International Journal of EXERCISE SCIENCE

Original Research

A Comparison of Continuous and Interval Exercise on Cognition in Young Adults

EMILY C. TAGESEN†[1,2], LAWRENCE W. JUDGE‡[3], and DAVID M. BELLAR‡[1,4]

[1]School of Kinesiology, University of Louisiana-Lafayette, Lafayette, LA, USA; [2]Exercise Science and Exercise Physiology Program, Kent State University, Kent, OH, USA; [3]School of Kinesiology, Ball State University, Muncie, IN, USA; [4]Usha Kundu, MD College of Health, University of West Florida, Pensacola, FL, USA

†Denotes graduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 16(5): 458-468, 2023. Exercise stimulates the production and secretion of testosterone, cortisol, and brain-derived neurotrophic factor (BDNF) and affects cognitive performance. However, the interaction of these variables is unknown. To investigate these interactions, 21 college-aged men completed two work-matched exercise protocols: continuous (CONT) exercise and an interval protocol (INT). Blood and saliva samples were collected before and after exercise to quantify BDNF, cortisol, and testosterone. Participants completed a battery of cognitive assessments after exercise. A MANOVA analysis of condition demonstrated that no domains were significantly different after CONT and INT ($p > 0.05$). A repeated measures ANOVA of time by condition demonstrated increases in BDNF in after both CONT and INT ($p = 0.05$), elevated cortisol after CONT ($p = 0.05$), and an interaction of testosterone ($p = 0.027$). Work matched continuous and interval exercise appears to promote serum BDNF but do not result in different post exercise cognitive performance.

KEY WORDS: Executive function, cortisol, acute exercise, stress, BDNF

INTRODUCTION

Aerobic exercise appears to transiently improve cognitive function (2, 16, 18), assessed via attention, processing, and memory assessments. These domains of cognition comprise executive function. Executive function is of interest as it encompasses the ability to plan, organize, and regulate behavior (4). By improving performance in subdomains of cognition, overall executive function is improved. Performance on executive function can be measured via tests such as Stroop's color-word test, the Flanker Test, the Wisconsin Card Sort Test; or it can be measured via a battery assessment that includes tasks such as the N-back and Groton Maze task. Individual tests can evaluate individual domains, whereas a battery of tests is better suited for overall performance.

The timing of post exercise cognition tests appears to be a moderating variable of cognitive improvements. Investigations that have examined the time course of transient increases of post exercise cognitive performance indicate that exercise results in elevated cognitive function immediately after exercise (18, 31), 10- (16, 37) and up to 52-minutes (14) after exercise. The literature indicates that exercise intensity may influence the magnitude of improvement on cognitive tasks, as well as the duration of improvement (31, 37), although the effects of intensity on post exercise cognition are varied within the literature. A recent meta-analysis by McMorris indicated that moderate, compared to light or heavy, intensity exercise improves cognitive capacity (21), but this appears to be dependent on the timing of post exercise cognitive assessments. Moderate exercise is also supported in a study by Wang in which cognitive performance was impaired after exercise at 80% heart rate reserve compared after exercising at 30% and 50% heart rate reserve (34), potentially due to adequate stimulus without an overload of stimulus. Data has demonstrated that post exercise cognitive performance is not different between moderate and high intensity (31, 37), but that high intensity exercise results in prolonged improvements in cognitive performance (31). These effects are likely due to exercise mode and overall work, as running compared to cycling results in greater central fatigue (37). Interestingly, a study demonstrated that 20 minutes of moderate exercise evoked a greater magnitude of improvements relative to high intensity exercise (15); however, these protocols were not matched for total work, which may influence the response to exercise.

Although not well explored, circulating factors, such as brain-derived neurotrophic factor (BDNF), cortisol, and testosterone, may contribute to changes in cognitive performance. The hormonal response of exercise is dependent on exercise intensity, duration, mode, and training status of an individual, with the most emphasis placed on intensity (30). Research has demonstrated that the greater intensity and time, the greater the anabolic response to exercise (17, 33). Brain-derived neurotrophic factor (BDNF) promotes neural plasticity and neurogenesis (1), which may promote improved cognitive processes. Cortisol is a hormone associated with stress and anxiety (26) and appears to negatively affect working memory (26, 35, 36). Testosterone administration has been demonstrated to improve visuospatial cognition (23) and increase acutely with exercise. Aerobic exercise may decrease the threshold for programming memory (12) by optimizing brain plasticity potential (3), but the response of BDNF is exercise intensity-dependent (6). Likewise, cortisol appears to be intensity driven; whereby greater intensity provokes a greater response (10). Exercise increases the expression of nerve growth factor and BDNF through a cascade of transcription factors (1), and more specifically, it can increase peripheral BDNF concentration (5) which is readily measured and analyzed. Moderate-intensity exercise has been shown to increase BDNF concentration (8), although specific mechanisms of the interaction between BDNF, cognition, and exercise are unknown. Given that increases in BDNF concentration increases plasticity potential and that greater plasticity may lead to enhanced cognitive performance, the relationship between exercise induced increases in BDNF concentration and cognitive performance is of interest. While investigations examining healthy young adult men are sparse, animal designs have indicated that testosterone may improve synaptic plasticity (28), leading to improved memory and performance on cognitive

assessments that require memory. Furthermore, there has been an observed negative relationship between error rates and testosterone concentration (28). Testosterone concentrations are indicative of anabolic status and are associated with elevated BDNF (5).

BDNF, cortisol, and testosterone appear to be intensity driven, however, the effects of exercise intensity on cognition are not well elucidated due to contradicting results. Furthermore, the interaction between these circulating hormones and cognition is not fully understood. Therefore, the purpose of this investigation was to compare the differences between work-matched continuous and high-intensity interval exercise protocols on cognition, BDNF, cortisol, and testosterone in healthy adult males. To the author's knowledge, this is the first work-matched design examining measures of cognition, BDNF, cortisol, and testosterone. It was hypothesized that interval exercise, due to higher peak intensity, would elicit greater improvements in cognition, driven by elevated BDNF, cortisol, and testosterone.

METHODS

Participants

Twenty-two healthy, college-aged men were recruited for the study by word of mouth around the university and surrounding area. Participants were included if they had no known metabolic, cardiovascular, or muscular reasons why they should not engage in exercise. Power analysis performed from a similar study suggested that a sample size of 16 was needed to detect a difference on a similar cognitive task ($1 - \beta$) of 0.80 at an alpha level of 0.05 (Stroop Color-Word) (6). This was also the suggested sample size for studies that examined the effect of exercise on cortisol levels (11). Before the study, participants were informed of the experimental protocols, study purpose, and any associated risks and benefits. In accordance with the university institutional review board and the Declaration of Helsinki, participants gave their informed consent and completed a health history questionnaire before the first test session. All participants were assigned a coded number to ensure anonymity. The Institutional Review Board of University of Louisiana at Lafayette approved the informed consent form before beginning the experimental protocol (proposal number FA17-55 KNES). Additionally, this investigation follows the ethical policies of the International Journal of Exercise Science described by Navalta et al. (2019) (22).

Protocol

Participants underwent work-matched continuous (CONT) and interval (INT) cycling exercise conditions in a counterbalanced order, separated by one week. On visit one, participants reported to the exercise performance laboratory to review informed consent and medical history. Participants then completed a baseline cognitive examination utilizing a computerized test battery, given in an identical order (CogState, New York, NY, USA). At least 72 hours later, participants returned to the laboratory, having fasted for 10 hours, abstained from caffeine for 16 hours, alcohol and nicotine for 24 hours, and vigorous exercise for 72 hours. All experimental trials began by 10:00 am to account for diurnal fluctuations in cortisol. Participants were encouraged to consume a similar diet before both exercise trials. Participants then performed

the independently developed exercise protocol (INT: 6 intervals of 2 min 40% VO_2max or 1 min 90% VO_2max, or CONT: 20 min 21 seconds of 50% VO_2 max, counterbalanced and separated by one week). Before and immediately after exercise, saliva and blood were collected and processed in an identical manner, taking no more than 10 minutes total at each time point. Following biological sampling after exercise, participants completed a cognitive battery which took approximately 45-60 minutes to complete. Participants returned no sooner than seven days later, at an identical time to account for variations in cortisol, for the opposite exercise protocol.

Height, weight, and age were recorded on the medical history. Body fat percentage was measured using air displacement plethysmography (BodPod, CosMed USA, Inc., Concord, California, USA). Participant characteristics are listed in Table 1.

A metabolic cart (Cosmed USA INC, Concord, California, USA) and cycle ergometer (Monark, Cosmed USA INC) were utilized for a VO_2max measurement. VO_2max was recorded upon participant volitional fatigue, a plateau of VO_2, and an RER of greater than 1.0. VO_2 max and its correlating max wattage were used to calculate the workload for the following exercise trials.

Duration for the INT and CONT work-matched exercise protocols was determined by setting the equation for work in Joules (Watts * time) equal and solving for the time where 50% continuous VO_2 max watts produced the same amount of work as 6 intervals of 40% VO_2 max watts for 2 minutes and 90% VO_2 max watts for 1 minute.

Work (j) = Percent of max watts* max watts * time (high int) + Percent of max watts * max watts* time (low int)

Continuous exercise (50% of Watts at VO_2 max)

Work (j) = Percent of max watts * max watts * time

The present investigation utilized a computerized battery to measure cognition, designed for optimal test-retest reliability (CogState, New York, NY, USA). The exam included a series of tests, given in an identical order, to determine psychomotor, attentional, executive, and memory skills with minimum learning effects.

Within this program, the detection test (psychomotor speed) assesses reaction time for a given stimulus and is a validated measure of attention (27). The "detection test" consisted of a card flip task in which each participant pressed a key as soon as the card on the screen flips (25). The "identification test" (a choice reaction time test) was used to assess psychomotor learning speed and visual attention. Choice reaction tasks require increased attention processing and are validated to reflect processing speed (19). The "identification test" was administered by the screen showing either a red or black card and having the participant press the appropriate key ("k" for red or "d" for black) (25). The "one back memory test" was used to assess working memory and learning through a card flip task. This task required participants to recall

information in working memory (29) while also distinguishing previous stimuli from distractors (19). In this task, a series of cards were displayed on the screen, and the participant pressed "k" if the card was the same as the one before or pressed "d" if the card was different (25). The "Groton maze learning" task assesses executive function, which is defined as the integration of attention, visuomotor processing speed, integration, and decision making. This task measured the ability of the participant to store and utilize information about a hidden maze from one trial to the next. Participants utilized their working memory to recall the pattern and finish the maze. The participant repeated the assessment 3 times with a recall trial at the end of the complete battery (25). The propriety software provided a score for each test which was used to observe differences in cognitive domains.

Four mL of blood were collected before and after exercise. Participants were asked to fast for at least 10 hours before reporting to the laboratory. Blood was collected through a single puncture in the antecubital space. A 30-min period was allotted for the serum to clot before centrifuging, aliquoting, and storing in the freezer at -80°C. Serum BDNF was analyzed using a commercially available immunoassay kit (Human BDNF Elisa ELH-BDNF-1, Raybiotech Peachtree Corners, Georgia, USA).

One mL of saliva was collected before and after exercise. Participants were asked to refrain from brushing their teeth and consuming food or water before reporting to the laboratory. Each participant was instructed to tuck his head in and down to allow saliva to drip through a straw into the collecting tube. Saliva was collected over a period of five minutes, processed, and then frozen in a -80°C freezer for future analysis. Saliva was analyzed for cortisol (Expanded Range High Sensitivity Salivary Testosterone Enzyme Immunoassay Kit 1-3002, Salimetrics, College Park PA, USA) and testosterone concentrations and quantified utilizing a commercially available immunoassay kit (Expanded Range Salivary Testosterone Enzyme Immunoassay Kit 1-2402, Salimetrics, College Park PA, USA).

Statistical Analysis

This was a cross-over study in which all participants completed both conditions. Participants were recruited in a counterbalanced order to negate any trial order effects. Data were analyzed using SPSS (IBM SPSS Version 26). A one-way multivariate analysis of variance (MANOVA) was used to compare differences between post exercises condition cognitive battery assessments. A two condition (CONT exercise and INT) by two-time (pre and post) ANOVA repeated measures on condition and time was used to observe differences in blood and salivary variables. Post-hoc tests were conducted to further investigate significant interactions and or main effects. Alpha was set at ($p < 0.05$). Data is reported as mean ± standard deviation (SD).

RESULTS

Participant anthropometrics were measured and recorded on visit one and reported as mean ± SD (see Table 1). One participant was not included in the analysis due to the inability to provide a blood sample, so 21 participants were included in the analysis.

Table 1. Participant characteristics.

	Mean ± SD
n	21
Age (years)	22 ± 1
Height (inches)	70.0 ± 3.04
VO_2 max (mL/kg/min)	33.47 ± 6.59
Body Fat %	17.57 ± 8.12

VO_2max = maximal volume of oxygen consumed.

A one-way MANOVA revealed no significant differences between exercise conditions (F = 0.212, p = 0.991) for any of the cognitive domains. Cognitive assessment scores are reported as mean ± SD (see Table 2).

Table 2. Comparisons of cognitive domains.

Measurement	Post CONT	Post INT	p-value	F-statistic
Detection Accuracy (%)	97.9 ± 3.8	96.7 ± 4.9	0.539	0.383
Detection Speed (s)	339.4 ± 61.0	333.9 ± 50.6	0.713	0.137
Identification Accuracy (%)	93.6 ± 6.3	94.2 ± 5.6	0.680	0.173
Identification Speed (s)	513.8 ± 99.2	504.4 ± 85.6	0.761	0.093
One Card Learning Accuracy (%)	73.6 ± 8.6	72.9 ± 7.9	0.962	0.002
One Card Learning Speed (s)	972.0 ± 230.3	959.3 ± 166.3	0.998	0.000
One Back Accuracy (%)	93.6 ± 8.5	95.1 ± 5.5	0.456	0.566
One Back Speed (s)	737.0 ± 165.2	701.1 ± 171.3	0.477	0.516
Maze Errors	42.4 ± 12.1	41.2 ± 18.7	0.797	0.067

CONT= continuous exercise; INT= interval exercise.

A repeated-measures ANOVA (treatment by time) revealed no significant interaction (F = 1.13, p = 0.30, ηp^2 = 0.06) or a main effect of condition (F = 0.83, p = 0.37, ηp^2 = 0.04) for serum BDNF levels. There was a main effect of time pre- to post-exercise (F = 4.43, p =0.05, ηp^2 = 0.19) with exercise being associated with an acute 41.7% increase in serum BDNF from baseline. Data is presented as Mean ± SD (See Table 3).

The ANOVA analysis for cortisol revealed no main effect of the condition (F = 0.140, p = 0.712, ηp^2 = 0.007). There was a significant (F = 4.90, p = 0.04, ηp^2 = 0.20) condition by time interaction and a main effect of time in cortisol concentrations (F = 4.10, p = 0.05, ηp^2 = 0.19), such that after continuous exercise, cortisol concentrations were elevated, but after interval exercise, cortisol concentrations were unchanged. The ANOVA analysis for testosterone revealed a significant time x condition interaction (F = 5.919, p = 0.027, ηp^2 = 0.270). There were no main effects of time or condition (F < 0.001, p = 0.991, ηp^2 < 0.001; F = 0.088, p = 0.771, ηp^2 = 0.005, respectively).

Pairwise comparisons demonstrated no differences across time or conditions. BDNF, cortisol, and testosterone concentrations are reported as mean ± SD (see Table 3).

Table 3. Circulatory measures.

Measurement	Pre CONT	Post CONT	Pre INT	Post INT
BDNF (pg/mL)	393.4 ± 215.5	501.9 ± 244.4 *	393.3 ± 178.7	441.8 ± 192.3 *
Cortisol (ug/dL)	0.58 ± 0.35	0.79 ± 0.62 ^	0.63 ± 0.37	0.68 ± 0.42
Testosterone (pg/mL)	397.4 ± 182.6	471.4 ± 189.9	494.7 ± 278.9	410.4 ± 158.7

CONT = continuous exercise; INT= interval exercise.
(*) = $p < 0.05$, main effect of time. (^) = $p < 0.05$, interaction

DISCUSSION

The present investigation examined the effects of two aerobic exercise trials on cognition, BDNF, cortisol and testosterone in young, healthy adult men. Both exercise trials were work matched to analyze the role of intensity in these measures specifically. Differences in post exercise cognitive performance were not observed on learning, visual attention, psychomotor speed, or working memory. These data indicate that when exercise is short in duration and work matched, intensity is a negligible variable. The findings do not support a role of exercise intensity in enhancing overall cognition in a seemingly healthy population.

The results of this investigation contrast with previous studies, although this could be attributed to different methods of measuring cognition (6). Previous studies have utilized cognitive measures such as the Stroop's word and color and color-word tasks (6, 9), whereas the present investigation utilized a battery of assessments that examined a broader range of cognitive domains. In employing a cognitive battery, the current data set can be utilized to describe the overall influence of exercise on the entirety of executive function. Additionally, this software was proprietarily designed to limit the learning effect that is associated with the Stroop's test. Limitations of a cognitive battery include possible fatigue throughout the duration of the 45-minute test. Similarly, it is also impossible to assess how much one test may have influenced a subsequent test; however, this enhances external validity as it better simulates real-life cognitive tasks.

The results of the current investigation indicate that variations in exercise intensity did not alter post exercise cognitive performance, unlike previous investigations (15, 31, 34). These investigations demonstrate that exercise intensity is not predictive of post-exercise cognitive performance in a healthy population. While the current investigation and previous investigation used similar exercise intensities for high intensity intervals, 90% VO_2max, the current protocol consisted of work intervals of 1:2 compared to the previous 4:3 (31); thus, it is possible that greater overall work elicited greater improvements in post-exercise cognitive performance after high intensity exercise compared to moderate exercise. Additional differences include the use

of a Stroop's test compared to computerized battery, which is subjected to a possible learning effect.
There was an observed increase in serum BDNF concentrations after both exercise trials relative to pre-exercise values in the present study. A previous investigation compared serum BDNF concentrations after moderate exercise in a healthy population and demonstrated no increases in BDNF concentrations (8), however differences in data can be attributed to possible differences in measurement techniques and sample processing. Additionally, a study by Ferris and colleagues analyzed serum BDNF concentrations and observed an increase after graded exercise, endurance exercise, and higher intensity, but not low intensity (6); these results are in line with the current investigation's analysis of serum BDNF in that BDNF concentrations increased after high and moderate intensity exercise.

Salivary cortisol concentration was augmented after continuous exercise only. This contradicts previous studies in which cortisol concentrations increased after high-intensity exercise (10,13). In an investigation conducted by Jacks and colleagues, cycling at 76% of VO_2peak elicited a significantly higher cortisol concentration compared to lower intensities and rest (13). This could be attributed to different exercise durations utilized between the studies. In a study by Hill and colleagues, 30 minutes of both 60% and 80% VO_2max provoked a significantly greater cortisol response than 40% VO_2max and rest; however, aerobic capacity may play a role in the cortisol response (10). VanBruggen and colleagues compared salivary and serum cortisol after 30 minutes of low (40%) and moderate (60%) and high (80%) intensity cycling. Data demonstrate that only high intensity exercise resulted in increased circulating cortisol, without a difference between serum and salivary cortisol (32), indicating that a higher intensity is necessary for a salivary cortisol response to exercise. Previous literature utilized 30-minute bouts of exercise, whereas the current used a 20-minute intervention. It is likely that although intensity was great, there was an inadequate about of work executed within the 20-minute bout of exercise.

In the current study salivary testosterone was unchanged after both high-intensity interval exercise and continuous exercise. Previous literature indicates that high-intensity intervals yield greater testosterone concentration changes; however, previous studies have not used work-matched protocols (33). The current study findings align with those of Koklaas and colleagues in that continuous exercise induced a greater increase in testosterone when compared to interval exercise (17). Differences between studies can be attributed to different exercise intensities and durations, which are known to impact the acute hormonal response of exercise (7, 30). Furthermore, it is important to note the impact of training status on the measured variables. In the current data set, participants had an average relative VO_2max of 33.5 ml/kg/min, which indicates a poor training status (24). aWhile all participants completed both exercise interventions, it is difficult to compare the hormonal responses between the current data set and previous literature, given that a training adaptation is an augmented response of testosterone and cortisol in response to exercise (20).

This study investigated the interaction of BDNF, cortisol, testosterone, and cognition, but it is not without limitations. Although the exercise interventions were brief, a one-week separation

between conditions may have been insufficient, demonstrated by greater baseline testosterone and cortisol concentrations in INT compared to CONT. This study did not measure cerebral blood flow, so it cannot assess if changes in systolic blood pressure augmented cerebral blood flow. Given that the average VO_2max was low by ACSM standards, an inclusion of HR and RPE assessments during exercise would have provided a real time assessment of the exercise prescription for the included individuals. Additionally, it is possible that the cognitive battery was not sensitive enough for a healthy population. This investigation did not account for any potential caffeine withdrawal symptoms. Although cognition appeared to improve after exercise, it is possible that a lack of caffeine may have affected blood pressure, cognitive parameters, and exercise performance. Lastly, the present data can only be adapted to seemingly healthy, college-aged men, not the general population.

This investigation demonstrated that a short-duration of work-matched acute aerobic continuous and interval exercise increased serum BDNF levels without impacting executive function. While this is not what we had hypothesized, if exercise intensities do not negatively impact cognition, professionals may program either intervention based upon alternative variables such as preference. Future research should investigate longer exercise durations and alternative populations to better understand the interactions between aerobic exercise, cognition, BDNF, and cortisol.

ACKNOWLEDGEMENTS

The authors would like to thank all the participants who volunteered for this investigation.

REFERENCES

1. Bathina S, Das UN. Brain-derived neurotrophic factor and its clinical implications. Arch Med Sci 11(6): 1164-78, 2015.

2. Byun K, Hyodo K, Suwabe K, Fukuie T, Soya H. Possible neurophysiological mechanisms for mild-exercise-enhanced executive function: An fNIRS neuroimaging study. J Phys Fit Sports Med 5(5): 361–7, 2016.

3. Cotman CW, Berchtold NC, Christie L-A. Exercise builds brain health: Key roles of growth factor cascades and inflammation. Trends Neurosci 30(9): 464–72, 2007.

4. D'Esposito M, Grossman M. The physiological basis of executive function and working memory. Neuroscientist 2(6): 345–52, 1996.

5. Dinoff A, Herrmann N, Swardfager W, Liu CS, Sherman C, Chan S, et al. The effect of exercise training on resting concentrations of peripheral brain-derived neurotrophic factor (BDNF): A meta-analysis. PLoS One 11(9): e0163037, 2016.

6. Ferris LT, Williams JS, Shen C-L. The effect of acute exercise on serum brain-derived neurotrophic factor levels and cognitive function. Med Sci Sports Exerc 39(4): 728-34, 2007.

7. Galbo H, Hummer L, Petersen I, Christensen N, Bie N. Thyroid and testicular hormone responses to graded and prolonged exercise in man. Eur J Appl Physiol 36(2): 101–6, 1977.

8. Goda A, Ohgi S, Kinpara K, Shigemori K, Fukuda K, Schneider EB. Changes in serum BDNF levels associated with moderate-intensity exercise in healthy young Japanese men. Springerplus 2: 678, 2013.

9. Griffin ÉW, Mullally S, Foley C, Warmington SA, O'Mara SM, Kelly ÁM. Aerobic exercise improves hippocampal function and increases BDNF in the serum of young adult males. Physiol Behav 104(5): 934–41, 2011.

10. Hill E, Zack E, Battaglini C, Viru M, Viru A, Hackney A. Exercise and circulating cortisol levels: The intensity threshold effect. J Endocrinol Invest 31(7): 587–91, 2008.

11. Hough JP, Papacosta E, Wraith E, Gleeson M. Plasma and salivary steroid hormone responses of men to high-intensity cycling and resistance exercise. J Strength Cond Res 25(1): 23–31, 2011.

12. Intlekofer KA, Berchtold NC, Malvaez M, Carlos AJ, McQuown SC, Cunningham MJ, et al. Exercise and sodium butyrate transform a subthreshold learning event into long-term memory via a brain-derived neurotrophic factor-dependent mechanism. Neuropsychopharmacology 38(10): 2027-34, 2013.

13. Jacks De, Sowash J, Anning J, McGloughlin T, Andres F. Effect of exercise at three exercise intensities on salivary cortisol. J Strength Cond Res 16(2): 286–9, 2002.

14. Joyce J, Graydon J, McMorris T, Davranche K. The time course effect of moderate intensity exercise on response execution and response inhibition. Brain Cogn 71(1): 14–9, 2009.

15. Kamijo K, Hayashi Y, Sakai T, Yahiro T, Tanaka K, Nishihira Y. Acute effects of aerobic exercise on cognitive function in older adults. J Gerontol B Psychol Sci Soc Sci 64(3): 356–63, 2009.

16. Kashihara K, Maruyama T, Murota M, Nakahara Y. Positive effects of acute and moderate physical exercise on cognitive function. J Physiol Anthropol 28(4): 155–64, 2009.

17. Kokalas N, Tsalis G, Tsigilis N, Mougios V. Hormonal responses to three training protocols in rowing. Eur J Appl Physiol 92(1–2): 128–32, 2004.

18. Kujach S, Olek RA, Byun K, Suwabe K, Sitek EJ, Ziemann E, et al. Acute sprint interval exercise increases both cognitive functions and peripheral neurotrophic factors in humans: the possible involvement of lactate. Front Neurosci 13: 1455, 2020.

19. Maruff P, Thomas E, Cysique L, Brew B, Collie A, Snyder P, et al. Validity of the Cogstate brief battery: Relationship to standardized tests and sensitivity to cognitive impairment in mild traumatic brain injury, schizophrenia, and AIDS dementia complex. Arch Clin Neuropsychol 24(2): 165–78, 2009.

20. McGuigan MR, Egan AD, Foster C. Salivary cortisol responses and perceived exertion during high intensity and low intensity bouts of resistance exercise. J Sports Sci Med 3(1): 8-15, 2004.

21. McMorris T, Hale BJ. Differential effects of differing intensities of acute exercise on speed and accuracy of cognition: A meta-analytical investigation. Brain Cogn 80(3): 338–51, 2012.

22. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. Int J Exerc Sci 12(1): 1-8, 2019.

23. O'Connor DB, Archer J, Hair WM, Wu FC. Activational effects of testosterone on cognitive function in men. Neuropsychologia 39(13): 1385–94, 2001.

24. Pescatello LS, Riebe D, Thompson PD. ACSM's guidelines for exercise testing and prescription, 9th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2014.

25. Pietrzak RH, Maruff P, Mayes LC, Roman SA, Sosa JA, Snyder PJ. An examination of the construct validity and factor structure of the Groton Maze Learning Test, a new measure of spatial working memory, learning efficiency, and error monitoring. Arch Clin Neuropsychol 23(4): 433–45, 2008.

26. Roozendaal B. Glucocorticoids and the regulation of memory consolidation. Psychoneuroendocrinology 25(3): 213–38, 2000.

27. Salthouse T, Davis H. Organization of cognitive abilities and neuropsychological variables across the lifespan. Dev Rev 26(1): 31–54, 2006.

28. Schulz K, Korz V. Hippocampal testosterone relates to reference memory performance and synaptic plasticity in male rats. Front Behav Neurosci 4: 187, 2010.

29. Shallice T, Marzocchi GM, Coser S, Del Savio M, Meuter RF, Rumiati RI. Executive function profile of children with attention deficit hyperactivity disorder. Dev Neuropsychol 21(1): 43–71, 2002.

30. Tremblay MS, Copeland JL, Van Helder W. Influence of exercise duration on post-exercise steroid hormone responses in trained males. Eur J Appl Physiol 94(5–6): 505–13, 2005.

31. Tsukamoto H, Suga T, Takenaka S, Tanaka D, Takeuchi T, Hamaoka T, et al. Greater impact of acute high-intensity interval exercise on post-exercise executive function compared to moderate-intensity continuous exercise. Physiol Behav 155: 224–30, 2016.

32. VanBruggen MD, Hackney AC, McMurray RG, Ondrak KS. The relationship between serum and salivary cortisol levels in response to different intensities of exercise. Int J Sports Physiol Perform 6(3): 396–407, 2011.

33. Wahl P, Mathes S, Köhler K, Achtzehn S, Bloch W, Mester J. Acute metabolic, hormonal, and psychological responses to different endurance training protocols. Horm Metab Res 45(11): 827–33, 2013.

34. Wang C-C, Chu C-H, Chu I-H, Chan K-H, Chang Y-K. Executive function during acute exercise: The role of exercise intensity. J Sport Exerc Psychol 35(4): 358–67, 2013.

35. Wolf O, Convit A, McHugh P, Kandil E, Thorn E, De Santi S, et al. Cortisol differentially affects memory in young and elderly men. Behav Neurosci 115(5): 1002-11, 2001.

36. Young A, Sahakian B, Robbins T, Cowen P. The effects of chronic administration of hydrocortisone on cognitive function in normal male volunteers. Psychopharmacology (Berl) 145(3): 260–6, 1999.

37. Yuxin Z, Fenghua S, of Analytics CP, Chiu Dmm, Siu AY-S. Effects of high-intensity interval exercise and moderate-intensity continuous exercise on executive function of healthy young males. Physiol Behav 239: 113505, 2021.