Acute effects of the cardiovascular exercise on retrieval and savings during the learning of a discrete motor skill

https://doi.org/10.11606/issn.1981-4690.2024e38195734

Sade Dannata Maria Ribeiro Rezende[*]
José Eduardo dos Martírios Luz[**]
Giordano Marcio Gatinho Bonuzzi[**/***/****]

*State University of Piauí, Department of Physical Education, Picos, PI, Brazil.
**Federal University of Vale do São Francisco, Department of Physical Education, Petrolina, PE, Brazil.
***University of Brasilia, Faculty of Physical Education, Brasília, DF, Brazil.
****Federal University of Piauí, Department of Physical Education, Teresina, PI, Brazil.

Abstract

We aimed to investigate the acute effects of a continuous cardiovascular exercise on retrieval and savings while learning a discrete motor skill. Forty participants, aged 18-35 years were randomly divided into 2 groups, Exercise Group (EG), which practiced an underarm dart-throwing task and performed cardiovascular exercise before the retention test, and Control Group (CG), which had the same practice conditions of EG without the exercise session. The groups were submitted to 14 blocks of 10 trials on 2 consecutive days. On day 1, there was an acquisition phase; on day 2, the first block was run the retention and the others for savings. We assessed the motor performance through absolute and variable errors. Our results demonstrated that cardiovascular exercise did not impact the accuracy and variability of the motor performance either on the retention test or relearning rate. We concluded that continuous cardiovascular exercise does not influence the retrieval and savings during discrete motor skill learning.

Keywords: Aerobic exercise; Motor memory; Motor learning; Relearning rate.

Introduction

Cardiovascular exercise induces positive effects on brain health and function[1]. Individuals who consistently are engaged in cardiovascular exercise routines demonstrate improvements in attention, information processing, executive function, and memory[1,2]. Interestingly, emerging findings have identified that even a cardiovascular exercise bout can benefit brain function[3], enhancing motor learning processes[1,4].

It has been suggested that cardiovascular exercise primes the Central Nervous System (CNS), promoting neuroplasticity and enhancing motor performance and learning mechanisms[1,5]. Multiple factors are involved in this condition, such as the increase of neurotransmitters related to cortical excitability, attention, and information processing, for instance, dopamine[6,7], serotonin[8]; and the increase in the expression of neurotrophic factors[1,5]. All these factors would have a convergence effect on a higher responsivity for motor memory creation.

Motor memory creation is mediated through at least three main phases: Encoding – corresponds to the motor practice and is the phase when the CNS forms motor memory engrams, Consolidation – occurs after the encoding and induces more robust engrams that are more resistant, stabilized and less susceptible to interference, and Retrieval – a phase that the memory is evocated after a period without practice[9]. In this way, if the cardiovascular exercise is allocated in temporal proximity to the encoding phase (before practice), better motor performance during practice is expected; but, if the exercise is allocated during the consolidation phase (after practice), there is less forgetfulness[10].

Several studies have investigated the effects of cardiovascular exercise on motor encoding and consolidation during learning a variety of laboratory-simple tasks such as visuomotor accuracy-tracking task[11,12,21,13-20], sequential visual isometric pinch task[22,23], motor sequence task[24], serial targeting task[25], rotational visuomotor adaptation task[26-28], serial reaction time task[29] and keyboard typing task[30]. Some studies also demonstrated cardiovascular exercise benefits on learning complex motor skills as in golf putting task[31], balance[32], and volleyball underhand serve[33]. Regarding the findings of those studies, a systematic review indicated that cardiovascular exercise induces enhancement mainly in consolidation processes, with an insignificant effect on motor encoding[4].

The increase in neurotransmitter and neurotrophic factors induced by the exercise is not prolonged after one hour following exercise[34]. Then, cardiovascular exercise effects on motor learning depend on its temporal proximity to the motor memory formation phase when the priming is more influential[10]. To the best of our knowledge, no studies have investigated the effect of cardiovascular exercise allocated in proximal proximity to motor memory retrieval or even whether cardiovascular exercise impacts a better relearning rate (savings). In other words, we have not had findings regarding the effects of the cardiovascular exercise allocated in temporal proximity to the retention test (retrieval phase and savings).

Given that motor memory retrieval is subsidized by higher cognitive resources[9,35], the lack of capability for retrieval may impair the performance or relearn motor skills already practiced[36,37], which reveals the importance of retrieval mechanisms in motor performance and learning. We hypothesized that cardiovascular exercise would induce better motor performance in 24hrs retention test and savings than no exercise condition. Thus, we aimed to investigate the acute effects of cardiovascular exercise on retrieval and saving phases during the learning of a discrete motor skill.

Methods

Participants

We used the power analysis software G*Power 3.1[38] to determine the sample size. The calculation estimated an effect size of 0.40, $\alpha = 0.05$, and a power of 0.80 indicates 12 participants per group.

We recruited 40 participants aged 18-35 years (30 men, 10 women) from the local university community. The inclusion criteria were: 1 - To have visual, neuromotor and cognitive conditions for understanding and executing the proposed tasks; 2 - To be right-handed regarding the Edinburgh Handedness Inventory. The exclusion criteria were: 1 - To have cardiovascular or osteoarticular diseases or dysfunction which unviable the performance of the proposed activities; 2 - Absence of a medical report confirming the non-risk to physical exercise; 3 - Do not use a corrective lens in case the participant has unsatisfactory visual acuity; 4 - To have previous experience in the dart-throwing task; 5 - To perform physical exercise 24 hours before or during the days planned to the experiment.

After the participants signed written informed consent, they were randomly allocated by a stratified process considering sex into two groups: the Control Group (CG) (n = 20), which only practiced the motor task, and the Exercise Group (EG) (n = 20) that practiced the motor task and performed cardiovascular exercise. The university's institutional review board approved the experimental protocol (protocol number. 25732019.7.0000.5209). All experiment was conducted following Helsinki Declaration.

Apparatus and Task

We used an underarm dart-throwing task used in previous motor learning studies[39,40]. The task goal was to score as many points as possible by throwing darts (Winmax® WMG50374) with the dominant arm towards a target dartboard. The target was placed on the floor 3 meters away from a throwing line. The darts had 30 grams and a length of 15 centimeters. The target contained 10 concentric circles, with the middle circle having a diameter of 2.25 centimeters, with each other circle increasing by 2.25 centimeters in radius. The dependent variable was the points achieved in each trial. We determined 10 points to trials that hit the bullseye with each concentric circle radiating out from the decreasing by one point, so the outermost circle was awarded only one point. If the dart hit the outside of the target, it was attributed 0 points.

Procedure

On day 1 of the experimental design, firstly, the participant was assessed by the International Physical Activity Questionnaire (IPAQ) to characterize their physical activity level. After that, they received instructions about the motor task. Regarding the task's goal, the participants were oriented verbally to "try to throw the dart as accurately as possible into the center of the target". Concerning instruction of the movement parameters, we provided a video of a skilled person performing the task.

After the instructions, the participant performed 3 trials to familiarize themself with the task. Following, they performed a pre-test composed of 10 trials. The acquisition phase was composed of 120 trials organized in 12 blocks. The participants rested 2 minutes among the blocks of practice to avoid deleterious effects from fatigue. After the acquisition phase, the participants performed a post-test with similar conditions to the pre-test. After 24 hours, the participants replied to all blocks performed on day 1. Otherwise, on day 2, the participants performed 14 blocks of 10 trials interspersed with 2 minutes of rest. The same instruction provided on day 1 was offered to participants at the beginning of day 2. We considered the first block on day 2 as a 24 hrs retention test, and the remaining 13 blocks were used to assess savings regarding the performance achieved in the post-test of the day 1. The participants received immediate external feedback about the points achieved in all trials performed during the experiment.

On day 2, the participants of the CG rested for 20 minutes before the motor practice. During this time, they were encouraged to read magazines. The participants of the EG performed cardiovascular exercise immediately before the motor practice only on day 2. We based the exercise protocol on Statton et al.[22] and Bonuzzi et al.[41] It consisted of comfortable walking for 5 minutes to warm-up, 20 minutes of running from moderate to intense intensity (65% to 85% of their age-predicted maximum heart rate), and 5 minutes of walking to cool down. The cardiovascular exercise was performed on a running track around a sports court. The experimental design can be verified in FIGURE 1.

The maximum heart rate was based on the Karvonen formula (220-age). We collected the exertion level during the exercise through the Borg Scale of Perceived Exertion (BORG) and the mean and maximum heart rate achieved during the exercise prescription. For the heart rate monitoring was used a Polar heart rate monitor, H10 model.

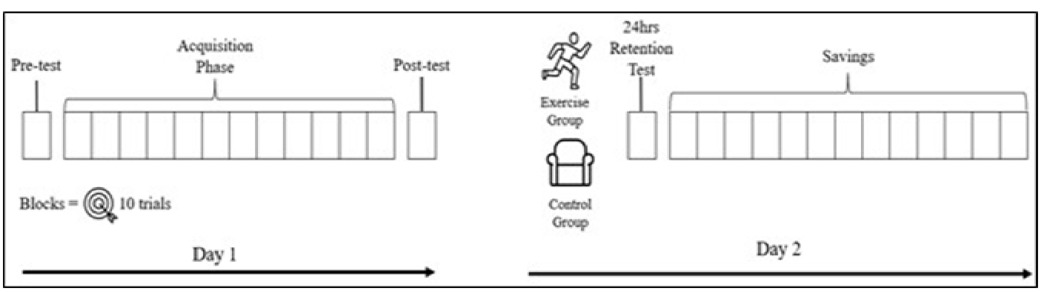

FIGURE 1 - Experimental design timeline.

Data collection and Analysis

We used STATISTICA 11.0 (StatSoft Inc., Tulsa, OK, USA) and Microsoft Excel 365 Software® for statistical analyses adopting a 5% significance level and partial eta squared to verify effect size (η^2). We evaluated the normality and homogeneity of the data with the Shapiro-Wilks and Levene tests, respectively. The data from the characterization of participants (age and number of minutes of vigorous and moderate physical activities per week - IPAQ) were analyzed using the Student's t-test.

We assessed the magnitude and variability of motor performance changes using the absolute and variable error, respectively. We calculated the mean of the points achieved for each participant in each block of trials to determine the absolute error. We computed the standard deviation of the points achieved for each participant in each block of trial for the variable error.

To verify whether the CG and EG demonstrated the same improvement and variability in the points comparing pre-test and post-test, we performed an ANOVA two-way - 2 groups (CG, EG) x 2 times (pre-test, post-test) with repeated measures in the second factor, with absolute and variable errors. Tukey test was used for post hoc analyses.

To assess the effects of cardiovascular exercise on retrieval, we compared the absolute and variable error in post-test and 24-hours retention test between CG and EG using an ANOVA two-way - 2 groups (CG, EG) x 2 times (post-test, 24-hours retention test), using a Tukey test for post hoc analyses.

We evaluated savings computing the number of blocks of trials required for the participants to reach on day 2 the mean performance achieved in the post-test. Thus, if a participant demonstrated a mean score of 4,5 points in the post-test, and the same participant showed an equal or superior mean score of 4,5 points only in the 4th block of trial on day 2. The savings was 4 for this participant. Then, we verified the effects of cardiovascular exercise on savings, comparing the number of blocks between CG and EG through a Student's t-test.

Results

Characterization and physical exercise parameters

TABLE 1 demonstrates no significant difference in age between EG and CG participants. In TABLE 1, the physical activity level in the EG and CG groups also can be verified.

Regarding the internal overload of the EG during exercise (TABLE 1), heart rate measures indicate that the exercise was performed close to the anaerobic threshold, considering most participants' age (i.e., for the mean age of 23 years of the participants, an estimated 85% for maximum heart rate is 167 bpm). It corroborates with BORG, indicating that the participants exercised between ‘somewhat hard’ and ‘hard’ levels of exertion. Our findings suggest that the EG participants performed the exercise in the most intense condition for a long-term continuous cardiovascular exercise.

TABLE 1 - Participants' characterization measures.

Demographic Information	Exercise Group (n = 20)	Control Group (n = 20)	T-test *p* value
Age (years)	23.15 ± 4.48	22.95 ± 3.85	0.88
Sex	15 M / 5 W	15 M / 5 W	-
IPAQ classification			
Very active	7	5	-
Active	6	4	-
Irregularly active A	4	3	-
Irregularly active B	2	3	-
Sedentary	1	5	-
Physical Exercise Parameters During the Experiment			
Mean heart rate	166.15 ± 13.77	-	-
Maximum heart rate	176.2 ± 11.34	-	-
Borg Scale of Perceived Exertion	12.52 ± 2.87	-	-

Data are presented as mean ± standard deviation.
IPAQ = International Physical Activity Questionnaire;
n = number;
M = Men;
W = Women.

Cardiovascular exercise on retrieval and savings

For absolute error (FIGURE 2 - A), our analysis demonstrated that the CG and EG improved their score comparing pre-test and post-test [$F_{1,38}$ = 26.65, p < .0001, η^2 = .41], without significant differences between them [$F_{1,38}$ = .84, p = .36]. In another analyses, we also verified that both groups did not demonstrate the persistence of this improvement in the 24 hrs retention test, because there was a significant difference in time factor (post-test x 24hrs retention test) [$F_{1,38}$ = 17.97, p = .0001, η^2 = .32], without significant difference in group factor [$F_{1,38}$ = .25, p = .61]. These results suggest that both groups demonstrated improvement in the score during the practice but did not maintain it in the 24hrs retention test; besides, the exercise did not impact this trend.

Our analysis demonstrated an interaction effect to variable error comparing pre-test and post-test between CG and EG [$F_{1,38}$ = 6.8, p = .01, η^2 = .15] (FIGURE 2 - B). Tukey's post hoc test revealed that only the CG demonstrated an increase in the variability between pre-test and post-test (p < .05), and the EG had a lower variability in the post-test than CG (p < .05). Regarding the comparison between post-test and retention test, there was no significant difference in the time factor [$F_{1,38}$ = .65, p = .42], only for group factor [$F_{1,38}$ = 8.23, p > .001, η^2 = .17] (FIGURE 2 - B), with CG demonstrating a superior variability. Thus, our findings suggested that the EG demonstrated a lower variability than CG in function of practice. However, the lower variability of the EG was not determined by the cardiovascular exercise, given that there was no significant difference in time factor for EG comparing post-test and 24 hrs retention test.

Data are presented as mean ± standard deviation.
* = within significant difference;
† = group significant difference;
# = within significant difference for Experimental Group.

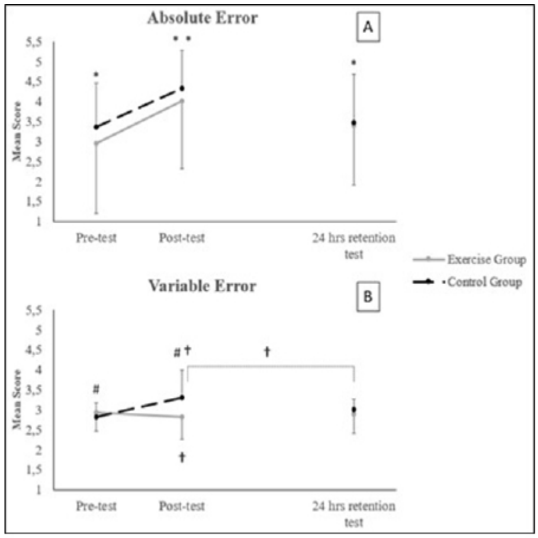

FIGURE 2 - A - Mean absolute error in the pre-test, post-test and 24 hrs retention test for Control Group and Experimental Group. B - Mean variable error in the pre-test, post-test and 24 hrs retention test for Control Group and Experimental Group.

Finally, our savings analysis through the Students' t-test revealed no significant difference between CG and EG regarding the relearning rate on day 2 (p = .21, EG: M = 4.35, SD = 4.35, CG: M = 6.25, SD = 5.17) (FIGURE 3). These findings indicate that the cardiovascular exercise did not impact the relative retention (savings) of a motor skill previously practiced when allocated before the retention test.

Data show the mean of blocks in each group (solid line) and individual data (dots).

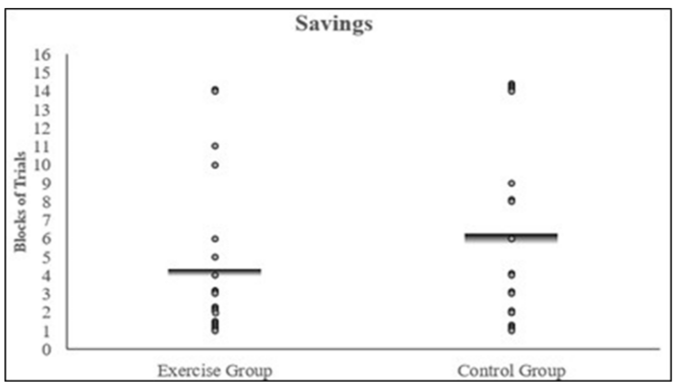

FIGURE 3 - Blocks of day 2 required to reach the post-test mean performance.

Discussion

We aimed to investigate the acute effects of a moderate-high intensity continuous cardiovascular exercise on the retrieval and savings of a discrete motor skill. Previous studies identified that a cardiovascular exercise bout performed before declarative memory encoding could enhance the performance during this phase[10]. More specifically, for motor learning studies, we have findings that a cardiovascular exercise bout induces better motor performance in a subsequent motor practice[14,22,42]. Then, we hypothesized that the priming effects of the cardiovascular exercise on the CNS could induce a better condition to perform a motor skill previously practiced.

However, our results did not support our hypothesis. We identified that cardiovascular exercise performed in temporal proximity to the retention test did not enhance absolute retention and savings of a discrete motor skill. The EG and CG demonstrated: 1 - the same motor performance improvement during practice (there was no significant difference between groups regarding absolute error comparing pre-test and post-test. We identified an interaction effect for variable error; however, the mean difference between groups in the post-test was 0.47 points, which suggests a small effect size ($\eta^2 = .15$)); this slight difference in variability between groups during the acquisition phase was maintained in retention. Nevertheless, we assume that this difference can be attributed to interindividual differences (for example, mood, motivation, or internal states (e.g., mental fatigue)) between groups instead of the effect of cardiovascular exercise. Because EG did not demonstrate a significant difference in variable error comparing post-test and retention. 2 - no persistence the motor performance improvement after 24 hours, 3 - the same relearning rate for both groups in a second motor practice. These results suggest that continuous cardiovascular exercise does not enhance retrieval and savings processes.

Some aspects can be related to the difference between our findings and the studies that identified positive effects of cardiovascular exercise on motor performance in subsequent practice[14,22,42]. In these studies, the participants were naïve regarding the motor task[14,22,42]. Oppositely, our study investigated the cardiovascular effects on the motor performance of a previously practiced motor skill. So, our participants had already gone through encoding and consolidation processes, contrary to the previous study. Thus, we can suppose that the cardiovascular exercise effects are more evident in motor performance at the beginning than in the later phases of the motor skill acquisition.

It is well established that at the beginning of the motor skill acquisition, the practitioner has a higher cognitive demand for learning, which is shifted to a higher automatic motor demand in the latter motor learning phase[43]. We could speculate that the effects of cardiovascular exercise on motor performance could interact with the practitioner's experience in the motor task, being more evident in remarkable cognitive demands at the beginning of motor skill acquisition. Even with some findings demonstrating that the beneficial effect of exercise is present on motor responses and cognitive tasks[44], the investigation of the effects of cardiovascular exercise on motor performance in function of the practitioner's experience is still an interesting issue to further investigations.

Another aspect related to our results is that the exercise has a restricted effect on consolidation instead of generalizing to encoding, retrieval, or savings, which corroborates with a systematic review that shows the more evident effect of the exercise on consolidation and a non-effect on the encoding process[4].

From a mechanistic perspective, the neurobiological processes involved in encoding and "re-encoding" differ notably from those promoting consolidation[45-47]. Then, considering the effects of the cardiovascular exercise that could enhance motor performance and learning, maybe the mechanisms that impact consolidation, as brain neurotrophic factors[1,48] are more consistent than those that could enhance motor performance, like arousal, information processing, cortical excitability[6,7,49,50].

However, regarding this question, in a mechanistic study, Skriver, et al.[12] demonstrated that norepinephrine (which can be related to the improvement of arousal and information processing) and lactate (which can be an energetic substrate for the CNS enhancing brain function) were correlated to better motor performance during practice, and higher concentration of brain-derived neurotrophic factor was associated with better consolidation. Thus, the determinant mechanisms that support the effects of cardiovascular exercise on motor performance and learning are still unknown, and further studies should address this critical issue for a better understanding.

In fact, the relationship between cardiovascular exercise and motor memory is complex[1,4,10], and can be modulated by several aspects, such as the motor task characteristics used to assess motor learning or exercise parameters. Most studies that identified the positive effect of cardiovascular exercise on motor learning used continuous tasks[11,12,51,52,13,15-21]. Studies that used serial motor tasks did not identify the positive effect of the cardiovascular on motor learning[22,26,29,30,53-55].

We know that the processes involved in improving motor performance depend on the type of motor task. For continuous tasks, tempo-spatial synchronization improvement is critical, while in serial motor tasks, a capability to chunk functional subsequences is determinant to success[56]. Previous studies demonstrated that the exercise might influence tempo-spatial synchronization and, consequently, enhance continuous tasks more than serial tasks.

For discrete ballistic motor skills, such as underarm dart-throwing, the component of motor planning and reorganization through feedback is the primary process of motor improvement during practice[56]. In this way, we can not extrapolate the aforementioned findings to this motor task. Only Bonuzzi et al.[41] investigated the effects of a continuous cardiovascular exercise on the learning of a discrete motor skill (underhand volleyball serve). They identified that the group who performed cardiovascular exercise after motor practice demonstrated better 24hrs retention than the control group. This result reinforces that our findings are derived from the timing between exercise and motor memory creation phase (close to retrieval and "re-encoding" phases) instead of the type of task (discrete motor skill) or exercise (continuous cardiovascular exercise) that we used in our experiment.

Future investigations could address the interaction between task characteristics (serial, continuous and discrete tasks), participant characteristics (novice x experient practitioners), and exercise characteristics (intensity, duration, type) on motor memory consolidation processes, which seems to be the phase of the motor memory creation more susceptible for cardiovascular exercise priming effects.

Concerning our study's limitations, we did not estimate the maximum heart rate using an ergoespirometric test. It is essential to highlight that the Karvonen formula may overestimate or underestimate the maximum heart rate and exercise prescription intensity. However, considering age, fitness level and the mean heart rate during the exercise, most participants can be performed the exercise at close to 85% of the maximum heart rate. Then, the intensity of the exercise protocol was enough to induce a priming effect that could influence retrieval and savings.

Another study's limitation was that the participants demonstrated variability in their physical activity levels on IPAQ. Participants of the EG demonstrated less sedentary behaviors than CG. However, it is unlikely that this characteristic can be an important covariable, given that both groups demonstrated motor improvement at a very similar rate. Regarding this, recent findings reveal that the cardiovascular fitness level may not be a factor that influences the acute impact of cardiovascular exercise on motor learning[57].

Finally, on day 2, before motor practice, CG rested for 20 minutes while EG exercised for 30 minutes (5 minutes for warm-up, 20 minutes for exercise, 5 minutes for cooldown). We assume that it was a study's limitation, given that the total time previously motor practice was not the same between groups.

Conclusion

We concluded that a continuous cardiovascular exercise bout did not impact the magnitude and variability of the motor performance during a 24 hours retention test and did not influence savings in subsequent practice.

Conflict of interest

Nothing to declare.

Resumo

Efeitos agudos do exercício cardiovascular sobre a evocação e savings durante a aprendizagem de uma habilidade motora discreta.

Nosso objetivo foi investigar os efeitos agudos do exercício cardiovascular contínuo sobre a evocação e savings durante a aprendizagem de uma habilidade motora discreta. Quarenta participantes, com idades entre 18 e 35 anos, foram divididos aleatoriamente em 2 grupos: Grupo Exercício (GE), que praticou uma tarefa de arremesso de dardo por baixo e realizou exercício cardiovascular antes do teste de retenção; e Grupo Controle (GC), que teve as mesmas condições de prática do GE sem a sessão de exercício. Os grupos foram submetidos a 14 blocos de 10 tentativas em 2 dias consecutivos. No dia 1, houve uma fase de aquisição; no dia 2, o primeiro bloco foi destinado ao teste de retenção e os outros à taxa de reaprendizagem. Avaliamos o desempenho motor por meio de erros absolutos e variáveis. Nossos resultados demonstraram que o exercício cardiovascular não impactou a precisão e a variabilidade do desempenho motor, tanto no teste de retenção quanto na taxa de reaprendizagem. Concluímos que o exercício cardiovascular contínuo não influencia a evocação e os savings durante a aprendizagem de habilidades motoras discretas.

Palavras-Chave: Exercício aeróbio; Memória motora; Aprendizagem motora; Taxa de reaprendizagem.

References

1. Taubert M, Villringer A, Lehmann N. Endurance exercise as an "Endogenous" neuro-enhancement strategy to facilitate motor learning. Front Hum Neurosci. 2015;9.
2. Smith PJ, Blumenthal JA, Hoffman BM, Cooper H, Strauman TA, Welsh-Bohmer K, et al. Aerobic exercise and neurocognitive performance: a meta-analytic review of randomized controlled trials. Psychosom Med. 2010;72:239-52.
3. Roig M, Nordbrandt S, Geertsen SS, Nielsen JB. The effects of cardiovascular exercise on human memory: a review with meta-analysis. Neurosci Biobehav Rev. 2013;37:1645-1666.
4. Wanner P, Cheng FH, Steib S. Effects of acute cardiovascular exercise on motor memory encoding and consolidation: a systematic review with meta-analysis. Neurosci Biobehav Rev. 2020;116:365-381.
5. Dishman RK, Berthoud HR, Booth FW, Cotman CW, Edgerton VR, Fleshner MR, et al. Neurobiology of exercise. Obesity. 2006;14:345-356.
6. Singh AM, Neva JL, Staines WR. Aerobic exercise enhances neural correlates of motor skill learning. Behav Brain Res. 2016;301:19-26.
7. McMorris T. Exercise and cognitive function: a neuroendocrinological explanation. In: McMorris T, Tomporowski PD, Audiffren M. Exercise and cognitive function. Chichester: John Wiley & Sons; 2009. p 41-68.
8. Cotman C. Exercise: a behavioral intervention to enhance brain health and plasticity. Trends Neurosci. 2002;25:295-301.
9. Kantak SS, Winstein CJ. Learning-performance distinction and memory processes for motor skills: a focused review and perspective. Behav Brain Res. 2012;228:219-231.
10. Roig M, Thomas R, Mang CS, Snow NJ, Ostadan F, Boyd LA, et al. Time-dependent effects of cardiovascular exercise on memory. Exerc Sport Sci Rev. 2016;44:81-88.
11. Roig M, Skriver K, Lundbye-Jensen J, Kiens B, Nielsen JB. A single bout of exercise improves motor memory. PLoS One. 2012;7:e44594.
12. Skriver K, Roig M, Lundbye-Jensen J, Pingel J, Helge JW, Kiens B, et al. Acute exercise improves motor memory: exploring potential biomarkers. Neurobiol Learn Mem. 2014;116:46-58.
13. Mang CS, Snow NJ, Campbell KL, Ross CJD, Boyd LA. A single bout of high-intensity aerobic exercise facilitates response to paired associative stimulation and promotes sequence-specific implicit motor learning. J Appl Physiol. 2014;117:1325-36.
14. Snow NJ, Mang CS, Roig M, McDonnell MN, Campbell KL, Boyd LA. The effect of an acute bout of moderate-intensity aerobic exercise on motor learning of a continuous tracking task. PLoS One. 2016;11:1-16.
15. Thomas R, Johnsen LK, Geertsen SS, Christiansen L, Ritz C, Roig M et al. Acute exercise and motor memory

consolidation: the role of exercise intensity. PLoS One. 2016;11:e0159589.
16. Thomas R, Beck MM, Lind RR, Korsgaard Johnsen L, Geertsen SS, Christiansen L, et al. Acute exercise and motor memory consolidation: the role of exercise timing. Neural Plast. 2016;2016:1-11.
17. Thomas R, Flindtgaard M, Skriver K, Geertsen SS, Christiansen L, Korsgaard Johnsen L, et al. Acute exercise and motor memory consolidation: does exercise type play a role? Scand J Med Sci Sports. 2017;27:1523-1532.
18. Lundbye-Jensen J, Skriver K, Nielsen JB, Roig M. Acute exercise improves motor memory consolidation in preadolescent children. Front Hum Neurosci. 2017;11:1-10.
19. Lauber B, Franke S, Taube W, Gollhofer A. The effects of a single bout of exercise on motor memory interference in the trained and untrained hemisphere. Neuroscience. 2017;347:57-64.
20. Dal Maso F, Desormeau B, Boudrias MH, Roig M. Acute cardiovascular exercise promotes functional changes in cortico-motor networks during the early stages of motor memory consolidation. Neuroimage. 2018;174:380-392.
21. Beck MM, Grandjean MU, Hartmand S, Spedden ME, Christiansen L, Roig M, et al. Acute exercise protects newly formed motor memories against rTMS-induced interference targeting primary motor cortex. Neuroscience. 2020;436:110-121.
22. Statton MA, Encarnacion M, Celnik P, Bastian AJ. A single bout of moderate aerobic exercise improves motor skill acquisition. PLoS One. 2015;10:e0141393.
23. Stavrinos EL, Coxon JP. High-intensity interval exercise promotes motor cortex disinhibition and early motor skill consolidation. J Cogn Neurosci. 2017;29:593-604.
24. Rhee J, Chen J, Riechman SM, Handa A, Bhatia S, Wright DL. An acute bout of aerobic exercise can protect immediate offline motor sequence gains. Psychol Res. 2016;80:518-531.
25. Mang CS, Snow NJ, Wadden KP, Campbell KL, Boyd LA. High-intensity aerobic exercise enhances motor memory retrieval. Med Sci Sport Exerc. 2016;48:2477-2486.
26. Ferrer-Uris B, Busquets A, Lopez-Alonso V, Fernandez-del-Olmo M, Angulo-Barroso R. Enhancing consolidation of a rotational visuomotor adaptation task through acute exercise. PLoS One. 2017;12:e0175296.
27. Ferrer-Uris B, Busquets A, Angulo-Barroso R. Adaptation and retention of a perceptual-motor task in children: effects of a single bout of intense endurance exercise. J Sport Exerc Psychol. 2018;40:1-9.
28. Neva JL, Ma JA, Orsholits D, Boisgontier MP, Boyd LA. The effects of acute exercise on visuomotor adaptation, learning, and inter-limb transfer. Exp Brain Res. 2019;0:0.
29. Ostadan F, Centeno C, Daloze J-F, Frenn M, Lundbye-Jensen J, Roig M. Changes in corticospinal excitability during consolidation predict acute exercise-induced off-line gains in procedural memory. Neurobiol Learn Mem. 2016;136:196-203.
30. Stranda H, Haga M, Sigmundsson H, Lorås H. The effect of aerobic exercise on speed and accuracy task components in motor learning. Sports. 2019;7:54.
31. Lorås H, Haga M, Sigmundsson H. Effect of a single bout of acute aerobic exercise at moderate-to-vigorous intensities on motor learning, retention and transfer. Sports. 2020;8:15.
32. Wanner P, Müller T, Cristini J, Pfeifer K, Steib S. Exercise intensity does not modulate the effect of acute exercise on learning a complex whole-body task. Neuroscience. 2020;426:115-128.
33. Bonuzzi GMG, Alves ÉJM, Perotti A. Effects of the aerobic exercise on the learning of a sports motor skill. Motriz. 2020;26.
34. Knaepen K, Goekint M, Heyman EM, Meeusen R. Neuroplasticity? exercise-induced response of peripheral brain-derived neurotrophic factor. Sport Med. 2010;40:765-801.
35. Levy B. Inhibitory processes and the control of memory retrieval. Trends Cogn Sci. 2002;6:299-305.
36. Krakauer JW, Hadjiosif AM, Xu J, Wong AL, Haith AM. Motor learning. Compr Physiol. 2019;9:613-663.
37. Kitago T, Ryan SL, Mazzoni P, Krakauer JW, Haith AM. Unlearning versus savings in visuomotor adaptation: comparing effects of washout, passage of time, and removal of errors on motor memory. Front Hum Neurosci. 2013;7:1-7.
38. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007;39:175-191.
39. Al-Abood SA, Davids K, Bennett SJ, Ashford D, Marin MM. Effects of manipulating relative and absolute motion information during observational learning of an aiming task. J Sports Sci. 2001;19:507-520.
40. Bruzi AT, Benda RN, Palhares LR, Fialho JVAP, Ugrinowitsch H. Discrete motor skill acquisition: effect of number of visual demonstrations. J Phys Educ. 2019;30:1-11.
41. Bonuzzi GMG, Alves ÉJM, Perotti Junior A. Effects of the aerobic exercise on the learning of a sports motor skill. Mot Rev Educ Física. 2020;26:1-8.
42. Perini R, Bortoletto M, Capogrosso M, Fertonani A, Miniussi C. Acute effects of aerobic exercise promote learning. Sci Rep. 2016;6:25440.

43. Kal E, Prosée R, Winters M, Van Der Kamp J. Does implicit motor learning lead to greater automatization of motor skills compared to explicit motor learning? a systematic review. PLoS One. 2018;13:e0203591.
44. Joyce J, Graydon J, McMorris T, Davranche K. The time course effect of moderate intensity exercise on response execution and response inhibition. Brain Cogn. 2009;71:14-19.
45. Krakauer JW, Shadmehr R. Consolidation of motor memory. Trends Neurosci. 2006;29:58-64.
46. Robertson EM, Cohen DA. Understanding consolidation through the architecture of memories. Neurosci. 2006;12:261-271.
47. Robertson EM. From creation to consolidation: a novel framework for memory processing. PLoS Biol. 2009;7.
48. Mang CS, Campbell KL, Ross CJD, Boyd LA. Promoting neuroplasticity for motor rehabilitation after stroke: considering the effects of aerobic exercise and genetic variation on brain-derived neurotrophic factor. Phys Ther. 2013; 93:1707-1716.
49. Singh AM, Staines WR. The effects of acute aerobic exercise on the primary motor cortex. J Mot Behav. 2015;47:328-339.
50. Hasegawa H, Takatsu S, Ishiwata T, Tanaka H, Sarre S, Meeusen R. Continuous monitoring of hypothalamic neurotransmitters and thermoregulatory responses in exercising rats. J Neurosci Methods. 2011;202:119-123.
51. Tomporowski PD, Pendleton DM. Effects of the timing of acute exercise and movement complexity on young adults' psychomotor learning. J Sport Exerc Psychol. 2018;40:240-248.
52. Opie GM, Semmler JG. Acute exercise at different intensities influences corticomotor excitability and performance of a ballistic thumb training task. Neuroscience. 2019;412:29-39.
53. Chartrand G, Kaneva P, Kolozsvari N, Li C, Petrucci AM, Mutter AF et al. The effects of acute aerobic exercise on the acquisition and retention of laparoscopic skills. Surg Endosc. 2015;29:474-480.
54. Baird JF, Gaughan ME, Saffer HM, Sarzynski MA, Herter TM, Fritz SL et al. The effect of energy-matched exercise intensity on brain-derived neurotrophic factor and motor learning. Neurobiol Learn Mem. 2018;156:33-44.
55. Jo JS, Chen J, Riechman S, Roig M, Wright DL. The protective effects of acute cardiovascular exercise on the interference of procedural memory. Psychol Res. 2019;83:1543-1555.
56. Schmidt RA, Lee TD, Winstein CJ, Wulf G, Zelaznik HN. Motor control and learning: a behavioral emphasis. 6. ed. Champaign: Human Kinetics; 2019.
57. Hung A, Roig M, Gillen JB, Sabiston CM, Swardfager W, Chen JL. Aerobic exercise and aerobic fitness level do not modify motor learning. Sci Rep. 2021;11:5366.

Address
Giordano Marcio Gatinho Bonuzzi
Faculty of Physical Education
University of Brasilia
Campus Universitário Darcy Ribeiro,
70910-900 - Brasília - DF - Brazil
E-mail: giordano.bonuzzi@unb.br

Submitted: 03/16/2022
Revised: 08/22/2022
Accepted: 07/07/2023