


Changes in cognitive control and mood across repeated exercise sessions

Teran Nieman¹ | Maximilian Bergelt² | Jessica Clancy¹ |
Kayla Regan² | Nic Hobson² | Alexander dos Santos² |
Laura E. Middleton² 

¹Western University, London, ON, Canada

²The University of Waterloo, Waterloo, ON, Canada

Correspondence

Laura E. Middleton, Department of Kinesiology, University of Waterloo, 200 University Ave W, BMH 1114, Waterloo, ON N2L 3G1, Canada.
Email: laura.middleton@uwaterloo.ca

Funding information

Natural Sciences and Engineering Research Council of Canada (NSERC)

Abstract

Acute exercise elicits benefits to cognition and mood. The consistency and accumulation of benefits across exercise sessions remains unclear. This exploratory study evaluated the reproducibility and accumulation of changes in cognitive control and mood across multiple exercise sessions. Thirty young healthy adults (18–35 years) were recruited to exercise ($N = 14$; age: 21.71 [$SD = 1.64$]; 57% female) or control ($N = 16$; age: 22.25 [$SD = 3.68$]; 56% female) groups. Participants attended six sessions over 2 weeks (EX = 20-min mod-intensity cycling; CO = 20-min reading). Cognitive control was assessed using a Flanker task (accuracy-adjusted response time, RT_{LISAS}) pre-/post-intervention. Mood was reported 5×/day on exercise and non-exercise days (pre, post, 11:30 am, 3 pm, and 8 pm) using the Bond–Lader VAS. Cognitive control and mood improved acutely (within session) following exercise compared with control ($F(1, 592) = 6.11, p = .0137$; $F(1, 305.93) = 38.68, p < .0001$; $F(1, 307.06) = 13.69, p = .0003$) and were consistent across sessions. Cognitive control also improved across sessions in both groups ($F(5, 282.22) = 11.06, p < .0001$). These results suggest that: (1) acute effects of exercise on cognition and mood are

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2021 The Authors. *Applied Psychology: Health and Well-Being* published by John Wiley & Sons Ltd on behalf of International Association of Applied Psychology

consistent across multiple sessions; (2) the Flanker task learning effects continue over many trials/sessions; and (3) accumulated mood effects require further investigation. Future studies should further explore the connection between acute exercise exposures and accumulated cognitive benefits.

KEYWORDS

affect, cognition, exercise, inhibition, mood

INTRODUCTION

Maintaining cognitive function throughout the life span is vital to academic success, occupational attainment, and healthy aging. Furthermore, mental well-being and cognitive function are inherently linked. Positive mood states are associated with enhanced cognitive function (Harmon-Jones et al., 2013), while young- and mid-adulthood depression is one of the strongest risk factors for dementia in later life (Bennett & Thomas, 2014). Mental well-being is also critical to health as people age (Dickerson, 1993; Harmon-Jones et al., 2013). A substantial body of research shows that people who are more physically active have better cognitive function and mental well-being in early and mid-life, and are more likely to maintain or even improve cognitive function in late life (Hamer et al., 2018; Loprinzi et al., 2013; Plassman et al., 2010; Sofi et al., 2011). In addition, growing research supports the notion that participation in an exercise program as short as 3 months can improve cognitive function and positively influence mood (Basso & Suzuki, 2017; Craft & Perna, 2004; Kramer & Erickson, 2007; Northey et al., 2018).

Both chronic training and acute exercise sessions elicit specific benefits in cognitive function across all ages (Basso & Suzuki, 2017; Bherer et al., 2013; Chang et al., 2012; Loprinzi et al., 2013; van Uffelen et al., 2008). These exercise-associated benefits are well documented when testing executive functions, including cognitive control. Improvements in executive functions following acute exercise have been associated with improvements in cortical activation patterns linked to allocation of attentional resources (Basso & Suzuki, 2017; Kamijo et al., 2009). As the executive functions are particularly susceptible to age-related cognitive decline, methods to preserve function across the life span are vital to reducing the impact of cognitive aging (Coxon et al., 2016; Harada et al., 2013; McNab et al., 2015; Wasylshyn et al., 2011).

Despite transient behavioral and neurophysiological changes following acute exercise, the maintenance of such changes, and the subsequent transition toward chronic changes, remains less clear. It has been suggested that the acute benefits to cognitive function after exercise may last anywhere from 30 min to 2 h post-exercise (Joyce et al., 2009, 2014). Specifically, one study showed that exercise-induced improvements on executive function may be sustained up to 2 h post-exercise in young adults (Basso et al., 2015). Though cognitive improvements have been tracked over a short period of time following a single session of exercise, it is not clear whether the effects are consistent or cumulative over repeated acute sessions.

Similar to its role in cognition, improvements in mood are also observed after a single session of aerobic exercise. Though there is variability in individual response, acute benefits to affect and mood are consistently observed across studies (Basso & Suzuki, 2017; Reed and Ones, 2006; Stevens et al.,

2016), despite variable exercise dose and individual characteristics (Basso & Suzuki, 2017; Yeung, 1996). Similar to cognition, variability in magnitude of affect and mood response to exercise may be due to varying dose characteristics and assessment timing and type across studies (Ekkekakis et al., 2005). While moderate-intensity exercise seems to be optimal for improvements in affect with benefits becoming less predictable in higher intensities (Ekkekakis et al., 2005), other research has suggested that as little as 10 min of moderate-intensity aerobic exercise was sufficient to elicit reductions in negative mood states while greater improvements are seen with up to 30 min of aerobic exercise (Hansen et al., 2001). A recent study examining varying bouts of acute exercise concluded that an exercise bout could elicit improvements in mood states despite varying durations from 10 to 60 min (Crush et al., 2018). Though mood is considered a sustained, low-intensity construct, it also plays a role in lowering the threshold for provoking emotions and psychologically preparing for future events (Ekkekakis, 2013). Efforts to promote positive mood may subsequently provoke positive emotions and promote positive affective memories toward exercise.

The translation of immediate improvements in mood following acute exercise to sustained positive mood states is less understood. Research exploring the effects of an acute bout of walking on affective response suggested that effects may not be sustained beyond the recovery period and are only present when heart rate remains elevated (Ekkekakis et al., 2000). However, research exploring the benefits of a session of exercise on mood states suggested that benefits may last for several hours after exercise, even in those with mental health disorders (Craft & Perna, 2004; Gligoroska & Manchevska, 2012; Mikkelsen et al., 2017). One study examined the effect of one session of aerobic exercise on the total mood disturbance score (using The Profile of Mood States) and found that improvements in mood after exercise had not fully regressed to baseline at 24 h post-exercise (Maroulakis & Zervas, 1993). While these improvements were centered on a single exercise bout, participants had been exercising regularly for at least one month prior to collection.

Though exercise appears to induce positive changes in cognitive function and mood after a single session of exercise and over a period of exercise training, the consistency of acute effects over a period of training and the trajectory of change in these outcomes over repeated exposures to exercise (which may lead to chronic neural adaptations) are less understood. One study investigated the effects of repeated acute aerobic exercise on mood in young adults, measuring both the acute effects of each session and the changes from baseline at mid-intervention (6 weeks) and post-intervention (12 weeks) (Walter et al., 2013). Acute improvements in mood were consistent over the course of 10 weeks of aerobic endurance training, but no mid-term changes in mood states were observed from baseline (Walter et al., 2013). However, this study was limited by deteriorating compliance to electronic mood assessments, which precluded the examination of changes post-intervention. Though we identified no studies that examined the acute changes in cognition following repeated exercise sessions, research does suggest that a single session of exercise can influence learning, which is a long-term cognitive change (Colcombe & Kramer, 2003; Lambourne & Tomporowski, 2010). Moreover, a single session of exercise may facilitate angiogenesis, neurogenesis, and the synthesis of various neurotransmitters in different cerebral structures involved in cognition (Paillard, 2015; Tillman & Wiens, 2011).

Given the scarcity of research examining cognition and mood over repeated exposures to exercise, the consistency of acute changes and the presence of accumulated benefits is unclear. This study is a preliminary exploration of the reproducibility and accumulation of changes in cognitive control and mood across multiple exercise sessions among healthy young adults. Compared with a non-exercise control group, we hypothesised that: (1) exercise would prompt acute (pre- to post-) improvements in cognitive control and mood, as measured by a modified Flanker task and Bond-Lader Visual Analog Scale (BL-VAS), respectively; (2) acute improvements in cognitive control and mood would not differ significantly across exercise sessions; and (3) cognitive control would improve across multiple

exercise sessions. Note that the latter two hypotheses are exploratory, given the paucity of related research.

MATERIALS AND METHODS

Participants

A total of 30 young healthy adults (aged 18–35 years) were recruited to this exploratory study, including 14 people who were recruited to the exercise (EX) group and 16 people who were recruited to the control (CO) group (non-randomized). Given the lack of previous research based on the acute effects of exercise on cognitive control and mood across a number of exercise sessions, sample size was based on feasibility for an exploratory study rather than established effect sizes.

Participants were recruited using posters in university health science buildings and word of mouth from research team members, other members of the Health Sciences faculty, and previous participants. Participants were screened with the Physical Activity Readiness Questionnaire (PAR-Q+) to ensure safety to exercise (“PAR-Q+ and ePARmed-X+,” 2013). Participants were excluded if they: had a history of heart disease (heart attack or operation, heart murmur, coronary artery disease, congenital heart disease, pacemaker); had uncontrolled hypertension; had drop in blood pressure when rising from a seated position; had neurological conditions (e.g. concussion within last 6 months/post-concussion syndrome, stroke, epilepsy, Parkinson's disease, or dementia); were taking beta blockers, anticoagulants, or anticholinergics; had chronic obstructive pulmonary disease; or had musculoskeletal impairments that cause more pain during exercise than tolerable. This study was approved by a University of Waterloo research ethics committee. All participants provided written informed consent.

Study design

This study used a repeated-measures design within two groups (EX and CO) to examine the influence of exercise on cognitive control. Each participant came into the laboratory for a total of six sessions across 2 weeks (three per week, generally Monday, Wednesday, and Friday). Experimental sessions were scheduled to start between 8:00 am and 9:30 am. All participants were asked to refrain from caffeine prior to all experimental sessions. (Study design is shown in Figure 1.)

Experimental protocol

In the first session, participants reported demographics and medical history and completed the PAR-Q+ (“PAR-Q+ and ePARmed-X+,” 2013) and International Physical Activity Questionnaire (IPAQ) (Craig et al., 2003). In all sessions, participants performed a 100-trial practice block of a modified Flanker task. The participants then completed the BL-VAS to assess mood (described below) (Bond & Lader, 1974). Heart rate and blood pressure were then measured, and participants were fitted with a heart rate monitor (Polar, Bethpage, New York). Cognitive control was subsequently assessed by administering 200 trials of the modified Flanker task.

The EX group performed 3 min of self-paced warm-up followed by 20 min of moderate-intensity aerobic exercise (70% of age-predicted maximum heart rate) and 3 min of self-paced cool down on a stationary cycle ergometer. Twenty-minutes of moderate-intensity was chosen to align with previously

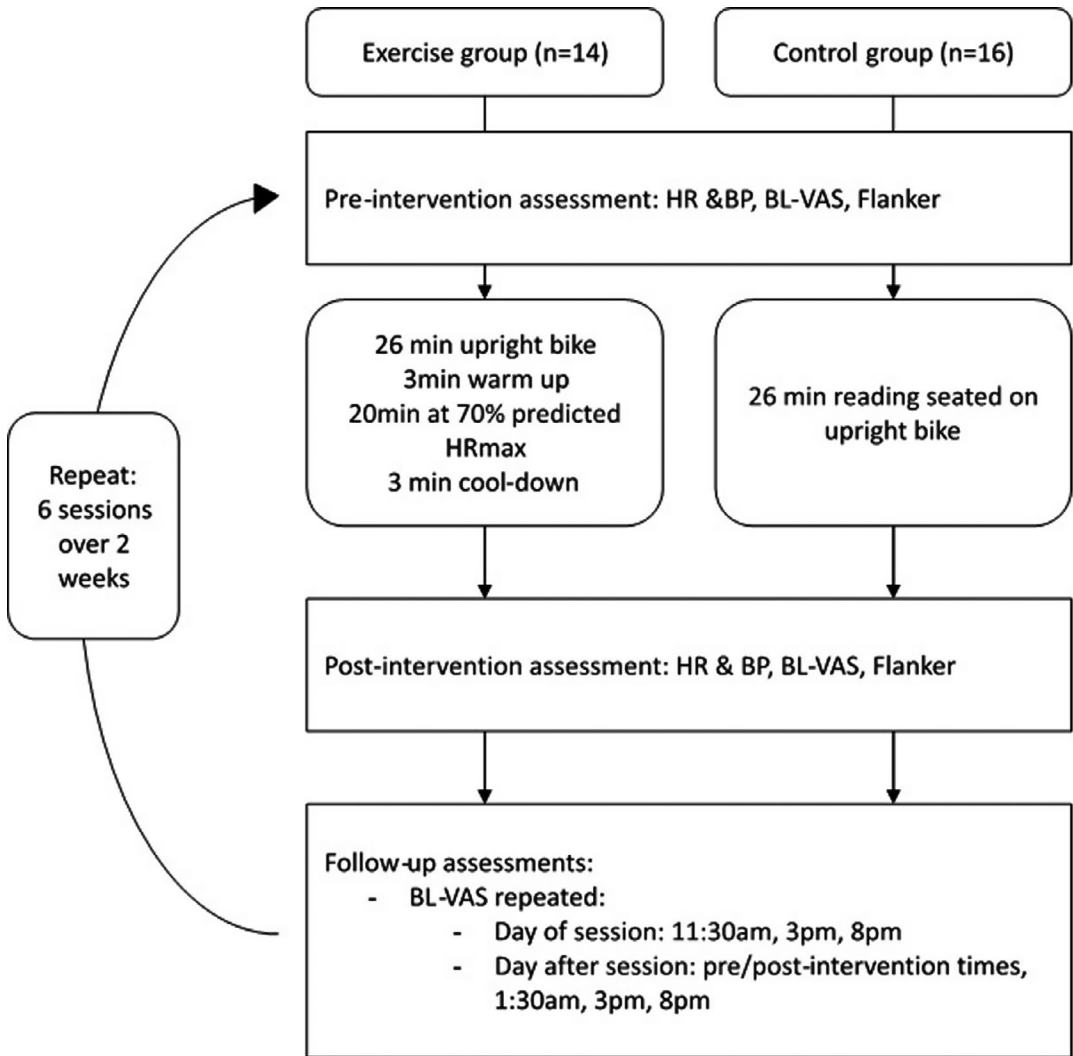


FIGURE 1 Study design, showing study activities completed for each session with six sessions completed over 2 weeks (3 sessions/week)

published literature regarding cognitive effects following acute exercise (Chang et al., 2012). A frequency of three sessions per week for 2 weeks mimics a weekly dose rate often seen in exercise training studies and provides six sessions over which to observe acute effects. Participants were instructed to maintain a cadence of 90 ± 10 rpm. Cycle ergometer resistance was adjusted to maintain heart rate at 70 per cent of age-predicted maximum (± 10 bpm) and a rating of perceived exertion (RPE) of 13 (Borg, 1982), consistent with moderate-intensity exercise. RPE and resistance (watts) were recorded every 2 min. The CO group completed 26 min of quiet reading. Heart rate was recorded every 2 min in both the EX and CO interventions.

Following the intervention, participants filled out another BL-VAS to assess mood. After having heart rate and blood pressure assessed, they completed another 200 trials of the modified Flanker task to assess cognitive control. Participants were then asked to fill out the BL-VAS at three more times throughout the day at 11:30 am, 3:00 pm, and 8:00 pm.

On weekdays without laboratory sessions (generally Tuesday and Thursday), participants filled out the BL-VAS at the same five time points throughout the day (at the same time as their pre-intervention and post-intervention) and at 11:30 am, 3 pm, and 8 pm.

Measures

Cognitive measure: a modified Flanker task

The primary cognitive outcome was a modified Flanker task (Eriksen & Eriksen, 1974), used to probe cognitive control. The modified Flanker task consisted of five arrowheads displayed horizontally on the screen. The participant was asked to respond to the direction of the center target arrow by pressing one button if it pointed left and another if it pointed right. The flanking arrows on either side could point in the same direction as the center arrow as in a congruent condition (e.g. >>>>>), or in the opposite direction from the center arrow as in an incongruent condition (e.g. <<<<<). There was an even distribution of congruent and incongruent trials within each 200-trial block. The modified Flanker task was created and delivered using LabView (National Instruments).

The task was performed in an enclosed soundproof booth to reduce visual and auditory distraction. Participants were instructed to look at a small white fixation cross in the middle of a black screen where the target stimuli appeared and respond as quickly as possible to the stimulus when it appeared. The response buttons were mounted to a table shoulder width apart. Participants responded with their left thumb for arrows pointing left and their right thumb for arrows pointing right. Participants were seated 120 cm away from a 24-inch computer monitor. The stimuli on screen had a height of approximately 10 cm. Each stimulus was displayed for 100 ms with a 1000-ms response window. There was a varying interstimulus interval of 1500 or 2000 ms. A minimum response time of 200 ms was required for correct responses to eliminate anticipatory responses.

Accuracy and response time were collected using LabView (National Instruments). Only response times from correct trials were included in analysis. Since accuracy varied by condition and time, the modified Flanker task performance was quantified by an accuracy and variability adjusted response time score, the Linear Integrated Speed Accuracy Score (RT_{LISAS}) (Vandierendonck, 2017, 2018). The RT_{LISAS} score is calculated using the following equation:

$$RT_{LISAS} = RT + (SD RT / SD PE) \times PE.$$

RT and PE are the participant's mean response time and proportion error (1-accuracy) for each block of the Flanker trials (divided by condition, time, and congruency). The terms $SD RT$ and $SD PE$ refer to the participants' overall standard deviation in response time and proportion error within the Flanker block. If PE was zero, such that there was 100 per cent accuracy, the latter portion of the equation was set to zero.

Mood measures: Bond–Lader Visual Analog Scale

The BL-VAS is a visual analog rating scale comprising 16 dimensional items, each with a 100-mm response line representing a continuum of possible responses (Bond & Lader, 1974). The participant is instructed to make a perpendicular mark along each of these lines to indicate their subjective

feelings at that moment. Items 4, 6, 8, 9, 10, 12, 14, and 16 are reversed to correct polarity prior to calculating scores. Scores are measured from the left to the participant's indicated point. Definitions for uncommon items are listed with the scale to ensure clarity. The 16 items load onto three factors: alertness (alert, attentive, energetic, clear-headed, well-coordinated, quick-witted, strong, interested, proficient), contentedness (happy, amicable, tranquil, contented, gregarious), and calmness (calm, relaxed) (Bond & Lader, 1974). Loading of each item was allocated based on previously published factor analysis (Bond & Lader, 1974). Counterintuitively, lower scores indicate more alertness, contentedness, or calmness. Pre-intervention BL-VAS and post-intervention BL-VAS on intervention days were collected immediately before and after the intervention. Participants received a package of 8 BL-VAS at each in-laboratory visit which they were asked to complete at designated times and return at the subsequent visit.

Statistical analysis

Data analysis was performed using R v3.6.3 (R Core Team, 2020). Linear mixed-effects models were built using the `lmer()` function from the `lme4` v1.1-23 package (Bates et al., 2015), and type III ANOVA tests were obtained using the `lmerTest` v3.1-2 package (Kuznetsova et al., 2017). Standardised effect sizes in the form of partial Eta-squared (in this paper referred to as η^2) were obtained from the model ANOVA tables using the `effectsize` v0.4.1 package (Ben-Shachar et al., 2020). Assumptions were assessed graphically using residual Q–Q plots (to examine residual normality) and residual versus fit plots (to examine heteroskedasticity). A logarithmic transformation was applied to dependent variables where required in order to normalize model residuals. All variables were categorical and sum-contrast-coded to allow the interpretation of main effects and lower order interactions in the models. A significance level of $p = .05$ was used for all main outcome analyses. To correct for the non-independence of measures within participants, PARTICIPANT was included as a random effect (random intercept) in all models. Observed power analysis was conducted using simulations run with the `simr` v1.0.5 package (Green & MacLeod, 2016).

Effect of exercise on cognitive control

To analyze the acute effect of exercise and changes in this effect across sessions, the modified Flanker task data were analyzed using a linear mixed-effects model with the fixed independent variables GROUP, TIME, DAY (experimental session), and CONGRUENCY (congruent vs. incongruent conditions). The fixed independent variables were all fully interacted.

Repeated effect of exercise on cognitive control

In order to analyze the repeated effect of exercise, the modified Flanker task data from the pre-intervention TIME were analyzed using a linear mixed-effects model with the fixed independent variables GROUP, DAY, and CONGRUENCY. The fixed independent variables were all fully interacted.

Acute effect of exercise on mood

In order to analyze the acute effect of exercise on mood and changes in this effect across sessions, BL-VAS data from exercise days were submitted to a linear mixed-effects model with the fixed independent variables GROUP and TIME. The fixed independent variables were fully interacted.

Long-term effect of exercise on mood

In order to analyze the repeated effect of exercise, BL-VAS data from the pre-intervention TIME on exercise days were analyzed using a linear mixed-effects model with the fixed independent variables GROUP and DAY (experimental session). The fixed independent variables were fully interacted.

Effect of exercise days on mood

In order to analyze the effect of days where participants exercised versus days they did not, BL-VAS data from 11:30 am, 3:00 pm, and 8:00 pm were analyzed using a linear mixed-effects model with the fixed independent variables GROUP and DAY (exercise, non-exercise). The fixed independent variables were fully interacted.

RESULTS

Participants

The EX and CO groups were similar in most characteristics (Table 1). The EX group had an average age of 21.71 years (standard deviation(*SD*) = 1.64, range: 20–25) with 57 per cent [8] female, while the CO group had an average age of 22.25 years (*SD* = 3.68, range: 18–34) with 56 per cent [9] female (see Table 1 for a detailed description of participant characteristics by group).

Exercise characteristics, mean (*SD*)

Participants in the EX group had a higher mean heart rate during the intervention (150.53, 21.8 bpm) compared with the CO group (73.02, 6.40 bpm), as expected. The EX group reported a mean RPE of

TABLE 1 Participant characteristics by group (mean \pm *SD* or *n* [%])

	Exercise group (<i>n</i> = 14)	Control group (<i>n</i> = 16)
Age	21.71 \pm 1.64	22.25 \pm 3.61
Sex, female	8 [57%]	9 [56%]
BMI	23.14 \pm 2.62	23.28 \pm 2.29
IPAQ score	4197.52 \pm 2242.46	3985.08 \pm 2711.96
History of concussion, yes	4 [29%]	5 [31%]

13.14 (1.3), which aligns with moderate-intensity exercise; 91.25 per cent of participants had a mean RPE within the target range of 12–15.

Acute effect of exercise on cognitive control

In order to normalize model residuals, a logarithmic transformation was applied to the modified Flanker task RT_{LISAS} scores. There was a main effect of GROUP ($F(1, 28) = 4.22, p = .0494, \eta^2 = .131$), TIME ($F(1, 592) = 15.95, p = .0001, \eta^2 = .026$), DAY ($F(5, 592.25) = 12.43, p < .0001, \eta^2 = .095$), and CONGRUENCY ($F(1, 592) = 564.97, p < .0001, \eta^2 = .488$). There was an interaction between GROUP and TIME ($F(1, 592) = 6.11, p = .0137, \eta^2 = .010$), with a greater improvement from pre- to post-intervention in the EX group compared with the CO group (Figure 2). Observed power in our study was 59 per cent. Observed power analyses suggest that a future study to replicate this effect should enroll at least 50 participants (see Appendix S1 for power curves).

There was no interaction between GROUP and DAY ($F(5, 592.25) = 1.08, p = .3712, \eta^2 = .009$), TIME and DAY ($F(5, 592) = 1.78, p = .1155, \eta^2 = .015$), GROUP and CONGRUENCY ($F(1, 592) = 1.38, p = .2401, \eta^2 = .002$), TIME and CONGRUENCY ($F(1, 592) = .2, p = .6543, \eta^2 < .001$), DAY and CONGRUENCY ($F(5, 592) = .79, p = .5556, \eta^2 = .007$), GROUP \times TIME \times DAY ($F(5, 592) = .17, p = .973, \eta^2 = .002$), GROUP \times TIME \times CONGRUENCY ($F(1, 592) = .26, p = .6138, \eta^2 < .001$), GROUP \times DAY \times CONGRUENCY ($F(5, 592) = .11, p = .9897, \eta^2 < .001$), TIME \times DAY \times CONGRUENCY ($F(5, 592) = .06, p = .9975, \eta^2 = .001$), or GROUP \times TIME \times DAY \times CONGRUENCY ($F(5, 592) = .13, p = .9856, \eta^2 = .001$).

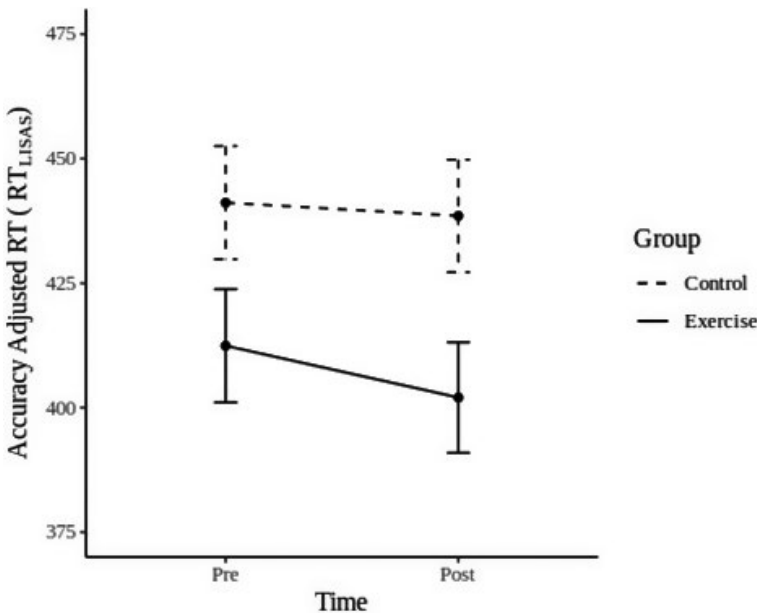


FIGURE 2 Flanker RT_{LISAS} (estimated mean and SE) before and after exercise and a control condition

Repeated effect of exercise on cognitive control

In order to normalize model residuals, a logarithmic transformation was applied to the modified Flanker task RT_{LISAS} scores. There was a main effect of DAY ($F(5, 282.22) = 11.06, p < .0001, \eta^2 = .164$) and CONGRUENCY ($F(1, 282) = 319.05, p < .0001, \eta^2 = .531$), but no main effect of GROUP ($F(1, 28) = 3.38, p = .0765, \eta^2 = .108$). The effect of DAY was similar across both groups, with the Flanker RT_{LISAS} scores improving with each subsequent day (Figure 3).

There was no interaction between GROUP and DAY ($F(5, 282.22) = .99, p = .4223, \eta^2 = .017$), GROUP and CONGRUENCY ($F(1, 282) = .26, p = .6077, \eta^2 = .001$), DAY and CONGRUENCY ($F(5, 282) = .47, p = .8017, \eta^2 = .008$), or GROUP, DAY, and CONGRUENCY ($F(5, 282) = .18, p = .97, \eta^2 = .003$). Observed power in our study was 41 per cent. Power analyses suggest at least 80 participants would be required to detect the observed effect size between GROUP and DAY, indicating a different rate of improvement between groups (see Appendix S1 for power curves).

Acute effect of exercise on mood

In order to normalize model residuals, a logarithmic transformation was applied to all BL-VAS sub-scale scores except where noted.

Alertness

There was a main effect of TIME ($F(1, 305.93) = 32.69, p < .0001, \eta^2 = .097$), but no main effect of GROUP ($F(1, 27.9) = 1.38, p = .2508, \eta^2 = .047$). There was an interaction between GROUP and

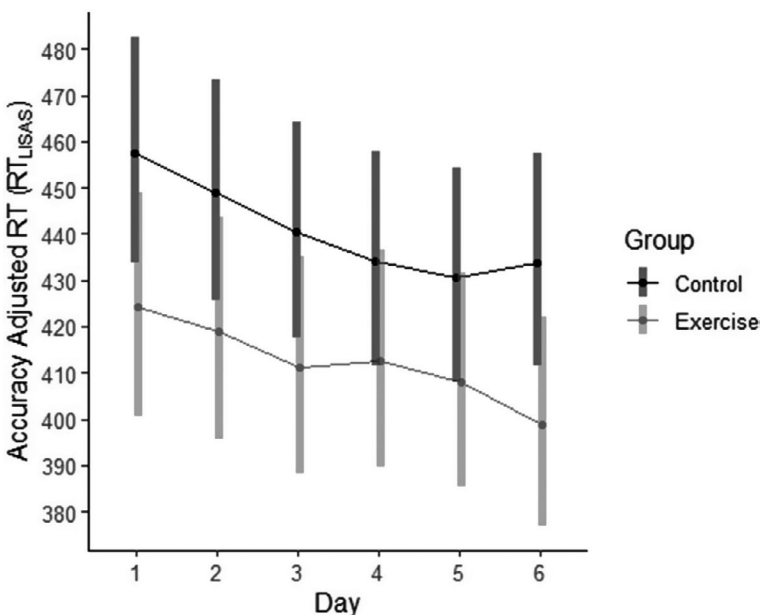


FIGURE 3 Flanker RT_{LISAS} (estimated mean and SE) before exercise and control conditions on six sessions over 2 weeks

TIME ($F(1, 305.93) = 38.68, p < .0001, \eta^2 = .112$) such that the exercise group showed more alertness (lower score) post-intervention (Figure 4). Observed power in our study was 99 per cent.

Contentedness

There was a main effect of GROUP ($F(1, 28.05) = 4.81, p = .0367, \eta^2 = .146$) and TIME ($F(1, 307.06) = 19.75, p < .0001, \eta^2 = .060$). There was also an interaction between GROUP and TIME ($F(1, 307.06) = 13.69, p = .0003, \eta^2 = .043$) such that the exercise group showed more contentedness (lower score) post-intervention (Figure 4). Observed power in our study was 97 per cent.

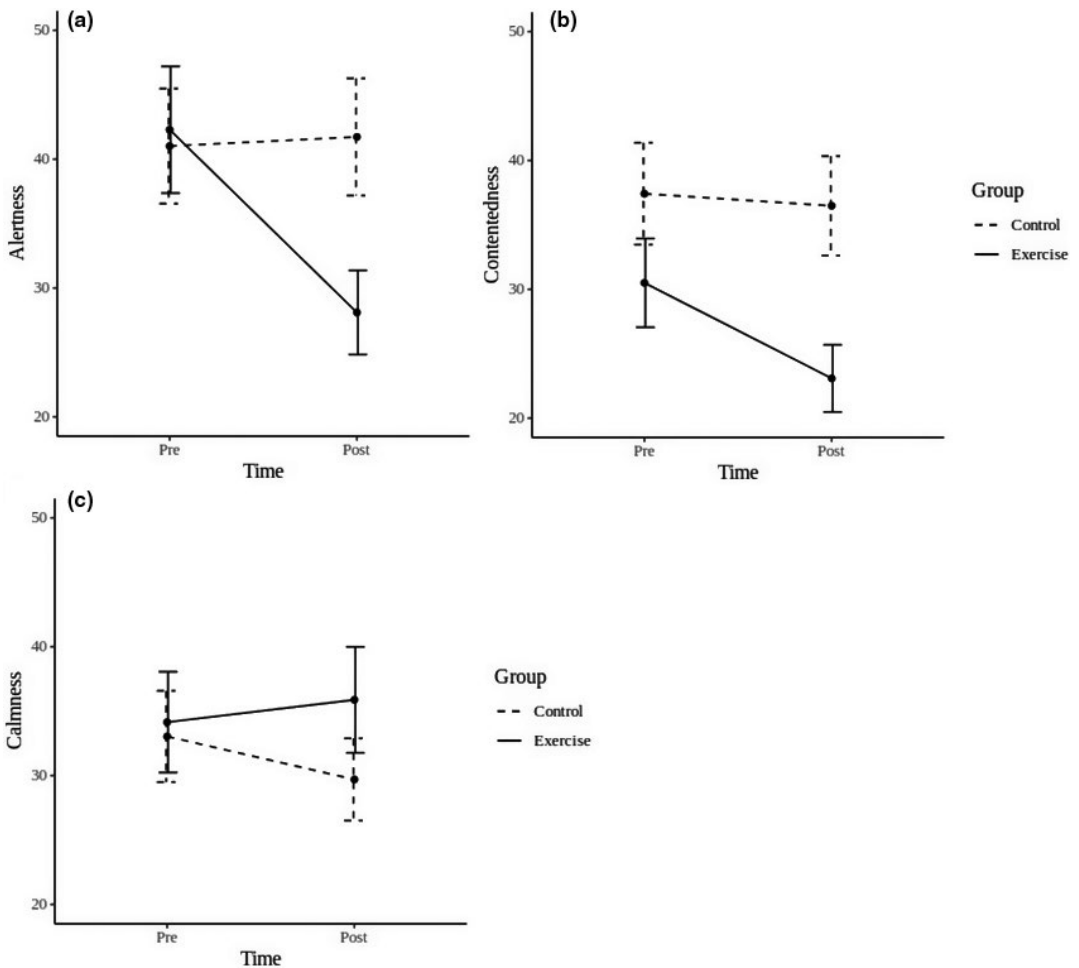


FIGURE 4 Mood before and after an exercise and control condition, averaged across six sessions over 2 weeks by domain (a) alertness; (b) contentedness; and (c) calmness. Note that lower scores indicate more alertness, contentedness, or calmness. Solid line shows the exercise group, and the dashed line shows the control group

Calmness

There was no main effect of GROUP ($F(1,27.82) = .55, p = .466, \eta^2 = .0193$) or TIME ($F(1,306.85) = .4, p = .5295, \eta^2 = .0013$). There was also no interaction between GROUP and TIME ($F(1,306.85) = 2.96, p = .0864, \eta^2 = .0096$) (see Figure 4).

Long term effect of exercise on mood

In order to normalize model residuals, a logarithmic transformation was applied to all BL-VAS subscale scores.

Alertness

There was no main effect of GROUP ($F(1,27.77) = .03, p = .8551$), or DAY ($F(5,130.11) = 1.94, p = .0913$). There was also no interaction between GROUP and DAY ($F(5,130.11) = 1.52, p = .1882$).

Contentedness

There was no main effect of GROUP ($F(1,28.08) = 1.78, p = .1932$) or DAY ($F(5,130.44) = .95, p = .4528$). There was also no interaction between GROUP and DAY ($F(5,130.44) = 1.8, p = .1171$).

Calmness

There was no main effect of GROUP ($F(1,27.58) = .06, p = .8151$) or DAY ($F(5,130.27) = 1.78, p = .1212$). There was also no interaction between GROUP and DAY ($F(5,130.27) = .47, p = .8016$).

Effect of exercise-days on mood

Alertness

In order to normalize model residuals, a logarithmic transformation was applied to the BL-VAS alertness scores. There was no main effect of GROUP ($F(1, 28.05) = 1.96, p = .1729$) or exercise DAY ($F(1,803.25) = .03, p = .8705$). There was also no interaction between GROUP and exercise vs non-exercise DAY ($F(1,803.25) = .1, p = .7566$).

Contentedness

In order to normalize model residuals, a logarithmic transformation was applied to the BL-VAS contentedness scores. There was a main effect of GROUP ($F(1,28.09) = 6.45, p = .0169$) but no main effect of exercise vs. non-intervention DAY ($F(1,800.27) = 2.07, p = .1505$). There was also no interaction between GROUP and exercise vs. non-exercise DAY ($F(1,800.27) = 2.2, p = .1388$).

Calmness

No transformations were applied to the dependent variable. There was no main effect of GROUP ($F(1, 28.05) = .33, p = .5694, \eta^2 = .019$) or exercise DAY ($F(1, 803.44) = 3.2, p = .0739, \eta^2 = .001$). There was also no interaction between GROUP and exercise DAY ($F(1, 803.44) = 1.29, p = .2573, \eta^2 = .010$).

Observed power in our study was 44 per cent. Power analyses suggest that a future study looking at the effect on calmness should enroll at least 80 participants (see Appendix S1 for power curves).

DISCUSSION

The results of this exploratory study support a consistent, positive acute effect of exercise on both cognitive control and mood. Conversely, our results do not suggest sustained improvements following exercise in cognitive control or mood over 2 weeks, as the EX and CO group showed similar improvements session to session. Accumulation of sustained, chronic benefits of exercise may require more time or greater power to detect.

In our study, participants who exercised improved acutely on the modified Flanker task to a greater extent than participants who did not. This is consistent with previous literature that suggests that exercise carries with it a small positive effect for select cognitive domains including cognitive control (Chang et al., 2012). Additionally, the positive effect was consistent across all six sessions over 2 weeks, indicating a consistency of benefits from each individual exercise session. To our knowledge, this is the first study to test this repeated acute effect across multiple sessions and suggests that exercise will continue to improve cognitive control among young adults even if one is exercising at frequent intervals.

We hypothesised that improvements in cognitive control would be observed over the six sessions, contributing to improved cognitive control seen in training periods short as a month (Colcombe & Kramer, 2003; Stern et al., 2019). However, improvements across sessions were similar between EX and CO groups, indicating a positive change not due to exercise. This improvement across sessions is likely due to a learning effect. However, our null finding regarding an effect of exercise should be taken with caution. A larger sample size and/or follow-up period may be required to observe improvements across sessions. Inspections of cognitive changes across sessions (Figure 3) showed that the CO group exhibited a learning curve that appeared to plateau between day 5 and 6, while the EX group still appeared to be improving between days 5 and 6. Our power analyses suggest that a future study would need a larger sample size (at least 80 participants) to detect differences in the rate of improvement between exercise and control groups should the observed effect sizes hold true.

In this study, mood improved immediately following EX but not following the CO sessions. This improvement was particularly evident in alertness and contentedness domains of the BL-VAS, which aligns with prior research that suggested that exercise elicits positive acute changes in a variety of mood dimensions (Basso & Suzuki, 2017; Stevens et al., 2016; Yeung, 1996). While exercisers may become more alert due to increased arousal during exercise, contentedness may be linked to an overall enjoyment and satisfaction following exercise. Importantly, this acute improvement in mood occurred following each exercise session, which suggests a consistent response to exercise for mood and cognitive control. This finding is somewhat different from a prior study exploring the consistency of exercise-associated mood improvements across three identical acute exercise sessions 1–2 weeks apart (Unick et al., 2015). Consistent with our study, authors reported acute (pre–post) affective improvements within the sample with no differences in the magnitude of change between sessions. Of

note, despite the consistency of group-level changes across sessions, individual participants did not consistently fall into responders (improved mood) or non-responders (no change, decrease) within this prior study, demonstrating an ongoing challenge of identifying who will benefit from exercise. To our knowledge, no other study has explicitly examined the reproducibility of exercise-associated mood improvements across multiple acute exercise sessions within our time frame. Consistent benefits over multiple sessions may play a role in promotion of exercise and adherence. Positive changes to affect after one or more exercise sessions may promote future exercise behavior (Kwan et al., 2017).

Though acute improvements in mood were consistent across repeated exercise sessions, this study did not support the hypothesis that improvements were sustained across the day of exercise or the day following the intervention. This conflicts with one prior study that suggested that improvements in mood were sustained 24 h post-exercise (Maroulakis & Zervas, 1993). It is possible that repeated administration of the BL-VAS confounded our ability to detect sustained mood effects, where participants may not have attended to the task consistently. Our results do correlate well with a recent study that suggested that exercise days featured greater positive affect later in the day (post-exercise) compared with non-exercise days during a 6-month walking program (Emerson et al., 2018). It is possible that any sustained benefits of exercise were overpowered by external influences throughout the day.

Though exercise sessions consistently elicited acute improvements in mood, there was no evidence to suggest accumulated benefits across sessions. Some, but not all, prior studies suggest chronic benefits to mood over as little as 6 weeks (Arent et al., 2000; Awick et al., 2017; Walter et al., 2013). However, one study that examined acute and chronic changes following a 10-week running intervention observed discrepancies in acute and accumulated effects similar to our findings. The authors observed acute effects when mood was examined intermittently over the training period; however, no accumulation of effects was observed when mood was measured at 6 weeks (Walter et al., 2013).

An understanding of the trajectory for accumulated benefits may help us plan the duration of exercise interventions and programming necessary for sustained benefits. Current clinical trials have tested as little as a month and as much as 2 years, with little consistent connection between intervention duration and benefits (Colcombe & Kramer, 2003; Northey et al., 2018). It may be that the trajectory of change varies across individuals or due to an interaction between individual characteristics and dose. Studies should probe for an association between the magnitude of acute and chronic changes due to exercise, which could help predict which people would be most likely to benefit and at which doses. Including biomarkers within the study could help clarify the mechanisms for both the acute and chronic effects of exercise on mood or cognitive control to understand how acute exposures contribute to sustained effects. Such evidence would be helpful in informing personalized guidance for exercise to promote cognitive health.

This study was the first to examine the repeatability and accumulation of cognitive and mood benefits with exercise. However, it has several limitations that should be considered when interpreting our results. Firstly, group allocation was not randomized, and the EX group was completed before the CO group. The CO group added post hoc to better isolate whether improvement in cognitive control was due to exercise or learning effects. While consecutive recruitment is not optimal, the groups (EX vs. CO) did not differ in demographic or baseline activity levels and the recruitment process was identical for both groups. In addition, the repeated administration of a modified Flanker task may introduce learning effects or reduce participant attention during the assessments such as the BL-VAS. Lack of additional breadth in cognitive assessments limits the scope of our understanding to cognitive functions assessed with the Flanker task (cognitive control). Examination of executive functions beyond inhibitory control, such as working memory and cognitive flexibility, and broader cognitive function may provide greater insight into cognitive effects. In addition, this study did not measure any negative mood state constructs. Additionally, we cannot guarantee timing compliance for completion

of out-of-laboratory BL-VAS. Participants did receive specific times for completion of each BL-VAS and were encouraged to set reminders on their phones while in the laboratory. We acknowledge that 30 per cent of participants reported a history of concussion, though no participants reported a concussion in the past 6 months or presences of post-concussion syndrome. The sample was recruited by posters and word of mouth in university health science buildings, which may have led to a greater proportion of athletes who experienced concussion. Lastly, this was an exploratory study. A larger sample size may help detect smaller changes between sessions and create a more representative sample. To examine the possible cumulative effect of exercise, we suggest that a future study enroll at least 80 participants (see Appendix S1 for associated power curve). With this being said, it is important to recognize that these power calculations are based on the effect sizes that This we observed which, due to our small sample size, are not necessarily equivalent to population effect sizes. As such, these are relatively crude estimates and should be used with appropriate caution.

Consistent positive effects to cognitive control and mood across multiple sessions contribute to the strength of evidence supporting the acute benefits of exercise. However, this study did not yet yield insights into the accumulation of sustained benefits for cognitive control or mood that have been observed in clinical trials. While the observed effect of acute exercise appears to be robust, the lack of evidence for a cumulative effect should not yet be taken as an absence of effect. Future studies should build on this exploratory study with an increased number of sessions and/or increased sample size to yield insights into the connection between acute exercise exposures and accumulated chronic benefits.

ETHICAL STATEMENT

The study was approved by a University of Waterloo Human Ethics Committee

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in OSF at <https://osf.io/jgya7/>.

ORCID

Laura E. Middleton  <https://orcid.org/0000-0001-8624-3123>

REFERENCES

- Arent, S. M., Landers, D. M., & Etnier, J. L. (2000). The effects of exercise on mood in older adults: A meta-analytic review. *Journal of Aging and Physical Activity, 8*, 407–430. <https://doi.org/10.1123/japa.8.4.407>
- Awick, E. A., Ehlers, D. K., Aguiñaga, S., Daugherty, A. M., Kramer, A. F., & McAuley, E. (2017). Effects of a randomized exercise trial on physical activity, psychological distress and quality of life in older adults. *General Hospital Psychiatry, 49*, 44–50. <https://doi.org/10.1016/j.genhosppsych.2017.06.005>
- Basso, J. C., Shang, A., Elman, M., Karmouta, R., & Suzuki, W. A. (2015). Acute exercise improves prefrontal cortex but not hippocampal function in healthy adults. *Journal of the International Neuropsychological Society, 21*, 791–801. <https://doi.org/10.1017/S135561771500106X>
- Basso, J. C., & Suzuki, W. A. (2017). The effects of acute exercise on mood, cognition, neurophysiology, and neurochemical pathways: A review. *Brain Plasticity, 2*, 127–152. <https://doi.org/10.3233/bpl-160040>
- Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1). <https://doi.org/10.18637/jss.v067.i01>
- Bennett, S., & Thomas, A. J. (2014). Depression and dementia: Cause, consequence or coincidence? *Maturitas, 79*, 184–190. <https://doi.org/10.1016/j.maturitas.2014.05.009>

- Ben-Shachar, M., Lüdtke, D., & Makowski, D. (2020). effectsize: Estimation of effect size indices and standardized parameters. *Journal of Open Source Software*, 5, 2815. <https://doi.org/10.21105/joss.02815>
- Bherer, L., Erickson, K.I., & Liu-Ambrose, T. (2013). A review of the effects of physical activity and exercise on cognitive and brain functions in older adults. *Journal of aging research*, 2013, 657508. <https://doi.org/10.1155/2013/657508>
- Bond, A., & Lader, M. (1974). The use of analogue scales in rating subjective feelings. *British Journal of Medical Psychology*, 47, 211–218. <https://doi.org/10.1111/j.2044-8341.1974.tb02285.x>
- Borg, G. A. V. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, 14, 377–381.
- Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research*, 1453, 87–101. <https://doi.org/10.1016/j.brainres.2012.02.068>
- Colcombe, S., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: A meta-analytic study. *Psychological Science*, 14, 125–130. <https://doi.org/10.1111/1467-9280.t01-1-01430>
- Coxon, J.P., Goble, D.J., Leunissen, I., Van Impe, A., Wenderoth, N., & Swinnen, S.P. (2016). Functional Brain Activation Associated with Inhibitory Control Deficits in Older Adults. *Cerebral cortex*, 26(1), 12–22. <https://doi.org/10.1093/cercor/bhu165>
- Craft, L. L., & Perna, F. M. (2004). The benefits of exercise for the clinically depressed. *The Primary Care Companion to the Journal of Clinical Psychiatry*, 6, 104–111. <https://doi.org/10.4088/pcc.v06n0301>
- Craig, C. L., Marshall, A. L., Sjöström, M., Bauman, A. E., Booth, M. L., Ainsworth, B. E., Pratt, M., Ekkelund, U., Yngve, A., Sallis, J. F., & Oja, P. (2003). International physical activity questionnaire: 12-Country reliability and validity. *Medicine and Science in Sports and Exercise*, 35, 1381–1395. <https://doi.org/10.1249/01.MSS.0000078924.61453.FB>
- Crush, E., Frith, E., & Loprinzi, P. (2018). Experimental effects of acute exercise duration and exercise recovery on mood state. *Journal of Affective Disorders*, 229, 282–287. <https://doi.org/10.1016/j.jad.2017.12.092>
- Dickerson, A. E. (1993). The relationship between affect and cognition. *Occupational Therapy in Mental Health*, 12(1), 47–59. https://doi.org/10.1300/J004v12n01_04
- Ekkekakis, P. (2013). *The measurement of affect, mood, and emotion: A guide for health-behavioral research*. Cambridge University Press. <https://doi.org/10.1017/CBO9780511820724>
- Ekkekakis, P., Hall, E. E., & Petruzzello, S. J. (2005). Variation and homogeneity in affective responses to physical activity of varying intensities: An alternative perspective on dose–response based on evolutionary considerations. *Journal of Sports Sciences*, 23(5), 477–500. <https://doi.org/10.1080/02640410400021492>
- Ekkekakis, P., Hall, E., VanLanduyt, L., & Petruzzello, S. (2000). Walking in (affective) circles: Can short walks enhance affect? *Journal of Behavioral Medicine*, 23, 245–275. <https://doi.org/10.1023/A:1005558025163>
- Emerson, J. A., Dunsiger, S., & Williams, D. M. (2018). Reciprocal within-day associations between incidental affect and exercise: An EMA study. *Psychology and Health*, 33, 130–143. <https://doi.org/10.1080/08870446.2017.1341515>
- 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, 143–149. <https://doi.org/10.3758/BF03203267>
- Gligoraska, J., & Manchevska, S. (2012). The effect of physical activity on cognition – Physiological mechanisms. *Materia Socio Medica*, 24, 198. <https://doi.org/10.5455/msm.2012.24.198-202>
- Green, P., & MacLeod, C. J. (2016). simr: An R package for power analysis of generalised linear mixed models by simulation. *Methods in Ecology and Evolution*, 7(4), 493–498. <https://doi.org/10.1111/2041-210X.12504>
- Hamer, M., Terrera, G. M., & Demakakos, P. (2018). Physical activity and trajectories in cognitive function: English longitudinal study of ageing. *Journal of Epidemiology and Community Health*, 72, 477–483. <https://doi.org/10.1136/jech-2017-210228>
- Hansen, C. J., Stevens, L. C., & Coast, J. R. (2001). Exercise duration and mood state: How much is enough to feel better? *Health Psychology*, 20, 267–275. <https://doi.org/10.1037//0278-6133.20.4.267>
- Harada, C. N., Natelson Love, M. C., & Triebel, K. L. (2013). Normal cognitive aging. *Clinics in geriatric medicine*, 29(4), 737–752. <https://doi.org/10.1016/j.cger.2013.07.002>
- Harmon-Jones, E., Gable, P. A., & Price, T. F. (2013). Does negative affect always narrow and positive affect always broaden the mind? Considering the influence of motivational intensity on cognitive scope. *Current Directions in Psychological Science*, 22, 301–307. <https://doi.org/10.1177/0963721413481353>
- Joyce, J., Graydon, J., McMorris, T., & Davranche, K. (2009). The time course effect of moderate intensity exercise on response execution and response inhibition. *Brain and Cognition*, 71, 14–19. <https://doi.org/10.1016/j.bandc.2009.03.004>

- Joyce, J., Smyth, P. J., Donnelly, A. E., & Davranche, K. (2014). The Simon task and aging: Does acute moderate exercise influence cognitive control? *Medicine and Science in Sports and Exercise*, *46*, 630–639. <https://doi.org/10.1249/MSS.0b013e3182a77980>
- Kamijo, K., Hayashi, Y., Sakai, T., Yahiro, T., Tanaka, K., & Nishihira, Y. (2009). Acute effects of aerobic exercise on cognitive function in older adults. *The journals of gerontology. Series B, Psychological sciences and social sciences*, *64*(3), 356–363. <https://doi.org/10.1093/geronb/gbp030>
- Kramer, A. F., & Erickson, K. I. (2007). Effects of physical activity on cognition, well-being, and brain: Human interventions. *Alzheimer's and Dementia*, *3*, S45–S51. <https://doi.org/10.1016/j.jalz.2007.01.008>
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13). <https://doi.org/10.18637/jss.v082.i13>
- Kwan, B., Stevens, C., & Bryan, A. (2017). What to expect when you're exercising: An experimental test of the anticipated affect-exercise relationship. *Health Psychology*, *36*, 309. <https://doi.org/10.1037/hea0000453>
- Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research*, *1341*, 12–24. <https://doi.org/10.1016/j.brainres.2010.03.091>
- Loprinzi, P. D., Herod, S. M., Cardinal, B. J., & Noakes, T. D. (2013). Physical activity and the brain: A review of this dynamic, bi-directional relationship. *Brain Research*, *1539*, 95–104. <https://doi.org/10.1016/j.brainres.2013.10.004>
- Maroulakis, E., & Zervas, Y. (1993). Effects of aerobic exercise on mood of adult women. *Perceptual and Motor Skills*, *76*, 795–801. <https://doi.org/10.2466/pms.1993.76.3.795>
- McNab, F., Zeidman, P., Rutledge, R.B., Smittenaar, P., Brown, H.R., Adams, R.A., & Dolan, R.J. (2015). Age-related changes in working memory and the ability to ignore distraction. *Proceedings of the National Academy of Sciences*, *112*(20), 6515–6518. <https://doi.org/10.1073/pnas.1504162112>
- Mikkelsen, K., Stojanovska, L., Polenakovic, M., Bosevski, M., & Apostolopoulos, V. (2017). Exercise and mental health. *Maturitas*, *106*, 48–56. <https://doi.org/10.1016/j.maturitas.2017.09.003>
- Northey, J.M., Cherbuin, N., Pumpa, K.L., & Rattray, B. (2018). Exercise interventions for cognitive function in adults older than 50: A systematic review with meta-analysis. *British journal of sports medicine*, *52*(3), 154–160. <https://doi.org/10.1136/brjsports-2016-096587>
- Paillard, T. (2015). Preventive effects of regular physical exercise against cognitive decline and the risk of dementia with age advancement. *Sports Medicine – Open*, *1*, 20. <https://doi.org/10.1186/s40798-015-0016-x>
- PAR-Q+ and ePARmed-X+. (2013). *Canadian Family Physician*, 3rd ed. (vol. 59, pp. 273–277).
- Plassman, B. L., Williams, J. W., Burke, J. R., Holsinger, T., & Benjamin, S. (2010). Systematic review: Factors associated with risk for and possible prevention of cognitive decline in later life. *Annals of Internal Medicine*, *153*, 182. <https://doi.org/10.7326/0003-4819-153-3-201008030-00258>
- R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Reed, J., & Ones, D. S. (2006). The effect of acute aerobic exercise on positive activated affect: A meta-analysis. *Psychology of Sport and Exercise*, *7*(5), 477–514.
- Sofi, F., Valecchi, D., Bacci, D., Abbate, R., Gensini, G. F., Casini, A., & Macchi, C. (2011). Physical activity and risk of cognitive decline: A meta-analysis of prospective studies. *Journal of Internal Medicine*, *269*, 107–117. <https://doi.org/10.1111/j.1365-2796.2010.02281.x>
- Stern, Y., Mackay-Brandt, A., Lee, S., McKinley, P., McIntyre, K., Razlighi, Q., Agarunov, E., Bartels, M., & Sloan, R. P. (2019). Effect of aerobic exercise on cognition in younger adults: A randomized clinical trial. *Neurology*, *92*(9), e905–e916. <https://doi.org/10.1212/WNL.0000000000007003>
- Stevens, C. J., Smith, J. E., & Bryan, A. D. (2016). A pilot study of women's affective responses to common and uncommon forms of aerobic exercise. *Psychology and Health*, *31*, 239–257. <https://doi.org/10.1080/08870446.2015.1095917>
- Tillman, C. M., & Wiens, S. (2011). Behavioral and ERP indices of response conflict in Stroop and flanker tasks. *Psychophysiology*, *48*, 1405–1411. <https://doi.org/10.1111/j.1469-8986.2011.01203.x>
- Unick, J. L., Strohacker, K., Papandonatos, G. D., Williams, D., O'Leary, K. C., Dorfman, L., Becofsky, K., & Wing, R. R. (2015). Examination of the consistency in affective response to acute exercise in overweight and obese women. *Journal of Sport and Exercise Psychology*, *37*, 534–546. <https://doi.org/10.1123/jsep.2015-0104>
- Vandierendonck, A. (2017). A comparison of methods to combine speed and accuracy measures of performance: A rejoinder on the binning procedure. *Behavior Research Methods*, *49*, 653–673. <https://doi.org/10.3758/s13428-016-0721-5>

- Vandierendonck, A. (2018). Further tests of the utility of integrated speed-accuracy measures in task switching. *Journal of Cognition*, *1*, 8. <https://doi.org/10.5334/joc.6>
- van Uffelen, J.G., Paw, M.J.C.A., Hopman-Rock, M., & van Mechelen, W. (2008). The effects of exercise on cognition in older adults with and without cognitive decline: A systematic review. *Clinical Journal of Sport Medicine*, *18*(6), 486–500. <https://doi.org/10.1097/JSM.0b013e3181845f0b>
- Walter, K., von Haaren, B., Löffler, S., Härtel, S., Jansen, C. P., Werner, C., Stumpp, J., Bös, K., & Hey, S. (2013). Acute and medium term effects of a 10-week running intervention on mood state in apprentices. *Frontiers in Psychology*, *4*, 411. <https://doi.org/10.3389/fpsyg.2013.00411>
- Wasylyshyn, C., Verhaeghen, P., & Sliwinski, M. J. (2011). Aging and task switching: A meta-analysis. *Psychology and aging*, *26*(1), 15–20. <https://doi.org/10.1037/a0020912>
- Yeung, R. R. (1996). The acute effects of exercise on mood state. *Journal of Psychosomatic Research*, *40*, 123–141. [https://doi.org/10.1016/0022-3999\(95\)00554-4](https://doi.org/10.1016/0022-3999(95)00554-4)

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.
Appendix S1

How to cite this article: Nieman T, Bergelt M, Clancy J, et al. Changes in cognitive control and mood across repeated exercise sessions. *Appl Psychol Health Well-Being*. 2021;13:853–870. <https://doi.org/10.1111/aphw.12275>