Aerobic exercise enhances positive emotional reactivity in individuals with depressive symptoms: Evidence from neural responses to reward and emotional content

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Abstract

Reward sensitivity and emotional reactivity have been identified as two candidate mechanisms of anhedonia in depression. However, there is a paucity of research examining whether deficits in reward sensitivity and emotional reactivity can be modified through brief, behavioral interventions. Therefore, the purpose of this study was to examine the effects of continuous moderate-intensity aerobic exercise on the reward positivity (RewP) and late positive potential (LPP) among individuals reporting variable symptoms of depression. Using a within-subjects design, 66 young adults completed a 30-min session of aerobic exercise and seated rest on separate days. Reward sensitivity and emotional reactivity were assessed following each session using the RewP and LPP event-related brain potentials. Results indicated that the LPP to positive stimuli was potentiated following exercise, while no effect on RewP was observed. Notably, individuals who experienced greater emotional reactivity to positive stimuli following exercise also exhibited increased sensitivity to rewards. Depressive symptom severity failed to moderate any effects, suggesting beneficial effects of acute exercise on positive emotional reactivity across depressive symptom profiles. These findings suggest that aerobic exercise increases emotional engagement to positive stimuli, which may have implications for protecting against the development of anhedonia and resolving the blunted emotional reactivity to positive content in depression.

Keywords: Affect; Depression; Event-Related Potentials; Late Positive Potential; Acute Exercise; Reward Positivity

Introduction

Major depressive disorder (MDD) is among the most prevalent mental health disorders worldwide (Kessler et al., 2003; Kessler & Bromet, 2013) and imposes a staggering burden to society. Unfortunately, current treatments for depression are only mildly effective (Trivedi et al., 2006), highlighting the need for alternative or adjunctive treatments to improve treatment response and clinical outcomes. Aerobic exercise performed alone (Olson et al., 2017; Schuch et al., 2016) or in combination with antidepressant medication (Blumenthal et al., 1999) has been shown to be effective in remediating depression. However, several issues remain regarding the optimal exercise stimulus (e.g., mode, intensity, duration) and mechanisms underlying the antidepressant response to exercise. Recently, investigators have begun to examine the effects of a single session of exercise in order to optimize exercise as a symptom management tool for patients with depression (e.g., Meyer et al., 2016; Perez et al., 2020).

According to the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5), one of the cardinal symptoms of a major depressive episode is anhedonia—a lack of interest or pleasure in typically enjoyable experiences. Anhedonia is a predictor of worse prognosis in terms of course and treatment of depression (McMakin et al., 2012; Uher et al., 2012) and has been increasingly conceptualized as a multifaceted process that includes interest/desire (wanting a reward), anticipation (state of readiness for a reward), motivation (initial energy expenditure to attain a reward), effort (sustained energy expenditure to attain reward), hedonic response (e.g., enjoyment of reward), and learning of stimulus-reward associations (Rizvi et al., 2016). Two candidate mechanisms of anhedonia include reward sensitivity and emotional reactivity (Foti, Novak, Hill, & Oumeziane, 2018), which have been broadly implicated in affective and motivational impairment.

Deficits in reward sensitivity and emotional reactivity have been examined using a variety of self-report, behavioral, and neuroimaging measures (Foti et al., 2018). These deficits

can also be quantified using event-related brain potentials (ERPs), which reflect objective, direct measures of neural activity. Given their excellent temporal resolution, ERPs are ideally suited for tracking reward and emotion processing in real time (Hajcak et al., 2011). In particular, the reward positivity (RewP) and late positive potential (LPP) components have been used to study reward-related and emotion processing deficits in depression (Foti et al., 2018; Proudfit, 2015; Proudfit et al., 2015). The RewP is a frontocentral positivity in the ERP waveform peaking around 200-350 ms following feedback indicating rewards versus losses, and is thought to reflect activity of the reward circuit (i.e., ventral striatum, caudate, medial prefrontal cortex, and orbitofrontal cortex; Becker, Nitsch, Miltner, & Straube, 2014; Carlson, Foti, Mujica-Parodi, Harmon-Jones, & Hajcak, 2011). The LPP, on the other hand, is a sustained positive potential at midline parietal sites that arises approximately 400 ms after participants view emotional content and reflects enhanced (or sustained) attentional engagement to salient environmental stimuli (Hajcak et al., 2015). Previous research has revealed that greater symptoms of depression are associated with a blunted RewP (Brush, Ehmann, Hajcak, Selby, & Alderman, 2018; Klawohn et al., 2020; Liu et al., 2014; Proudfit, 2015) and a reduced LPP to both pleasant and unpleasant stimuli (Hill, South, Egan, & Foti, 2019; Klawohn et al., 2020). This modulation of RewP and LPP amplitudes offers insight into reward processing and emotional reactivity deficits in depression (Brush et al., 2018; Hill, South, Egan, & Foti, 2019), and suggests potential treatment targets for anhedonia in depression.

Few studies have experimentally examined whether aerobic exercise modifies the RewP (Walsh et al., 2019) or LPP (Tartar, Salzmann, Pierreulus, & Antonio, 2018; Thom, O'Connor, Clementz, & Dishman, 2019), and no studies to date have examined the influence of exercise on these neural indicators within the context of depressive symptomatology. Walsh and colleagues found that an 11-min bout of high-intensity interval exercise diminished the

RewP elicited by a probabilistic reward task approximately 10 min following exercise cessation. The authors suggested that reward-based reinforcement learning is down-regulated during the initial post-exercise recovery period, possibly due to heightened physiological arousal. In terms of the LPP, Tartar et al. (2018) and Thom et al. (2019) observed opposing effects following acute exercise. Tartar and colleagues found that a 30 min bout of vigorous aerobic exercise performed at 75-85% of an individual's estimated maximal heart rate (HR) decreased LPP amplitude to negative pictures. Conversely, Thom et al. (2019) found that a 30 min bout of moderate-to-vigorous exercise performed at approximately 65% of an individual's peak aerobic capacity (VO_2 peak) did not alter the LPP to pictures with variable emotional content (i.e., anger, fear, pleasantness, and neutral). Interestingly, Tartar et al. reported significant improvements in mood following vigorous exercise, with reductions observed in the depression subcomponent and an increase in the vigor subcomponent of the Profile of Mood States (POMS). In the Thom et al. study, moderate-to-vigorous intensity exercise reduced angry mood among men with elevated levels of trait anger and mitigated against any increases in angry mood as a result of viewing the emotional images. The discrepant findings in the LPP may potentially be explained by the dose of exercise used in these studies. Previous evidence suggests that more vigorous exercise intensities may suppress rather than promote favorable affective responses both during and immediately following exercise (Pronk, Crouse, & Rohack, 1995; Reed & Ones, 2006), which may influence subsequent emotional and reward processing. Indeed, several previous studies have examined post-exercise changes in affect or mood along with psycho-physiological responses to emotional content (e.g., Crabbe, Smith, & Dishman, 2007; Monroe, Patel, McCully, & Dishman, 2020; Smith, O'Connor, Crabbe, & Dishman, 2002; Schmitt et al., 2019). However, there are important limitations in several of the measures that have been used to measure post-exercise changes in affect, mood, and emotion (e.g.,

POMS; Ekkekakis, 2013)¹ and therefore it remains to be determined whether post-exercise affective responses influence subsequent emotional reactivity. Nonetheless, these studies highlight the potential state-like properties of the RewP and LPP, indicating that these components may be modulated by acute exercise.

The aim of the present study was to examine the effects of continuous moderate-intensity aerobic exercise on reward processing and emotional engagement among individuals with variable symptoms of depression, as indicated by the RewP and LPP. We predicted that exercise would increase the RewP and the LPP to pleasant pictures, and that the magnitude of these exercise-related increases would be associated with more favorable post-exercise affective responses. Conversely, we expected a decrease in LPP amplitude to unpleasant pictures following exercise, consistent with evidence showing reduced self-reported arousal to unpleasant pictures post-exercise (Crabbe, Smith, & Dishman, 2007). Although this hypothesis opposes previous findings (Tartar et al., 2018; Thom et al., 2019; Walsh et al., 2019), we predicted that the dose of exercise used in this study would potentiate reactivity to positively-valenced content and buffer reactivity to negatively-valenced content given evidence suggesting that moderate-intensity exercise elicits greater affective benefits relative to higher exercise intensities (Ekkekakis, Parfitt, & Petruzzello, 2011; Reed & Ones, 2006).

A secondary aim was to examine whether individual differences in depression would moderate post-exercise modulations of the RewP and LPP. In line with the emotion context insensitivity (ECI) hypothesis of depression indicating broad dampening of reactivity to emotional content (Rottenberg, Gross, & Gotlib, 2005) and considering that individuals with greater depression severity exhibit blunted RewP and LPP amplitudes (Proudfit et al., 2015), we hypothesized that post-exercise modulations of the RewP and LPP would be moderated by

¹ As highlighted by Ekkekakis (2013), the POMS was constructed to assess six distinct states (i.e., anger, confusion, depression, fatigue, tension, vigor) and was never intended to reflect the global domain of mood.

depressive symptoms, such that larger effects would be found among individuals reporting greater depressive symptom severity.

Method

Participants

Individuals were recruited from [university omitted for peer review] and the surrounding community using flyers and advertisements posted around the campus. Participants were native English speakers and reported normal or corrected-to-normal vision. Exclusion criteria consisted of the presence or history of any cardiovascular, neurological, or musculoskeletal problems contraindicated to exercise, as well as a history of any head injury with a loss of consciousness. Given the potential influence of emerging developmental changes (Lukie, Montazer-Hojat, & Holroyd, 2014) and advancing age (e.g., Fernandes et al., 2019; Mather, 2016) on emotional and reward processing, we restricted our sample to adults between the ages of 18 and 35 years of age. All participants were physically able to engage in aerobic exercise as indicated by responses to the physical activity readiness questionnaire (PAR-Q; Thomas, Reading, & Shephard, 1992). Participants provided written informed consent and all study procedures were carried out in accordance with the Declaration of Helsinki and were approved by the university's institutional review board.

Sample Size Determination

Using a within participants design, we conducted an a priori power analysis using G*Power version 3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2014) to detect acute changes in RewP and LPP following exercise. Although conducted among an unselected sample of healthy undergraduates, findings from Tartar et al. (2018) indicated a moderate reduction ($d = 0.48$) in LPP amplitude to negative stimuli following high-intensity aerobic exercise. Given that no previous studies have examined the influence of acute exercise on both RewP and LPP components simultaneously, we used a more conservative, small-to-medium effect size

estimate of $f = 0.20$ and correlation among repeated measures of $r = .40$. Specifically, with $\beta = .20$ (80% power) and a two-sided $\alpha = 0.05$ assuming a nonsphericity correction factor of $\epsilon = 1$, 61 participants were required to detect a main effect of Condition (exercise vs. control) on either the RewP or LPP difference wave amplitudes, assuming an equivalent effect size. We aimed to a larger sample size to account for possible data loss due to EEG recording issues.

Measures

Demographics and general health history. Participants completed a standard health history and demographics questionnaire that assesses basic demographic information (i.e., age, gender, researcher-administered height and weight), family medical history, current and past medical diagnoses, past surgeries and injuries including any head injury with loss of consciousness, tobacco/alcohol use, and current and past medication use.

Clinical symptoms. The 21-item version of the Depression Anxiety Stress Scale (DASS-21; Lovibond & Lovibond, 1995) was used to assess the presence of total internalizing symptoms over the past week, including depression, anxiety, and psychological stress. Three subscales (depression, anxiety, and stress) of the DASS-21 comprise seven items each, with each subscale indexing aspects of internalizing psychopathology symptoms that often share common variance. The DASS-21 ranges from 0 to 42 for each subscale and the total score exhibited excellent reliability ($\alpha = .91$), while each of the three subscales also demonstrated acceptable-to-good reliability (Depression subscale: $\alpha = .87$; Anxiety subscale: $\alpha = .77$; Stress subscale: $\alpha = .80$) in the present sample. Based on established recommendations (Lovibond & Lovibond, 1995), cut-off scores for clinical symptom severity are: normal (0-9), mild (10-13), moderate (14-20), severe (21-27), and extremely severe (≥ 28).

Feeling and felt arousal scales. Affective valence (pleasure-displeasure) was assessed using the Feeling Scale (FS; Hardy, 1989), while perceived activation was examined by the Felt Arousal Scale (FAS; Svebak & Murgatroyd, 1985). The FS is an 11-point, single-item bipolar

rating scale (-5 = *very bad* and 5 = *very good*) that has been used to assess the dimension of valence (pleasure-displeasure) while the FAS (arousal) is a 6-point, single-item rating instrument (1 = *low arousal* and 6 = *high arousal*) that has been commonly used to index perceived activation (low-high arousal) during and following exercise (e.g., Ekkekakis, Hall, & Petruzzello, 2004). These two, single-item scales are relatively quick and easy to administer and together reflect the bipolar and orthogonal dimensions of affective valence and perceived activation within Russell's (1980) circumplex model of affect.

Positive and Negative Affect Schedule (PANAS). The PANAS (Watson, Clark, & Tellegen, 1988) was administered during each testing session as a secondary measure of self-reported affective or emotional responses. Participants were asked to rate "how much you feel right now" on 5-point scales (1 = *very slightly or not at all* and 5 = *extremely*) for each of 20 different adjectives. The positive affect (PA) subscale consists of ten positive adjectives (proud, excited, strong, enthusiastic, determined, attentive, inspired, alert, interested, and active), while the negative affect (NA) subscale consists of ten negative adjectives (distressed, upset, guilty, scared, hostile, irritable, ashamed, nervous, jittery, and afraid). Although the items of the PANAS appear to represent a mixture of emotions, moods, and core affect (Ekkekakis, 2013), this scale has been widely used in exercise and health-behavioral research and was recently used in study investigating the effects of aerobic exercise on emotional processing (Schmitt et al., 2019). Thus, the scale's use in the present study facilitates comparison between present and past results. The PA and NA subscales demonstrated good-to-excellent reliability (PA subscale: $\alpha = .90$; NA subscale: $\alpha = .86$), which was determined during the baseline assessment during the seated rest control day.

Stimulus Presentation Parameters

The administered tasks were programmed and presented using E-Prime Professional version 2.0 software (Psychology Software Tools, Inc. Pittsburgh, PA, USA). During the EEG

assessment, participants sat approximately 28 in. (70 cm) from the monitor, which was centered to the nasion.

Doors gambling task. This task consisted of three blocks of 20 trials. On each trial, a fixation cross was presented at the center of the screen for 1,000 ms followed by the presentation of two doors, which remained on the screen until participants made a left or right button press corresponding to the left or right door using a Logitech® F310 response gamepad. Following stimulus offset, another fixation cross was presented for 2,000 ms before displaying the feedback stimulus for 2,000 ms. Feedback indicated whether the participant won \$0.50 (gain trial) or lost \$0.25 (loss trial). A green upwards arrow and red downwards arrow was used to signal gains and losses, respectively. After feedback, another fixation cross was presented for 1,500 ms, which was followed by a short break prior to the next trial. Across the entirety of the doors task, 30 gain and 30 loss trials were randomly presented. Following each experimental session, participants were compensated their total winnings of \$7.50.

Picture viewing task. Stimuli for the picture viewing task included 42 pleasant (e.g., smiling faces, babies), 42 neutral (e.g., household objects, neutral faces), and 42 unpleasant (e.g., sad faces, violent scenes) pictures from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1997).² Ratings of valence and arousal were assessed before the study among a sample of 17 volunteer undergraduate students, who were comparable to the study sample in terms of age, sex, and sociocultural background. The three categories of images were different on normative ratings of valence, which were based on 9-point Likert scales (1 = *maximally unpleasant* and 9 = *maximally pleasant*). The means (standard deviations) of valence ratings for pleasant, unpleasant, and neutral images were 5.90 (2.05), 3.69 (2.23), and

² IAPS image numbers: 1050, 1200, 1300, 1301, 1463, 1601, 1710, 1811, 2000, 2053, 2070, 2080, 2091, 2092, 2120, 2165, 2190, 2311, 2320, 2340, 2345, 2480, 2570, 2710, 2730, 2800, 2840, 2880, 2900, 3010, 3160, 3170, 3230, 3261, 3300, 3350, 3500, 3530, 4002, 4180, 4240, 4290, 4532, 4572, 4608, 4658, 4659, 4660, 4664, 4800, 4810, 5390, 5470, 5500, 5510, 5532, 5534, 5621, 5626, 5628, 5731, 5740, 5800, 5900, 6200, 6212, 6250, 6312, 6313, 6370, 6540, 6550, 6560, 6570, 6571, 6821, 7000, 7002, 7004, 7006, 7009, 7010, 7025, 7030, 7034, 7035, 7040, 7041, 7060, 7080, 7090, 7100, 7130, 7140, 7150, 7175, 7190, 7217, 7224, 7233, 7234, 7235, 7325, 7491, 8032, 8080, 8200, 8320, 8330, 8370, 8400, 8461, 8465, 8490, 8540, 9040, 9042, 9050, 9300, 9400, 9405, 9410, 9433, 9520, 9600, 9810

4.21 (1.86), respectively. The three picture categories also differed on normative ratings of arousal, which were based on a 9-point Likert scale (1 = *maximally* calm and 9 = *maximally* excited). The means (standard deviations) of arousal ratings for pleasant, unpleasant, and neutral stimuli were 4.56 (2.38), 5.60 (1.73), and 3.82 (2.54), respectively. Each stimulus was displayed in color for 2,000 ms on the entirety of the display. After stimulus offset, there was a variable intertrial interval (ITI range = 1,700-2,300 ms), in which a white fixation cross was displayed in the center of a black screen. There were six blocks of 21 pictures in total.

ERP Measurement and Processing

Continuous EEG was recorded from a 33-electrode actiCap system (Brain Products, GmbH; Munich, Germany) arranged according to the 10/20 system. Electrooculogram (EOG) activity was recorded from 2 electrodes placed 2 cm outside the outer canthus of the left eye and 2 cm below the right eye. EEG was amplified using an Electrical Geodesics, Inc. (EGI; Eugene, OR, USA) system (20,000 nominal gain, bandpass of 0.10–100 Hz) and sampled at 250 Hz with a 24-bit analog-to-digital converter referenced to the vertex electrode (Cz) at acquisition. Impedances were kept at or below 20 k Ω throughout recording.

EEG data were processed offline using a combination of open-source software packages, including EEGLAB toolbox version 14.1.1 (Delorme & Makeig, 2004) in Matlab version R2018a (The Mathworks, Inc., Natick, MA, USA), ERPLAB toolbox version 7.0.0 (Lopez-Calderon & Luck, 2014), and the ERP PCA toolkit version 2.75 (Dien, 2010). First, data were bandpass filtered using a 2nd order infinite impulse response Butterworth filter of 0.10-30 Hz and adjusted for DC offset. For the doors and picture viewing tasks, the continuous EEG was visually inspected for artifacts or extreme offsets and then segmented to create time-locked epochs by trial type. For the doors gambling task, gain and loss trials were segmented separately using a -200 to 800 ms time window, while pleasant, unpleasant, and neutral picture types were segmented separately to create stimulus-locked epochs using a -500 to 2,000 ms

time window. Artifact rejection and correction procedures were performed using the ERP PCA toolkit, where ICA blink templates provided by the toolkit author (J. Dien) and blink templates generated from the current datasets for each task were used to remove oculomotor artifacts. Components that correlated with one of the two templates ($r \geq .90$) were removed from the dataset. For both tasks, all epochs were re-referenced to the mean of the two mastoids (TP9, TP10). For the doors gambling task, a prestimulus period of -200 to 0 ms was used for baseline correction, while a prestimulus period of -500 to 0 ms was used for baseline correction in the picture-viewing task. For both tasks, we isolated ERPs related to reward processing (RewP) and emotional engagement (LPP) by constructing subtraction-based difference waves for each participant. These subtraction-based difference waves served as the ERP dependent variables of interest for all ERP analyses.

For the doors gambling task, a collapsed localizers approach (see Luck & Gaspelin, 2017) was used to determine the time window for the RewP, which was scored as the difference in neural activity to gain and loss trials. The RewP was quantified using the average activity in a 20 ms window surrounding the peak that was first identified within an a priori time window of 200 and 300 ms (Brush et al., 2018). Given the jittered latency of peak amplitude across conditions (224 ms for exercise; 244 ms for control), the time windows used to quantify the RewP were as follows: 214-234 ms for exercise and 234-254 ms for the control condition.

For the picture viewing task, the LPP to pleasant and LPP to unpleasant pictures were created by subtracting out neural activity related to the processing of neutral pictures. Thus, the LPP to pleasant pictures was scored as the difference between neural activity to pleasant and neutral pictures. The LPP to unpleasant pictures was calculated as the difference between neural activity to unpleasant and neural activity to neutral pictures. Using both a collapsed localizers and an a priori decision process, LPP amplitudes were quantified in an a priori time

window of 400-1,000 ms post-stimulus at the Pz electrode site (Hill et al., 2019; Klawohn et al., 2020), where activity was maximal.

Procedure

Participants visited the laboratory on two separate days approximately 48-72 hours apart at the same time of day. During the initial session, participants were given a description of the study, provided written informed consent, and completed a series of self-report measures that included demographics, health history, and the FS, FAS, and PANAS questionnaires. Participants then completed either the aerobic exercise or seated rest condition, which were counterbalanced across participants. Prior to each condition, participants were fitted with a Polar V800 heart rate monitor (Polar Electro Oy, Kempele, Finland) to assess heart rate responses throughout the testing session. During the control condition, participants sat quietly at rest for 30 minutes on the cycle ergometer (Lode Corival, Lode B.V., Groningen, Netherlands). The exercise condition consisted of 30 minutes of continuous moderate-intensity aerobic exercise performed at a rating of perceived exertion (RPE) of 12-14 (American College of Sports Medicine, 2018), on the original 6 (low-intensity) to 20 (high-intensity) scale (Borg, 1998). To enhance attention and motivation and to help minimize demand characteristics and boredom, participants were allowed to choose between a series of neutral films from *Wonders of the Universe* (Cooter, Holt, & Lachmann, 2011) to watch during both experimental conditions (see Pontifex, Parks, Henning, & Kamijo, 2015 for a similar approach). FS, FAS, and PANAS measures were administered prior to and following both conditions. Immediately following each condition, a 33-electrode net was fitted to assess EEG activity during the doors gambling and passive picture viewing tasks, which were administered in a counterbalanced order across participants and days. In order to account for the time taken to prepare the participant with the EEG electrode cap following each condition, the time elapsed from completion of the exercise or rest condition to beginning of the EEG assessment was recorded.

At the conclusion of the final session, participants were compensated and briefed on the purpose of the study. See Figure 1 for a study overview.

Statistical Analysis

Statistical analyses were conducting using SPSS version 26.0 (IBM Corporation, Armonk, NY, USA) with a two-tailed familywise error rate for tests set at $\alpha = .05$. Repeated measures analysis of variance (rANOVA) was used to compare differences in heart rate (HR) across each condition. Although the order of the experimental conditions and task manipulations were counterbalanced, separate rANOVAs with experimental condition and task order as between-subjects factors were conducted to determine any potential influence on the dependent variables. Bivariate Pearson correlations were performed to determine relationships between clinical internalizing symptoms and the ERP measures on the control day. Given the range of depressive symptoms across the sample, the effects of depressive symptom severity were statistically controlled for in all the primary analyses. That is, all repeated measures analyses of covariance (rANCOVAs) included depressive symptom severity (DASS-21 depression subscale score) as a continuous covariate.

To assess the effects of the experimental manipulation, rANCOVAs were conducted with experimental condition (control, exercise) as the within-subjects factor. For the passive viewing task, picture type (pleasant, unpleasant, neutral) was entered as an additional within-subjects factor in the rANCOVA. Changes in the self-reported affective variables were analyzed with 2 (Time: baseline, post-condition) x 2 (Condition: control, exercise) rANCOVAs. Bivariate Pearson correlations were conducted to determine relationships between self-reported affective variables and ERP measures following exercise. All change scores for the affective variables were calculated as post-condition minus the baseline (pre-condition) score.

For all analyses, the Greenhouse-Geisser epsilon correction was applied in cases when the sphericity assumption was violated, and follow-up t tests were conducted using the Bonferroni correction. Lastly, when there was a significant condition x depressive symptom interaction, indicating the presence of moderation, follow-up ordinary least squares (OLS) regression analyses were conducted with depressive symptoms as a moderator of change in outcome variables. These OLS regression analyses were conducted using the MEMORE macro for SPSS (Montoya, 2019), which permits testing and probing moderation in repeated measures designs, wherein the dependent variable is change in outcome variable ($Y_2 - Y_1 = \text{exercise minus control}$) and the predictor variable is depressive symptoms (continuous).

Results

The final sample consisted of 66 individuals ($n = 34$ female; $M = 20.59$ years, age range = 18-31 years). The race breakdown was 41 White individuals, 22 Asian individuals, 2 individuals self-identifying as more than one race, and 1 Black individual. Of the total sample, 11 individuals identified as Hispanic or Latino. The sample composition included individuals with a range of depressive symptom severity (Normal: $n = 46$; Mild: $n = 7$; Moderate: $n = 8$; Severe-to-Extremely Severe: $n = 5$). The CONSORT study flowchart is shown in Figure 2, while sample characteristics are displayed in Table 1.

The mean time elapsed from the cessation of experimental condition to the start of the EEG assessment was approximately 21.61 min, 95% CI [19.25, 23.97] and did not differ by condition (exercise: $M = 20.83$ min, $SD = 12.28$; control: $M = 22.38$ min, $SD = 11.33$), $t(65) = 0.92$, $p = .363$, $d = 0.11$. A significant condition x time interaction for mean HR was observed, $F(1,65) = 325.89$, $p < .001$, $\eta^2_p = 0.83$, with elevated HR during exercise ($M = 120.70$ bpm, $SD = 13.94$) relative to seated rest ($M = 81.02$ bpm, $SD = 11.94$), $t(65) = 20.64$, $p < .001$, $d = 2.54$. Additionally, mean HR remained slightly elevated during the EEG assessment post-exercise ($M = 77.79$ bpm, $SD = 10.67$) compared to seated rest ($M = 71.23$ bpm, $SD = 10.63$), $t(65) =$

6.59, $p < .001$, $d = 0.81$. No other significant condition or task order effects were observed, $ps > .05$.

On the control day, there was a significant relationship between depressive symptoms and RewP, $r(64) = -.28$, $p = .021$, indicating that increased depressive symptoms was related to a blunted RewP amplitude. There was also a significant relationship between depressive symptoms and LPP to pleasant pictures, $r(64) = -.25$, $p = .042$, suggesting that increased depressive symptoms was associated with a blunted LPP amplitude to pleasant pictures; however, there was a nonsignificant relationship between depressive symptoms and LPP to unpleasant pictures, $r(64) = -.21$, $p = .099$. See Table 2 for correlations between clinical symptoms and ERPs on the control day.

ERP Analyses

Refer to Figure 3 for mean RewP and LPP amplitudes by condition.

RewP. There was no significant difference in RewP following exercise ($M = 3.43 \mu V$, $SD = 4.47$) relative to the control day ($M = 2.42 \mu V$, $SD = 4.77$), $F(1,64) = 0.50$, $p = .482$, $\eta^2_p = 0.01$. There was also no significant condition x depressive symptom interaction, $F(1,64) = 0.78$, $p = .381$, $\eta^2_p = 0.01$. See Figure 4 for the RewP difference waveforms by condition.

LPP. The condition main effect approached significance, $F(1,64) = 3.51$, $p = .066$, $\eta^2_p = 0.05$, such that, regardless of picture type, LPP amplitude increased following exercise ($M = 2.77 \mu V$, $SD = 2.66$) relative to the seated rest control ($M = 2.05 \mu V$, $SD = 2.61$). There was also a significant condition x picture type interaction, $F(1,64) = 6.54$, $p = .013$, $\eta^2_p = 0.09$, with Bonferroni corrected t tests ($\alpha_{\text{corr}} = .05/2 = .025$) indicating a significant increase in LPP to pleasant pictures following exercise ($M = 2.87 \mu V$, $SD = 3.04$) compared to seated rest ($M = 1.81 \mu V$, $SD = 2.62$), $t(65) = 2.55$, $p = .013$, $d = 0.33$. There were no differences by condition for LPP to unpleasant pictures, and no significant interactions between condition, valence, and

depressive symptoms. See Figure 5 for LPP difference waveforms to pleasant and unpleasant pictures by condition.

Self-Reported Affective and Emotional Responses

FS. For affective valence (pleasure–displeasure from the FS), there was a condition main effect that approached significance, $F(1,64) = 3.57, p = .063, \eta^2_p = 0.05$, with increased pleasure following exercise compared to the seated rest control. There were no significant differences by time or interactions between condition, time, and depressive symptoms, $ps > .391$.

FAS. For perceived activation (arousal from the FAS), there was a significant main effect of condition, $F(1,64) = 22.84, p < .001, \eta^2_p = 0.26$, which was superseded by a significant condition x time interaction, $F(1,64) = 11.80, p = .001, \eta^2_p = 0.16$. Decomposition of the interaction with Bonferroni corrected ($\alpha_{\text{corr}} = 0.05/4 = 0.0125$) paired-sample t -tests indicated that participants reported higher arousal following exercise compared to the pre-exercise baseline, $t(65) = 6.04, p < .001, d = 0.76$. There was a significant reduction in arousal from the pre-seated rest to post-seated rest, $t(65) = 2.60, p = .011, d = 0.37$. Arousal was also significantly increased following exercise relative to post-seated rest, $t(65) = 7.21, p < .001, d = 0.89$. See Table 3 for means and standard deviations of affective response scores by experimental condition.

PA. For the PA component of the PANAS, a condition main effect approached significance, $F(1,64) = 3.68, p = .060, \eta^2_p = 0.05$, and a significant main effect of time was observed, $F(1,64) = 19.22, p < .001, \eta^2_p = 0.23$, which was superseded by a significant condition x time interaction, $F(1,64) = 4.60, p = .036, \eta^2_p = 0.07$. Decomposition of this interaction with Bonferroni corrected ($\alpha_{\text{corr}} = 0.05/4 = 0.0125$) t tests revealed greater PA scores following exercise relative to seated rest, $t(65) = 3.36, p = .001, d = 0.42$. There was also a significant reduction in PA scores following seated rest relative to the baseline period, $t(65) = 4.98, p < .001, d = 0.64$. The total PA score was not significantly different by condition at baseline, $t(65)$

$= 0.04, p = .966, d = 0.01$, and was maintained from pre-exercise to post-exercise, $t(65) = 0.11, p = 0.914, d = 0.01$.

NA. For the NA component of the PANAS, a significant main effect of time was observed, $F(1,64) = 7.85, p = .007, \eta^2_p = 0.11$, indicating lower reported NA following both conditions relative to pre-condition baselines. A condition x time x depressive symptom interaction, $F(1,64) = 4.40, p = .040, \eta^2_p = 0.06$, with a follow-up regression analysis indicating that changes in negative affect ($\Delta NA = \text{post-condition minus pre-condition NA}$) were significantly moderated by depressive symptoms only on the control day, $b = -0.32, t(64) = -4.32, p < .001, 95\% \text{ CI } [-0.46, -0.17]$. This indicates that a one-unit increase in depressive symptoms was associated with a 0.32 decrease in the NA component of the PANAS from pre- to post-condition on the control day.

Correlations Between Self-Reported Affective and Emotional Responses and Post-Exercise RewP and LPP

Bivariate Pearson correlations were conducted to determine relationships between the following variables: (1) changes in positive affect (ΔPA) and positively-valenced ERPs (RewP, LPP to pleasant pictures); (2) changes in negative affect (ΔNA) and negatively-valenced ERPs (LPP to unpleasant pictures); (3) changes in affective valence (ΔFS) and perceived activation (ΔFAS) with all positively- and negatively-valenced ERPs (RewP, LPP to pleasant pictures, LPP to unpleasant pictures); and (4) RewP and LPP. There was a significant relationship between ΔPA and RewP, $r(64) = 0.30, p = .015$, indicating that an increase in PA was associated with a larger RewP post-exercise. There was also a significant relationship between ΔFS and LPP to unpleasant pictures, $r(64) = -0.24, p = .050$, such that increased pleasure was related to a smaller ΔLPP amplitude to unpleasant pictures following exercise. Lastly, there was a significant relationship between RewP and LPP to pleasant pictures following exercise,

$r(64) = 0.34, p = .006$, with larger RewP and LPP to pleasant picture amplitudes observed following exercise within the same individuals (Figure 6).

Discussion

Deficits in reward sensitivity and emotional reactivity have been highlighted as two potential candidate mechanisms of anhedonia (Foti et al., 2018). However, whether neural indices of reward processing (RewP) and emotional engagement (LPP) are modifiable through treatment (state-like) or are stable vulnerability markers (trait-like) remains unknown. The purpose of this study was to examine the effects of a single session of continuous moderate-intensity aerobic exercise on RewP and LPP and whether these effects were moderated by depressive symptoms. A secondary purpose was to examine the association between changes in these neural measures and self-reported affective and emotional responses following exercise. Findings revealed that a single session of moderate-intensity aerobic exercise did not influence RewP amplitude; however, larger LPP amplitudes to pleasant pictures were observed following exercise. That is, exercise selectively bolstered emotional reactivity to pleasant stimuli. The hypothesis that post-exercise changes in RewP and LPP would be moderated by depressive symptom severity was not supported, even though individuals reporting greater depressive symptoms showed a blunted RewP and LPP amplitude to pleasant pictures on the control day. This finding suggests that the influence of aerobic exercise on the RewP and LPP to pleasant pictures generalizes to individuals regardless of depressive symptom severity. Interestingly, exercise-related increases in positive affect was related to a larger RewP amplitude, while an increase in pleasure following exercise was correlated with a smaller LPP amplitude to unpleasant pictures. Overall, these findings contribute to the extant evidence of post-exercise emotional responses (Crabbe, Smith, & Dishman, 2007; Monroe et al., 2020; Schmitt et al., 2019; Smith, 2013; Smith et al., 2002; Thom et al., 2019), and suggest that

exercise enhances emotional reactivity to positively-valenced content, regardless of current depressive symptomatology.

A potentiated LPP to pleasant pictures was observed following exercise. Previous research has demonstrated that LPP amplitude may be influenced by acute arousal and stress manipulations (Gable & Harmon-Jones, 2013; Tartar et al., 2018) and top-down regulatory processes (e.g., cognitive control processes; Hajcak, Dunning, & Foti, 2009). For instance, Gable and Harmon-Jones used a stationary cycling protocol to manipulate physiological arousal and found that elevated heart rate in the cycling condition was positively related to greater left frontal LPP amplitudes to pleasant pictures that were administered during the activity, a finding that was not observed during a no-pedaling control condition. Notably, heart rate in the cycling condition was only 10 beats per min above resting values, suggesting that subtle increases in physiological arousal might influence the LPP. As previously mentioned, Tartar et al. (2018) and Thom et al. (2019) observed opposing effects of acute exercise on the LPP. Tartar and colleagues found that vigorous aerobic exercise performed at 75-85% of maximal heart rate decreased the LPP to negative pictures while Thom et al. (2019) found that moderate-to-vigorous exercise did not alter the LPP to images varying in emotional content. Notably, nearly opposite effects on the LPP were found in the current study with a potentiated LPP to positive images following exercise. One plausible explanation for these discrepant findings is the different doses (intensity) of exercise used in these studies as well as the nature of the subject population. Tartar et al. used a vigorous bout of running on a treadmill among an unselected sample of undergraduates, which may have resulted in a suppressing effect on post-exercise affective responses. Although they found that the depression and vigor subscales of the POMS were favorably influenced by exercise, the POMS is restricted to six discrete states (i.e., anger, tension, vigor, confusion, fatigue, and depression) and may not fully capture the influence of exercise on global affective states (Ekkekakis, 2013). Thom et al. (2019) used an

exercise stimulus that was more similar to the dose of exercise in this study; however, participants in their study included men with elevated levels of trait anger while participants in this study were young adults reporting variable symptoms of depression. Although we did not observe differences in post-exercise LPP responses by depressive symptom severity, participants in this study were encouraged to exercise at self-selected intensity corresponding to moderate-intensity, which may have resulted in an overall positive net effect on post-exercise affective and emotional responses.

Consistent with the depression and RewP literature (Brush et al., 2018; Proudfit, 2015), we observed a significant association between blunted RewP and depressive symptom severity. Numerous findings have found a blunted RewP in depression (Brush et al., 2018; Foti & Hajcak, 2009; Klawohn et al., 2020; Proudfit, 2015), while ERP studies have demonstrated that acute stress (Burani et al., 2020), approach-motivated states (Threadgill & Gable, 2016; Threadgill & Gable, 2018), and brief motivation manipulations (Pegg & Kujawa, 2020) can modulate reward processing. However, only one previously published study has examined the acute effects of exercise on RewP. Walsh and colleagues (2019) demonstrated that an 11-min bout of high intensity interval exercise diminished the RewP elicited by a probabilistic reward task. The authors concluded that mechanisms of reinforcement learning are downregulated during the initial post-exercise recovery period, possibly due to the heightened physiological arousal from the vigorous-intensity bout of exercise. Importantly, the task used in the Walsh et al. study (probabilistic reward task) includes a learning effect that is not present in the doors gambling task used in this study; thus, it is possible that immediate hedonic responses are intact or even potentiated following exercise, but more difficult tasks that include a probabilistic learning component become impaired. Although there was no significant effect of aerobic exercise on RewP, a relationship between post-exercise RewP and LPP to pleasant pictures was found, suggesting that the same individuals experiencing a larger LPP to pleasant content

also exhibited a larger RewP following exercise. These findings suggest that rather than a selective effect of exercise on emotional engagement and reward sensitivity *per se*, exercise may increase reactivity to appetitive stimuli more generally.

In terms of self-reported affective and emotional responses, a trend towards greater pleasure and higher self-reported arousal were observed following exercise relative to the seated rest. This finding is consistent with the Reed and Ones (2006) meta-analysis indicating that acute exercise has a moderate effect on positive activated affect ($d = 0.47$), which reflects a combination of positive valence (increased pleasure) and increased activation (high arousal), or what Russell (2003) describes as core affect. We did not assess FS and FAS during exercise, thus limiting our understanding of how affect during exercise might influence subsequent emotional and reward processing. The positive affect (PA) dimension of the PANAS was significantly increased following exercise relative to the control condition; however, this was mainly due to a suppression of PA during the seated rest condition. The negative affect (NA) dimension was reduced following both experimental conditions. Suterwala et al. (2016) used the PANAS to assess psychological responses to an initial session of exercise in the 12-week TrEAD (Treatment with Exercise Augmentation for Depression) trial, and found that more positive responses following the first exercise session was predictive of greater improvements in depressive symptoms, response and remission at the end of the 12-week exercise intervention. Thus, it is possible that the PANAS may have clinical utility within the context of exercise and depression and may be related to reward processing given the association of the PA dimension with RewP following exercise. However, the PANAS has known limitations as a measure of affective responses to exercise (Ekkekakis, 2013) and this observed correlation may be spurious and thus warrants future replication.

According to the emotion context insensitivity (ECI) hypothesis, individuals with depression exhibit diminished emotional reactivity to positively-valenced content and

attenuated reactivity to negatively-valenced stimuli. In a broader context, the ECI hypothesis postulates that depression is characterized by emotional disengagement from the environment (Rottenberg, Gross, & Gotlib, 2005) and indeed, a recent study by Hill and colleagues (2019) found blunted LPP amplitudes to both pleasant and unpleasant images, but not to neutral images, providing further support for the ECI hypothesis. In the present study, we observed a significant association between blunted LPP to pleasant pictures and depressive symptom severity on the non-exercise control day, and we also observed a boost in emotional reactivity to both positively- and negatively-valenced pictures post-exercise; however, the effects were only significant for the positively-valenced content. Thus, a single session of exercise may have the potential to modulate reactivity to positively-valenced components of the environment, which may help to normalize the blunted emotional reactivity to positive stimuli characteristic in depression. It is also possible that the post-exercise increase in LPP to positive stimuli represents an important neurophysiological marker of the affective and mood-enhancing benefits of exercise, although this speculation warrants future investigation.

Limitations

Despite its strengths, this study had a few limitations. Although we documented the start time of the EEG assessment following cessation of exercise, the time-course of affective and emotional responding following exercise remains relatively unexplored (e.g., Bixby, Spalding, & Hatfield, 2001). Future studies should continue to include the precise timing of the post-exercise assessments to determine the nature and persistence of post-exercise benefits (Brush, Olson, Ehmann, Osovsky, & Alderman, 2016; Pontifex et al., 2019). Although we did not measure self-reported arousal and valence of the emotional images, previous studies have documented exercise-related changes in these variables (e.g., Crabbe, Smith, & Dishman, 2007; Monroe et al., 2020). It is important for future studies to examine the (non)correspondence between psychological and physiological responses to emotion elicitation

following exercise. Although this study only focused on *post-exercise* affective and emotional responses, future research should also consider measuring affective responses during-exercise in order to determine whether affective responses are influenced by similar or different mechanisms across an exercise session, and whether any changes in affect influence subsequent emotional reactivity. We had participants watch neutral films during both conditions to reduce any potential influences of having them sit completely passively on an ergometer for 30 min on subsequent emotional and affective processing. It is important for future studies to examine the most optimal comparators for acute exercise studies (e.g., Lindheimer et al., 2017). Lastly, we did not include individuals with a current diagnosis of MDD, but rather recruited individuals with varying levels of self-reported depressive and internalizing psychopathology symptoms. Future work should attempt to replicate the present findings among clinical samples.

Conclusions

This study examined the effects of acute, continuous moderate-intensity aerobic exercise on well-validated neural markers of reward sensitivity (i.e., RewP) and emotional engagement (i.e., LPP), and examined associations between these neural measures with self-reported affective and emotional responses. Given that individuals with greater depression severity exhibit blunted RewP and LPP amplitudes (Proudfit et al., 2015), we also examined the moderating influence of depressive symptoms on post-exercise modulations of the RewP and LPP. Relative to seated rest, acute moderate-intensity aerobic exercise resulted in an increase in the LPP to positively-valenced content, along with increased self-reported pleasure and PA dimension of the PANAS. Although depressive symptoms were related to RewP and LPP to pleasant pictures on the non-exercise control day, depressive symptom severity did not significantly moderate any of the effects. Overall, these findings suggest that aerobic exercise increases emotional engagement to pleasant stimuli, which may have implications for protecting against the development of anhedonia or resolving the blunted emotional reactivity

to positive content in depression. Future research should incorporate ERPs to further examine the temporal dynamics of emotional, affective, and cognitive responding following acute exercise.

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Table 1

Sample Characteristics

Variable	Sample (<i>N</i> = 66)
Age (years)	20.59 (2.24)
Gender (% Male)	48%
BMI (kg/m ²)	24.50 (4.57)
DASS	
Depressive Symptoms	7.12 (8.26), range: 0-34
Anxiety Symptoms	6.61 (6.92), range: 0-32
Stress Symptoms	10.27 (8.14), range: 0-30
Total Internalizing Symptoms	24.00 (20.04), range: 0-78

Note. BMI = body mass index; DASS = Depression Anxiety and Stress Scale; Standard deviations are in parentheses.

Table 2

Pearson Correlation Matrix between Clinical Symptoms and ERP Measures on the Control Day

Variables	1	2	3	4	5	6
1. Total Internalizing Symptoms	—					
2. Depressive Symptoms	.88***	—				
3. Anxiety Symptoms	.79***	.50***	—			
4. Stress Symptoms	.90***	.71***	.59***	—		
5. Δ RewP	-.29*	-.28*	-.19	-.27*	—	
6. Δ LPP to pleasant pictures	-.17	-.25*	-.07	-.11	.02	—
7. Δ LPP to unpleasant pictures	-.18	-.21 [†]	-.11	-.14	.02	.83***

Note. Zero-order correlations across the entire sample ($N = 66$). Values are presented as Pearson's correlation coefficient.

[†] $p < .10$

* $p < .05$

*** $p < .001$

Table 3

Means (and Standard Deviations) of Pre- and Post-Affective Responses by Experimental Condition

Variable	Control		Exercise	
	Pre	Post	Pre	Post
FS	2.33 (1.93)	2.17 (1.73)	2.52 (1.48)	2.71 (1.67)
FAS	2.95 (1.39)	2.61 (1.44)	3.11 (1.37)	3.97 (1.16)
PA	28.71 (8.29)	24.74 (10.03)	28.77 (10.66)	28.68 (9.74)
NA	16.70 (6.53)	13.38 (4.29)	16.80 (7.46)	14.15 (6.18)

Note. FS = Feeling Scale; FAS = Felt Arousal Scale; PA = positive affect; NA = negative affect.

Figure Captions

Figure 1. Study procedures.

Figure 2. Participant flow chart following Consolidated Standards of Reporting Trials (CONSORT) guidelines.

Figure 3. Mean ($\pm$ SE) amplitude values (μ V) for grand-average RewP (gain minus loss; left) and LPP (controlling for neutral; right) difference waveforms by experimental condition. There was no difference in RewP by condition, but there was a significant increase in LPP to pleasant pictures for the exercise condition. #condition x picture type interaction: exercise condition significantly different from control condition for pleasant pictures only.

Figure 4. Grand-average RewP (gain minus loss) difference waveforms by experimental condition (left) and scalp distributions depicting mean activity in a time window of 234-254 ms for the control condition and 214-234 ms for the exercise condition (right).

Figure 5. Grand-average LPP (controlling for neutral) difference waveforms by experimental condition (left) and scalp distributions depicting mean activity in a time window of 400-1,000 ms (right).

Figure 6. Scatter plots depicting relationships between exercise-related change in positive affect (Δ PA) and RewP amplitude following exercise (left), exercise-related change in affective valence (Δ FS) and LPP amplitude to unpleasant pictures following exercise (middle), and LPP amplitude to pleasant pictures and RewP amplitude following exercise (right).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6