 and 96 participants in Study 2. This number varied slightly in analyses, depending on the outcome of interest, due to missing or incomplete data for the specific physical activity or sedentary behavior in question.

Informed consent was obtained prior to each study. Handedness was assessed by having participants report with which hand they performed 13 tasks (e.g., throw a snowball, write, etc.; Chapman & Chapman, 1987). Right-handedness was defined as performing no more than one item with their left hand. All participants were right-handed.

Participants came into the laboratory and completed measures of handedness, a health screening questionnaire, and the short form of the International Physical Activity Questionnaire (IPAQ-SF). Upon completion of these measures, Electroencephalography (EEG) electrodes were applied, and 8 min of resting baseline activity was recorded (4 min with eyes open [O] and 4 min with eyes closed [C]). Two sequences were used and alternated between participants: C–O–O–C–O–C–C–O and O–C–C–O–C–O–O–C (Gable, Mechin, Hicks, & Adams, 2015).

2.2 | Measures

2.2.1 | Health screening questionnaire

Participants completed a health screening questionnaire prior to any experimental procedures. The questionnaire gathered information regarding participant demographics (e.g., age, sex, race, height, and weight), pertinent medical history (e.g., history of or current medication use for anxiety, depression, attention-deficit/hyperactivity disorder [ADHD] as these health conditions can influence frontal asymmetry; Nelson et al., 2012; Reznik & Allen, 2018), and exposure to other stressors that could influence their affective state (e.g., recent consumption of caffeine or food, participation in physical activity or exercise, hours slept before reporting to the laboratory, and current stress level). Participants were also asked to rate their current level of physical activity using a five-point rating scale: sedentary (<1 day/week), low (1–2 day/week), moderate (3 day/week), recreationally active (3–4 day/week), and highly active/athlete (5–7 day/week), as well as report how long (in months) they have maintained their current level of physical activity. Last, body mass index (BMI) was calculated from self-reported height and weight.

2.2.2 | Physical activity and sedentary behavior

Self-reported physical activity and sedentary behaviors were assessed using a modified version of the IPAQ-SF, a self-report questionnaire that has demonstrated to be a valid and reliable measure of habitual physical activity and sedentary behavior in diverse adult populations (Celis-Morales et al., 2012; Cerin et al., 2016; Craig et al., 2003; Dyrstad, Hansen, Holme, & Anderssen, 2014; Healy et al., 2011; Kim, Park, & Kang, 2013; Rosenberg, Bull, Marshall, Sallis, & Bauman, 2008), as well as in college student populations (Dinger, Behrens, & Han, 2006; Moulin, Truelove, Burke, & Irwin, 2019; Murphy et al., 2017; Nelson, Taylor, & Vella, 2019). The IPAQ-SF documents the amount of time (minutes per day and number of days per week) spent in three physical activity domains—vigorous-intensity, moderate-intensity, and walking—during the last seven days. Time spent in vigorous-, moderate-, and walking physical activity domains were then weighted by standard MET estimates (8.0, 4.0, and 3.3 METs, respectively) and expressed in terms of weekly physical activity volume using the following calculation:

$$\text{Volume}(\text{MET}-\text{minutes}/\text{week}) = \text{intensity}(\text{MET}) \times \frac{\text{daysofactivity}}{\text{week}} \times \frac{\text{minutesofactivity}}{\text{week}}$$

A measure of participants' total physical activity volume was calculated as the sum of vigorous, moderate, and walking activities expressed in MET-minutes per week. Total physical activity volume was then converted to a categorical variable to describe one's physical activity level ("Low," "Moderate," or "High") per IPAQ guidelines (Craig et al., 2003).

The IPAQ-SF also includes an estimate of sedentary behavior during the last seven days, based on the time spent sitting (minutes per day) on a typical weekday. We did not calculate weekly volume for sitting per IPAQ-SF recommendations (Craig et al., 2003). We did, however, include an additional question from the long version of the IPAQ to capture the time spent sitting on a typical *weekend* day (*During the last seven days, how much time did they spend sitting on a weekend day?*).

Both physical activity and sedentary behavior data were collected using the IPAQ-SF, and all data cleaning and scoring processes were in accordance with standard IPAQ procedures, when applicable (Craig et al., 2003). It should be noted that instructions for cleaning and scoring sitting data were not provided by the IPAQ-SF. Hence, the IPAQ protocol for physical activity was used as a guide. Briefly, we truncated and re-coded vigorous-intensity, moderate-intensity, and walking levels of physical activity that exceeded 3 hr (180 min) as "180 min" (Study 1: $n = 2$, Study 2: $n = 5$). We re-coded physical activity or sitting time responses of less than 10 min as "0 min" (Study 1: $n = 4$, Study 2: $n = 9$). Finally, we excluded any invalid or missing data (Study 1: $n = 9$, Study 2: $n = 11$) and physical activity or sitting time responses (reported on the IPAQ-SF) exceeding 16 hr (960 min) per day ($n = 2$ excluded based on sitting time reported on a typical weekend day in Study 1 only) from analyses.

2.3 | Electroencephalography assessment and processing

EEG was recorded from 64 tin electrodes mounted in a stretch lycra Quick-Cap (Electro-Cap, Eaton, OH; Study 1 and Study 2) or a 64-channel actiCap (Brain Products GmbH, Gilching, Germany; Study 2 only) and referenced online to the left earlobe. A ground electrode was mounted midway between FPz and Fz (Quick-Cap) or at site FPz (actiCap). Electrode caps were based on the 10–20 system, and a sodium chloride-based conductance gel was used to assist in the decrease of impedances. Electrode impedances were kept under 5,000 Ω (Quick-Cap) or 30,000 Ω (actiCap). Electro-Cap recordings were amplified with NeuroScan SynAmps RT amplifier units (El Paso, TX). Brain Products recordings were amplified with a Brain Vision actiCHamp amplifier (Brain Products GmbH, Gilching, Germany). All data were digitized at 500 Hz.

All recordings were analyzed offline using Brain Vision Analyzer 2.1 (Brain Products, Gilching, Germany). Data were re-referenced to the average of the mastoid sensors. Data were then low-pass filtered at 100 Hz, high-pass filtered at 0.05 Hz, and notch filtered at 60 Hz (Butterworth zero phase filters). A filter slope was set at 12 dB per octave. Eye-blinks were corrected by using an ICA-based ocular artifact rejection function within the Brain Vision Analyzer software (electrode FP1 served as the VEOG channel). In both studies, individual channels were then rejected using an automated procedure, with artifacts defined as a step of 50 μV in a 100-ms interval, a 200 μV change within a 160-ms interval, a change <0.5 μV within a 100-ms interval, and signals exceeding ±180 μV. After automatic artifact rejection, data were visually inspected again to ensure proper correction.

For both Study 1 and Study 2, epochs 1.024 s in duration were extracted using a sinusoidal-shaped Hamming window to reduce spectral leakage (50% taper of distal ends; Davidson, Jackson, & Larson, 2000). Consecutive epochs were overlapped by 50% to avoid data loss. Next, power values corresponding to alpha (8–13 Hz) were extracted using a Fast Fourier Transformation and averaged across epochs. An asymmetry difference score was created by subtracting log left from log right for homologous sites. Alpha activity was examined at frontal sites F6 and F5 (Allen & Cohen, 2010; Neal & Gable, 2016), since that is where left frontal alpha asymmetry was greatest across frontal sites. Because alpha power is inversely related to cortical activation (Laufs et al., 2003), higher scores reflect greater relative left frontal activity.

2.4 | Data analysis

2.4.1 | Study 1

To examine the relationship between relative left frontal activity and our main outcomes of interest, (a) physical activity (expressed as MET-minutes per week), i.e., vigorous-intensity, moderate-intensity, walking, and total, and (b) sedentary behavior (expressed as minutes per day), i.e., time spent sitting on a typical weekday and weekend day, we ran a series of Pearson correlations. We also included select sample demographics (e.g., sex, age, BMI, and diagnosis of depression and/or anxiety) in our correlation matrix as we were interested in the associations of these variables with left frontal activity and our measures of habitual physical activity and sedentary behavior. Further exploration of how these covariates may modulate the relationship between relative left frontal activity and physical activity and sedentary behavior was precluded due to our small sample.

2.4.2 | Study 2

Consistent with Study 1, we first investigated the relationship between relative left frontal activity and our main outcomes of interest, (a) physical activity (expressed as MET-minutes per week), i.e., vigorous-intensity, moderate-intensity, walking, and total, and (b) sedentary behavior (expressed as minutes per day), i.e., time spent sitting on a typical week day and weekend day, in our larger and more diverse sample, by way of Pearson correlations.

Second, we wanted to explore the potential moderating effect of several sample demographics identified a priori (e.g., sex, age, BMI, and diagnosis of depression and/or anxiety) on the relationship between relative left frontal activity and physical activity and sedentary behavior. Consistent with our exploratory approach to data analysis (Behrens, DiCerbo, Yel, & Levy, 2013; Jebb, Parrigon, & Woo, 2017; Velleman & Hoaglin, 2012), we conducted several linear regressions (also decided a priori) for each physical activity and sedentary behavior outcome that controlled for sex (coded −1 = *women*, 1 = *men*), age, BMI, diagnosis of depression and/or anxiety (coded −1 = *no*, 1 = *yes*), and their interaction with the physical activity or sedentary behavior outcome. Multiple regressions that had significant interactions were further explored using simple slopes analysis.

3 | RESULTS

3.1 | Study 1

Descriptive data for Study 1 participants are shown in Table 1. On average, our sample included young adults (18.9 years of age), mainly women (71.9%), of normal weight (BMI of 23.5 kg/m^2). Using the self-reported physical activity question, a large proportion of participants in our sample (43.8%) rated their current physical activity level as being *recreationally active* (engage in physical activity 3–4 days/week), while only 15.6% reported being *highly active/athletic* (engage in physical activity 5–7 days/week). Based on the IPAQ-SF categorical physical activity rating (derived from weekly total physical activity volume), exactly half of our sample (50.0%) were considered *moderately active* and 37.5% were considered *highly active*. In terms of sedentary behavior, participants reported, on average, sitting for 4 hr on a typical weekday and 3 hr on a typical weekend day.

Bivariate correlational analyses revealed that the volume of physical activity, expressed as MET-minutes per week, spent in vigorous-intensity ($r(29) = -.24$, $p = .204$), moderate-intensity ($r(29) = -.22$, $p = .229$), and walking ($r(29) = -.17$, $p = .358$) activities was unrelated to relative left frontal activity. Total physical activity volume (the sum of vigorous, moderate, and walking activities) was also unrelated to left frontal activity ($r(29) = -.30$, $p = .100$; see Table 2 for correlations among study variables of interest). Time spent in vigorous-intensity activity was positively related to age, $r(29) = .41$, $p = .023$.

Bivariate correlational analyses revealed that time spent sitting, expressed as minutes per day, on a typical weekday was associated time spent sitting on a weekend day, $r(22) = .79$, $p < .001$. Time spent sitting on a weekday was also associated with less relative left frontal activity, $r(22) = -.45$, $p = .027$ (see Figure 1). Time spent sitting on a typical weekend day was associated with less relative left frontal activity, $r(22) = -.55$, $p = .005$ (see Figure 2), suggesting that less relative left frontal activity is related to time spent engaging in sedentary behaviors. Less relative left frontal activity was also related to BMI, $r(30) = -.36$, $p = .041$.

3.2 | Study 2

Descriptive data for Study 2 participants are shown in Table 3. On average, our sample ($n = 96$) included young adults (19.0 years of age), mainly men (68.8%), and of normal weight (BMI of 23.3 kg/m^2). Using the self-reported physical activity question, a large proportion of participants in our sample (39.6%) rated their current physical activity level as being *moderately active* (engage in physical activity 2–3 days/week), compared to only 14.6% reporting being *recreationally active* (engage in physical activity 3–4 days/week) and 16.7% reporting being *highly active/athletic* (engage in physical activity 5–7 days/week). Based on the IPAQ-SF categorical physical activity rating (derived from weekly total physical activity volume), nearly half of our sample (47.9%) were considered *moderately active* and 43.8% were considered *highly active*. In terms of sedentary behavior, participants reported, sitting for an average of 4.21 hr on a typical weekday and 3.86 hr on a typical weekend day.

Bivariate correlations revealed that greater relative left frontal activation was positively related to physical activity volume (expressed as MET-minutes per week; see Table 4 for correlations among study variables of interest). Specifically, greater left frontal activation was positively related to moderate-intensity ($r(94) = .27$, $p = .007$) and total physical activity ($r(94) = .29$, $p = .005$) volume. Vigorous-intensity physical activity volume also followed a trend in the same direction, but did not reach significance ($r(94) = .19$, $p = .060$). Greater left frontal activity was also positively related to age ($r(91) = .22$, $p = .037$).

Bivariate correlations revealed that left frontal activation was not significantly related to sedentary behaviors, i.e., time spent sitting on a typical weekday or weekend day (ps > .10). Sedentary behavior on a weekday was positively related with sedentary behavior on a weekend day ($r(76) = .59$, $p < .001$) and followed a similar, but non-significant, trend with walking ($r(77) = .19$, $p = .095$). Sedentary behavior on a weekday was also related to sex ($r(78) = -.30$, $p = .007$, indicating greater sitting time among women). Sedentary behavior on a weekend day was positively related with moderate-intensity physical activity ($r(91) = .22$, $p = .031$) and BMI ($r(91) = .27$, $p = .009$).

In light of the results of Study 1, we sought to probe our initial findings more deeply and attempt to identify potential

TABLE 1 Descriptive statistics of study 1 participants

Variables	Mean, % (*n*)	*SD*	Min	Max
Age (in years)	18.94	0.95	18	22
Gender, % (*n*) women	71.9 (23)			
Race, % (*n*)				
African American	18.8 (6)			
White	78.1 (25)			
Asian	3.1 (1)			
Anxiety, % (*n*)	9.4 (3)			
Depression, % (*n*)	9.4 (3)			
Body mass index (kg/m^2)	23.54	3.34	18.31	32.89
Alpha_F56	0.04	0.28	−0.61	0.65
PA Level Rating, % (*n*)[a]				
Low (<1 d/wk)	12.5 (4)			
Moderately active (3 d/wk)	18.8 (6)			
Recreationally active (3–4 d/wk)	43.8 (14)			
Highly active/athlete (5–7 d/wk)	15.6 (5)			
PA level duration (months)[b]	84.31	77.45	2	246
IPAQ-SF PA (MET-min/wk)				
Total	3,238.79	2,651.81	396	10,965
Vigorous-intensity	1,793.55	2,243.21	0	10,080
Moderate-intensity	514.32	568.96	0	2,520
Walking	930.82	890.61	0	4,158
IPAQ-SF: PA level, % (*n*)				
Low	9.4 (3)			
Moderate	50.0 (16)			
High	37.5 (12)			
IPAQ-SF: Sitting (min/d)				
Sitting on a weekday	161.88	128.95	30	550
Sitting on a weekend day[c]	188.33	153.54	30	600

Note: Total $n = 32$.

Abbreviations: IPAQ-SF, International Physical Activity Questionnaire-Short Form; MET, Metabolic equivalent; PA, physical activity.

[a]Self-reported; participants were asked to rate their current PA level.

[b]Self-reported; participants were asked how long they had been at their current PA level rating.

[c]Added to IPAQ-SF to obtain time spent sitting on a weekend day.

moderators on the relationship between frontal asymmetry and sedentary behavior as well as physical activity. Consistent with exploratory research methods, several regression analyses were performed for each of our independent variables of interest (i.e., sitting on a week day, sitting on a weekend day, total, vigorous-intensity, moderate-intensity, and walking physical activity), controlling for different combinations of our covariates (e.g., sex, age, BMI, diagnosis of depression and/or anxiety), and habitual physical activity and sedentary behavior, and their interaction terms (we examined approximately 4–6 covariates for each of our independent variables). Given our interest in identifying potential moderators of these relationships, we report only the results of regression models with significant (or trending, $p < .10$) interaction effects with the sedentary behavior or physical activity outcome of interest.

For sedentary behavior, we first entered sex, time spent sitting on a weekday, and their interaction, with frontal activity as the dependent variable. This regression model was marginally significant, $F(3, 76) = 2.49$, $p = .067$, $R^2 = .09$. Importantly, the interaction between sex and sedentary behavior on a weekday was significant, $\beta = .62$, $t = 2.61$, $p = .011$. Simple slopes analysis indicated that that decreased left frontal activity was observed mainly among women exhibiting increased amounts of sedentary behavior, $t = -2.04$, $p = .045$, while men did not show a relationship between left frontal activity and sedentary behavior, $t = 1.64$, $p = .106$ (see Figure 3).

TABLE 2 Study 1: correlations between variables of interest

Variables	1	2	3	4	5	6	7	8	9	10	11	12
1. Frontal asymmetry[a]	–											
2. Sex[b]	0.26 (n = 32)	–										
3. Age (y)	0.00 (n = 32)	−0.19 (n = 32)	–									
4. BMI (kg/m^2)	−0.36* (n = 32)	0.06 (n = 32)	0.09 (n = 32)	–								
5. Depression[c]	0.03 (n = 29)	−0.07 (n = 29)	−0.22 (n = 29)	−0.03 (n = 29)	–							
6. Anxiety[c]	−0.06 (n = 29)	−0.07 (n = 29)	−0.22 (n = 29)	−0.29 (n = 29)	0.63*** (n = 29)	–						
7. Total PA[d]	−0.30† (n = 31)	−0.24 (n = 31)	0.35† (n = 31)	0.30 (n = 31)	−0.19 (n = 29)	−0.16 (n = 29)	–					
8. Vigorous-intensity PA[d]	−0.24 (n = 31)	−0.16 (n = 31)	0.41* (n = 31)	0.19 (n = 31)	−0.18 (n = 29)	−0.18 (n = 29)	0.88*** (n = 31)	–				
9. Moderate-intensity PA[d]	−0.22 (n = 31)	−0.21 (n = 31)	0.26 (n = 31)	0.22 (n = 31)	0.14 (n = 29)	0.19 (n = 29)	0.48** (n = 31)	0.15 (n = 31)	–			
10. Walking PA[d]	−0.17 (n = 31)	−0.17 (n = 31)	−0.14 (n = 31)	0.26 (n = 31)	−0.20 (n = 31)	−0.12 (n = 29)	0.44* (n = 31)	0.02 (n = 31)	0.43* (n = 31)	–		
11. Sitting—Weekday[e]	−0.45* (n = 24)	−0.32 (n = 24)	0.03 (n = 24)	−0.09 (n = 24)	0.42† (n = 22)	0.63** (n = 22)	0.19 (n = 23)	0.13 (n = 23)	0.22 (n = 23)	0.09 (n = 23)	–	
12. Sitting—Weekend day[e]	−0.55** (n = 24)	−0.22 (n = 24)	0.11 (n = 24)	0.08 (n = 24)	0.01 (n = 22)	0.13 (n = 22)	0.22 (n = 23)	0.20 (n = 23)	0.14 (n = 23)	0.08 (n = 23)	0.79*** (n = 24)	–

Abbreviations: BMI, body mass index; PA, physical activity.

[a]Frontal alpha asymmetry (F6–F6); higher values indicate greater relative left frontal activity.

[b]Sex: −1 = Women, 1 = Men.

[c]Depression/Anxiety: −1 = No, 1 = Yes.

[d]PA outcome; reported as metabolic equivalent (MET)-minutes per week.

[e]Sedentary behavior outcome; reported as minutes per day.

†$p < .10$; *$p < .05$; **$p < .01$; ***$p < .001$.

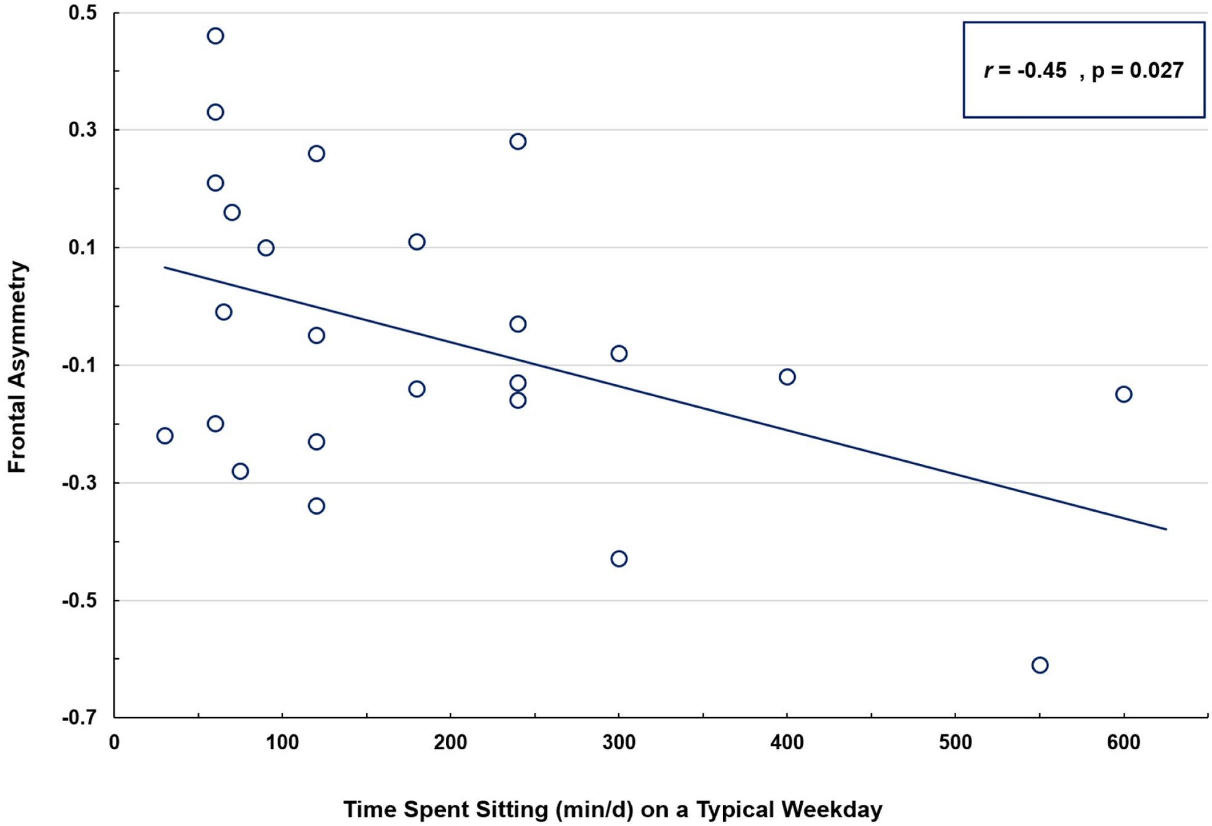

FIGURE 1 The relationship between frontal alpha activity (F6–F5) and sedentary behavior in study 1: time spent sitting on a typical weekday ($N = 24$). Higher frontal asymmetry values indicate greater relative left frontal activity

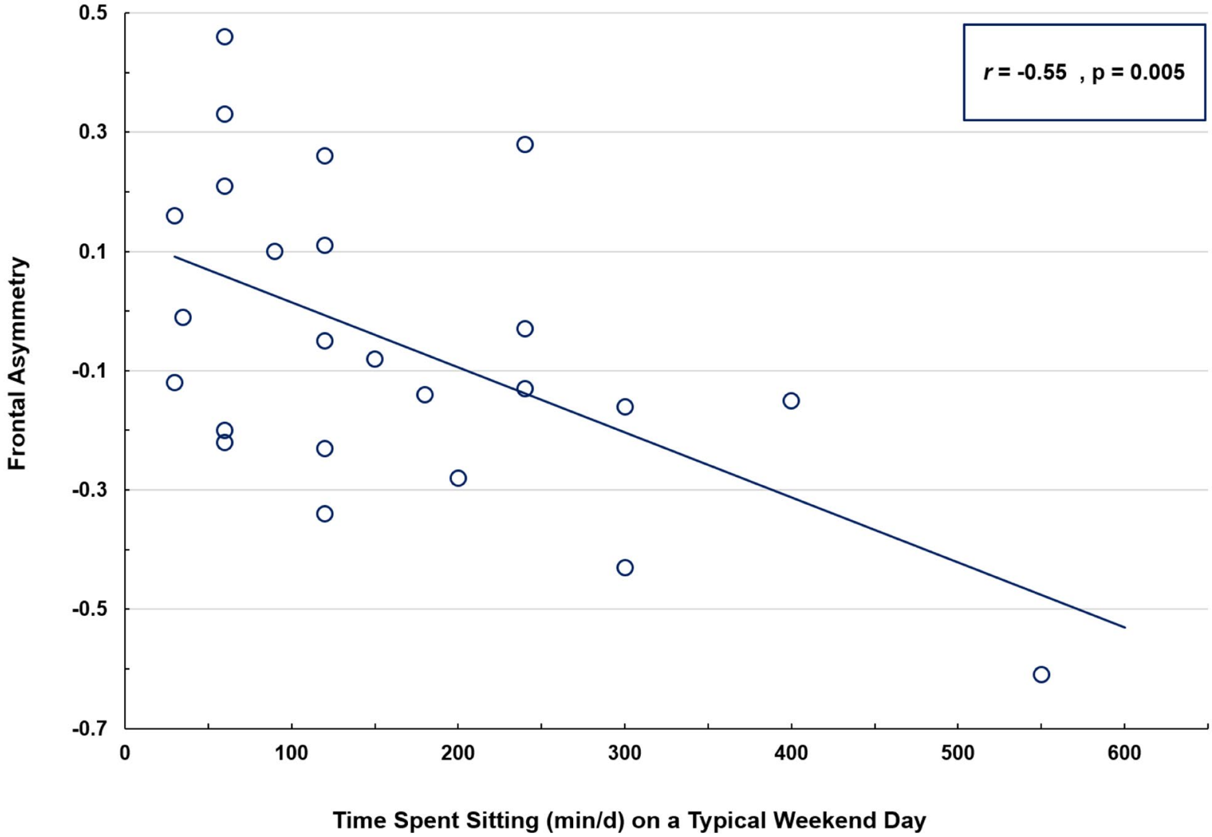

FIGURE 2 The relationship between frontal alpha activity (F6–F5) and sedentary behavior in study 1: time spent sitting on a typical weekend day ($N = 24$). Higher frontal asymmetry values indicate greater relative left frontal activity

TABLE 3 Descriptive statistics of study 2 participants

Variables	Mean, % (*n*)	*SD*	Min	Max
Age (in years)	18.99	1.70	18	31
Gender, % (*n*) women	31.3 (30)			
Anxiety, % (*n*)	27.1 (26)			
Depression, % (*n*)	16.7 (16)			
Body mass index (kg/m^2)	23.31	4.08	17	40
Alpha_F56	0.05	0.41	−1.04	1.37
PA level rating, % (*n*)[a]				
Sedentary (<1 d/wk)	8.3 (8)			
Low (1–2 d/wk)	20.8 (20)			
Moderately active (3 d/wk)	39.6 (38)			
Recreationally active (3–4 d/wk)	14.6 (14)			
Highly active/athlete (5–7 d/wk)	16.7 (16)			
PA level duration (months)[b]	30.14	39.10	1	180
IPAQ-SF PA (MET-min/wk)				
Total	2,763.83	2,285.78	0	12,333
Vigorous-intensity	1,046.88	1,523.23	0	8,640
Moderate-intensity	732.71	966.01	0	5,040
Walking	1,005.18	1,027.46	0	4,950
IPAQ-SF: PA level, % (*n*)				
Low	8.3 (9)			
Moderate	47.9 (46)			
High	43.8 (42)			
IPAQ-SF: sitting (min/d)				
Sitting on a weekday	252.69	139.86	45	720
Sitting on a weekend day[c]	231.55	165.26	20	720

Note: Total $n = 96$.

Abbreviations: IPAQ-SF, International Physical Activity Questionnaire-Short Form; MET, Metabolic equivalent; PA, physical activity.

[a]Self-reported; participants were asked to rate their current PA level.

[b]Self-reported; participants were asked how long they had been at their current PA level rating.

[c]Added to IPAQ-SF to obtain time spent sitting on a weekend day.

For the second multiple regression analysis involving sedentary behavior, we entered sex, time spent sitting on a weekend day, and their interaction, with frontal activity as the dependent variable. A marginal regression equation was found, $F(3, 89) = 2.06$, $p = .11$, $R^2 = .07$. Similar to the interaction between sex and sedentary behavior on a weekday, the interaction between sex and sedentary behavior on a weekend day was significant, $\beta = .40$, $t = 2.16$, $p = .034$. Simple slopes analysis failed to show any significant trends in women, $t = -1.34$, $p = .182$. However, increased left frontal activity tended to occur among men exhibiting increased amounts of sedentary behavior, $t = 1.88$, $p = .063$ (see Figure 4).

Finally, when total physical activity and sitting on a weekday were regressed on frontal asymmetry, an interaction involving physical activity and sitting on a weekday emerged, approaching statistical significance ($p = .056$). In essence, those individuals with higher levels of total physical activity exhibited higher levels of left frontal activity but only if they also exhibited low levels of sitting. That is, in these individuals, higher levels of sitting attenuated the positive relationship between total physical activity and frontal asymmetry.

No other multiple regression analyses revealed any significant models that encompassed any other interactions of interest (e.g., age, BMI, sex, depression, and/or anxiety), even when including up to all five health variables of interest as predictors.

4 | DISCUSSION

Results from two studies indicate relationships between sedentary behavior and reduced left frontal activity, as well as between physical activity and increased left frontal

TABLE 4 Study 2: correlations between variables of interest

Variables	1	2	3	4	5	6	7	8	9	10	11	12
1. Frontal asymmetry[a]	–											
2. Sex[b]	0.09 ($n = 96$)	–										
3. Age (y)	0.22* ($n = 93$)	−0.22* ($n = 93$)	–									
4. BMI (kg/m^2)	0.03 ($n = 96$)	−0.17† ($n = 96$)	0.06 ($n = 93$)	–								
5. Depression[c]	−0.15 ($n = 96$)	0.24* ($n = 96$)	0.00 ($n = 93$)	−0.13 ($n = 96$)	–							
6. Anxiety[c]	0.02 ($n = 96$)	0.21* ($n = 96$)	0.06 ($n = 96$)	−0.05 ($n = 96$)	0.55*** ($n = 96$)	–						
7. Total PA[d]	0.29** ($n = 96$)	−0.07 ($n = 96$)	−0.11 ($n = 93$)	0.11 ($n = 96$)	−0.21* ($n = 96$)	−0.17† ($n = 96$)	–					
8. Vigorous-intensity PA[d]	0.19† ($n = 96$)	−0.16 ($n = 96$)	−0.04 ($n = 93$)	0.05 ($n = 96$)	−0.13 ($n = 96$)	−0.16 ($n = 96$)	0.71*** ($n = 96$)	–				
9. Moderate-intensity PA[d]	0.27** ($n = 96$)	0.06 ($n = 96$)	−0.13 ($n = 93$)	0.21* ($n = 96$)	−0.18† ($n = 96$)	−0.12 ($n = 96$)	0.69*** ($n = 96$)	0.21* ($n = 96$)	–			
10. Walking PA[d]	0.11 ($n = 94$)	0.04 ($n = 94$)	−0.06 ($n = 91$)	−0.03 ($n = 94$)	−0.13 ($n = 94$)	−0.05 ($n = 94$)	0.52*** ($n = 94$)	−0.09 ($n = 94$)	0.33** ($n = 94$)	–		
11. Sitting—Weekday[e]	−0.05 ($n = 80$)	−0.30** ($n = 80$)	−0.13 ($n = 77$)	0.14 ($n = 80$)	−0.18 ($n = 80$)	−0.14 ($n = 80$)	0.16 ($n = 80$)	0.10 ($n = 80$)	−0.01 ($n = 80$)	0.19† ($n = 79$)	–	
12. Sitting—Weekend Day[e]	0.07 ($n = 93$)	−0.13 ($n = 93$)	−0.13 ($n = 90$)	0.27** ($n = 93$)	0.00 ($n = 93$)	−0.07 ($n = 93$)	0.12 ($n = 93$)	−0.04 ($n = 93$)	0.22* ($n = 93$)	0.12 ($n = 92$)	0.59*** ($n = 78$)	–

Abbreviations: BMI, body mass index; PA = physical activity.

[a]Frontal alpha asymmetry (F6–F6); higher values indicate greater relative left frontal activity.

[b]Sex: −1 = Women, 1 = Men.

[c]Depression/Anxiety: −1 = No, 1 = Yes.

[d]PA outcome; reported as metabolic equivalent (MET)-minutes per week.

[e]Sedentary behavior outcome; reported as minutes per day.

†$p < .10$; *$p < .05$; **$p < .01$; ***$p < .001$.

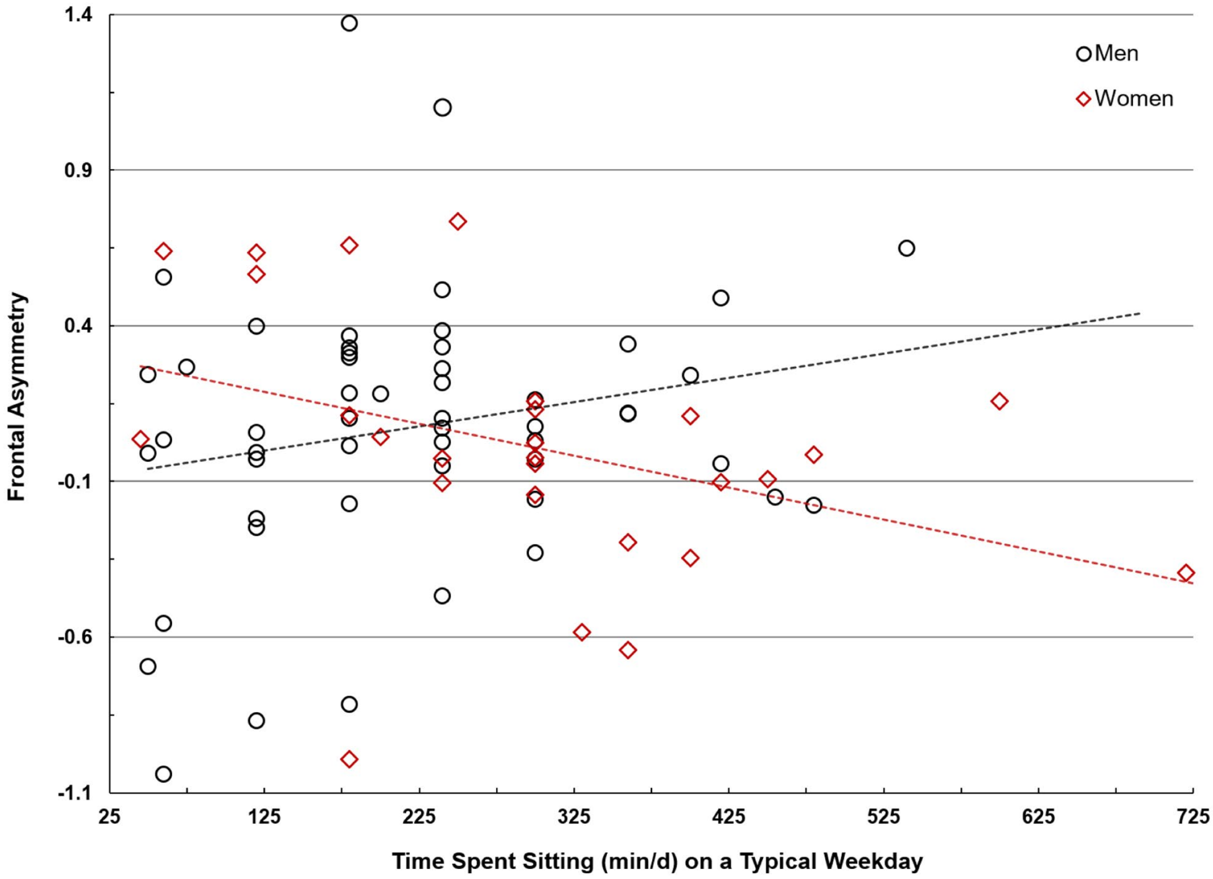

FIGURE 3 The relationship between frontal alpha activity (F6–F5) and sedentary behavior in study 2: time spent sitting on a typical weekday through an interaction with sex ($N = 80$). Higher frontal asymmetry values indicate greater relative left frontal activity

activity. To our knowledge, our data are the first to find a link between neurobiological markers of approach motivation and both sedentary and physical activity behavior, suggesting that frontal activity might be a novel neurological indicator for both of these important health-related behaviors. In Study 1, the relationship between sitting and frontal asymmetry was strong for both time spent sitting during the week and time spent sitting during the weekend. Presumably, this distinction suggests that the relationship between frontal asymmetry and time spent sitting was not only driven by obligatory sitting (e.g., time spent in class or working), but also occurred during the weekend, when participants were free to spend their time doing whatever activity they desired. Time spent in sedentary behavior during the weekend suggests that this was the preferred activity when participants were free to engage in this behavior. Individual differences in frontal asymmetry appear to be a strong predictor of this behavior.

Although we found a relationship between less left frontal asymmetry and sedentary behavior in Study 1, given that it was a small and fairly homogenous sample, we were not confident that we had captured a sample that was truly representative of young, college-aged adults. To provide additional support for our exciting, but preliminary, findings between frontal asymmetry and sedentary behavior, we recruited a larger and more diverse sample for Study 2. We were also interested in exploring the potential influence of moderators (e.g., sex) on the relationship between frontal asymmetry and both physical activity and sedentary behavior. In Study 2, we observed a positive relationship between greater left frontal activity and physical activity. These relationships were consistent with both moderate-intensity and total physical activity. This is similar to other research that found that greater relative left frontal activation predicted greater self-selected walking speeds (Hall et al., 2000).

It is uncertain why greater left frontal activity was not significantly related to vigorous-intensity physical activity and walking in Study 2. The correlation with vigorous-intensity physical activity ($r = .19$) approached statistical significance ($p = .060$), and both vigorous-intensity physical activity ($r = .73$) and walking ($r = .51$) were significantly related to total physical activity ($ps < .001$). Finally, the interaction that emerged in our multiple regression model between total physical activity and sitting on a weekday in relation to

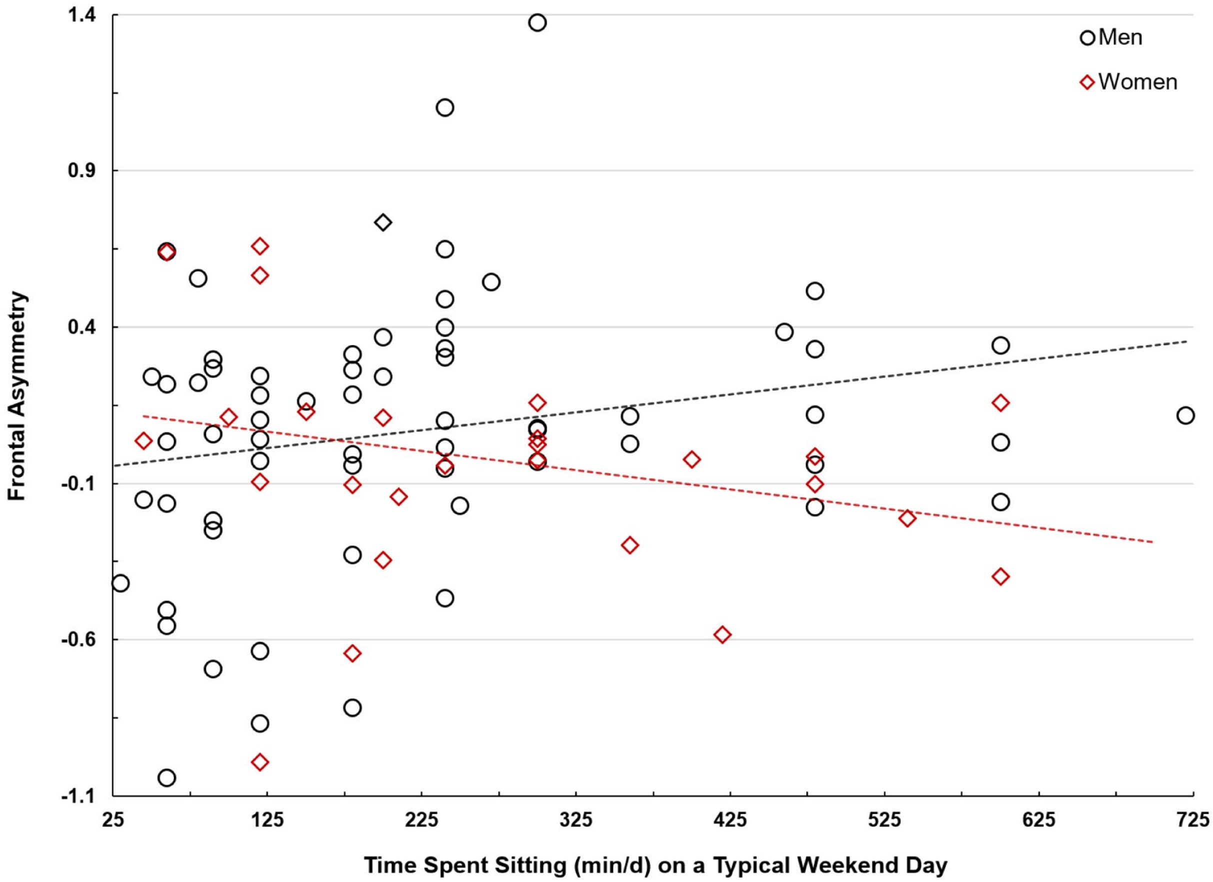

FIGURE 4 The relationship between frontal alpha activity (F6–F5) and sedentary behavior in study 2: time spent sitting on a typical weekend day through an interaction with sex ($N = 92$). Higher frontal asymmetry values indicate greater relative left frontal activity

frontal asymmetry (approaching statistical significance, $p < .06$) is noteworthy.[1]

Investigation of moderators of the relationship between frontal asymmetry and sedentary behavior in Study 2 revealed sex as a moderator. Two significant interaction terms emerged in the prediction of frontal asymmetry during multiple regression analyses (sex × sitting on a weekday and sex × sitting on a weekend day). That is, the relationship between sitting and frontal asymmetry was different in men and women, with women more clearly demonstrating an inverse relationship between frontal asymmetry and time spent sitting. These interactions involving sex and sedentary behavior are consistent with the results of Study 1. Specifically, Study 2 revealed that sex may be a moderator to the degree and direction that frontal asymmetry relates to sedentary behaviors. Study 2 revealed that, in addition to those exhibiting higher levels of total physical activity across the entire sample, women were driving the negative relationship between frontal asymmetry and sedentary behavior on weekdays, while men were driving the positive relationship between frontal asymmetry and sedentary behavior on weekend days. Consistent with this finding, the sample in Study 1 was 72% female (23 women, 9 men) for analyses between frontal asymmetry and sitting behavior. Interestingly, this is reversed in Study 2 where the sample is predominantly male. To summarize, the relationship between less left frontal activity and increased sedentary behavior appeared to manifest among women in general, whereas greater left frontal activity manifested in both men and women who were more physically active. Nevertheless, because these are the first studies linking frontal asymmetry with physical activity and sedentary behavior, our results should be viewed as *hypothesis generating* and be interpreted with caution.

Logically, individual differences in reduced approach motivation may underlie sedentary behavior, because a reduced drive to approach would facilitate engagement in sedentary behavior. By decreasing neural activity associated with increased approach motivation, the likelihood of engaging in

[1] To understand this interaction better, we dichotomized total physical activity and sitting on a weekday into those engaging in higher versus lower levels of physical activity and sedentary behavior (based on the median values in our sample), respectively, and graphed sitting versus asymmetry for both the most and least active groups (Figure S1). In essence, those individuals with higher levels of total physical activity exhibited higher levels of frontal asymmetry only if they exhibited low levels of sitting. That is, in these individuals, higher levels of sitting attenuated the positive relationship between total physical activity and frontal asymmetry. In contrast, for the least active group, frontal asymmetry was lower in general, and sitting was less related to asymmetry.

sedentary activities increases (Cheval et al., 2018). This occurs because the organism is not in a motivational state to overcome the tendency to be sedentary. Thus, by decreasing approach motivation, the likelihood of sedentary behavior increases. In contrast, increasing neural activity associated with approach motivation relates to increases in physical activity. This occurs because the organism is in a heightened motivational state. By increasing approach motivation, the likelihood of physical activity increases.

The results of the current studies suggest a neurophysiological correlate as to why some individuals are inherently more or less physically active and more or less sedentary. It may be the case that, as left frontal activity decreases, individuals are more likely to engage in sedentary behavior. In turn, people may then develop health conditions which prevent them from engaging in physical activity or increase sedentary activity, because individuals who participate in less physical activity and more sedentary activity are at greater risk for developing adverse physical and mental health conditions (U.S. Department of Health & Human Services, 2018). For example, low levels of physical activity increase the risk for developing depression (Camacho, Roberts, Lazarus, Kaplan, & Cohen, 1991; Strawbridge, Deleger, Roberts, & Kaplan, 2002). Because they are unable to engage in physical activity or exhibit more habitual sedentary behavior due to increased symptoms of depression, it might be the case that individuals exhibit a reduction in left frontal activity, as compared to before the development of depression (since reduced left frontal activity relates to depression; Allen et al., 2018). This perpetuates a cycle between less motivation to participate in physical activity and greater likelihood to develop health risks that preclude the inability to participate in physical activity or increase sedentary behaviors.

Greater left frontal activity was related to increased physical activity levels in Study 2. The reason for a lack of relationship between frontal asymmetry and physical activity in Study 1 remains uncertain. Interestingly, Study 1 (predominately female) demonstrated univariate relationships between asymmetry and sitting, while Study 2 (predominately male) demonstrated univariate relationships between asymmetry and physical activity. Although Study 2 indicated a significant interaction between sitting and sex in relation to asymmetry, it did not indicate any such interaction between physical activity and sex. Also, Study 2 indicated a potential interaction between physical activity and sitting in relation to asymmetry. Unfortunately, the sample size of Study 1 precludes any meaningful analysis of potential moderators. As such, any potential sex differences in the relationship between asymmetry and both sedentary and physical activity should be interpreted with caution. Future investigations with larger and more diverse study samples are warranted to confirm our exploratory findings.

It should be appreciated that the smaller sample in Study 1 may have been more influenced by the inherent measurement error associated with self-report measures of physical activity (Shephard, 2003). While the IPAQ-SF has demonstrated acceptable reliability and validity as a measure of habitual physical activity and sedentary behavior in diverse adult populations (Celis-Morales et al., 2012; Cerin et al., 2016; Craig et al., 2003; Dyrstad et al., 2014; Healy et al., 2011; Kim et al., 2013; Rosenberg et al., 2008) and among college student populations (Dinger et al., 2006; Moulin et al., 2019; Murphy et al., 2017; Nelson et al., 2019), like other self-report measures, it is subject to different biases, i.e., response bias (social desirability) and recall bias (Kozey-Keadle, Libertine, Lyden, Staudenmayer, & Freedson, 2011; Sallis & Saelens, 2000). Indeed, adults (including college students), consistently underreport time spent in sedentary behaviors and overreport time spent in moderate-to-vigorous physical activity when measured using questionnaires compared to more objective measures (i.e., accelerometers; Healy, 2011; Moulin, 2019; Nelson, 2019; Rosenberg, 2008). It should also be noted that our sample in Study 2, regardless of the potential measurement biases, self-identified as being somewhat less physically active than our sample in Study 1, with more representation of individuals engaging in low levels of physical activity and higher levels of sedentary behavior.

Another potential limitation is that our samples included college students exclusively. Additionally, the participants in our sample generally met the recommended levels of physical activity as put forth by the U.S. Department of Health and Human Services (2018). By focusing on college students, we are limited in our ability to generalize our results to other adult populations, such as working adults and older adults, who also tend not to meet the recommended levels of physical activity. In order to better understand the relationship between asymmetric cortical activity, physical activity, and sedentary behavior, future research should investigate whether these relationships also exist among individuals who engage in lower than recommended levels of physical activity.

The exploratory data analysis techniques used in the current studies aimed to inspire and generate data-driven hypotheses that will subsequently undergo rigorous and structured testing in future confirmatory studies (Behrens et al., 2013; Goeman & Solari, 2011; Jebb et al., 2017; Velleman & Hoaglin, 2012; Wang, Sparks, Gonzales, Hess, & Ledgerwood, 2017). With this flexibility (i.e., examining multiple independent variables in multiple comparisons) also comes increased risk of one or more Type I errors. However, because of the novel and exploratory nature of this research, we decided to examine multiple possible relationships, rather than take a more conservative approach. To that point, our study also included multiple independent variables as measures of physical activity ($n = 4$) and sedentary behavior ($n = 2$), which could possibly lead to overconfidence in the meaning of the results. While our independent variables represented related behaviors, each variable measured a distinct aspect of that behavior (for example, walking vs. vigorous-intensity physical activity and sedentary behavior on week days vs. weekend days). Given that there are likely distinct psychological processes associated with each measurement (Ekkekakis, Hall, & Petruzzello, 2005), and that we observed a similar pattern of relationships across two distinct samples, we are confident that our current results provide the first evidence of a relationship between resting left frontal activity, physical activity, and sedentary behavior.

Across two studies, results suggest a link between frontal asymmetry and both sedentary and physical activity. Past work has linked increased left frontal activity with greater approach-motivated behaviors and reduced left frontal activity with less approach-motivated behaviors (Harmon-Jones & Gable, 2018). The relationships between frontal asymmetry and levels of sedentary and physical activity may stem from the theoretical foundation that reduced left frontal activity is related to reduced approach motivation, but increased left frontal activity is related to greater approach motivation.

The current findings have implications for promoting increased physical activity and decreased sedentary behavior. Perhaps individuals with reduced left frontal activity may be more responsive to interventions to enhance physical activity if they participate in methods that have been found to increase left frontal activity. For example, individuals with reduced left frontal activity might be responsive to brain stimulation techniques (such as transcranial direct current stimulation or transcranial magnetic stimulation) that are able to increase left frontal activity (Kelley, Gallucci, Riva, Lauro, & Schmeichel, 2019; Lucchiari, Kelley, Vanutelli, & Ferrucci, 2019). Alternatively, individuals with reduced left frontal activity may also use non-invasive methods such as neurofeedback (Allen, Harmon-Jones, & Cavender, 2001) or hand contractions (Gable, Poole, & Cook, 2013) to increase left frontal activity, all of which might lead to increases in physical activity and decreases in sedentary activity. Given the correlational and exploratory nature of the present work, future research should examine the causal relationship between left frontal activity, physical activity and sedentary behavior. The ability to increase relative left frontal asymmetry might be a predictor for responsiveness to interventions aimed at decreasing sedentary behavior and increasing physical activity.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

A. Hunter Threadgill https://orcid.org/0000-0003-3620-5959
Ricardo A. Wilhelm https://orcid.org/0000-0003-2600-0263

REFERENCES

Allen, J. J. B., & Cohen, M. X. (2010). Deconstructing the "resting" state: Exploring the temporal dynamics of frontal alpha asymmetry as an endophenotype for depression. *Frontiers in Human Neuroscience*, *4*, 232. https://doi.org/10.3389/fnhum.2010.00232

Allen, J. J. B., Harmon-Jones, E., & Cavender, J. H. (2001). Manipulation of frontal EEG asymmetry through biofeedback alters self-reported emotional responses and facial EMG. *Psychophysiology*, *38*(4), 685–693. https://doi.org/10.1111/1469-8986.3840685

Allen, J. J., Iacono, W. G., Depue, R. A., & Arbisi, P. (1993). Regional electroencephalographic asymmetries in bipolar seasonal affective disorder before and after exposure to bright light. *Biological Psychiatry*, *33*(8–9), 642–646. https://doi.org/10.1016/0006-3223(93)90104-L

Allen, J. J. B., Keune, P. M., Schönenberg, M., & Nusslock, R. (2018). Frontal EEG alpha asymmetry and emotion: From neural underpinnings and methodological considerations to psychopathology and social cognition. *Psychophysiology*, *55*(1), 1–6. https://doi.org/10.1111/psyp.13028

Allen, J. J. B., Urry, H. L., Hitt, S. K., & Coan, J. A. (2004). The stability of resting frontal electroencephalographic asymmetry in depression. *Psychophysiology*, *41*(2), 269–280. https://doi.org/10.1111/j.1469-8986.2003.00149.x

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Arlington, VA: Author.

Behrens, J. T., DiCerbo, K. E., Yel, N., & Levy, R. (2013). Exploratory data analysis. In J. A. Schinka, W. F. Velicer, & I. B. Weiner (Eds.), *Handbook of psychology: Research methods in psychology* (pp. 34–70). Hoboken, NJ: John Wiley & Sons Inc.

Camacho, T. C., Roberts, R. E., Lazarus, N. B., Kaplan, G. A., & Cohen, R. D. (1991). Physical activity and depression: Evidence from the Alameda county study. *American Journal of Epidemiology*, *134*(2), 220–231. https://doi.org/10.1093/oxfordjournals.aje.a116074

Carlson, S. A., Adams, E. K., Yang, Z., & Fulton, J. E. (2018). Percentage of deaths associated with inadequate physical activity in the United States. *Preventing Chronic Disease*, *15*(38), 1–11. https://doi.org/10.5888/pcd18.170354

Carlson, S. A., Fulton, J. E., Pratt, M., Yang, Z., & Adams, E. K. (2015). Inadequate physical activity and health care expenditures in the United States. *Progress in Cardiovascular Diseases*, *57*, 315–323. https://doi.org/10.1016/j.pcad.2014.08.002

Celis-Morales, C. A., Perez-Bravo, F., Ibañez, L., Salas, C., Bailey, M. E., & Gill, J. M. (2012). Objective vs. self-reported physical activity and sedentary time: Effects of measurement method on relationships with risk biomarkers. *PLoS One*, *7*(5), e36345. https://doi.org/10.1371/journal.pone.0036345

Cerin, E., Cain, K. L., Oyeyemi, A. L., Owen, N., Conway, T. L., Cochrane, T., … Sallis, J. F. (2016). Correlates of agreement between accelerometry and self-reported physical activity. *Medicine and Science in Sports and Exercise*, *48*(6), 1075–1084. https://doi.org/10.1249/MSS.0000000000000870

Chapman, L. J., & Chapman, J. P. (1987). The measurement of handedness. *Brain and Cognition*, *6*(2), 175–183. https://doi.org/10.1016/0278-2626(87)90118-7

Chastin, S. F. M., De Craemer, M., Lien, N., Bernaards, C., Buck, C., Oppert, J.-M., … Cardon, G. (2016). The SOS-framework (Systems of Sedentary behaviours): An international transdisciplinary consensus framework for the study of determinants, research priorities and policy on sedentary behaviour across the life course: A DEDIPAC-study. *International Journal of Behavioral Nutrition and Physical Activity*, *13*(1), 83. https://doi.org/10.1186/s12966-016-0409-3

Cheval, B., Boisgontier, M. P., Bacelar, M. F. B., Feiss, R., & Miller, M. W. (2019). Opportunities to sit and stand trigger equivalent reward-related brain activity. *International Journal of Psychophysiology*, *141*, 9–17. https://doi.org/10.1016/j.ijpsycho.2019.04.009

Cheval, B., Radel, R., Neva, J. L., Boyd, L. A., Swinnen, S. P., Sander, D., & Boisgontier, M. P. (2018). Behavioral and neural evidence of the rewarding value of exercise behaviors: A systematic review. *Sports Medicine*, *48*, 1389–1404. https://doi.org/10.1007/s40279-018-0898-0

Conroy, D. E., Maher, J. P., Elavsky, S., Hyde, A. L., & Doerksen, S. E. (2013). Sedentary behavior as a daily process regulated by habits and intentions. *Health Psychology*, *32*(11), 1149–1157. https://doi.org/10.1037/a0031629

Craig, C. L., Marshall, A. L., Sjostrom, M., Bauman, A. E., Booth, M. L., Ainsworth, B. E., … Oja, P. (2003). International physical activity questionnaire: 12-country reliability and validity. *Medicine and Science in Sports and Exercise*, *35*(8), 1381–1395. https://doi.org/10.1249/01.Mss.0000078924.61453.Fb

Davidson, R. J., Jackson, D. C., & Larson, C. L. (2000). Human electroencephalography. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of psychophysiology* (pp. 27–52). New York, NY: Cambridge University Press.

Dinger, M. K., Behrens, T. K., & Han, J. L. (2006). Validity and reliability of the International Physical Activity Questionnaire in college students. *American Journal of Health Education*, *37*(6), 337–343. https://doi.org/10.1080/19325037.2006.10598924

Dyrstad, S. M., Hansen, B. H., Holme, I. M., & Anderssen, S. A. (2014). Comparison of self-reported versus accelerometer-measured physical activity. *Medicine and Science in Sports and Exercise*, *46*(1), 99–106. https://doi.org/10.1249/MSS.0b013e3182a0595f

Ekkekakis, P., Hall, E. E., & Petruzzello, S. J. (2005). Variation and homogeneity in affective responses to physical activity of varying intensities: An alternative perspective on dose-response based on evolutionary considerations. *Journal of Sports Sciences*, *23*, 477–500. https://doi.org/10.1080/02640410400021492

Gable, P. A., Mechin, N. C., Hicks, J. A., & Adams, D. L. (2015). Supervisory control system and frontal asymmetry: Neurophysiological traits of emotion-based impulsivity. *Social, Cognitive, and Affective Neuroscience*, *10*(10), 1310–1315.

Gable, P. A., Neal, L. B., & Threadgill, A. H. (2018). Regulatory behavior and frontal activity: Considering the role of revised-BIS in relative right frontal asymmetry. *Psychophysiology*, *55*(1), e12910. https://doi.org/10.1111/psyp.12910

Gable, P. A., Poole, B. D., & Cook, M. S. (2013). Asymmetrical hemisphere activation enhances global-local processing. *Brain and Cognition*, *83*(3), 337–341. https://doi.org/10.1016/j.bandc.2013.09.012

Goeman, J. J., & Solari, A. (2011). Multiple testing for exploratory research. *Statistical Science*, *26*(4), 584–597. https://doi.org/10.1214/11-STS356

Grande, I, Berk, M, Birmaher, B, & Vieta, E (2016). Bipolar Disorder. *The Lancet*, *387*, 1561–1572.

Hall, E. E., Ekkekakis, P., & Petruzzello, S. J. J. B. P. (2007). Regional brain activity and strenuous exercise: Predicting affective responses using EEG asymmetry. *Biological Psychology*, *75*(2), 194–200. https://doi.org/10.1016/j.biopsycho.2007.03.002

Hall, E. E., Ekkekakis, P., Van Landuyt, L. M., & Petruzzello, S. J. (2000). Resting frontal asymmetry predicts self-selected walking speed but not affective responses to a short walk. *Research Quarterly for Exercise and Sport*, *71*(1), 74–79. https://doi.org/10.1080/02701367.2000.10608883

Harmon-Jones, E., Abramson, L. Y., Nusslock, R., Sigelman, J. D., Urosevic, S., Turonie, L. D., & Fearn, M. (2008). Effect of bipolar disorder on left frontal cortical responses to goals differing in valence and task difficulty. *Biological Psychiatry*, *63*, 693–698. https://doi.org/10.1016/j.biopsych.2007.08.004

Harmon-Jones, E., Abramson, L. Y., Sigelman, J., Bohlig, A., Hogan, M. E., & Harmon-Jones, C. (2002). Proneness to hypomania/mania symptoms or depressive symptoms and asymmetrical frontal cortical responses to an anger-evoking event. *Journal of Personality and Social Psychology*, *82*(4), 610–618.

Harmon-Jones, E., & Allen, J. J. B. (1997). Behavioral activation sensitivity and resting frontal EEG asymmetry: Covariation of putative indicators related to risk for mood disorders. *Journal of Abnormal Psychology*, *106*(1), 159–163. https://doi.org/10.1037/0021-843X.106.1.159

Harmon-Jones, E., & Gable, P. A. (2018). On the role of asymmetric frontal cortical activity in approach and withdrawal motivation: An updated review of the evidence. *Psychophysiology*, *55*(1), e12879. https://doi.org/10.1111/psyp.12879

Healy, G. N., Clark, B. K., Winkler, E. A. H., Gardiner, P. A., Brown, W. J., & Matthews, C. E. (2011). Measurement of adults' sedentary time in population-based studies. *American Journal of Preventative Medicine*, *41*(2), 216–227. https://doi.org/10.1016/j.amepre.2011.05.005

Henriques, J. B., & Davidson, R. J. (1991). Left frontal hypoactivation in depression. *Journal of Abnormal Psychology*, *100*(4), 535–545. https://doi.org/10.1037/0021-843X.100.4.535

Hogan, C. L., Catalino, L. I., Mata, J., & Fredrickson, B. L. (2015). Beyond emotional benefits: Physical activity and sedentary behaviour affect psychosocial resources through emotions. *Psychology & Health*, *30*(3), 354–369. https://doi.org/10.1080/08870446.2014.973410

Jacobs, G. D., & Snyder, D. (1996). Frontal brain asymmetry predicts affective style in men. *Behavioral Neuroscience*, *110*, 3–6. https://doi.org/10.1037/0735-7044.110.1.3

Jebb, A. T., Parrigon, S., & Woo, S. E. (2017). Exploratory data analysis as a foundation of inductive research. *Human Resource Management Review*, *27*(2), 265–276. https://doi.org/10.1016/j.hrmr.2016.08.003

Kelley, N. J., Gallucci, A., Riva, P., Lauro, L. J. R., & Schmeichel, B. J. (2019). Stimulating self-regulation: A review of non-invasive brain stimulation studies of goal-directed behavior. *Frontiers in Behavioral Neuroscience*, *12*, 337. https://doi.org/10.3389/fnbeh.2018.00337

Kim, Y., Park, I., & Kang, M. (2013). Convergent validity of the International Physical Activity Questionnaire (IPAQ): Meta-analysis. *Public Health Nutrition*, *16*(3), 440–452. https://doi.org/10.1017/S1368980012002996

Kozey-Keadle, S., Libertine, A., Lyden, K., Staudenmayer, J., & Freedson, P. S. (2011). Validation of wearable monitors for assessing sedentary behavior. *Medicine and Science in Sports and Exercise*, *43*(8), 1561–1567. https://doi.org/10.1249/MSS.0b013e31820ce174

Lattari, E., Portugal, E., Moraes, H., Machado, S., Santos, T. M., & Deslandes, A. C. (2014). Acute effects of exercise on mood and EEG activity in healthy young subjects: A systematic review. *CNS & Neurological Disorders-Drug Targets*, *13*(6), 972–980. https://doi.org/10.2174/1871527313666140612125418

Laufs, H., Kleinschmidt, A., Beyerle, A., Eger, E., Salek-Haddadi, A., Preibisch, C., & Krakow, K. (2003). EEG-correlated fMRI of human alpha activity. *NeuroImage*, *19*(4), 1463–1476. https://doi.org/10.1016/S1053-8119(03)00286-6

Lucchiari, C., Kelley, N. J., Vanutellie, M. E., & Ferrucci, R. (2019). Brain stimulation and behavioral change. *Frontiers in Behavioral Neuroscience*, *13*, 20. https://doi.org/10.3389/fnbeh.2019.00020

Mechin, N., Gable, P. A., & Hicks, J. A. (2016). Frontal asymmetry and alcohol cue reactivity: Influence of core personality systems. *Psychophysiology*, *53*(8), 1224–1231. https://doi.org/10.1111/psyp.12659

Moulin, M. S., Truelove, S., Burke, S. M., & Irwin, J. D. (2019). Sedentary time among undergraduate students: A systematic review. *Journal of American College Health*, 1–8. https://doi.org/10.1080/07448481.2019.1661422

Murphy, J. J., Murphy, M. H., MacDonncha, C., Muphy, N., Nevill, A. M., & Woods, C. B. (2017). Validity and reliability of three self-report instruments for assessing attainment of physical activity guidelines in university students. *Measurement in Physical Education and Exercise Science*, *21*(3), 134–141. https://doi.org/10.1080/1091367X.2017.1297711

Neal, L. B., & Gable, P. A. (2016). Neurophysiological markers of multiple facets of impulsivity. *Biological Psychology*, *115*, 64–68. https://doi.org/10.1016/j.biopsycho.2016.01.006

Neal, L. B., & Gable, P. A. (2017). Regulatory control and impulsivity relate to resting frontal activity. *Social, Cognitive, and Affective Neuroscience*, *12*(9), 1377–1383. https://doi.org/10.1093/scan/nsx080

Neal, L. B., & Gable, P. A. (2019). Shifts in frontal asymmetry underlying impulsive and controlled decision-making. *Biological Psychology*, *140*, 28–34. https://doi.org/10.1016/j.biopsycho.2018.11.002

Nelson, B. D., Sarapas, C., Robison-Andrew, E. J., Altman, S. E., Campbell, M. L., & Shankman, S. A. (2012). Frontal brain asymmetry in depression with comorbid anxiety: A neuropsychological investigation. *Journal of Abnormal Psychology*, *121*(3), 579–591. https://doi.org/10.1037/a0027587579

Nelson, M. C., Taylor, K., & Vella, C. A. (2019). Comparison of self-reported and objectively measured sedentary behavior and physical activity in undergraduate students. *Measurement in Physical Education and Exercise Science*, *23*(3), 237–248. https://doi.org/10.1080/1091367X.2019.1610765

Petruzzello, S. J., & Landers, D. M. (1994). State anxiety reduction and exercise: Does hemispheric activation reflect such changes? *Medicine & Science in Sports & Exercise.*, *26*(8), 1028–1035. https://doi.org/10.1249/00005768-199408000-00015

Reznik, S. J., & Allen, J. J. B. (2018). Frontal asymmetry as a mediator and moderator of emotion: An updated review. *Psychophysiology*, *55*(1), e12965. https://doi.org/10.1111/psyp.12965

Rosenberg, D. E., Bull, F. C., Marshall, A. L., Sallis, J. F., & Bauman, A. E. (2008). Assessment of sedentary behavior with the International Physical Activity Questionnaire. *Journal of Physical Activity and Health*, *5*(S1), S30–S44. https://doi.org/10.1123/jpah.5.s1.s30

Rutherford, H. J. V., & Lindell, A. K. (2011). More than evaluation: Lateralization of the neural substrates supporting approach and avoidance motivational systems. *Emotion Review*, *3*(3), 347–348. https://doi.org/10.1177/1754073911402404

Sallis, J. F., & Saelens, B. E. (2000). Assessment of physical activity by self-report: Status, limitations, and future directions. *Research Quarterly for Exercise and Sport*, *71*(S2), 1–14. https://doi.org/10.1080/02701367.2000.11082780

Schaffer, C. E., Davidson, R. L., & Saron, C. (1983). Frontal and parietal electroencephalogram asymmetry in depressed and nondepressed subjects. *Biological Psychiatry*, *18*, 753–762.

Shackman, A. J., McMenamin, B. W., Maxwell, J. S., Greischar, L. L., & Davidson, R. J. (2009). Right dorsolateral prefrontal cortical activity and behavioral inhibition. *Psychological Science*, *20*(12), 1500–1506. https://doi.org/10.1111/j.1467-9280.2009.02476.x

Shephard, R. J. (2003). Limits to the measurement of habitual physical activity by questionnaires. *British Journal of Sports Medicine*, *37*(3), 197–206. https://doi.org/10.1136/bjsm.37.3.197

Strawbridge, W. J., Deleger, S., Roberts, R. E., & Kaplan, G. A. (2002). Physical activity reduces the risk of subsequent depression for older adults. *American Journal of Epidemiology*, *156*(4), 328–334. https://doi.org/10.1093/aje/kwf047

Sutton, S. K., & Davidson, R. J. (1997). Prefrontal brain asymmetry: A biological substrate of the behavioral approach and inhibition systems. *Psychological Science*, *8*(3), 204–210. https://doi.org/10.1111/j.1467-9280.1997.tb00413.x

Thibodeau, R., Jorgensen, R. S., & Kim, S. (2006). Depression, anxiety, and resting frontal EEG asymmetry: A meta-analytic review. *Journal of Abnormal Psychology*, *115*(4), 715–729. https://doi.org/10.1037/0021-843X.115.4.715

Tremblay, M. S., Aubert, S., Barnes, J. D., Saunders, T. J., Carson, V., Latimer-Cheung, A. E., … Chinapaw, M. J. M. (2017). Sedentary behavior research network (SBRN) – Terminology consensus project process and outcome. *International Journal of Behavioral Nutrition and Physical Activity*, *14*(1), 75. https://doi.org/10.1186/s12966-017-0525-8

U.S. Department of Health and Human Services, Office of Disease Prevention and Health Promotion, 2018 Physical Activity Guidelines Advisory Committee. (2018). *2018 Physical activity guidelines advisory committee scientific report* (Document No. 2018-04307). Retrieved from https://health.gov/paguidelines/second-edition/report/pdf/PAG_Advisory_Committee_Report.pdf

Velleman, P. F., & Hoaglin, D. C. (2012). Exploratory data analysis. In H. Cooper, P. M. Camic, D. L. Long, A. T. Panter, D. Rindskopf, & K. J. Sher (Eds.), *APA handbooks in psychology®. APA handbook of research methods in psychology, Vol. 3. Data analysis and research publication* (pp. 51–70). Washington, DC: American Psychological Association. https://doi.org/10.1037/13621-000

Wang, Y. A., Sparks, J., Gonzales, J. E., Hess, Y. D., & Ledgerwood, A. (2017). Using independent covariates in experimental designs: Quantifying the trade-off between power boost and Type I error inflation. *Journal of Experimental Social Psychology*, *72*, 118–124. https://doi.org/10.1016/j.jesp.2017.04.011

Woo, M., Kim, S., Kim, J., Petruzzello, S. J., & Hatfield, B. D. (2009). Examining the exercise-affect dose–response relationship: Does duration influence frontal EEG asymmetry? *International Journal of Psychophysiology*, *72*(2), 166–172. https://doi.org/10.1016/j.ijpsycho.2008.12.003

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the Supporting Information section.

Fig S1

How to cite this article: Threadgill AH, Wilhelm RA, Zagdsuren B, MacDonald HV, Richardson MT, Gable PA. Frontal asymmetry: A novel biomarker for physical activity and sedentary behavior. *Psychophysiology*. 2020;00:e13633. https://doi.org/10.1111/psyp.13633