The effect of acute exercise for reducing cognitive alterations associated with individuals high in anxiety

Matthew B. Pontifex [a,*], Andrew C. Parks [a], Anthony G. Delli Paoli [a], Hans S. Schroder [b], Jason S. Moser [b]

[a] Department of Kinesiology, Michigan State University, United States of America
[b] Department of Psychology, Michigan State University, United States of America

ABSTRACT

Single bouts of exercise have been observed to exhibit therapeutic benefits for reducing affective responses associated with anxiety. However, anxiety has also been found to relate to less efficient cognitive processing as well as a greater reliance on action monitoring processes. Given the extant body of evidence demonstrating that single bouts of exercise result in cognitive enhancements; the present investigation sought to determine the extent to which exercise might be effective at reducing these anxiety-related impairments in cognition. Using a randomized within-subjects crossover design in a sample of high-anxious and low-anxious college-aged adults, measures of inhibition, attention, and action monitoring were assessed before and after 20-min of either aerobic exercise or a cognitively engaging control condition during two separate, counterbalanced sessions. Findings from this investigation revealed that both high anxious and low anxious individuals exhibited enhancements in behavioral indices of performance on an inhibitory control task with faster and more accurate responses following 20 min of moderate intensity aerobic exercise. Additionally, both high anxious and low anxious individuals demonstrated exercise induced enhancements in the allocation of attentional resources (as indexed by P3 amplitude) as well as action monitoring (as indexed by ERN amplitude). Accordingly, these findings provide evidence consistent with broad-base claims regarding the benefits of exercise, suggesting that both high and low anxious individuals appear to incur cognitive benefits.

Anxiety disorders represent one of the most common psychiatric conditions within the United States, placing substantial burden on both the individual and society given the economic implications of diminished work productivity and greater utilization of healthcare services (Remes et al., 2016). Although aerobic exercise has been observed to exhibit therapeutic benefits for reducing anxiety (DeBoer et al., 2012; Jacquart et al., 2019; Petruzzello et al., 1991), the extant literature has largely focused on the effect of exercise on affective responses and has ignored its potential effects on cognitive symptomologies. That is, beyond symptoms associated with excess worry and psychological arousal, anxiety also appears to relate to pervasive cognitive impairments (Eysenck et al., 2007). These cognitive impairments are believed to result from worry competing for attentional resources such that when resources are constrained during effortful cognitive control operations, attentional control is impaired (Berggren et al., 2013). Accordingly, given the extant body of evidence demonstrating enhancements in cognitive control and attention following engagement in acute bouts of aerobic exercise (Pontifex et al., 2019), the present investigation sought to determine the extent to which exercise might be effective at reducing these anxiety-related impairments.

Despite worry competing for attentional resources, individuals with anxiety are largely able to sustain behavioral performance, with high-anxious individuals performing comparably to low anxious individuals albeit with lengthened response time when performing cognitive assessments tapping aspects of cognitive control — and inhibitory control in particular (Eysenck et al., 2007). Accordingly, beyond relying only upon overt behavioral outcomes, greater insight into the relationship between cognition and anxiety has been provided through the assessment of event-related potentials (ERPs). A key finding from the extant body of research into the neural basis of anxiety is that there is a robust association between anxiety and the error-related negativity (ERN), such that anxiety — and in particular anxious apprehension or worry — is associated with enlarged ERN amplitude (Moser, 2017). Elicited by the dorsal anterior cingulate/midcingulate cortex and supplementary

motor regions of the medial prefrontal cortex following the commission of an error, the ERN is thought to reflect activation of action-monitoring processes such that a larger ERN is indicative of a greater signal for the need for further control (Buzzell et al., 2017; Gehring et al., 1993; Miltner et al., 2003). Thus, whether as a result of relying upon compensatory action monitoring processes to sustain behavioral performance or inefficient signaling between neural regions involved with action monitoring and subsequent control regions; this enlarged ERN signal has been taken as a key hallmark of individuals with high anxiety (Moser, 2017).

Interestingly, although single bouts of aerobic exercise have been found to generally result in improvements across a wide range of cognitive processes including information processing, academic achievement, and even memory, the vast majority of the extant literature has demonstrated enhancements in inhibitory aspects of cognition control (Pontifex et al., 2019). Across the lifespan, investigations have generally observed a greater ability to focus attention and ignore distraction following the cessation of a 20 to 30 min bout of moderate intensity aerobic exercise (Hillman et al., 2009; Hillman et al., 2003; Hogervorst et al., 1996; Kamijo et al., 2009; Kamijo et al., 2007; Lichtman and Poser, 1983; Pontifex et al., 2013; Sibley et al., 2006; Tomporowski et al., 2005). Although considerably less research has investigated the effect of acute bouts of exercise on neuroelectric indices of action monitoring, Pontifex et al. (2013) observed a normalizing effect of exercise on action monitoring in children with attention-deficit/hyperactivity disorder (ADHD). Specifically, although children with ADHD exhibited reduced action monitoring (as indexed by smaller ERN amplitude) relative to their typically developing peers in response to the control condition, following a 20-min bout of moderate intensity aerobic exercise those impairments in action monitoring were ameliorated such that there was no difference in action monitoring between children with ADHD and their typically developing peers. However, it is important to acknowledge that in extremely high performing college-aged adults, Themanson and Hillman (2006), failed to observe any effect of acute exercise on ERN amplitude. Thus, it remains to be seen if acute exercise only serves to normalize impaired action monitoring or if enhancements in action monitoring can only be observed when task demands necessitate greater reliance on such processes.

To date however, the vast majority of investigations assessing neuroelectric measures to gain insight into the effects of acute bouts of exercise have focused upon the P3 event-related potential. Elicited in response to the onset of a stimulus, the amplitude of the P3 ERP component is proportional to the attentional resources allocated towards the suppression of extraneous neuronal activity in order to facilitate attentional processing (Polich, 2007). Investigations assessing the extent to which acute bouts of exercise might impact upon attention have observed enhanced P3 amplitude following the cessation of a 20 to 30 min bout of moderate intensity aerobic exercise across the lifespan (Hillman et al., 2003, 2009; Kamijo et al., 2007, 2009; O'Leary et al., 2011; Pontifex et al., 2015; Pontifex et al., 2013). Given that acute bouts of exercise appear to enhance attentional processes related to suppressing extraneous neural operations, it would seem that exercise might be particularly beneficial for high anxious individuals who struggle with anxious apprehensive thoughts competing for attentional resources. Specifically, given the supposition of a coactive link between attention and action monitoring in individuals with high anxiety (Moser, 2017), enhancements in attention should result in reductions in action monitoring. Therefore, if anxious apprehensive thoughts are competing for attentional resources and thereby causing an individual with high anxiety to rely upon compensatory action monitoring processes; exercise induced enhancements in attention may reduce competition for resources and reduce such reliance on compensatory action monitoring resulting in a reduction in ERN amplitude for individuals with high anxiety.

Accordingly, behavioral and neuroelectric indices of inhibition, attention, and action monitoring were assessed in response to an inhibitory control task to examine the extent to which these cognitive processes were impacted by exercise in high anxious individuals. These measures were assessed prior to and following 20-min of either aerobic exercise or a cognitively engaging control condition during two separate, counterbalanced sessions both in a sample of high-anxious and low-anxious college-aged adults. Given the disproportionate prevalence of anxiety among females — who experience longer courses of anxiety as well as greater comorbidity and illness associated with their anxiety-related disorder (Baxter et al., 2014; McLean et al., 2011) — as well as evidence demonstrating that the relationship between anxiety and action monitoring is most consistently observed among females (Moran et al., 2012; Moser et al., 2016); the present investigation restricted the sample to only college-aged females. This randomized within-subjects repeated-measures cross-over design enabled characterizing the effect of acute exercise for reducing cognitive alterations in high anxious individuals and contrasting these effects relative to a low anxious sample. It was hypothesized that acute bouts of exercise would serve to normalize action monitoring processes in high anxious females while subsequently enhancing inhibition and attention for both high and low anxious samples.

1. Method

1.1. Participants

Participants were recruited through Michigan State University's research participation pool, where as a part of a battery of screening tests participants completed the Penn State Worry Questionnaire (Meyer et al., 1990) to assess chronic anxious apprehension. The high anxious group was comprised of 37 college-aged females (mean age = 19.6 ± 1.1 years) who exhibited a composite score greater than or equal to 61 on the Penn State Worry Questionnaire which is the standard cutoff for generalized anxiety disorder on this measure (Behar et al., 2003). A group of 33 college-aged females (mean age = 19.4 ± 1.1 years) with a composite score less than 54 on the Penn State Worry Questionnaire served as the low anxious control group. See Fig. 1 for a CONSORT flow diagram of enrollment.

An initial sample of 39 high anxious and 34 low anxious females were recruited; however, given prior evidence suggesting action monitoring might modulate only if the task is sufficiently difficult to require action monitoring (Themanson and Hillman, 2006), participants who exhibited performance on the inhibitory control task above 99% correct were excluded from analysis (n = 2 high anxious, 1 low anxious). All participants provided written informed consent in accordance with the Institutional Review Board at Michigan State University. Further, all participants reported as being free of any neurological disorder, previous history of head trauma, cardiovascular disease, physical disabilities, and indicated normal or corrected to normal vision. Demographic data are provided in Table 1.

1.2. Inhibitory control task

Inhibitory control was assessed using a letter version of the Eriksen flanker task (Eriksen & Eriksen, 1974; Moser, Schroder, Heeter, Moran, & Lee, 2011). For this task participants were required to attend to a centrally presented stimulus amid either congruous ('MMMMM') or incongruous ('NNMNN') flanking stimuli. Participants completed 480 trials grouped into six blocks of 80 trials, presented with equiprobable congruency and directionality. For each block of this task, participants were presented with perceptually similar letter pairs (i.e., block 1: M – N, block 2: E – F, block 3: O – Q, block 4: I – T, block 5: U – V, block 6: P – R), and were instructed to respond by pressing the button assigned to the letter presented in the middle of the flanking letters. To ensure a high degree of task difficulty in order to necessitate error processing, the button assignments for the letters were switched halfway through each block (e.g., left button click for "M" through 40 trials, then right button
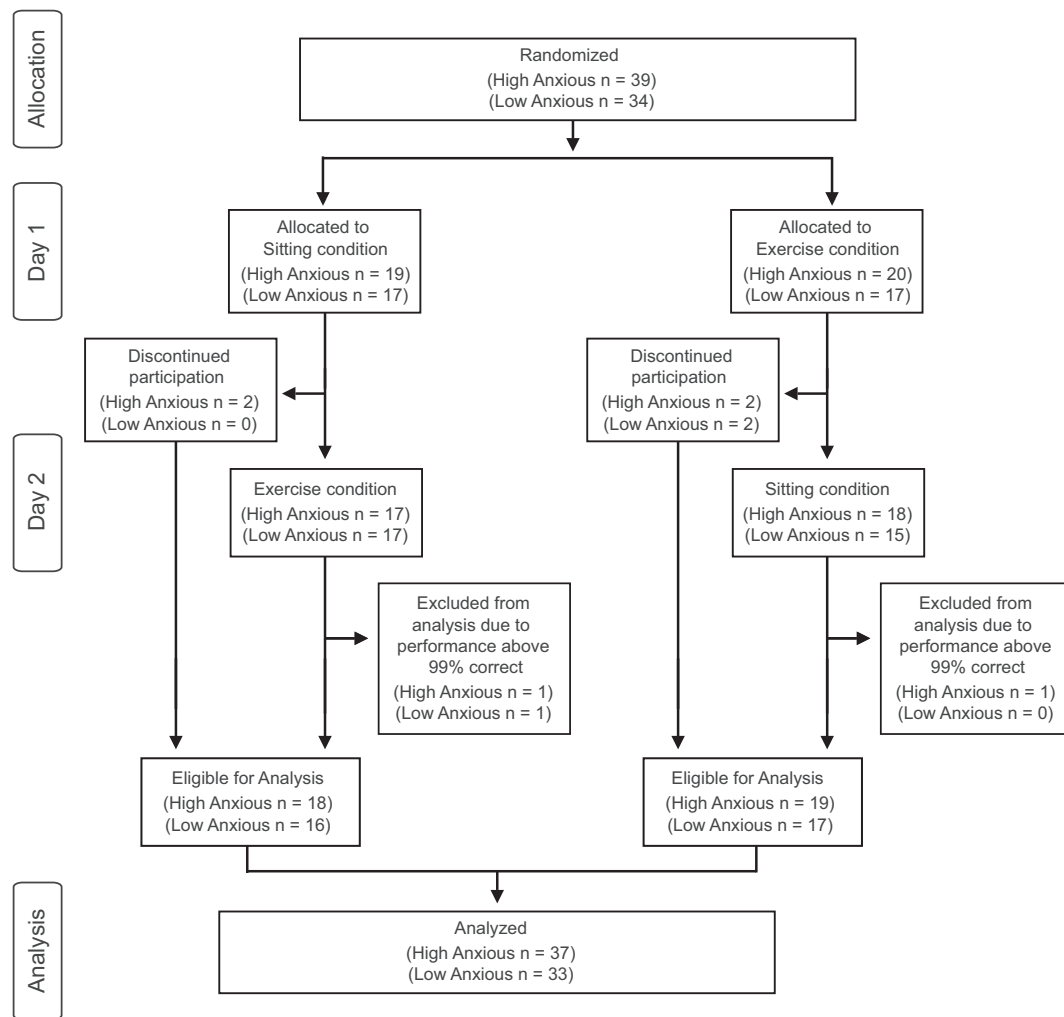
Fig. 1. Consort flow diagram.

Table 1
Mean (± SD) values for participant demographics.

Measure	High Anxious	Low Anxious
N	37	33
Age (years)	19.6 ± 1.1	19.4 ± 1.1
Percent identifying as Hispanic	8.1%	6.1%
Percent identifying as a race other than white	16.2%	21.2%
Penn State Worry Questionnaire (composite score)	67.3 ± 4.7	39.7 ± 7.9
Lowest observed heart rate (bpm)	66.0 ± 8.3	65.3 ± 10.3
Age predicted heart rate max (bpm)	192.4 ± 0.7	192.6 ± 0.8

press for "M" through the last 40 trials). Flanking letters were presented 35 ms prior to the onset of the target stimulus, with the entire array then being presented for a subsequent 100 ms (total stimulus presentation time was 135 ms). All stimuli were 3 cm tall white block letters presented focally on a black background. The inter-trial interval was equally distributed between 1200, 1325, 1450, 1570, and 1700 ms. Stimulus presentation and timing were controlled using PsychoPy, 1.81 (Peirce, 2009).

1.3. ERP recording

Electroencephalographic activity was recorded from 64 electrode sites (Fpz, Fz, FCz, Cz, CPz, Pz, POz, Oz, Fp1/2, F7/5/3/1/2/4/6/8, FT7/8, FC3/1/2/4, T7/8, C5/3/1/2/4/6, M1/2, TP7/8, CB1/2, P7/5/3/1/ 2/4/6/8, PO7/5/3/4/6/8, O1/2) arranged in an extended montage based on the International 10–10 system (Chatrian et al., 1985) using a Neuroscan Quik-Cap (Compumedics, Inc., Charlotte, NC). Recordings were referenced to averaged mastoids (M1, M2), with AFz serving as the ground electrode and impedance less than 10 kΩ. In addition, electrodes were placed above and below the left orbit and on the outer canthus of both eyes to monitor electrooculographic (EOG) activity with a bipolar recording. Continuous data were digitized at a sampling rate of 1 kHz and amplified 500 times with a DC to 70 Hz filter using a Neuroscan SynAmps RT amplifier. The EEG data was then imported into EEGLAB (Delorme and Makeig, 2004) and prepared for temporal ICA decomposition. Data more than 2 s prior to the first event marker and 2 s after the final event marker were removed to restrict computation of ICA components to task-related activity. The continuous data were filtered using a 0.05 Hz high-pass filter to remove slow drifts (Pontifex et al., 2017a), and the mastoid electrodes were removed prior to ICA decomposition. ICA decomposition was performed using the extended infomax algorithm to extract sub-Gaussian components using the default settings called in the MATLAB implementation of this function in EEGLAB with the block size heuristic (floor [sqrt(EEG.pnts/3)]) drawn from MNE-Python (Gramfort et al., 2013). Following the ICA decomposition, the eyeblink artifact components were identified using the icablinkmetrics function (Pontifex et al., 2017b) and the EEG data was reconstructed without the eyeblink artifact.

Following removal of the eye blink components, stimulus-locked epochs were created for correct trials from −100 to 1000 ms around the stimulus, baseline corrected using the −100 to 0 ms prestimulus

period, and filtered using a zero-phase shift low-pass filter at 30 Hz. Trials with artifact exceeding ±100 μV were rejected. To ensure the integrity of the signal, stimulus-locked epochs were visually inspected blind to the group, experimental condition, time point, and congruency prior to computing mean waveforms. The P3 component was evaluated as the mean amplitude within a 50 ms interval surrounding the largest positive going peak within a 250 to 700 ms latency window following stimulus onset. Response-locked epochs were created from −600 to 1000 ms around the response, baseline corrected using the −100 to 0 ms preresponse period and filtered using a zero-phase shift 0.1 to 12 Hz band-pass filter. Mean ERP waveforms were created for error of commission trials and correct trials — which were individually matched (without replacement) to an error of commission trial with the closest possible RT latency (Coles et al., 2001), in order to account for potential artifacts that may exist due to differences in response latency between correct and incorrect trials (Falkenstein et al., 2001; Mathewson et al., 2005). Trials with an error of omission or artifact exceeding ±100 μV were rejected. To ensure the integrity of the signal, response-locked epochs were visually inspected blind to the group, experimental condition, and time point prior to computing mean waveforms. Mean response-locked waveforms with fewer than six accepted trials were excluded from analysis (Pontifex et al., 2010). The ERN was evaluated as the mean amplitude within a 50 ms interval surrounding the largest negative going peak in a − 20 to 150 ms window relative to the response.

1.4. Procedure

Using a within-participants design, participants visited the laboratory on two separate days in which they had not exercised for a period of at least 8 h prior. Following provision of informed consent, on the first day participants completed the physical activity readiness questionnaire (Thomas et al., 1992) and a health history and demographics questionnaire. Participants were then randomly counterbalanced into two different session orders (day 1: sitting, day 2: exercise; or day 1: exercise, day 2: sitting) to ensure that any observed effects were unrelated to the order in which the experimental conditions were completed. The exercise and control sessions occurred approximately 7.4 ± 4.8 days apart and at approximately the same time of day with 1.2 ± 1.4 h different between sessions. During each session, heart rate was measured at 2 min intervals throughout the experimental condition using a Bluetooth heart rate monitor (Mio Link®, Mio Global, Canada) alongside OMNI ratings of perceived exertion (Robertson et al., 2000). Consistent with previous investigations in this area (Hillman et al., 2009; Pontifex et al., 2013, 2015), each experimental condition consisted of 20 min of either sitting (HR = 73.0 bpm [95% CI: 70.8 to 75.2]; Heart Rate Reserve = 5.8% [95% CI: 5.0 to 6.6]) or exercise on a motor-driven treadmill at an intensity between 65% and 75% of their age predicted maximum (205.8 − (0.685*Age)) (Robergs and Landwehr, 2002) heart rate (HR = 135.5 bpm [95% CI: 132.9 to 138.0]; Heart Rate Reserve = 55.0% [95% CI: 52.9 to 57.0]), see Table 2. To ensure that any observed effects were unrelated to experimenter interaction or non-exercise related stimuli; experimenters were blinded to the group assignment of participants, and participants watched an emotionally neutral video (minutes 65–85 and 85–105 from Wonders of the Universe) (Wonders of the Universe, 2011) during the entire 20 min experimental period for both the sitting and exercise conditions. Assessment of neuroelectric and behavioral indices of cognition were performed in a sound-attenuated testing chamber prior to each experimental condition (23.7 min [95% CI: 22.7 to 24.7] prior to sitting; 23.1 min [95% CI: 22.2 to 24.0] prior to exercise), and again once heart rate returned to within 10% of pre-experimental condition levels (6.4 min [95% CI: 5.8 to 7.0] following sitting; 7.6 min [95% CI: 7.0 to 8.1] following exercise). So as to not bias participants regarding the focus of the investigation, participants were administered the Penn State Worry Questionnaire (Meyer et al., 1990) for a second time only following the completion of the final posttest assessment on

Table 2
Mean (SD) values for the experimental sessions.

Measure	High Anxious		Low Anxious	
	Sitting	Exercise	Sitting	Exercise
Pretest assessment				
Time prior to the experimental session (min)	23.6 ± 3.3	32.0 ± 3.5	23.8 ± 4.8	22.0 ± 8.4
Heart rate (bpm)	77.2 ± 9.4	78.1 ± 11.4	75.6 ± 12.2	77.7 ± 9.8
Experimental condition				
Heart rate (bpm)	73.4 ± 8.6	136.8 ± 8.8	72.6 ± 9.3	134.2 ± 11.7
Heart rate reserve (%)	5.8 ± 3.0	55.9 ± 7.2	5.8 ± 3.5	54.1 ± 9.3
Percent of heart rate max (%)	38.1 ± 4.5	71.1 ± 4.6	37.6 ± 4.9	69.7 ± 6.2
OMNI perceived exertion	0.5 ± 1.0	3.1 ± 1.7	0.4 ± 0.9	3.1 ± 1.6
Posttest assessment				
Time following the experimental session (min)	6.7 ± 2.5	7.7 ± 1.7	6.1 ± 2.4	7.4 ± 2.8
Heart rate (bpm)	72.6 ± 9.0	81.0 ± 9.9	73.2 ± 11.2	80.8 ± 9.3

the final testing session. Therefore, 36 participants completed the Penn State Worry Questionnaire for the second time only following the sitting whereas 34 participants completed the Penn State Worry Questionnaire for the second time only following the exercise condition.

1.5. Statistical analysis

Analyses were conducted with α = 0.05 and Benjamini-Hochberg false discovery rate control = 0.05 for post-hoc decompositions. All analyses were conducted separately using a 2 (Group: high anxious, low anxious) × 2 (Mode: sitting, exercise) × 2 (Time: pretest, posttest) univariate multi-level model including the random intercept of Participant and Participant by within-subjects main effect interactions. Analysis of reaction time and response accuracy included Congruency (congruent, incongruent) as an additional factor; while analysis of P3 amplitude included the additional factors of Congruency (congruent, incongruent) and Site (Fz, FCz, Cz, CPz, Pz). Analysis of ERN amplitude at the FCz electrode site included Accuracy (error, match correct) as an additional factor. All analysis were performed using the lme4 (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017), and emmeans (Lenth et al., 2017) packages in R version 3.4.0 with Kenward-Roger degrees of freedom approximations. This approach maximized experimental power by allowing participants with missing data to be retained within the analysis (see Table 3 for the number of missing cases for each group, mode, and time). To examine the effects of exercise on chronic anxious apprehension, analysis of the composite score of the Penn State Worry Questionnaire were conducted with Group (high anxious, low anxious) and Mode (sitting, exercise) as between-subjects factors and Time (prescreening, posttest) as a within-subjects factor using a univariate multi-level model including the random effects of Participant and the interaction of Participant × Time.

For each inferential finding, Cohen's d with 95% confidence intervals were computed as a standardized measure of effect size, using appropriate variance corrections for repeated-measures comparisons (d_{rm}; Lakens, 2013). Given a sample size of 70 participants (37 High Anxious, 33 Low Anxious) and beta of 0.20 (i.e., 80% power) with a two-sided alpha, the present research design theoretically had sufficient sensitivity to detect t-test differences exceeding d = 0.5 within each group and d = 0.34 overall, as computed using G*Power 3.1.2 (Faul et al., 2007). For the purposes of brevity and clarity of reporting, main effects of Site and interactions not involving Group or Mode × Time are not reported. Table 3 provides mean (± SD) behavioral and neuroelectric characteristics as a function of group, mode, and time.

Table 3

Mean (SD) behavioral and neuroelectric characteristics for group, mode, and time.

Measure	High Anxious				Low Anxious			
	Sitting		Exercise		Sitting		Exercise	
	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest
Reaction time (ms)	404.7 ± 38.3	401.6 ± 40.3	408.5 ± 45.9	400.9 ± 41.8	395.4 ± 50.3	393.2 ± 41.4	401.4 ± 38.9	393.4 ± 38.0
Missing data (cases)	2	2	2	2	2	2	0	0
Response accuracy (% correct)	88.4 ± 8.2	88.1 ± 9.0	87.6 ± 10.1	88.2 ± 9.3	85.3 ± 12.3	85.3 ± 12.3	84.8 ± 11.0	87.1 ± 9.3
Missing data (cases)	2	2	2	2	2	2	0	0
P3 amplitude (μV)	16.0 ± 5.4	16.2 ± 6.0	15.2 ± 5.0	16.1 ± 6.3	16.0 ± 5.9	16.2 ± 5.6	15.5 ± 6.2	17.5 ± 7.1
Number of trials based upon	166.2 ± 29.5	164.0 ± 32.4	164.2 ± 35.0	155.3 ± 38.6	165.8 ± 37.0	163.0 ± 38.2	162.7 ± 36.0	159.1 ± 39.9
Missing data (cases)	2	2	2	2	2	2	0	0
ERN amplitude (μV)	−10.3 ± 6.5	−10.7 ± 5.8	−10.2 ± 5.3	−11.3 ± 6.7	−11.4 ± 6.9	−10.9 ± 7	−9.4 ± 5.9	−11.2 ± 6.7
Number of trials based upon	43.5 ± 23.2	44.3 ± 23.0	45.0 ± 29.4	42.5 ± 26.9	46.9 ± 33.0	42.7 ± 27.7	41.4 ± 23.4	36.9 ± 22.6
Missing data (cases)	2	2	2	2	2	2	0	0
Match Correct amplitude (μV)	0.4 ± 2.9	−1.5 ± 4.2	−0.5 ± 4.5	−1.3 ± 4.1	−1.4 ± 3.6	−1.8 ± 4.2	−1.2 ± 3.8	−0.9 ± 7.1
Number of trials based upon	43.0 ± 23.1	43.6 ± 22.6	44.8 ± 29.2	41.9 ± 26.1	46.4 ± 32.5	42.3 ± 27.5	41.1 ± 23.2	36.7 ± 22.1
Missing data (cases)	2	2	2	2	2	2	0	0

Note: Data for reaction time and response accuracy are collapsed across congruency. Data for P3 amplitude are collapsed across congruency and site.

2. Results

2.1. Penn State Worry Questionnaire

Analysis of the composite score of the Penn State Worry Questionnaire revealed an interaction of Group × Time, $F(1, 62) = 4.5$, $p = 0.039$, $f^2 = 0.01$ [95% CI: 0.00 to 0.07]. Post-hoc decomposition of the Group × Time interaction was conducted by examining the effect of Time within each Group. High anxious individuals demonstrated a reduction in anxious apprehension from prescreening (67.3 ± 4.7) to posttest (63.7 ± 7.8) regardless of the experimental condition, $t(63) = 3.1$, $p = 0.003$, $d_{rm} = 0.63$ [95% CI: 0.22 to 1.03]. In contrast, low anxious individuals exhibited no changes in anxious apprehension from prescreening (39.8 ± 7.9) to posttest (39.7 ± 8.6), $t(62) = 0.1$, $p = 0.9$, $d_{rm} = 0.01$ [95% CI: −0.20 to 0.22].

2.2. Behavioral performance

2.2.1. Reaction time

Analysis of reaction time revealed a main effect of Congruency, $F(1, 67) = 1314.3$, $p < 0.001$, $d_{rm} = 1.40$ [95% CI: 1.15 to 1.64], with faster reaction time for congruent (377.0 ± 35.1 ms) relative to incongruent (422.8 ± 35.3 ms) trials. Further, analysis revealed an interaction of Mode × Time, $F(1, 261) = 9.2$, $p = 0.003$, $f^2 = 0.01$ [95% CI: 0.00 to 0.04]. Post-hoc decomposition of the Mode × Time interaction was conducted by examining the effect of Time within each Mode. In response to the exercise experimental condition, reaction time was observed to decrease from pretest (405.0 ± 42.6 ms) to posttest (397.1 ± 39.9 ms), $t(93) = 3.7$, $p < 0.001$, $d_{rm} = 0.26$ [95% CI: 0.11 to 0.40]. However, no significant differences in reaction time were observed between pretest (400.0 ± 44.4 ms) and posttest (397.4 ± 40.8) for the sitting experimental condition, $t(96) = 1.2$, $p = 0.2$, $d_{rm} = 0.08$ [95% CI: −0.05 to 0.21], see Fig. 2.

2.2.2. Response accuracy

Analysis of response accuracy revealed a main effect of Congruency, $F(1, 67) = 1314.3$, $p < 0.001$, $d_{rm} = 1.45$ [95% CI: 1.15 to 1.74], with more accurate responses for congruent (92.8 ± 6.5%) relative to incongruent (81.0 ± 9.9%) trials. Further, analysis revealed an interaction of Mode × Time, $F(1, 266) = 7.5$, $p = 0.007$, $f^2 = 0.02$ [95% CI: 0.00 to 0.10]. Post-hoc decomposition of the Mode × Time interaction was conducted by examining the effect of Time within each Mode. In response to the exercise experimental condition, response accuracy was observed to improve from pretest (86.2 ± 10.6%) to posttest (87.7 ± 9.3%), $t(157) = 3.1$, $p = 0.003$, $d_{rm} = 0.23$ [95% CI: 0.08 to 0.38]. However, no significant differences in response accuracy were observed
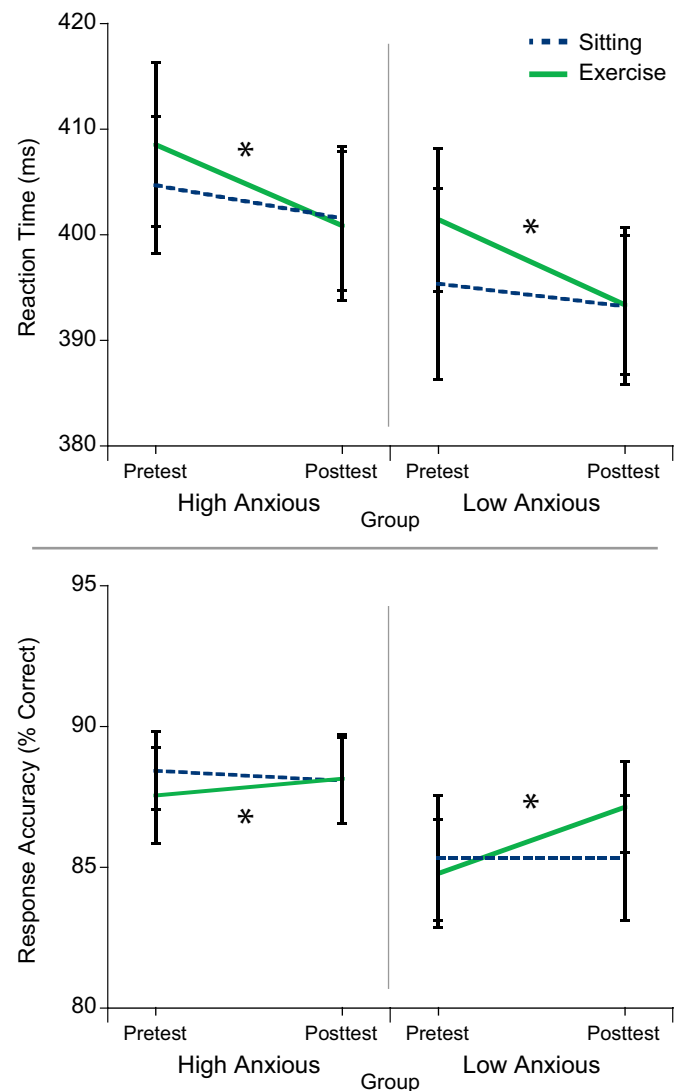

Fig. 2. Mean (± SE) reaction time (top) and response accuracy (bottom) collapsed across congruency for each group, mode, and time point.

between pretest (86.9 ± 10.4%) and posttest (86.7 ± 10.7%) for the sitting experimental condition, $t(160) = 0.4$, $p = 0.7$, $d_{rm} = 0.03$ [95% CI: −0.12 to 0.17], see Fig. 2.

2.3. Neuroelectric activity

2.3.1. P3 amplitude

Fig. 3 illustrates the grand-mean stimulus-locked ERP waveform for each group, mode, and time point. Analysis of P3 amplitude revealed a main effect of Congruency, $F(1, 67) = 41.1$, $p < 0.001$, $d_{rm} = 0.24$ [95% CI: 0.16 to 0.32] with smaller P3 amplitude for congruent (15.5 ± 5.7 μV) relative to incongruent (16.7 ± 6.2 μV) trials. Further, analysis revealed an interaction of Group × Mode × Time, $F(1, 2377) = 5.7$, $p = 0.017$, $f^2 = 0.02$ [95% CI: 0.00 to 0.08]. Post-hoc decomposition of the

Group × Mode × Time interaction was conducted by examining the interaction of Mode × Time within each Group. For both high and low anxious individuals, an interaction of Mode × Time was observed, Fs(1, 1287) ≥ 4.1, p's ≤ 0.043, f^2's ≥ 0.54 [95% CI: 0.18 to 1.64]. For the sitting experimental condition, both high and low anxious individuals demonstrated no significant differences in P3 amplitude between pretest and posttest, t's(50) ≤ 0.4, p's ≥ 0.7, d_{rm}'s ≤ 0.03 [95% CI: −0.19 to 0.24]. However, in response to the exercise experimental condition, P3 amplitude was observed to increase from pretest to posttest to a greater extent for low anxious individuals, relative to high anxious individuals,
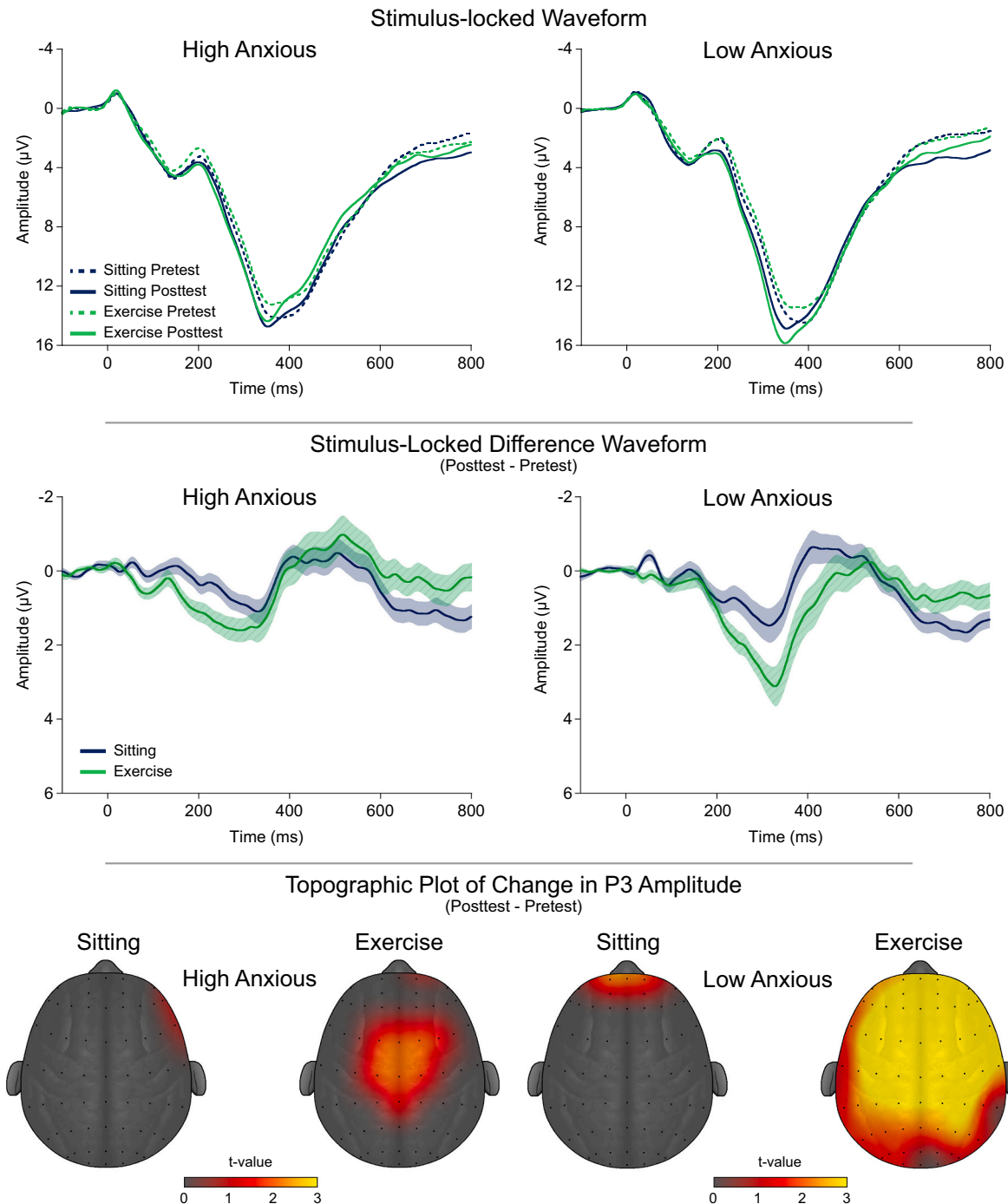

Fig. 3. Grand-mean stimulus-locked ERP waveforms for each group, mode, and time point (top). Grand-mean stimulus-locked difference waveforms (posttest – pretest) for each group and mode (middle). Stimulus-locked waveforms are collapsed across congruency and midline electrode sites (Fz, FCz, Cz, CPz, Pz). Topographic maps of the statistical change (t-value statistic) from pre- to posttest for each group and mode for P3 amplitude (bottom). Topographic plots of P3 amplitude are collapsed across congruency. Note t-values with $p > 0.1$ have been set to 0.

see Fig. 3. Specifically, for the high anxious group, P3 amplitude increased from pretest (15.2 ± 5.0 µV) to posttest (16.1 ± 6.3 µV) following the exercise experimental condition; $t(54) = 2.2$, $p = 0.036$, $d_{rm} = 0.19$ [95% CI: 0.01 to 0.37]. Whereas, for the low anxious group, P3 amplitude increased from pretest (15.5 ± 6.2 µV) to posttest (17.5 ± 7.1 µV) following the exercise experimental condition; $t(47) = 4.1$, $p < 0.001$, $d_{rm} = 0.55$ [95% CI: 0.26 to 0.84].

2.3.2. ERN amplitude

Fig. 4 illustrates the grand-mean response-locked ERP waveform for each group, mode, and time point. Analysis of ERN amplitude revealed no main effects or interactions involving Group, F's(1, 721) ≤ 2.4, p's ≥ 0.06, f^{2}'s ≤ 0.01 [95% CI: 0 to 0.07]. However, an interaction of Mode × Time × Accuracy was observed, $F(1, 255) = 4.6$, $p = 0.032$, $f^{2} = 0.02$ [95% CI: 0.00 to 0.08]. Post-hoc decomposition of the Mode × Time × Accuracy interaction was conducted by examining the interaction of Mode × Time within each Accuracy. For error trials, a Mode × Time interaction was observed, $F(1, 67) = 5.1$, $p = 0.027$, $f^{2} = 0.47$ [95% CI: 0.19 to 0.93]. In response to the exercise experimental condition, ERN amplitude was observed to increase from pretest (−9.8 ± 5.6 µV) to posttest (−11.3 ± 6.6 µV), $t(132) = 3.2$, $p = 0.002$, $d_{rm} = 0.22$ [95% CI: 0.08 to 0.36]. However, in response to the sitting experimental condition, no significant differences in ERN amplitude were observed between pretest (−10.8 ± 6.7 µV) and posttest (−10.8 ± 6.3 µV), $t(132) = 0.0$, p
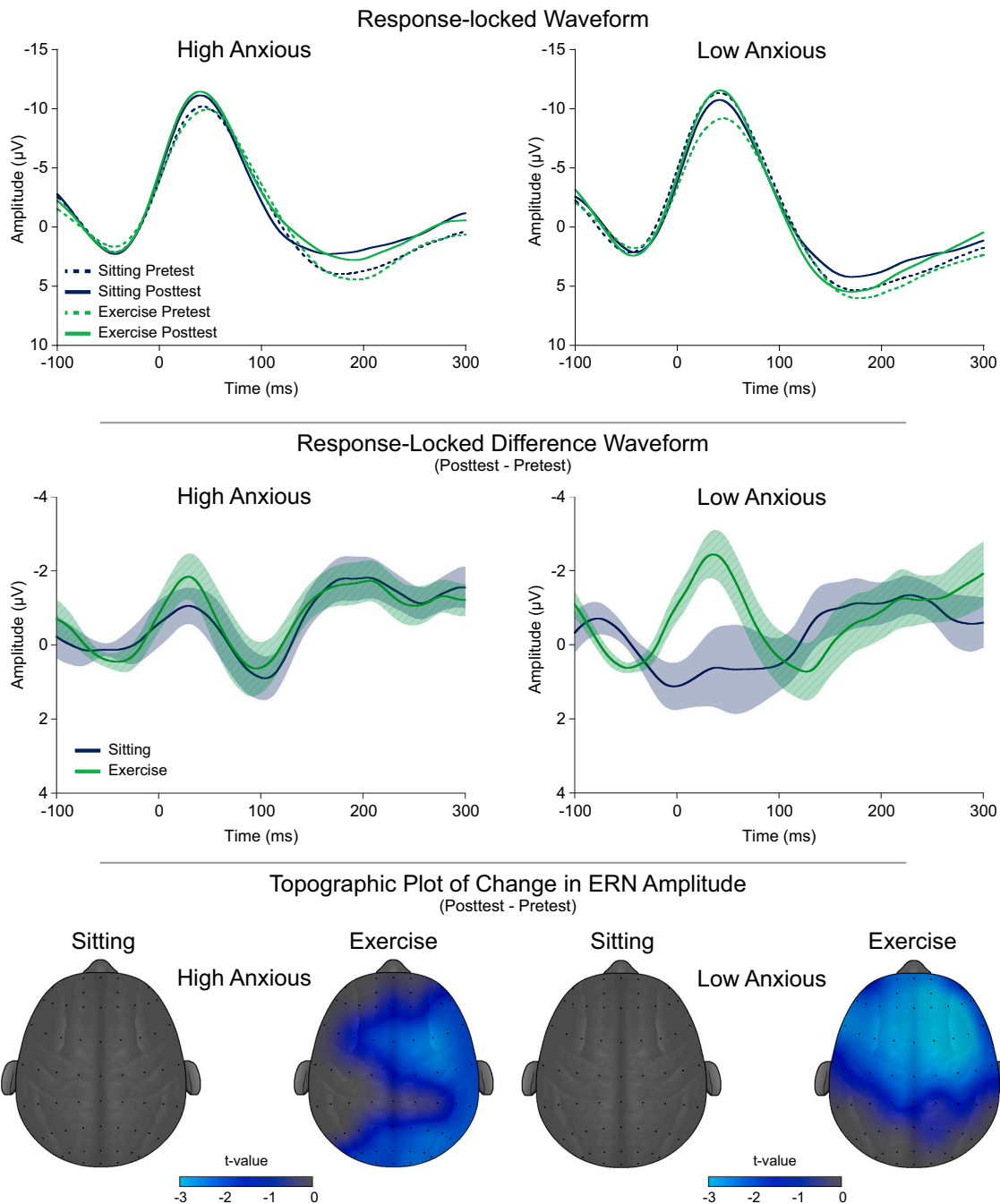

Fig. 4. Grand-mean response-locked ERP waveforms for each group, mode, and time point (top). Grand-mean response-locked difference waveforms (posttest – pretest) for each group and mode (middle). Response-locked waveforms are from the FCz electrode site in response to errors of commission. Topographic maps of the statistical change (t-value statistic) from pre- to posttest for each group and mode for ERN amplitude (bottom). Note t-values with $p > 0.1$ have been set to 0.

= 0.99, d_{rm} = 0.00 [95% CI: −0.15 to 0.15]. For match correct trials, no main effects or interactions were observed, F's(1, 67) ≤ 2.6, p's ≥ 0.1, f^2's ≤ 0.55 [95% CI: 0 to 1.06].

3. Discussion

The aim of the present investigation was to examine the extent to which an acute bout of exercise might be effective at attenuating cognitive symptomologies associated with individuals who exhibit characteristically high anxiety, specifically examining the effect of exercise on behavioral and neuroelectric indices of inhibition, attention, and action monitoring in this population. Findings from the present investigation are in agreement with a growing body of evidence demonstrating that single bouts of moderate intensity aerobic exercise are effective at enhancing inhibitory aspects of cognitive control (Pontifex et al., 2019). Indeed, in response to a cognitively demanding flanker task, both high anxious and low anxious individuals exhibited reductions in reaction time latency and increased response accuracy from pre to post-test following the exercise condition. However, no such enhancements in inhibitory control were observed in response to the sitting condition, which provided a control for cognitive engagement through the utilization of watching the same emotionally neutral video as watched during the exercise condition. Although the net change in both reaction time and accuracy in response to the exercise condition was relatively small, it is important to note that this may have resulted from utilizing the within-subjects repeated measures cross-over design. That is, a strength of this approach is that it utilizes the experimental design to control for the effects of practice by balancing practice related improvements over time against the diminished potential for improvements with repeated exposure to the cognitive assessment (Bartels et al., 2010; Calamia et al., 2012; Collie et al., 2003). This conservative approach, however, inherently minimizes the magnitude of the effect of interest. The utilization of a multi-level model to account for random variance associated with individual subjects unrelated to the factors of interest (i.e., Group, Mode, Time, and Congruency) ultimately helped to reduce the error variance in the model and enable the present investigation to detect the small effect of exercise on behavioral outcomes in response to the flanker task (95% confidence interval surrounding Cohen's d_{rm} ranging from 0.08 to 0.4).

Similarly, the present investigation replicated the extant literature demonstrating that neuroelectric indices of attention are enhanced in response to acute aerobic exercise. Specifically, within the present investigation, enhancements in the allocation of attentional resources (as indexed by P3 amplitude) were observed following a 20 min bout of moderate intensity aerobic exercise. Interestingly, however, these exercise-induced enhancements in attention were smaller for high anxious (95% confidence interval surrounding Cohen's d_{rm} ranging from 0.01 to 0.37), relative to low anxious (95% confidence interval surrounding Cohen's d_{rm} ranging from 0.26 to 0.84), individuals. Accordingly, based upon the interpretation of P3 amplitude as an index of the successful suppression of extraneous neuronal activity in order to facilitate attentional processing (Polich, 2007), exercise may be unable to fully suppress anxious apprehensive thoughts in high anxious individuals. The presence of these anxious apprehensive thoughts in high anxious individuals may mitigate the exercise-induced enhancements in attentional processing as these thoughts ultimately take up available neural resources resulting in smaller exercise-induced increase in P3 amplitude, relative to that exhibited by low anxious individuals in whom anxious apprehensive thoughts are not competing for neural resources.

In contrast to our a priori hypothesis, rather than serving to normalize action monitoring only within high anxious individuals; action monitoring (as indexed by ERN amplitude) was enhanced for both high and low anxious individuals following a 20 min bout of moderately intensity aerobic exercise. Although visually it would appear that high and low anxious individuals might differ in this exercise-induced enhancement in action monitoring; statistically, there was no difference between groups in the response to exercise or the cognitively engaging control condition. Accordingly, one interpretation of these findings draws upon the framework proposed by Braver (2012) for how cognitive control operations are regulated through the utilization of two strategies referred to as 'proactive' and 'reactive' control. While 'proactive' control strategies work to continually exert top-down control, 'reactive' control is transiently engaged in order to make compensatory adjustments following conflicts or errors (Braver, 2012). The Compensatory Error Monitoring Hypothesis thus suggests that anxious individuals may have insufficient neural resources available to support worry-related processes as well as support the extended activation of neural networks required by 'proactive' control strategies; therefore anxious individuals rely more heavily on 'reactive' control (Moser, 2017). When individuals commit an error, this greater reliance on 'reactive' control results in a more prominent action monitoring signal (as indexed by the ERN) (Yeung et al., 2004; Yeung and Cohen, 2006). Since exercise serves to enhance aspects of cognitive control and neuroelectric indices of attention in a manner suggestive of enhancements in 'proactive' control (Pontifex et al., 2011); one might have expected high anxious individuals to be able to diminish their reliance upon 'reactive' control to some degree which would be signaled by reductions in ERN amplitude. However, findings from the present investigation suggest that acute bouts of exercise appear to also enhance ERN amplitude — both in high and low anxious individuals. The lack of a coactive link between attention and action monitoring in high anxious individuals, thus, is in contrast to the supposition that the enlarged ERN associated with high anxiety results from the need for compensatory processing. However, such findings would still fit within 'leaky pipe' frameworks suggesting that the enlarged ERN associated with high anxiety results from inefficient signaling between neural regions involved with action monitoring and subsequent control regions (Moser, 2017).

Accordingly, it may be that acute bouts of exercise not only enhances 'proactive' control, but also makes neural resources available to enhance 'reactive' control processes. Indeed, such speculation would appear to fit the extant acute exercise and action monitoring literature. When the task demands are such that high levels of performance can be achieved without bringing online 'reactive' control processes — such as observed within high performing college-aged adults (Themanson and Hillman, 2006) or typically developing children (Pontifex et al., 2013); action monitoring processes as indexed by the ERN appear to be unaffected by acute bouts of exercise. However, when the task demands necessitate relying on 'reactive' control — either as a result of deficient action monitoring (Pontifex et al., 2013), greater task difficulty or competition for neural resources — acute bouts of moderate intensity aerobic exercise appear to enhance signaling for greater compensatory processing. Thus, acute bouts of exercise appear able to induce a global boost in control through both 'proactive' and 'reactive' processes.

Collectively, findings from the present investigation suggest that acute bouts of moderate intensity aerobic exercise are effective for enhancing inhibitory control, attentional processing, and even action monitoring — when task parameters necessitate the utilization of 'reactive' control. Clearly, however, further research is necessary to examine to what extent such findings manifest in response to other dosages of exercise. Indeed, to date the extant literature provides very little insight into the potential for bouts of exercise utilizing other durations, intensities, and types of exercise to impact upon cognition (Pontifex et al., 2019). Further, there may be other types of exercise that are better suited to optimizing the outcomes of acute bouts such that both affective responses and cognition are enhanced in high anxious populations. However, within the context of the present investigation, the overall pattern of findings is consistent with broad-base claims regarding the benefits of exercise, suggesting that both high and low anxious individuals appear to incur cognitive benefits.

CRediT authorship contribution statement

Matthew B. Pontifex: Conceptualization, Methodology, Resources, Software, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration, Supervision, Validation. **Andrew C. Parks:** Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Anthony G. Delli Paoli:** Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Hans S. Schroder:** Investigation, Data curation, Writing – review & editing. **Jason S. Moser:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Validation.

Declaration of competing interest

No conflicting financial interests exist.

References

Bartels, C., Wegrzyn, M., Wiedl, A., Ackermann, V., Ehrenreich, H., 2010. Practice effects in healthy adults: a longitudinal study on frequent repetitive cognitive testing. BMC Neurosci. 11, 118 https://doi.org/10.1186/1471-2202-11-118.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67, 1–48. https://doi.org/10.18637/jss.v067.i01.

Baxter, A.J., Vos, T., Scott, K.M., Ferrari, A.J., Whiteford, H.A., 2014. The global burden of anxiety disorders in 2010. Psychol. Med. 44, 2363–2374. https://doi.org/10.1017/S0033291713003243.

Behar, E., Alcaine, O., Zuellig, A.R., Borkovec, T.D., 2003. Screening for generalized anxiety disorder using the Penn State Worry Questionnaire: a receiver operating characteristic analysis. J. Behav. Ther. Exp. Psychiatry 34, 25–43. https://doi.org/10.1016/S0005-7916(03)00004-1.

Berggren, N., Richards, A., Taylor, J., Derakshan, N., 2013. Affective attention under cognitive load: reduced emotional biases but emergent anxiety-related costs to inhibitory control. Front. Hum. Neurosci. 7 https://doi.org/10.3389/fnhum.2013.00188.

Braver, T.S., 2012. The variable nature of cognitive control: a dual mechanisms framework. Trends Cogn. Sci. 16, 106–113. https://doi.org/10.1016/j.tics.2011.12.010.

Buzzell, G.A., Richards, J.E., White, L.K., Barker, T.V., Pine, D.S., Fox, N.A., 2017. Development of the error-monitoring system from ages 9–35: unique insight provided by MRI-constrained source localization of EEG. NeuroImage 157, 13–26. https://doi.org/10.1016/j.neuroimage.2017.05.045.

Calamia, M., Markon, K., Tranel, D., 2012. Scoring higher the second time around: meta-analyses of practice effects in neuropsychological assessment. Clin. Neuropsychol. 26, 543–570. https://doi.org/10.1080/13854046.2012.680913.

Chatrian, G.E., Lettich, E., Nelson, P.L., 1985. Ten percent electrode system for topographic studies of spontaneous and evoked EEG activity. Am. J. EEG Technol. 25, 83–92. https://doi.org/10.1080/00029238.1985.11080163.

Coles, M.G.H., Scheffers, M.K., Holroyd, C.B., 2001. Why is there an ERN/Ne on correct trials? Response representations, stimulus-related components, and the theory of error-processing. Biol. Psychol. 56, 173–189. https://doi.org/10.1016/S0301-0511(01)00076-X.

Collie, A., Maruff, P., Darby, D.G., McStephen, M., 2003. The effects of practice on the cognitive test performance of neurologically normal individuals assessed at brief test–retest intervals. J. Int. Neuropsychol. Soc. 9, 419–428. https://doi.org/10.1017/S1355617703930074.

DeBoer, L.B., Powers, M.B., Utschig, A.C., Otto, M.W., Smits, J.A., 2012. Exploring exercise as an avenue for the treatment of anxiety disorders. Expert. Rev. Neurother. 12, 1011–1022. https://doi.org/10.1586/ern.12.73.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics. J. Neurosci. Methods 134, 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009.

Eriksen, B.A., Eriksen, C.W., 1974. Effects of noise letters upon the identification of a target letter in a nonsearch task. Perception & Psychophysics 16 (1), 143–149.

Eysenck, M.W., Derakshan, N., Santos, R., Calvo, M.G., 2007. Anxiety and cognitive performance: attentional control theory. Emotion 7, 336–353. https://doi.org/10.1037/1528-3542.7.2.336.

Falkenstein, M., Hoormann, J., Hohnsbein, J., 2001. Changes of error-related ERPs with age. Exp. Brain Res. 138, 258–262.

Faul, F., Erdfelder, E., Lang, A.G., Buchner, A., 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav. Res. Methods 29, 175–191. https://doi.org/10.3758/BF03193146.

Gehring, W.J., Goss, B., Coles, M.G.H., Meyer, D.E., Donchin, E., 1993. A neural system for error detection and compensation. Psychol. Sci. 4, 385–390. https://doi.org/10.1111/j.1467-9280.1993.tb00586.x.

Gramfort, A., Luessi, M., Larson, E., Engemann, D.A., Strohmeier, D., Brodbeck, C., Hämäläinen, M., 2013. MEG and EEG data analysis with MNE-Python. Front. Neurosci. 7, 1–13. https://doi.org/10.3389/fnins.2013.00267.

Hillman, C.H., Snook, E.M., Jerome, G.J., 2003. Acute cardiovascular exercise and executive control function. Int. J. Psychophysiol. 48, 307–314. https://doi.org/10.1016/S0167-8760(03)00080-1.

Hillman, C.H., Pontifex, M.B., Raine, L.B., Castelli, D.M., Hall, E.E., Kramer, A.F., 2009. The effect of acute treadmill walking on cognitive control and academic achievement in preadolescent children. Neuroscience 159, 1044–1054. https://doi.org/10.1016/j.neuroscience.2009.01.057.

Hogervorst, E., Riedel, W., Jeukendrup, A., Jolles, J., 1996. Cognitive performance after strenuous physical exercise. Percept. Mot. Skills 83, 479–488. https://doi.org/10.2466/pms.1996.83.2.479.

Jacquart, J., Dutcher, C.D., Freeman, S.Z., Stein, A.T., Dinh, M., Carl, E., Smits, J.A.J., 2019. The effects of exercise on transdiagnostic treatment targets: a meta-analytic review. Behav. Res. Ther. 115, 19–37. https://doi.org/10.1016/j.brat.2018.11.007.

Kamijo, K., Nishihira, Y., Higashiura, T., Kuroiwa, K., 2007. The interactive effect of exercise intensity and task difficulty on human cognitive processing. Int. J. Psychophysiol. 65, 114–121. https://doi.org/10.1016/j.ijpsycho.2007.04.001.

Kamijo, K., Hayashi, Y., Sakai, T., Yahiro, T., Tanaka, K., Nishihira, Y., 2009. Acute effects of aerobic exercise on cognitive function in older adults. J. Gerontol. B Psychol. Sci. 64, 356–363. https://doi.org/10.1093/geronb/gbp030.

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest package: tests in linear mixed effects models. J. Stat. Softw. 82, 1–26. https://doi.org/10.18637/jss.v082.i13.

Lakens, D., 2013. Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. Frontiers in Psychology 4 (863), 1–12. https://doi.org/10.3389/fpsyg.2013.00863.

Lenth, R., Love, J., Herve, M., 2017. Emmeans: Estimated Marginal Means, Aka Least-squares Means. Retrieved from. https://github.com/rvlenth/emmeans.

Lichtman, S., Poser, E.G., 1983. The effects of exercise on mood and cognitive functioning. J. Psychosom. Res. 27, 43–52. https://doi.org/10.1016/0022-3999(83)90108-3.

Mathewson, K.J., Dywan, J., Segalowitz, S.J., 2005. Brain bases of error-related ERPs as influenced by age and task. Biol. Psychol. 70, 88–104. https://doi.org/10.1016/j.biopsycho.2004.12.005.

McLean, C.P., Asnaani, A., Litz, B.T., Hofmann, S.G., 2011. Gender differences in anxiety disorders: prevalence, course of illness, comorbidity and burden of illness. J. Psychiatr. Res. 45, 1027–1035. https://doi.org/10.1016/j.jpsychires.2011.03.006.

Meyer, T.J., Miller, M.L., Metzger, R.L., Borkovec, T.D., 1990. Development and validation of the penn state worry questionnaire. Behav. Res. Ther. 28, 487–495. https://doi.org/10.1016/0005-7967(90)90135-6.

Miltner, W.H.R., Lemke, U., Weiss, T., Holroyd, C., Scheffers, M.K., Coles, M.G.H., 2003. Implementation of error-processing in the human anterior cingulate cortex: a source analysis of the magnetic equivalent of the error-related negativity. Biol. Psychol. 64, 157–166. https://doi.org/10.1016/S0301-0511(03)00107-8.

Moran, T.P., Taylor, D., Moser, J.S., 2012. Sex moderates the relationship between worry and performance monitoring brain activity in undergraduates. Int. J. Psychophysiol. 85, 188–194. https://doi.org/10.1016/j.ijpsycho.2012.05.005.

Moser, J.S., 2017. The nature of the relationship between anxiety and the error-related negativity across development. In: Current Behavioral Neuroscience Reports, 4, pp. 309–321. https://doi.org/10.1007/s40473-017-0132-7.

Moser, J.S., Moran, T.P., Kneip, C., Schroder, H.S., Larson, M.J., 2016. Sex moderates the association between symptoms of anxiety, but not obsessive compulsive disorder, and error-monitoring brain activity: a meta-analytic review. Psychophysiology 53, 21–29. https://doi.org/10.1111/psyp.12509.

Moser, J.S., Schroder, H.S., Heeter, C., Moran, T.P., Lee, Y.H., 2011. Mind your errors: Evidence for a neural mechanism linking growth mind-set to adaptive posterror adjustments. Psychological Science 22 (12), 1484–1489. https://doi.org/10.1177/0956797611419520.

O'Leary, K.C., Pontifex, M.B., Scudder, M.R., Brown, M.L., Hillman, C.H., 2011. The effects of single bouts of aerobic exercise, exergaming, and videogame play on cognitive control. Clin. Neurophysiol. 122, 1518–1525. https://doi.org/10.1016/j.clinph.2011.01.049.

Peirce, J.W., 2009. Generating stimuli for neuroscience using PsychoPy. Front. Neuroinformatics 2, 10. https://doi.org/10.3389/neuro.11.010.2008.

Petruzzello, S.J., Landers, D.M., Hatfield, B.D., Kubitz, K.A., Salazar, W., 1991. A meta-analysis on the anxiety-reducing effects of acute and chronic exercise. Sports Med. 11, 143–182. https://doi.org/10.2165/00007256-199111030-00002.

Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. Clin. Neurophysiol. 118, 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019.

Pontifex, M.B., Scudder, M.R., Brown, M.L., O'Leary, K.C., Wu, C.-T., Themanson, J.R., Hillman, C.H., 2010. On the number of trials necessary for stabilization of error-

related brain activity across the life span. Psychophysiology 47, 767–773. https://doi.org/10.1111/j.1469-8986.2010.00974.x.

Pontifex, M.B., Raine, L.B., Johnson, C.R., Chaddock, L., Voss, M.W., Cohen, N.J., Hillman, C.H., 2011. Cardiorespiratory fitness and the flexible modulation of cognitive control in preadolescent children. J. Cogn. Neurosci. 23, 1332–1345. https://doi.org/10.1162/jocn.2010.21528.

Pontifex, M.B., Saliba, B.J., Raine, L.B., Picchietti, D.L., Hillman, C.H., 2013. Exercise improves behavioral, neurocognitive, and scholastic performance in children with ADHD. J. Pediatr. 162, 543–551. https://doi.org/10.1016/j.jpeds.2012.08.036.

Pontifex, M.B., Parks, A.C., Henning, D.A., Kamijo, K., 2015. Single bouts of exercise selectively sustain attentional processes. Psychophysiology 52, 618–625. https://doi.org/10.1111/psyp.12395.

Pontifex, M.B., Gwizdala, K.L., Parks, A.C., Billinger, M., Brunner, C., 2017a. Variability of ICA decomposition may impact EEG signals when used to remove eyeblink artifacts. Psychophysiology 54, 386–398. https://doi.org/10.1111/psyp.12804.

Pontifex, M.B., Miskovic, V., Laszlo, S., 2017b. Evaluating the efficacy of fully automated approaches for the selection of eyeblink ICA components. Psychophysiology 54, 780–791. https://doi.org/10.1111/psyp.12827.

Pontifex, M.B., McGowan, A.L., Chandler, M.C., Gwizdala, K.L., Parks, A.C., Fenn, K., Kamijo, K., 2019. A primer on investigating the after effects of acute bouts of physical activity on cognition. Psychol. Sport Exerc. 40, 1–22. https://doi.org/10.1016/j.psychsport.2018.08.015.

Remes, O., Brayne, C., van der Linde, R., Lafortune, L., 2016. A systematic review of reviews on the prevalence of anxiety disorders in adult populations. Brain Behav. 6, e00497 https://doi.org/10.1002/brb3.497.

Robergs, R.A., Landwehr, R., 2002. The surprising history of the "HRmax=220-age" equation. J. Exerc. Physiol. Online 5, 1–10.

Robertson, R.J., Goss, F.L., Boer, N.F., Peoples, J.A., Foreman, A.J., Dabayebeh, I.M., Thompkins, T., 2000. Children's Omni scale of perceived exertion: mixed gender and race validation. Med. Sci. Sports Exerc. 32, 452–458.

Sibley, B.A., Etnier, J.L., Le Masurier, G.C., 2006. Effects of an acute bout of exercise on cognitive aspects of stroop performance. J. Sport Exerc. Psychol. 28, 285–299.

Themanson, J.R., Hillman, C.H., 2006. Cardiorespiratory fitness and acute aerobic exercise effects on neuroelectric and behavioral measures of action monitoring. Neuroscience 141, 757–767. https://doi.org/10.1016/j.neuroscience.2006.04.004.

Thomas, S., Reading, J., Shephard, R.J., 1992. Revision of the physical activity readiness questionnaire (PAR-Q). Can. J. Sport Sci. 17, 338–345.

Tomporowski, P.D., Cureton, K., Armstrong, L.E., Kane, G.M., Sparling, P.B., Millard-Stafford, M., 2005. Short-term effects of aerobic exercise on executive processes and emotional reactivity. Int. J. Sport Exerc. Psychol. 3, 131–146. https://doi.org/10.1080/1612197X.2005.9671763.

Wonders of the Universe, 2011. BBC America.

Yeung, N., Cohen, J.D., 2006. The impact of cognitive deficits on conflict monitoring: predictable dissociations between the error-related negativity and N2. Psychol. Sci. 17, 164–171.

Yeung, N., Botvinick, M.M., Cohen, J.D., 2004. The neural basis of error detection: conflict monitoring and the error-related negativity. Psychol. Rev. 111, 931–959. https://doi.org/10.1037/0033-295X.111.4.939.