Mini-review/Systematic review

Cardiovascular exercise and motor learning in non-disabled individuals: A systematic review with a behavioral emphasis

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Abstract - Aim: This systematic review aimed to investigate the acute effects of cardiovascular exercise on motor learning of non-disabled individuals. **Methods:** Forty studies were identified through database searching (PsycINFO, CENTRAL, Google Scholar, Scielo, and PUBMED). The studies demonstrated heterogeneity and were classified into two categories to guide the analyses: (1) – studies that investigated the effects of exercise-induced fatigue during practice on the performance in the retention test; (2) – studies that verified the acute impact of the cardiovascular exercise in close temporal proximity to the task practice on motor learning. **Results:** The studies demonstrated that (1) - the practice under fatigue conditions did not impair motor learning and that (2) – the cardiovascular exercise bout performed in close temporal proximity to task practice enhances the motor learning processes. **Conclusion:** Cardiovascular exercise enhances motor learning processes; however, these priming effects are dependents on the timing between practice and exercise, type of exercise, and task characteristics.

Keywords: aerobic exercise, motor learning, cardiovascular exercise, priming.

Introduction

The development of neuromodulatory strategies to enhance motor skill acquisition can benefit the intervention of several movement professionals (e.g., physical education professionals, personal trainers, yoga and pilates instructors, sports coaches, physiotherapists, physicians). Among other alternatives, cardiovascular exercise is a cost-effective approach to enhance the capacity of the neuromotor system to be more receptive to practice and optimize motor learning and recovery[1-3].

Cardiovascular exercise stimulates neuropsychological mechanisms associated with better motor learning outcomes, such as better blood flow and oxygenation[4], an increase of cerebral volume[5,6] and secretion of neurotransmitters and catecholamines[7], and enhancement of neuroplasticity and neurogenesis through a hyperregulation of Brain-Derived Neurotrophic Factor (BDNF) and Neurotrophin-3[8-11].

These positive effects on the Central Nervous System (CNS) have been associated with enhancements on the motor memory creation process and, consequently, on motor learning[3,12]. Cardiovascular exercise may induce better motor performance during the acquisition phase and retention test, when performed in temporal proximity to the motor practice (immediately before or after). These results suggest that cardiovascular exercise improves the encoding and consolidation processes of motor memory creation[13-15].

Nevertheless, the impact of cardiovascular exercise on the motor learning process is mediated by multiple factors, such as the nature of the motor task and exercise characteristics (i.e., intensity and type). This systematic review aimed to investigate the acute effects of cardiovascular exercise on motor learning of non-disabled individuals. We presented the impacts of each potential factor that influence the relationship between cardiovascular exercise and motor learning (i.e., motor task characteristics, the timing between cardiovascular exercise and practice, exercise intensity, and exercise features).

Material and methods

Identification and selection of studies

PsycINFO, Pubmed, CENTRAL, Google Scholar, and Scielo databases were searched from 1968 to April 2020. The selection of studies was run from January 2020 to June 2020. The search strategy comprised the following keywords and Boolean Operators: ("motor learning" OR "motor memory") AND ("aerobic exercise" OR "high-intensity interval training" OR HIIT OR "cardiovascular exercise"), without the addition of filters to the search.

Additionally, the reference list of the studies included was reviewed to identify other relevant studies.

Eligibility criteria

The eligibility criteria for include the studies were: 1) Experimental studies investigating the acute effects of cardiovascular exercise (before, during, or after practice) on motor learning. 2) Studies with non-disabled individuals, 3) Studies with an acquisition phase (motor practice), and a retention test or a transfer test in the experimental design. 4) Dependent variable based on the motor performance (either acquisition or retention and transfer test). 5) Studies in English.

The exclusion criteria were: 1 - Experimental studies that exclusively investigated mechanisms (without motor performance analysis) related to the effects of cardiovascular exercise on the motor learning process (i.e., neurophysiological, genetic, or neuroimages studies), 2 - Studies with disabling or clinical participants (i.e., stroke survivors and people with Parkinson's disease) or non-human sample. 3 - Studies with no retention (at least 1 h after practice) or transfer tests in the experimental design. 4 - Intervention-based studies that investigated resistance or strength exercises. 5 - Studies investigating the chronic impact of the cardiovascular exercise or fitness level on motor learning and executive function. 6 - Studies including tasks without motor demand (i.e., perceptual tasks). 7 - Pilot and review studies. 8 - Not published and preprint studies (e.g., thesis and dissertations), 9 - Methodological inconsistency or discrepancy in data analysis (e.g., to promote practice immediately before retention test).

Data extraction and analysis

Data extraction followed the items: sample characteristics, motor task characteristics, methodology (research design), exercise parameters, and results related to behavior outcome (motor performance).

The selected studies showed heterogeneity concerning method and procedures. Some studies investigated exercise as a neuromodulatory strategy to enhance motor performance and learning without exhausting exercise protocols and choosing motor tasks unrelated to exercise (i.e., stationary bike and upper limb motor tasks). In contrast, other studies investigated the effects of exercise-induced fatigue during task practice on motor learning, with exhaustion exercise protocols and/or choosing motor tasks related to exercise (i.e., running on treadmill and Bachman Ladder Climb). Thus, we separated these studies into two subcategories: fatigue studies and non-fatigued studies to better guide the studies analysis.

There is no specific instrument to assess methodological rigor in motor learning studies. This review used the methodological quality assessment employed in the motor learning systematic review developed by Subramanian et al.[16].

Firstly, the studies were evaluated using the PEDro Scale[17], with some items adapted to the motor learning background. PEDro Scale has been proposed to assess the quality of controlled trials; however, its acceptance as a strength criterion for experimental research quality allows its application in other contexts, including motor learning reviews[16]. In PEDro Scale, 11-items allow evaluating the generalizability of the findings (criteria 1), blinding methods, randomization and internal validity details (criteria 2-9), and data analysis and statistical reporting (criteria 10-11). The PEDro items adaptations and the assessment of each item of the scale for each study included in this review can be found in the Supplementary Material.

The assessment of the quality of the studies was performed based on the methodology described previoulsy[16]. Then, the score derived from the PEDro Scale was classified by following conditions proposed by Foley et al.,[18]: 9 to 10, excellent; 6 to 8, good; 4 to 5, fair; and < 4, poor. Following, Sackett's evidence levels were used to determine the strength of the conclusions for each analysis of this review[19]. The evidence was classified in 1A (≥ 2 good or excellent studies supported it), 1B (1 good or excellent study supported it), 2A (≥ 1 fair study supported it), 2B (PEDro score ≤ 3 studies or nonrandomized studies supported it), 3 (several pre-post design studies showed similar results), 4 (indicated contradictory results of ≥ 2 studies with similar design and quality) or 5 (absence of experimental studies).

Both authors evaluated the methodological quality of the studies included, including a third person who was consulted in case of incoherence in the PEDro scores (physiotherapist, Master Degree, and Ph.D. student in Motor Behavior area).

Results

It was found a total of 6542 records. Removing duplicates and screening for title and abstract resulted in 54 articles considered for full-text assessment. In the eligibility criteria assessment, 14 studies were excluded (7 with no retention test, 1 duplicated, 1 showed methodological inconsistency in the data extraction and analyses, 2 studies investigated genetic and neurophysiological mechanisms exclusively, 1 study did not demonstrate motor performance analyses, 1 study used a perceptual task with no motor demand, and 1 study investigated the effect of the strength exercise). Figure 1 demonstrates the flow of study selection.

From 40 studies included, none were classified as excellent, 27 studies were considered good (6 to 8 points in the PEDro scale), 20 studies were classified as fair (4 to 5 points in the PEDro scale), and one study was classified as poor (< 4 points in PEDro scale). Ten studies did not perform the allocation process by a random process (or they did not relate it in the manuscript), which compro-

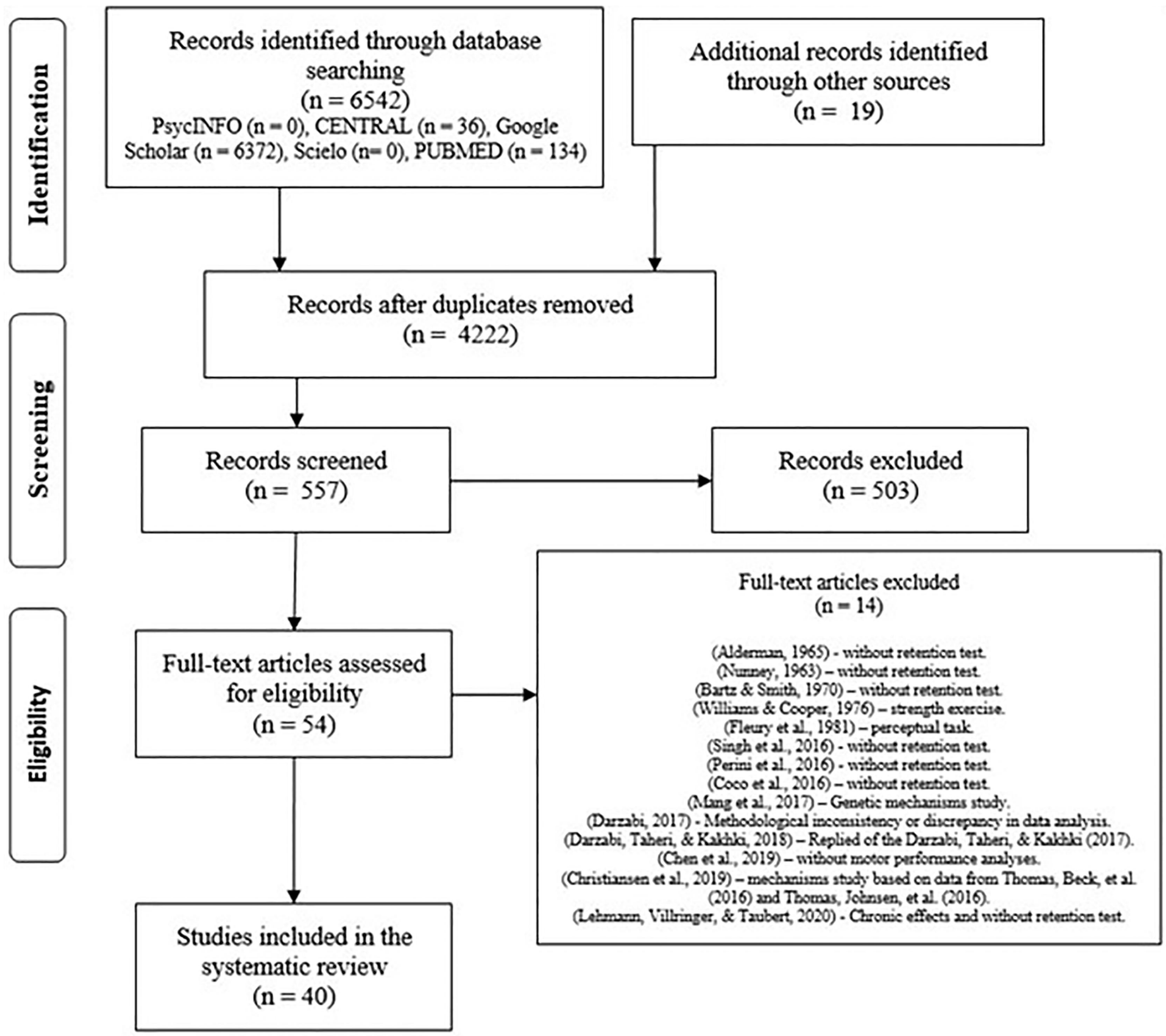

Figure 1 - Flowchart of the study.

mises their evidence level. Two studies were composed of 2 experiments[20,21]; each experiment was analyzed separately. Table 1 demonstrates the main characteristics and results of all studies included in this review.

Discussion

General findings

The main findings of this review show us the acute benefits effects of cardiovascular exercise on motor performance and learning. Previous studies showed that exercise-induced fatigue does not impair motor learning, mainly when exercise does not involve the same motor effector related to motor task performance. Also, the effects of cardiovascular exercise on motor learning are more evident when the exercise is carried out in temporal proximity to the practice; moreover, depending on the order between exercise and practice, the priming effects may have a different impact on the motor learning process.

Two fatigue studies demonstrated the adverse effects of fatigue on motor learning. Benson[23] demonstrated that the fatigue induced by stationary bike impaired the jumping task learning, and Carron & Ferchuk[31] reported that the fatigue induced by stationary bike mitigated the balance stabilometer task learning. In sum, the excessive fatigue induced by cardiovascular exercise only impacts motor performance. Fatigue conditions may not be related to motor learning. The level of this evidence is 2A.

Besides, cardiovascular exercise seems to be a possible strategy to prime the CNS and induce better motor

Table 1 - Characteristics and results from the included studies.

Reference/Methodological Rigor	Participants	Motor Task	Methodology	Exercise Parameters	Findings
Benson (1968) PEDro = 4 2B* Fatigue study	Forty-one young adults.	Jumping task and Juggle task.	Experimental Design: Parallel Group. Groups: Jumping practice + Exercise + Juggle practice Group; and Juggle practice + Exercise + Jumping practice Group. Intervention: 11 practice sessions in 6 weeks. Each practice session was composed of 3 min of juggling and 1 serie of 32 hopping and stepping movements. Retention test after 2 weeks.	Type: Stationary bike. Intensity: 180 bpm. Volume: 5-6 min. Cadence: 20 km/h, Condition: Continuous.	The learning of the speed component in the jumping task was impaired in the fatigue state. Fatigue effects improved the learning of the accuracy component of the jumping task. The fatigue effect improved juggle learning.
Schmidt (1969) PEDro = 4 2B* Fatigue study	Forty-seven young adults.	Bachman Ladder Climb.	Experimental Design: Parallel Group. Groups: Mild exercise and practice Group, Moderate exercise and practice group, and vowel-canceling task + practice group. Intervention: 10 trials of 30-s trials for practice. In the retention test was provided 4 blocks of 30 trials (without exercise). The exercise groups performed exercise before and during the intertrial intervals.	Type: Stationary bike. Intensity: 1200 kg m/min (for moderate exercise group) and 750 kg m/min (for mild exercise group). Volume: 2 min. Cadence: Not reported. Condition: Continuous.	The exercise-induced fatigue decremented motor performance during the practice. However, fatigue did not influence motor learning.
Carron & Ferchuk (1971) PEDro = 5 2B* Fatigue study	Forty young adults.	Balance stabilometer Task.	Experimental Design: Parallel Group. Groups: Practice Group, and Exercise before and interposed in the practice Group. Intervention: Practice - 24 trials (20 s each) divided in 2 days (48 h between them). The 48-h retention test had 6 trials without exercise.	Type: Stationary bike, Intensity: 180 bpm, Volume: 10 min before practice, and 2 min among practice blocks. Cadence: Not reported. Condition: Continuous.	The fatigue was detrimental to performance during practice and learning.
Godwin & Schmidt (1971) PEDro = 4 2A Fatigue study	Sixty-four young adults.	Sigma task.	Experimental design: Parallel Group. Groups: Just practice group, and Exercise before and interposed in the practice Group. Intervention: The practice was composed of 20 trials, and the 72-h retention test had 10 trials without exercise.	Type: Upper body ergometer. Intensity: 70.2 kg m/min. Volume: 2 min before practice, and 15 s among trials. Cadence: 60 rpm. Condition: Continuous.	The fatigue impacts motor performance negatively during practice. Both groups demonstrated retention without significant difference between them.
Michael Pack, Cotten, & Biasiotto (1974) PEDro = 5 2A Fatigue study	Forty-eight young adults.	Bachman Ladder Climb.	Experimental Design: Parallel Group. Groups: Just practice Group, practice interposed by exercise at 120 bpm Group, practice interposed by exercise at 150 bpm Group and practice interposed by exercise 180 bpm Group. Intervention: The practice had 20 blocks of 5 trials; each practice block was interposed by exercise (or rest). A 24-h retention test composed of 20 blocks was run (without exercise).	Type: Treadmill. Intensity: 120 bpm, 150 bpm, or 180 bpm. Volume: 3 min interposed in each practice block. Condition: Continuous.	The two more vigorous fatigue conditions had a detrimental effect during the practice. However, there were no differences among the groups in the retention test.
Cochran (1975) PEDro = 3 2B Fatigue study	Thirty-five young adults.	Balance stabilometer Task.	Experimental Design: Parallel Group. Groups: Just practice Group, and Exercise before and between practice trials Group. The practice had 2 trials of 3-min each/ per week, for 4 weeks. In week 5 was developed the retention test without exercise.	Type: Stationary bike. Intensity: 600 kg m/min. Volume: 8 min before trial 1, and 3 min between trials 1 and 2. Cadence: 50 rpm. Condition: Continuous.	The exercise group demonstrated better motor performance and learning.

(*continued*)

Table 1 - continued

Reference/Methodological Rigor	Participants	Motor Task	Methodology	Exercise Parameters	Findings
Williams & Singer (1975) PEDro = 4 2A Fatigue study	Forty-eight young adults.	Pursuit-rotor tracking task.	Experimental Design: Parallel Group. Groups: Just practice group, low-intensity exercise among practice trials Group, moderate-intensity exercise among practice trials Group, and high-intensity exercise among practice trials Group. Intervention: Practice was composed of 10 trials/ 20 s each. The 48-h retention also had 10 trials, without exercise.	Type: Upper body ergometer. Intensity: 90, 180, and 270 kg m/min; for low, medium and high fatiguing groups, respectively. Volume: 15 s interposed in each practice trial. Condition: Continuous.	All groups improved their performance between practice and retention test, without a significant difference between them.
Poolton et al. (2007) PEDro = 5 2A Fatigue study	Forty-six young adults.	Rugby pass.	Experimental Design: Parallel Group. Groups: Implicit Learning Group and Explicit Learning Group. Intervention: 10 blocks of 10 trials each. A Wingate test was run before practice. A 1-year retention test of 1 block of 10 trials was performed.	Type: Stationary bike, Protocol: Wingate test.	The implicit group demonstrated better motor performance. Both groups demonstrated retention after one year, without difference between them.
Masters et al. (2008) PEDro = 4 2B* Fatigue study	Forty-one young adults.	Rugby pass.	Experimental Design: Parallel Group. Groups: Implicit Learning Group and Explicit Learning Group. Intervention: 10 blocks of 10 trials each. After 15 min, a retention test and a dual-task test. Following, exercise was performed. Then, retention tests were replied.	Type: Treadmill. Protocol: $VO2_{max}$. Running test on a treadmill (voluntary exhaustion).	The implicit group demonstrated stable learning under aerobic fatigue, which the explicit learning group did not show.
Roig et al. (2012) PEDro = 7 1A Non-fatigue study	Forty-eight young adults.	Visuomotor Accuracy Tracking Task.	Experimental Desing: Parallel Group. Groups: Exercise Before Practice Group, Exercise After Practice Group, Just Practice Group. Intervention: 3 blocks of 5 min of practice. Retention test of 5 min of practice after 1 h, 24 h, and 7 days to the end of practice.	Type: Stationary bike, Intensity: ≥10 mmol/l lactate for high-intensity blocks, 50 W for low-intensity blocks, Cadence: 70 rpm, Volume: 3 x 3 min blocks of high-intensity interspersed with 3 x 2 min blocks of low-intensity in between. Condition: HIIT.	The exercise groups demonstrated better retention than the Just Practice Group. Yet, Exercise Group demonstrated better long-term retention than Before Exercise Group.
Mang et al. (2014) PEDro = 6 1A Non-fatigue study	Sixteen young adults.	Visuomotor Accuracy Tracking Task.	Experimental Design: Cross-Over. Condition 1: Rest + Practice and a 24-h retention test. Condition 2: Exercise + Practice and a 24-h retention test. Blocks of 10 trials composed the practice. The 24-h retention test has 1 block of 10 trials. Washout: 2 weeks.	Type: Stationary bike, Intensity: 90% $W_{máx}$ for high-intensity blocks, 50 W for low-intensity blocks, Cadence: > 70 rpm, Volume: 3 x 3 min blocks of high-intensity interspersed with 3 x 2 min blocks of low-intensity in between. Condition: HIIT.	There was retention only when the practice was preceded by aerobic exercise. The retention level correlated with the exercise-induced long-term potentiation.
Skriver et al. (2014) PEDro = 6 1A Non-fatigue study	Thirty-two young adults.	Visuomotor Accuracy Tracking Task.	Experimental Design: Parallel Group. Groups: Exercise Before Practice Group, and Just Practice Group. Intervention: Pre-test with 10 trials, practice with 3 blocks of 5 min each, retention tests of 5 min were run after 1 h, 24 h, and 7 days after the end of practice. Across the practice were collected biomarkers samples.	The same exercise parameters of Roig et al. (2012).	Cardiovascular exercise stimulated better long-term retention if compared to rest condition.
Chartrand et al. (2015) PEDro = 1A Non-fatigue study	Fifty-two young adults.	Laparoscopic surgery simulator tasks.	Experimental Design: Parallel Group. Groups: Practice + Exercise Group, Just Practice Group. Intervention: The practice was composed of 10 min of PT, 10 min of PC, and 15 min of IS. The participants were scored in	Type: Treadmill. Intensity: 60% $VO2_{max}$. Volume: 20 min.	There was no exercise effect on motor learning.

(*continued*)

Table 1 - continued

Reference/Methodological Rigor	Participants	Motor Task	Methodology	Exercise Parameters	Findings
			the 3 tasks by a proctor in the pre-test and during the 2-months retention test.		
Statton et al. (2015) Experiment 1 PEDro = 5 2B* Non-fatigue study	Twenty-four young adults.	Sequential Visual Isometric Pinch Task.	Experimental Design: Parallel Group. Groups: Running Immediately Before Practice Group, Running + 1-h rest + Practice Group, and Walking + Practice Group. Intervention: Pre-test with 30 trials, practice composed of 4 blocks of 30 trials each.	Type: Treadmill, Intensity: From 65 to 80% HR_{max}, Volume: 30 min, Condition: Continuous.	All groups improved motor performance across the practice. However, the Exercise Immediately Before Practice demonstrated better motor performance than the other groups.
Statton et al. (2015) Experiment 2 PEDro = 5 2B* Non-fatigue study	Twenty young adults.	Sequential Visual Isometric Pinch Task.	Experimental Design: Parallel Group. Groups: Running Before Practice Group, and Walking Before Practice Group. Intervention: 3 days of practice, each day composed of 4 blocks of 30 trials each, a retention test was run in the fourth day composed of 4 blocks of 30 trials each.	Type: Treadmill, Intensity: From 65% to 80% HR_{max}, Volume: 30 min, Condition: Continuous.	The running group demonstrated better motor performance across the practice. However, there was no significant difference between groups in the retention test.
Rhee et al. (2016) PEDro = 5 2B* Non-fatigue study	Sixty young adults.	Motor sequence task.	Experimental Design: Parallel Group. Groups: Practice A + 24 h test A Group; Practice A + Immediate test A Group; Practice A + Practice B + 24 h Test A Group; Practice A + Exercise + Practice B + 24 h Test A Group; Practice A + 2 h rest + Exercise + Practice B + 24 h test A Group. Intervention: 30 trials of 30 s, each composed practice. The tests were composed of 1 trial of 30 s.	Type: Stationary bike, Intensity: 80% and 100% HR_{max}. Volume: 18 min (80% HR_{max}) and 3 min (100% HR_{max}), Cadence: 70 rpm, Condition: Continuous.	Cardiovascular exercise induced better retention and decrease the retroactive interference of practice B. However, this effect only was reported when the cardiovascular exercise was performed in a temporal close to practice A.
Snow et al. (2016) PEDro = 7 1A Non-fatigue study	Sixteen young adults.	Visuomotor Accuracy Tracking Task.	Experimental Design: Cross-Over. Condition 1: Rest + Practice and a 24 h retention test. Condition 2: Exercise + Practice and a 24 h retention test. Intervention: 2 blocks of 5 min each. The retention test has 1 block of 5 min. Washout: ≥ 2 weeks.	Type: Stationary bike, Intensity: 60% $VO2_{peak}$. Volume: 30 min, Cadence: from 70 to 90 rpm, Condition: Continuous.	Cardiovascular exercise promoted better spatial accuracy during practice. There were no differences between the conditions (cardiovascular or rest) in the retention test; both demonstrated motor learning.
Thomas, Beck, et al. (2016) PEDro = 7 1A Non-fatigue study	Forty-eight young adults.	Visuomotor Accuracy Tracking Task.	Experimental Design: Parallel Group. Groups: Practice + 20 min of rest + exercise Group; Practice + 1 h of rest + exercise Group; Practice + 2 h of rest + exercise Group; and Just Practice Group. Intervention: 5 blocks of 4 min each of practice. Retention tests were performed after 1 day and 1 week to the end of practice.	Type: Stationary bike, Intensity: 90% W_{max} during high-intensity blocks, 60% W_{max} during low-intensity blocks. Cadence: 80 rpm, Volume: 3 x 3 min blocks of high-intensity interspersed with 3 x 2 min blocks of low-intensity in between, Condition: HIIT.	Cardiovascular exercise performed in a temporal close to the practice promoted better retention than other conditions.
Thomas, Johnsen, et al., (2016) PEDro = 7 1A Non-fatigue study	Thirty-six young adults.	Visuomotor Accuracy Tracking Task.	Experimental Design: Parallel Group. Groups: Practice + High-intensity Exercise Group; Practice +Low-intensity Exercise Group; and Just Practice Group. Intervention: 5 blocks of 4 min each of practice. Retention tests were performed after 1 day and 1 week to the end of practice.	Type: Stationary bike, Intensity: (high/low intensity groups): 90% / 45% W_{max} during high-intensity blocks, 60% / 25% W_{max} during low-intensity blocks. Cadence: ≥ 80 rpm, Volume: 3 x 3 min blocks of high-intensity interspersed with 3 x 2 min blocks of low-intensity in between. Condition: HIIT.	The high-intensity exercise group demonstrated better motor performance and learning than the other groups.

(*continued*)

Table 1 - continued

Reference/Methodological Rigor	Participants	Motor Task	Methodology	Exercise Parameters	Findings
Ostadan et al. (2016) PEDro = 7 1A Non-fatigue study	Forty-eight young adults.	Serial Reaction Time Task.	Experimental Design: Parallel Group. Groups: Practice + Exercise Group; Practice + Rest Group. Intervention: Pre-test with 15 trials, practice of 25 trials, post-test of 15 trials, and an 8-h retention test composed of 5 trials.	Type: Stationary bike, Intensity: 85-90% $VO2_{peak}$ during high-intensity blocks, 25% W_{max} during low-intensity blocks. Cadence: 70 rpm, Volume: Total volume 3 x 3 min blocks of high-intensity interspersed with 3 x 2 min blocks of low-intensity in between. Condition: HIIT.	Both groups demonstrated offline learning. There was no significant difference between groups. The cortical excitability was associated with better motor performance for the Exercise Group.
Mang et al. (2016) PEDro = 6 1A Non-fatigue study	Sixteen young adults.	Serial Targeting Task.	Experimental Design: Cross-Over. Condition 1: Rest + Practice and a 24-h retention test. Condition 2: Exercise + Practice and a 24-h retention test. 3 blocks of 15 trials composed the practice. The retention test has 1 block of 15 trials. Washout: ≥ 2 weeks.	Type: Stationary bike, Intensity: 90% $VO2_{peak}$ during high-intensity blocks, 50 W during low-intensity blocks. Cadence: 70 rpm, Volume: 3 x 3 min blocks of high-intensity interspersed with 3 x 2 min blocks of low-intensity in between. Condition: HIIT.	There was no significant difference between groups across the practice. However, in the retention test, the cardiovascular condition induced better relearning.
Lauber, Franke, Taube, & Gollhofer (2017) PEDro = 6 1A Non-fatigue study	Thirty young adults.	Ballistic task and Tracking accuracy task.	Experimental Design: Parallel Group. Groups: Ballistic practice + Tracking practice + HIIT Group; Ballistic practice + HIIT + Tracking practice Group; and Ballistic practice + rest + Tracking practice Group. Intervention: Pre-test in the ballistic task for both upper limbs (5 trials each), after practicing in ballistic task with the dominant hand (3 blocks/ 15 trials). The practice of the tracking accuracy task had 60 trials. After practice and after 24 h were performed a post-test and a retention test identical to the pre-test.	Type: Stationary bike, Intensity: 75% $VO2_{peak}$ during high-intensity blocks, 50 W during low-intensity blocks. Cadence: 75 rpm, Volume: 4 x 4 min blocks of high-intensity interspersed with 4 x 4 min blocks of low-intensity in between. Condition: HIIT.	The HIIT between two motor skills induced less interference on the learning of the ballistic task (in both upper limbs). When the HIIT was performed after the interfering motor task (accuracy task), there was harmful interference in the learning of the ballistic task; similar findings were found in the rest group.
Thomas et al. (2017) PEDro = 7 1A Non-fatigue study	Forty young adults.	Visuomotor Accuracy Tracking Task.	Experimental Design: Parallel Group. Groups: Practice + Strength training Group; Practice + Circuit training Group; Practice + Hockey Group; Just Practice Group. Intervention: Pre-test with 2 blocks of 16 trials. Practice with 3 blocks of 32 trials, and retention tests with blocks of 16 trials after 1 h and 1 day from the end to the practice.	The exercise was relative to the type of intervention.	The exercise groups demonstrated better retention, independently of the exercise type.
Helm et al. (2017) PEDro = 7 1A Non-fatigue study	Fifty-four young adults.	Split-belt locomotor skill.	Experimental Design: Parallel Group. Groups: Exercise + Practice Group; Just Practice Group. Intervention: Pre-test with 2 min with symmetric conditions, the practice was composed of 15 min in asymmetric conditions (3:1), and the 24-h retention test composed of 15 min in asymmetric conditions (3:1).	Type: Upper body ergometer, Intensity: ≥ 90% HR_{max} for high-intensity blocks; 50% of the load for low-intensity block. Volume: 2 x 1 min blocks of high-intensity interspersed with 2 x 1 min blocks of low-intensity in between. Condition: HIIT.	Both groups demonstrated adaptation improvement across practice and maintained it in the retention test. There was no significant difference between them.
Ferrer-Uris et al. (2017) PEDro = 7 1A Non-fatigue study	Twenty-nine young adults.	Rotational visuomotor adaptation task.	Experimental Design: Parallel Group. Groups: Exercise + Practice Group; Practice + Exercise Group and Just practice Group. Intervention: 20 trials for familiarization, 104 trials for baseline, 312 trials for adaptation practice (60°	Type: Running, Intensity: 85% $VO2_{max}$ during high-intensity blocks, 60% $VO2_{max}$ during low-intensity blocks. Volume: 3 x 3 min blocks of high-intensity interspersed with 3	There was no exercise effect on practice. The exercise groups were better than the control group in the 1-h retention test. In long-term retention, tests were not identified significant differences among groups.

(*continued*)

Table 1 - continued

Reference/Methodological Rigor	Participants	Motor Task	Methodology	Exercise Parameters	Findings
			clockwise rotational sets), and retention tests after 1 h, 1 day, and 7 days.	x 2 min blocks of low-intensity in between. Condition: HIIT.	
Lundbye-Jensen et al. (2017) PEDro = 7 1A Non-fatigue study	Seventy-seven pre-adolescent children.	Visuomotor Accuracy Tracking Task.	Experimental Design: Parallel Group. Groups: Practice + Floorball Group; Practice + Exercise Group and Just practice Group. Intervention: Pre-test with 1 block of 24 trials. Practice with 3 blocks of 24 trials, and retention tests with 4 blocks of 24 trials after 1 h and 1 day from the end to the practice.	Type: Running or Floorball, Intensity: It was not explicitly provided. Volume: 3 x 3 min blocks of high-intensity interspersed with 3 x 2 min blocks of low-intensity in between. Condition: HIIT and floorball game.	The exercise groups (running and floorball) demonstrated better retention without difference between them.
Stavrinos & Coxon (2017) PEDro = 6 1A Non-fatigue study	Twenty-four young adults.	Sequential visual isometric pinch task.	Experimental Design: Parallel Group. Groups: Exercise + Practice Group; and Just practice Group. Intervention: Pre-test with 2 blocks of 16 trials. Practice with 7 blocks of 8 trials, and a 5-h retention test with 4 blocks of 8 trials.	Type: Stationary bike, Intensity: 90% $HR_{reserve\ during\ high\text{-}intensity\ blocks}$, 50% $HR_{reserve}$ during low-intensity blocks. Volume: 4 x 2 min blocks of high-intensity interspersed with 4 x 3 min blocks of low-intensity in between. Condition: HIIT.	The groups were equal during practice. The exercise group demonstrated better retention than the control group.
Dal Maso, Desormeau, Boudrias, & Roig (2018) PEDro = 5 2B* Non-fatigue study	Twenty-five young adults.	Visuomotor Accuracy Tracking Task.	Experimental Design: Parallel Group. Groups: Practice + exercise Group; and Practice + rest Group. Intervention: Practice was composed of 5 blocks of 20 trials. The retention tests were run after 8 h and 24-h from practice; each of them was composed of 2 blocks of 20 trials.	Type: Stationary bike, Intensity: 90% $VO2_{peak}$ during high-intensity blocks, 50 W during low-intensity blocks. Volume: Total volume (20 min) - 3 x 3 min blocks of high-intensity interspersed with 3 x 3 min blocks of low-intensity in between. Cadence: 70-80 rpm. Condition: HIIT.	In the 24-h retention test, both groups retained motor performance, but the exercise group demonstrated better motor performance than the rest group.
Ferrer-Uris et al. (2018) PEDro = 7 1A Non-fatigue study	Thirty-three children.	Rotational visuomotor adaptation task.	Experimental Design: Parallel Group. Groups: Exercise + Practice Group; Practice + Exercise Group and Just practice Group. Intervention: 104 trials for baseline, 312 trials for adaptation practice and retention tests with 104 trials under adaptation after 1 h, 1 day, and 7 days.	Type: Running, Intensity: 85% $VO2_{max}$ during high-intensity blocks, 60% $VO2_{max}$ during low-intensity blocks. Volume: 3 x 3 min blocks of high-intensity interspersed with 3 x 2 min blocks of low-intensity in between. Condition: HIIT.	There was no difference among groups during the practice. The group that performed cardiovascular exercise before the practice demonstrated better retention than the control group.
Baird et al. (2018) PEDro = 6 1A Non-fatigue study	Forty-eight young adults.	Serial target task.	Experimental Design: Parallel Group. Groups: High-intensity exercise + Practice Group; Low-intensity exercise + Practice; Just practice Group. Intervention: 1 trial for pre-test, 114 trials for practice, and a 24-h retention test with 72 trials.	Type: Stationary bike, Intensity: 80% $VO2_{max}$ (high-intensity group) and 40% $VO2_{max}$ (low-intensity group). Volume: Individually modified so that each participant expended 200 kcals. Cadence: 60 rpm, Condition: Continuous.	All groups demonstrated motor learning, without difference among them. The exercise (high and low) modified the kinematic reach movements.
Tomporowski & Pendleton, (2018) Experiment 1 PEDro = 7 1A Non-fatigue study	Thirty-two young adults.	Pursuit-rotor tracking task.	Experimental Design: Parallel Group. Groups: Practice + Simple Exercise Group; Practice + Complex Exercise Group; Just practice Group. Intervention: 5 blocks of 10 trials for practice, it also was provided retention tests of 10 trials immediately after the exercise and after 1 and 7 days.	Type: Computer-based step dance (Dance Dance Revolution). Complexity: It was manipulated by the number and sequences of the steps. Volume: 10 min total, alternating periods of 2 min of exercise, and 30 s of rest.	The Complex Exercise Group demonstrated a better long-term retention test than the Control Group.
Tomporowski & Pendleton, (2018) Experiment 2 PEDro = 7	Thirty-one young adults.	Pursuit-rotor tracking task.	Experimental Design: Parallel Group. Groups: Simple Exercise + Practice Group; Complex Exercise + Practice Group; Just practice Group. Intervention: 5 blocks of 10 trials for	Type: Computer-based step dance (Dance Dance Revolution). Complexity: It was manipulated by the number and sequences of the steps. Volume: 10 min total, alternat-	The exercise did not impact motor learning independently of the complexity.

(*continued*)

Table 1 - continued

Reference/Methodological Rigor	Participants	Motor Task	Methodology	Exercise Parameters	Findings
1A Non-fatigue study			practice, it also was provided retention tests of 10 trials immediately after the exercise and after 1 and 7 days.	ing periods of 2 min of exercise, and 30 s of rest.	
Angulo-Barroso, Ferrer-Uris, & Busquets (2019) PEDro = 7 1A Non-fatigue study	Seventy-one children.	Rotational visuomotor adaptation task.	Experimental Design: Parallel Group. Groups: Long exercise + practice Group; Short exercise + practice Group; Rest + practice Group. Intervention: 20 trials for familiarization, 104 trials for baseline, 312 trials for adaptation practice (60° clockwise rotational sets), and retention tests with 104 trials under adaptation after 1 h, 1 and 7 days.	Type: Running. Intensity: 85% $VO2_{max}$ during high-intensity blocks, 60% $VO2_{max}$ during low-intensity blocks. Volume: for long exercise group (3 x 3 min blocks of high-intensity interspersed with 3 x 2 min blocks of low-intensity in between), for short exercise group (2 x 2 blocks of high-intensity separated by 1 min of low-intensity). Condition: HIIT.	The exercise did not impact adaptation. However, both exercise groups demonstrated better retention than the control group. The duration of the exercise did not influence motor learning.
Charalambous, French, Morton, & Reisman (2019) PEDro = 7 2B* Non-fatigue study	Twenty-six young adults.	Split-belt locomotor skill.	Experimental Design: Parallel Group. Groups: Practice + Exercise Group; Practice + Rest Group. Intervention: Pre-test of 2 min with symmetric conditions. The practice was composed of 5 min in asymmetric conditions (3:1). The 24-h and 7-days retention tests were composed of 5 min and 15 min, respectively. The retention tests were performed in asymmetric conditions (3:1).	Type: total body exerciser, Intensity:77-94% HR_{max} and ≥ 10 mmol/l lactate. Volume: 5 min. Cadence: Nor reported, Condition: Continuous	Both groups demonstrated improvement in the adaptation during the practice, retained, and relearned similarly.
Jo, Chen, Riechman, Roig, & Wright (2019) PEDro = 6 1A Non-fatigue study	Forty-six young adults.	Motor sequence task.	Experimental Design: Parallel Group. Groups: Just Practice Group; Practice + Interfering Practice Group, and Practice + Exercise + Interfering Practice Group. Intervention: Practice of 10 blocks of 20 trials. The interfering practice was composed of a new sequence that also had the practice of 200 trials. A 6-h retention test (10 trials) was run with the sequence of the first practice block.	Type: Stationary bike, Intensity: From 80% HR_{max}. Volume: 20 min. Cadence: Between 75 rpm, Condition: Continuous.	The exercise group did not demonstrate a significant difference if compared to the non-exercise group regarding retroactive interference.
Neva et al. (2019) PEDro = 6 1A Non-fatigue study	Seventeen young adults.	Visuomotor rotation task.	Experimental Design: Cross-Over. Firstly, a baseline with 32 trials per arm with veridical feedback. After the participant performs the following experimental design with rest or exercise prior. Intervention: Rest or Exercise + 200 trials with 45° CW or CCW rotated feedback + Inter-limb transfer 16 trials with 45° CW or CCW rotated feedback + 24-h retention test with 16 trials in left and right arms with 45° CW or CCW rotated feedback. Washout for exercise and rest conditions: ≥ 2 weeks.	Type: Stationary bike, Intensity: From 65% to 70% of HR_{max}. Volume: 25 min. Cadence: Between 70 and 90 rpm, Condition: Continuous.	Cardiovascular exercise induced better adaptation and motor learning. As well, it was identified that cardiovascular exercise did not influence inter-limb transfer. However, the reaction time of the opposite limb was better after the cardiovascular exercise bout.
Opie & Semmler (2019) PEDro = 7 1A Non-fatigue study	Thirteen young adults	Ballistic thumb abduction task	Experimental Design: Cross-Over. Condition 1: High-intensity exercise + practice + 24-h retention test. Condition 2: Low-intensity exercise + practice + 24-h retention test. Condition 3: Rest + practice + 24-h retention test. Intervention: The practice and the retention	Type: Running. Intensity: 85% $HR_{reserve}$ and 25% $HR_{reserve}$ for high-intense condition (HIIT). 50% $HR_{reserve}$ for the low-intense condition. Volume: 4 x 3.5 min in high and low-intensity blocks for the high-intense	Exercise improved retention and relearning. The low-intensity condition was better in the retention test than the high-intensity condition.

(*continued*)

Table 1 - continued

Reference/Methodological Rigor	Participants	Motor Task	Methodology	Exercise Parameters	Findings
			test were composed of 150 trials. On the retention test day, there was no exercise. Washout: 2 weeks.	condition. 30 min for a low-intense condition. Condition: HIIT or continuous.	
Stranda et al. (2019) PEDro = 7 1A Non-fatigue study	Twenty-six young adults.	Keyboard Typing Task.	Experimental Design: Parallel Group. Groups: Practice + Exercise Group; Just Practice Group. Intervention: 4 weeks, 3 sessions per week, 10 min of practice per day. A 7-days retention test was run with 3 min of practice.	Type: Stationary bike, Intensity: 65% HR_{max}. Volume: 15 min. Cadence: It was not reported. Condition: Continuous.	Both groups improved motor performance and similarly maintained it in the retention test.
Beck et al. (2020) PEDro = 8 1A Non-fatigue study	Forty-eight young adults.	Visuomotor Accuracy Tracking Task.	Experimental Design: Parallel Group. Groups: Practice + interfering rTMS Group, Practice + sham rTMS Group, Practice + Exercise + Interfering rTMS Group. Intervention: Pre-test of 12 trials, Practice of 3 blocks/ 20 trials, immediate retention test of 12 trials, and a 24-h retention composed of 20 trials.	Type: Stationary bike, Intensity: 90% $VO2_{peak}$ during high-intensity blocks, 60% $VO2_{peak}$ during low-intensity blocks. Cadence: 80 rpm, Volume: 3 x 3 min blocks of high-intensity interspersed with 3 x 2 min blocks of moderate-intensity in between. Condition: HIIT.	The rTMS impaired offline learning. The exercise prevented deleterious effects of the rTMS. The exercise group demonstrated offline learning paired with the sham rTMS group.
Lorås et al. (2020) PEDro = 7 1A Non-fatigue study	Forty young adults.	Golf putting task.	Experimental Design: Parallel Group. Groups: Moderate-intensity Exercise + Practice Group; High-intensity Exercise + Practice Group. Intervention: Practice of 6 blocks of 10 trials. 24-h retention and transfer (ball closer to the target) tests were composed of 10 trials each.	Type: Stationary bike, Intensity: 50% $HR_{máx}$, or 75% $HR_{máx}$. Volume: 20 min. Cadence: It was not reported. Condition: Continuous.	Both groups demonstrated motor improvement across the practice. In the retention and transfer tests, the groups did not demonstrate a significant difference between them.
Wanner et al. (2020) PEDro = 8 1A Non-fatigue study	Fifty young adults.	Balance stabilometer Task.	Experimental Design: Parallel Group. Groups: Minimal-intense exercise + Practice Group; Moderate-intensity Exercise + Practice Group; High-intensity Exercise + Practice Group. Intervention: Pre-test of 2 trials, 15 trials for practice, and a 24-h retention test with 10 trials.	Type: Stationary bike, Intensity (High/ moderate): 90/45% W_{max} for high-intensity blocks, 60/25% W_{max} for low-intensity blocks, for the minimal intense group was used 25% W_{max}. Cadence: ≥ 80 rpm, Volume: 3 x 3 min blocks of high-intensity interspersed with 2 x 2 min blocks of low-intensity in between, for the minimal-intense group - 17 min continuous. Condition: HIIT or continuous.	All groups demonstrated motor improvement during practice and maintained it in the retention test, without significant difference among them.

Legend: *: Nonrandomized study; HIIT: High-Intensity Interval Training; BDNF: Brain-Derived Neurotrophic Factor; PT: Peg transfer; PC: Pattern cut; IS: Intracorporeal suture; HR: Heart rate; HR_{max}: Maximum Heart Rate; $HR_{reserve}$: Reserve Heart Rate; Kcal: Kilocalorie; rTMS: repetitive transcranial magnetic stimulation.

practice. From the 30 non-fatigue studies investigating the cardiovascular effects on motor learning, 19 demonstrated some positive effects from cardiovascular exercise on motor performance[20,32,33] or learning[21,33-50]. In the 30 studies investigating the effects of cardiovascular exercise (without excessive fatigue) on motor learning (retention test), some of them reported null effects[20,32,51-59], but anyone demonstrated adverse effects.

Therefore, it can be supposed that the evidence that cardiovascular exercise enhances motor learning has a level of 4 (conflicting results). In this case, the positive effect of cardiovascular exercise on motor learning is multifactorial, and it depends mainly on the task and exercise characteristics and the timing of exposure of the exercise in relation to the practice.

Specifically, regarding the motor performance during practice, the findings demonstrated that a cardiovascular exercise bout before motor practice improves the subsequent motor performance concerning the error rate[20], temporal synchronization[32], kinematics reaching accuracy measures, time duration, and reaction time[33].

The cardiovascular exercise benefits on motor memory consolidation were reported in the retention tests from 5 h[36] to 7 days[21,35,38,43,45,48]. Nevertheless, it seems that cardiovascular exercise effects on motor memory consolidation are more robust in the long-term retention tests. For instance, some studies did not find the effect of the cardiovascular exercise in the short-term retention test (1-h or 1-day retention test); however, the exercise group demonstrated a better long-term retention test (7-days retention test) if compared to the control group[34,43,51].

Concerning the consolidation of motor memory, Mang and colleagues[60], and Opie and Semmler[40] demonstrated that a cardiovascular exercise bout impacts the relearning of a serial motor sequence task and a thumb abduction task, respectively. Thus, cardiovascular exercise may influence the following motor practice sessions, providing a faster relearning rate than original learning.

Finally, cardiovascular exercise effects on motor learning seem to be multifactorial, including motor tasks and exercise characteristics. In the following sections, each potential factor was analyzed separately.

Timing

The effects of cardiovascular exercise on the motor learning process may depend on exposure to the exercise concerning the practice. The exposure timing can be conjectured based on two aspects: 1 - The temporal proximity between cardiovascular exercise and practice. 2 - the order between cardiovascular exercise and practice.

Regarding the temporal proximity between cardiovascular exercise and practice, the findings have demonstrated that cardiovascular exercise must be performed in close temporal proximity to the practice to engage enhancements on motor performance and learning. Hence, Statton et al.[20] demonstrated that cardiovascular exercise performed immediately before the practice improves motor performance more than when cardiovascular exercise is performed 1 h before the practice. Thomas, Beck, et al.[47] demonstrated that performing cardiovascular exercise 20 min immediately after the practice induced better motor performance in the 1-day and 7-days retention tests than rest, or to perform cardiovascular exercise after 1 h or 2 h the practice. Therefore, the level of evidence for the temporal proximity between cardiovascular exercise and practice to enhance motor learning is 1B.

About the effects of the order between cardiovascular exercise and practice, it has been suggested that maybe the priming effects from the cardiovascular exercise on the motor memory creation processes are order-dependents[12,13]. Therefore, whether the practitioner performs exercise before or during the practice, better motor performance is expected. On the other hand, whether the cardiovascular exercise is performed after the motor practice, an improvement in the consolidation process is expected, and therefore, a better retention test[12,13].

However, the order-dependent hypothesis was not fully confirmed in the studies that investigated it. Roig et al.[43] and Tomporowski and Pendleton[21] demonstrated that performing cardiovascular exercise after the practice induced better retention than performing a cardiovascular exercise before the practice. In a contrary way, Ferrer-Uris et al.[57] did not demonstrate a significant difference in motor learning of adults who perform a cardiovascular exercise before or after the practice; and Ferrer-Uris et al.[38] demonstrated that the children who perform cardiovascular exercise before the practice demonstrated better retention if compared to children who perform cardiovascular exercise after the practice.

Therefore, the order-dependent hypothesis must be more investigated for further conclusions; 2 good studies (both 7 points in PEDro scale) supported it, but 2 other good studies (both 7 points on PEDro scale) did not corroborate with that.

Exercise characteristics

Type

Most studies that were incorporated in this review used running or stationary bikes in their exercise protocol. Concerning the running studies, 4 of the 8 studies reported positive cardiovascular exercise effects on motor learning[35,38-40]. While of the 20 studies that used the stationary bike, 6 studies demonstrated the null effect of cardiovascular exercise on motor performance and learning[32,51,52,54,55,58]. Only 1 study used an upper body ergometer for cardiovascular exercise prescription, and it did not report the positive effect of cardiovascular exercise on the learning of a locomotor skill[53]. Besides, 1 study used a whole-body exercise involving upper and lower limbs in the exercise, and it did not demonstrate the positive effects of the exercise on locomotor learning[59].

From these findings, it can be considered that maybe the effects of cardiovascular exercise on motor learning are more evident for exercises that use exclusively the motor effector that is not involved in the performance of the motor task. More investigations about this topic should be run because the level of this evidence is 4.

Additionally, 3 studies investigated different types of exercises on motor learning. Thomas et al.[34] identified that a rest group demonstrated better motor performance of a visuomotor tracking task in the 1-h retention test than the 3 groups with different exercise types after practice; strength training, circuit training, and hockey. However, in the 1-day retention test, the exercise groups demonstrated offline gains (without difference among them) that were not found in the rest group. These findings revealed that the fatigue might harm the short-term retention test; however, in a 24 h retention test (without fatigue effects), it is possible to verify that the exercise improved the consolidation processes. In agreement with these findings, Lundbye-Jensen et al.[35] also showed that a non-traditional exercise (floorball) could enhance motor learning compared to running; besides, both groups were superior in the retention test than rest condition.

In a complementary perspective, Tomporowski & Pendleton[21] demonstrated that performing an exercise after the practice based on a dance routine with a high complexity level (high complexity steps involved in the dance routine) improved more the consolidation processes than a simple dance routine. Though, when exercises (simple and complex) were performed before the practice, there was no enhancement effect on the retention of the pursuit-rotor task.

These studies demonstrated that the exercise priming effects might also be provided using non-traditional exercise types, with a level of evidence of 1A. It seems that mental engagement during the cardiovascular exercise session can be a factor that may influence the priming effect derived from cardiovascular exercise, with a level of evidence of 1B.

Intensity

Thomas, Johnsen, et al.[48] showed that the group that performed High-Intensity Interval Training (HIIT) demonstrated better retention if compared to the group that performed the interval training with the intensity of 45% W_{max}; yet, both groups were better in the retention test than the group that just had practice. Contrary, Opie & Semmler[40] related that a low-intense running protocol induced better 24-h retention of a ballistic thumb abduction task than a high-intense condition; also, they reported that both exercise conditions (low and intense) induced better retention than just practice condition.

On the other hand, Baird et al.[58] did not demonstrate a significant difference in motor performance and learning in the groups with interval training of high intensity 80% W_{max} and low intensity 40 W_{max} with the energy expenditure matched between them. In this case, this finding allows us to suppose that the effect on motor performance and learning is not derived from the intensity, but it is energy-expenditure dependent, in other words, total work dependent.

Another two studies did not demonstrate significant differences between high and low intensities on motor performance and learning. Wanner et al.[55] did not find a significant difference in the motor performance and learning of a balance task among the groups that had low-intensity (25% W_{max}), moderate-intensity (45% W_{max}), and high-intensity (90% W_{max}) exercises before practice. Lorås et al.[42] did not demonstrate a significant difference in the learning of golf putting task between the groups with a cardiovascular exercise at either 50% to 75% of the age-predicted maximal heart rate.

These results did not support the idea that exercise priming is dependent on high-intensity cardiovascular exercise. Contrary, perhaps the critical aspect can be the total volume instead of intensity per se.

Volume

As demonstrated by Baird et al.[58], the volume or total work may be more important than intensity concerning cardiovascular exercise effects on motor learning. However, Angulo-Barroso et al.[39] demonstrated that a long-High Intense Interval Training (HIIT) (total 13 min) was not significantly different from a short-HIIT (total 5 min); moreover, both exercise groups were better than the rest group in the retention test. In this case, there is no consensus about the volume or total work effect of cardiovascular exercise on motor learning.

Given the heterogeneity of the exercise protocols used in the studies incorporated in this review and the lack of information about the exercise, it was impossible to assess the volume exercise effects on motor learning compared to the other studies.

Task characteristics

Continuous, serial, and discrete skills

Most studies that identified positive effects of the cardiovascular exercise on consolidation processes used continuous and temporal synchronization tasks[21,34,35,37,40,41,43-45,47,48,50]. Nevertheless, most studies that used serial tasks did not demonstrate effects from cardiovascular exercise on the motor memory consolidation[20,51,52,54,56-58], or just demonstrated effect on relearning[60].

In this case, these findings revealed that cardiovascular exercise priming effects on motor learning are superior in continuous and temporal synchronization tasks than serial tasks. This evidence has a level of 1A.

Regarding discrete skills, only Lorås et al.[42] investigated the effect of different cardiovascular exercise intensities in golf putting task learning. However, this study can not infer the cardiovascular exercise effect; there was no control group (rest condition). It is necessary to investigate more discrete skills to create reliable conclusions for this motor skill type.

Simple and complex tasks

Most studies that were incorporated in this review used simple perceptual-motor laboratory skills. Among them were used visuomotor accuracy-tracking task[32,34,35,37,41,43-45,47,48,50], sequential visual isometric pinch task[20,36], motor sequence task[46], serial targeting task[60], rotational visuomotor adaptation task[33,38,57], serial reaction time task[52] and keyboard typing task[54].

Only 5 studies incorporated complex motor skills in their experimental design, demonstrating the necessity of the subsequent studies in this area to incorporate it. As mentioned before, Wanner et al.[55] and Lorås et al.[42] investigated the intensity effects of cardiovascular exercise on motor learning. Both studies demonstrated that the intensity did not impact the learning of balance and golf putting tasks, respectively.

Helm et al.[53] and Charalambous et al.[59] investigated cardiovascular exercise effects on locomotor skill learning. Both studies demonstrated that cardiovascular exercise did not benefit the learning of a locomotor skill; this evidence has level 1B. These studies used protocols of exercise mutually different. Helm et al.[53] proposed exercise using HIIT protocol in an upper-body ergometer before the practice (to avoid fatigue effect on motor effector related to the motor performance). Whereas Charalambous et al.[59] promoted exercise after motor practice using a continuous protocol in a total body exerciser ergometer. Both studies corroborated with the no effect of cardiovascular exercise on motor learning even with different exercise protocols, reinforcing the non-susceptibility of locomotor skill to exercise priming.

Finally, Chartrand et al.[56] identified that a moderate-intense continuous running session performed after the practice did not influence the learning of laparoscopic surgery simulator tasks. However, in this study, the participants practiced 3 tasks simultaneously, promoting an interfering effect.

Retroactive interference

The studies demonstrated that a cardiovascular exercise bout exerts a protective effect on retroactive interference[41,46,50]. However, when the retention test was performed on the same day of the practice, there was no protective effect against retroactive interference, suggesting that the cardiovascular exercise effects are sleep-dependent in this case[51]. It was also demonstrated that the protective effect of cardiovascular exercise is more evident when the cardiovascular exercise is performed in a temporal close to the task to be prioritized[46]. The evidence that cardiovascular exercise induces a protective effect against retroactive interference has a level 1A.

Adaptation

There was no effect of the cardiovascular exercise on motor adaptation across the practice in all of them. It was verified in young adults[39,57] and children[38]. Also, Angulo-Barroso et al.[39] verified that increasing the exercise duration (volume) did not impact the adaptation during motor performance. There is evidence of 1A that cardiovascular exercise did not influence the adaptation during motor performance.

Implicit x explicit

Some insights maybe support the hypothesis that cardiovascular exercise would be an attractive strategy to improve implicit motor learning. Mang et al.[57] demonstrated in a serial motor sequence task that the cardiovascular exercise improved motor performance related to the implicit representation, which did not occur in the pseudorandom sequences.

Besides, Poolton et al.[29] and Masters et al.[30] demonstrated that a high fatigue level impacts the motor learning process based on explicit mechanisms. Both studies demonstrated that implicit learning is resistant to the high level of effort and fatigue provided by cardiovascular (VO_2 max fatigue test) and anaerobic (Wingate anaerobic test peak power).

Then, the priming effects from the cardiovascular exercise are related to the type of motor learning process that was engaged during the skill acquisition. The implicit motor learning is more resilient and stable under stress and fatigue effects, suggesting that the exercise can induce better motor consolidation of implicit motor memories than explicit motor memories[29,30].

Methodological considerations

Some studies used cross-over designs in their experimental setup[32,33,40,44,60]. Cross-over designs induce significant limitations in the inference about motor learning. The participants may transfer the learning from the first phase to the second phase of the experiment, promoting fewer motor improvements in the second phase, which may induce misconceptions. The cross-over studies adopted some strategies to avoid problems with that, such as 1 - to allocate the participants by a random process such that half of the participants completed the rest condition first and the other half the cardiovascular exercise condition. 2 - to promote washout of at least two weeks between the phases of the study. 3 - to provide some modification in the task between the first and second study phases. However, even with all these methodological details, this experimental design must be avoided in further studies to ensure a reliable interpretation of the motor learning phenomenon.

Study limitations

Motor learning literature has not had any methodological quality assessment tool to evaluate motor learning studies. In this way, this review used health research science tools in an adapted approach that can be verified in the Supplementary Material. This methodological assessment was based on a previous systematic review of the motor learning area. The development of instruments for assessing the methodological quality of motor learning studies may have particular implications for further systematic reviews in this area. It may be useful to guide the subsequent studies in the motor learning field.

Conclusion

This systematic review of 40 studies provides a synopsis of evidence that indicates the benefit of the acute effects of cardiovascular exercise on motor performance and learning. Until now, the evidence suggests that exercise-induced fatigue does not impair motor learning, mainly when the exercise does not engage the same motor effector involved in the performance of the motor task.

The studies also demonstrated that the effects of cardiovascular exercise on motor learning are more evident when the exercise is performed in temporal proximity of the practice; besides, depending on the order between exercise and practice, the priming effects perhaps can impact the motor learning process differently.

There is evidence that different types of exercise may induce positive effects on motor learning. However, the exercise that involves a higher amount of muscle mass may stimulate priming effects with more regularity. Given that cardiovascular exercise that does not engage larger muscle groups during the performance (e.g., upper body ergometer) may be limited by local/neural fatigue, consequently, it does not stimulate in a high magnitude the metabolic/ cardiovascular systems, which may decrease the priming effects.

The exercise intensity was not more determinant than the total work for motor performance and learning enhancements. So, the importance attributed to high-intensity protocols needs to be revisited. In this case, the moderate-intensity protocols are equally effective as high-intensity protocols if the total work is pared between them.

Regarding task characteristics, the exercise priming on motor learning is more evident for continuous tasks than serial tasks. The cardiovascular exercise has an interesting effect on avoiding retroactive interference when allocated between the practice of 2 different motor skills; probably, this effect is sleep-dependent and occurs when the cardiovascular exercise is performed immediately after the practice of the first motor skill. Finally, the current evidence suggests that cardiovascular exercise does not influence adaptation. It was identified with different exercise protocols and the timing (before or after practice).

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