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SYSTEMATIC REVIEW

The Immediate Effects of Acute Aerobic Exercise on Cognition in Healthy Older Adults: A Systematic Review

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Abstract

Background Age-related cognitive decline is a worldwide challenge, highlighting the need for safe, effective interventions that benefit cognition in older adults. Harnessing the immediate and long-term pleiotropic effects of aerobic exercise is one approach that has gained increasing interest.

Objective The aim of this review is to provide knowledge on the immediate effects of acute aerobic exercise on cognitive function of healthy older adults and to assess the methodological quality of studies investigating these effects.

Methods A database search in PubMed, CINAHL, Cochrane Central Register of Controlled Trials, Embase, PsycINFO, Web of Science, ClinicalTrials.gov and Google Scholar was conducted using a systematic search strategy.

Results Fifteen studies were identified and cognitive domains investigated included executive function and visual perception. Results from 14 of 15 studies showed that an acute bout of aerobic exercise can enhance at least one subsequent cognitive performance of healthy older adults when measured within 15 min post-exercise.

Conclusion The small number of studies available, the limited domains of cognition investigated, the great variability between research protocols, and the low overall quality rating limits the conclusions that can be drawn. More comprehensive randomised controlled trials are needed to address these limitations and verify the potential benefits of acute aerobic exercise.

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Key Points

While there is increasing evidence of the beneficial effects of one single bout of aerobic exercise on cognitive functions of healthy young adults, the immediate effects of acute aerobic exercise on cognitive functions of healthy older adults remain unclear.

Fifteen studies examining cognitive functions post acute aerobic exercise were reviewed and all included studies measured post-exercise executive function performance, with one study also examining post-exercise audio-visual perception.

The results for executive performance and audio-visual perception assessed within 15 min post-exercise indicate that healthy older adults can cognitively benefit from a single bout of aerobic exercise.

1 Introduction

Worldwide, population ageing is a well-known public health challenge. According to the United Nation's 2015 world population prospects, the global population aged 60 years and above is expected to more than double by 2050 and more than triple by 2100 [1]. Age-related reductions in cognitive performance, such as a decrease in processing speed, attention, executive functions and memory are well-documented and can be associated with cognitive disorders such as dementia [2–5]. Therefore, with this rapid increase in population ageing and associated age-related cognitive decline, there is a need to identify innovative and effective treatments to prevent, reduce and delay functional impacts of normal age-related cognitive decline on the daily lives of healthy older adults.

Over the past few decades, chronic aerobic exercise has received increasing interest for its potential to provide a drug-free treatment for maintaining and reversing age-related cognitive decline in older adults [6, 7]. This increase in interest in long-term exercise effects is based in part on the premise that physiological responses induced by aerobic physical exercise, such as an increase in heart rate, have the potential to positively impact cognitive functions [7]. An increased heart rate during physical activity can trigger neurophysiological effects by inducing changes in the transcriptional profiles of growth and neurotrophic factors, such as vascular endothelial growth factor, insulin-like growth factor-1 and brain-derived neurotrophic factor (BDNF) [8]. As a result, these changes are thought to improve various aspects of cognition due to greater efficiency of the vascular system and enhanced neuroplastic mechanisms in the brain [8]. All of these neurophysiological changes are likely mediating improvements in cognitive function induced by chronic exercise.

More recently, a growing body of literature has investigated the effects of one single bout of aerobic exercise on cognitive functions, also referred to as the acute effects of aerobic exercise. As described by Roig et al. [9], the acute effects of exercise on cognition refers to performing one single bout of exercise in close temporal proximity to the measurement of the cognitive outcome of interest [9]. To date, the acute effects of aerobic exercise on cognitive functions have been mostly studied in samples of healthy young adults [10–14]. These studies have provided evidence that physiological responses to acute aerobic exercise can indeed positively impact cognitive performance in healthy young adults. These include changes in catecholamine levels, such as dopamine, as well as changes in the concentration of neurotrophic factors, such as BDNF [10, 14, 15].

The effects of acute exercise on the cognitive function of older adults have only been reviewed twice [16, 17]. Ludyga et al. [16] identified seven studies investigating the acute effects of moderate-intensity aerobic exercise on the executive functions of older adults aged 50 years and above and reported a greater benefit from acute exercise in the older adult group ($g = 0.67$) compared with other age groups when reaction time was considered as a dependent variable [16]. Chang et al. [17] identified six studies investigating the effects of a single bout of exercise on the cognitive functions of participants aged over 60 years and reported a small positive effect ($g = 0.181$; 95% confidence interval [CI] 0.073, 0.290) for this specific age group. Additionally, Chang et al. [17] reported a greater benefit from acute exercise when the assessment of cognitive functions was performed within 15 min post-exercise ($g = 0.139$; 95% CI 0.102, 0.176) in comparison with cognitive functions assessed more than 15 min post-exercise ($g = -0.054$, 95% CI −0.147, 0.038). Although that review suggested immediate cognitive benefits from a single bout of exercise in a population of older adults, it included healthy and cognitively impaired samples of participants, as well as anaerobic types of physical activity [17]. Therefore, it is difficult to draw conclusions from that review regarding the immediate effects of acute aerobic exercise on cognitive functions of healthy older adults.

Thus, the aims of this current review were to (1) systematically identify and review all studies investigating the immediate effects of acute aerobic exercise on cognitive functions of healthy older adults; (2) to review the dose–response relationship between acute aerobic exercise (i.e. exercise intensity, duration) and cognition in healthy older adults; and (3) provide a methodological quality assessment of all included studies.

2 Methods

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [18], which outline the preferred items to report in a systematic review, were applied in accordance with the needs of the current review.

2.1 Search Strategy

To identify all potentially relevant data from intervention studies, an initial systematic literature search was conducted on 20 October 2016. Updated searches were also conducted on 12 July 2017 and 28 August 2018 to include new citations made available between the initial search and 28 August 2018. The initial search, as well as the updated searches, included the following databases: PubMed (1951–2018), Embase (1966–2018), CINAHL (1982–2018), PsycINFO (1840–2018), the Cochrane Central Register of Controlled Trials (1996–2018) and Web of Science (1950–2018).

Search terms used in the PubMed database are presented in electronic supplementary material Appendix S1. In addition, a search through the Google Scholar and ClinicalTrials.gov databases was conducted to identify unpublished literature. Search terms used to identify unpublished literature included (cognition OR executive function OR problem solving OR memory OR attention OR language OR visual perception) AND (acute exercise OR single bout OR aerobic exercise). Moreover, searches included all languages and reference lists from included studies were further screened to identify additional relevant citations.

2.2 Study Selection

Two reviewers (MM and CM) independently screened the titles and abstracts of each identified citation. During this first screening stage, studies were classified as being relevant, potentially relevant or completely irrelevant. Consensus had to be reached between both reviewers for a study to be included in or excluded from further screening. In the second screening stage, a full-text review of the relevant and potentially relevant articles was performed and both reviewers had to come to an agreement for a study to be included in or excluded from the systematic review. During the second screening stage, a third reviewer (DC) was consulted when consensus could not be reached between the initial two independent reviewers.

Studies were included in this systematic review if they met all of the following inclusion criteria: (1) physically and cognitively healthy subject sample aged 60 years and above; (2) exercise intervention consisting of a single bout of aerobic exercise performed immediately prior (within 15 min) to the assessment of the cognitive outcome measure of interest; (3) cognitive function assessment beginning within 15 min post-exercise using a neuropsychological test dedicated to assessing cognition; and (4) randomized controlled trial or non-randomized controlled trial. Studies were excluded if they met one of the following exclusion criteria: (1) participants under the age of 60 years or participants presenting with neurological disorders, mental health disorders or chronic medical illnesses; (2) anaerobic exercise, concurrent exercise and cognitive training, single bout of exercise performed after assessing the cognitive outcome measure of interest, multiple sessions of exercise investigating the chronic effects of exercise (unless cognitive performance was assessed after the first bout of aerobic exercise), single bout of exercise combined with a pharmacological treatment; (3) cognitive functions were not measured, or were not assessed using a neuropsychological test dedicated to assessing cognition; and (4) qualitative study, single-case study, review, non-intervention study, abstract or dissertation.

For the purpose of this review, acute aerobic exercise refers to one single bout of any activity that uses large muscle groups, which can be maintained continuously, is rhythmic in nature and is performed within a single day [19]. The 'immediate' effect refers to cognitive outcome measures administered within 15 min following the acute bout of aerobic exercise [17]. It is relevant to acknowledge that immediate effects can also be observed in studies where exercise is performed during or after a cognitive task. Cognition refers to the following cognitive domains: executive function, attention, language, memory and visual perception as outlined by previous work in the field of cognition [20, 21]. Finally, healthy older adults are defined as adults aged 60 years and above, as per the standards of the United Nations [1], without known cognitive or physical impairments.

2.3 Data Extraction and Analysis

The data from all included studies were extracted by two independent reviewers (MM and CM) using a standardized form developed for this review. All relevant characteristics were extracted, including study design; sample size; participants' age and sex; the duration, intensity and type of exercise condition; the duration and type of the control condition; the type and timing of cognitive assessment; and the results from the cognitive outcome measures of interest. Extracted data forms were compared between both reviewers to ensure accurate and comprehensive data extraction. For the purpose of this review, our analysis focused on qualitatively describing the findings of each included study by focusing primarily on the cognitive outcome measures, and, secondarily, on additional moderator variables (e.g. fitness level, exercise intensity). Additionally, Cohen's d effect sizes [22] and the 95% CIs were derived for each cognitive outcome measure using reported data and statistics from each study. Effect sizes were interpreted as small ($d = 0.2$), medium ($d = 0.5$) or large ($d = 0.8$) [22].

2.4 Quality Appraisal

Two reviewers (MM and CM) independently assessed and scored the methodological quality of each included study using a modified version of the Physiotherapy Evidence Database (PEDro) scale [23], which is a reliable tool for primarily rating the quality of randomized controlled trials and is based on the Delphi list developed by Verhagen and colleagues [24]. For the purpose of this review, the PEDro scale was modified to disregard the blinding of participants and investigators. As described by Ludyga et al. [16], a true blinding of participants and investigators is almost impossible to achieve in studies investigating the effects of a single bout of exercise on cognitive functions. Moreover, the original PEDro scale does not include the 'eligibility criteria' item in the final quality score, and, as a result, the final quality score of each study included in this review is out of 8. For a score to be considered as final, an agreement had to be reached between the two independent reviewers.

3 Results

3.1 Study Selection

Fifteen studies met all the eligibility criteria and are included in this review. Figure 1 illustrates the selection process using a PRISMA flow diagram [18].

3.2 Study Characteristics and Participants

From the 15 included studies, study designs consisted of randomised controlled trials (n=4), pre-test/post-test designs (n=4), crossover designs (n=4), post-test designs (n=2), and quasi-experimental designs (n=1). The total number of participants in each study varied from 11 [25] to 58 [26], with a total of 410 participants over all 15 studies. Eleven of the 15 studies included both males and females, whereas two studies only recruited females and another two studies only recruited males. A total of 234 female and 176 male participants were included in this review. All included studies reported having participants aged 60 years and above, with Stones and Dawe [27] having the largest age range (i.e. 60–93 years). All included studies either explicitly stated that their participants were healthy, screened their participants for cognitive and physical impairments, or reported that they excluded participants with neurological disorders, mental health disorders or chronic medical illnesses. Cognitive screening assessments were used, such as the Mini-Mental State Examination [28], with various cut-offs used in each study [29–34]. In two specific studies [30, 35], the fitness levels of participants at baseline were taken into consideration, with participants divided into a lower-fitness group or a higher-fitness group. Additionally, O'Brien et al. [26] considered habitual activity levels and grouped their participants based on whether they were performing open

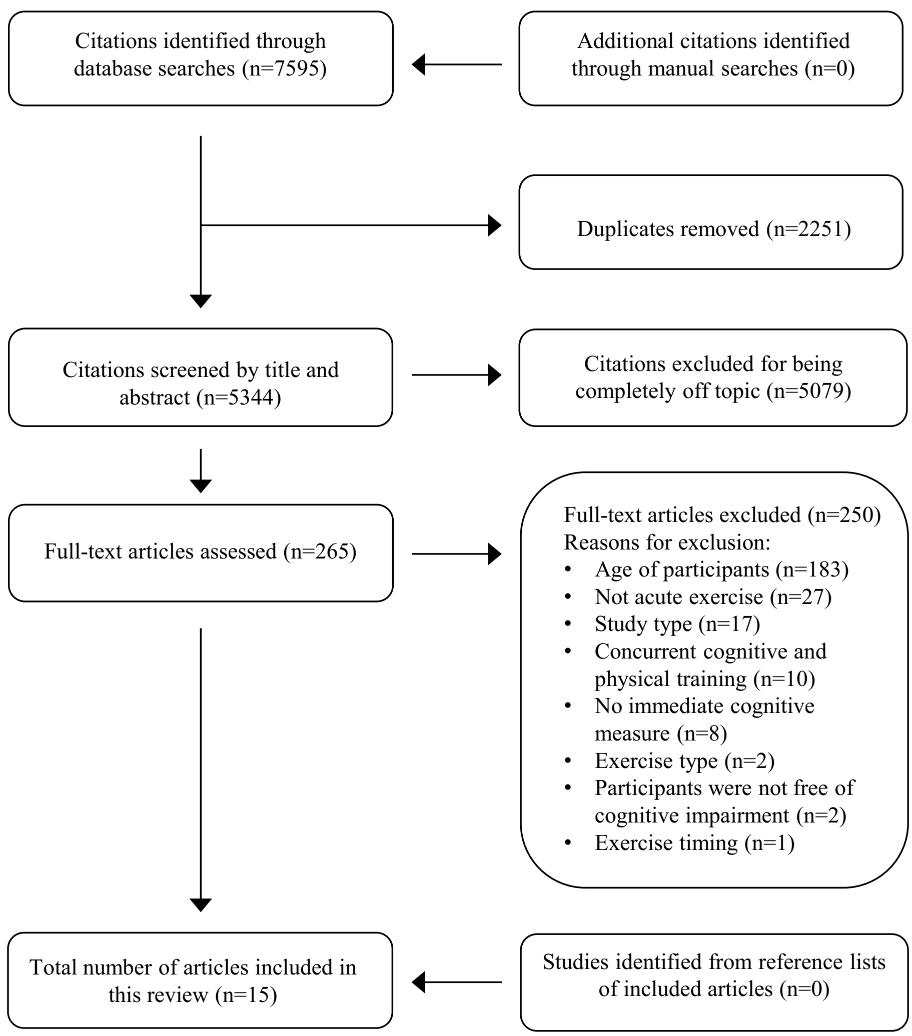

Fig. 1 PRISMA flow diagram of the selection process. *PRISMA* Preferred Reporting Items for Systematic reviews and Meta-Analyses

skill exercises (e.g. dance or tennis) or closed skill exercises (e.g. gym or swimming) in their everyday life. Table 1 provides a summary of the study designs and participant characteristics.

3.3 Intervention

For studies with a control group ($n=10$), control conditions included resting [29, 31, 36], sitting [33, 37], reading [30, 35], watching a video [27, 38] and playing card games in a group [26]. Exercise conditions included walking [25, 37, 39, 40], stepping while sitting [29], a combination of stretching, flexibility exercises and walking [27, 38], cycling [30–33, 35, 36], dancing [26, 34] and either tennis, gym or swimming [26]. In addition to having a group of participants performing a single bout of aerobic exercise, Johnson et al. [38] also had a group of participants performing resistance exercises, which are considered anaerobic exercises. Since this review focused on aerobic exercise, data from this group of participants were disregarded.

The total duration of the exercise interventions varied from 7 min [31] to 120 min [39], whereas the exercise intensity varied from a sedentary level for control conditions to a vigorous-intensity level for exercise conditions [25]. For the purpose of this review, and to compare intensity levels across studies, intensities reported in Table 1 have been presented according to an intensity classification system based on the terminology outlined by Norton et al. [41], and conversions to a percentage of maximal oxygen uptake (VO_{2max}) from the American College of Sports Medicine Guidelines Book were needed [19, 41]. According to Norton et al. [41], sedentary intensity consists of $<40\%$ maximum heart rate (HR_{max}), light intensity consists of 40 to $<55\%$ HR_{max}, moderate intensity consists of 55 to $<70\%$ HR_{max}, vigorous intensity consists of 70 to $<90\%$ HR_{max} and high intensity consists of $\geq 90\%$ HR_{max} [41]. Therefore, the new classification is based on the description within the journal articles, but may differ from the intensity-level term originally reported. Table 1 also presents the intervention characteristics, such as type and duration, for the control and exercise conditions of all 15 included studies.

3.4 Cognitive Outcome Measures

A variety of cognitive tasks were used to assess cognitive function in healthy older adults following an acute bout of aerobic exercise, and four studies used more than one task. These cognitive tasks included the Stroop task ($n=6$) [42], the set test ($n=2$) [43], a phonologically cued word fluency test ($n=2$) [44], the symbol digit test ($n=2$) [45], a modified version of the Flanker task ($n=2$) [46], digit span tasks ($n=2$), the Wisconsin Card Sorting Test (WCST; $n=1$) [47], the alternative uses test ($n=1$) [48], the d2 test ($n=1$) [49], a task-switching reaction time test ($n=1$) and the Sound-Induced Flash Illusion task ($n=1$) [50]. All cognitive tasks used were executive function tasks with the exception of the Sound-Induced Flash Illusion task, which assesses cross-modal perception. All 15 included studies reported a measure of cognitive function pre-intervention, with the exception of Chang et al. [30] and Chu et al. [35] due to their post-test design. When there was more than one administration of a cognitive measure within 15 min post-intervention, only the earliest measure is presented and discussed in this review. When combining all 15 studies, a total of 52 subtests of cognitive tasks were administered, with 33 of these 52 showing a significant enhancement post-intervention. In order to highlight the different findings across cognitive functions, results will be presented by cognitive task. Table 1 presents the cognitive tasks, cognitive domains assessed and the timing of the cognitive assessment for each included study.

3.4.1 The Stroop Task

Six studies used the Stroop task to assess executive function, as well as information processing speed, attention, inhibition and short-term memory following a single bout of acute aerobic exercise [29–32, 35, 37]. Findings from Barella et al. [37] suggest that the immediate effects of a 20-min bout of moderate-intensity walking ($60\% \pm 3\%$ of HR reserve) were limited to the Stroop color subtest ($d=0.54$), a measure of information processing speed. However, there was no effect on Stroop interference or the Stroop inhibition subtests, which are measures of executive function [37]. Results from Hyodo et al. [31] differ from Barella et al. [37] and suggest a significant effect ($d=1.05$) of a 7-min bout of moderate-intensity cycling (50% of VO_{2max}) on performance of the Stroop incongruent (interference) subtest, however not on the Stroop neutral (color) subtest when compared with a control condition [31]. Similar to Hyodo et al. [31], Abe et al. [29] reported an improved performance on the Stoop interference subtest ($d=0.09$) after performing a 10-min session of stepping exercises while sitting, but did not report an improved performance on the Stroop color subtest [29]. Abe et al. [29] did not provide a measure of intensity level for the stepping exercises. Additional discrepancies could also be found in the results from Johnson et al. [32]. Participants in the study by Johnson et al. [32] performed two exercise conditions, a 10-min and a 30-min moderate-intensity cycling bout (rate of perceived exertion of 13–14), and both conditions significantly ($d=0.40$ and $d=0.37$, respectively) enhanced the participant's performance on the Stroop inhibition subtest. However, no improvements were found on the Stroop color or Stroop interference subtest post-exercise [32]. Therefore, Johnson et al. [32] suggested an improvement on the more complex executive functioning task, the inhibition subtest, regardless of the duration of exercise.

Table 1 Characteristics of the included studies

Study	Design	Participants		Exercise intervention			Cognitive outcome		
		Age, years [mean (SD)]	Sample size (sex)	Type of exercise	Duration of exercise	Intensity of exercise	Cognitive task	Cognitive domain(s)	Timing of assessment
Abe et al. [29]	Counter-balanced crossover	Total: 71.8 (4.7)	CG: 26 EG: 26 Total: 26 (18F, 8M)	CG: Resting EG: Stepping while sitting	CG: 10 min EG: 10 min	CG: NA EG: Not reported	Stroop task: color-word matching	Executive functions	Pre-test and post-test (5 min after exercise)
Barella et al. [37]	RCT	Total: 69.5 (8.3)	CG: 20 EG: 20 Total: 40 (32F, 8M)	CG: Sitting at the end of the treadmill EG: Walking	CG: 25 min EG: 25 min, including a 5-min warm-up	CG: NA EG: Moderate (60% ± 3% of HR reserve)	Computerized version of the Stroop task: color, interference and inhibition	Executive functions	Pre-test, immediately after, 5, 10, 15, 20, 30, 45, 60, 75, 90, 105 and 120 min post-test
Chang et al. [30]	Counter-balanced randomized control group post-test	Total: 63.1 (2.9)	LFG: 21 HFG: 21 Total: 42 (42M)	CG: Reading EG: Cycling	CG: ND EG: 30 min, including a 5-min warm-up and cool-down	CG: NA EG: Light to moderate (50–60% of HR reserve)	Computerized version of the Stroop task: congruent and incongruent subtests	Executive functions	Post-test: 15 min after the cessation of exercise
Chu et al. [35]	Counter-balanced randomized control group post-test	LFG: 64.9 (4.0) HFG: 63.8 (2.3)	LFG: 24 HFG: 22 Total: 46 (22F, 24M)	CG: Reading EG: Cycling	CG: ND EG: 30 min, including a 5-min warm-up and cool-down	CG: Low arousal level EG: Moderate (65% of HR reserve)	Computerized version of the Stroop task: congruent and incongruent subtests	Executive functions	Post-test: Within 5 min after the cessation of exercise
Dawe and Moore-Orr [38]	RCT	CG: 85.1 (6.1) EG: 83.9 (4.8)	CG: 10 EG: 10 Total: 20 (16F, 4M)	CG: Watched a video EG: Walking, stretching and flexing exercises	CG: 15 min EG: 19 min, including a 2-min warm-up and cool-down	CG: NA EG: Sedentary to light (slight increase in HR but not maintained)	The set test, word fluency test and symbol digit test	Executive functions	Pre-test, immediately post-test and 30 min post-test
Hatta et al. [39]	Pre-test/post test	Total: 70.5 (3.4)	CG: NA EG: 20 Total: 20 (10F, 10M)	CG: NA EG: Self-paced walking (no specific distance)	CG: NA EG: 80–120 min	CG: NA EG: Moderate to vigorous (67.4% ± 8.0% of HR_{max})	Computerized Keio version of the Wisconsin Card Sorting Test	Executive functions	Pre-test (immediately before walking), post-test (immediately after walking)
Hyodo et al. [31]	Counter-balanced crossover	Total: 69.3 (3.5)	CG: 16 EG: 16 Total: 16 (3F, 13M)	CG: Resting EG: Cycling	CG: 25 min EG: 10 min, including a 3-min warm-up	CG: NA EG: Moderate (50% VO_{2max})	Stroop task: color-word matching	Executive functions	Pre-test and post-test (15 min after exercising or immediately after resting)

Table 1 (continued)

Study	Design	Participants		Exercise intervention			Cognitive outcome		
		Age, years [mean (SD)]	Sample size (sex)	Type of exercise	Duration of exercise	Intensity of exercise	Cognitive task	Cognitive domain(s)	Timing of assessment
Johnson et al. [32]	Pre-test/post test	Total: 71.7 (1.5)	Total: 31 (21F, 10M)	EG no. 1: Cycling EG no. 2: Resistance exercises	EG no. 1: 10 and 30 min EG no. 2: 10 and 30 min (in two sessions)	EG no. 1: Moderate (RPE 13–14) EG no. 2: Moderate (60% of 1RM)	Stroop task: color, interference and inhibition	Executive functions	Pre-test, immediately post-test, 30 min and 60 min post-test
Kamijo et al. [33]	Counter-balanced crossover	Total: 65.5 (1.5)	Total: 15 (15M) 3M were excluded, leaving 12M for analysis	CG: Sitting EG no. 1 and 2: Cycling	CG: ND EG no. 1 and 2: 25 min, including a 5-min warm-up	CG: NA EG no. 1: Light (30% VO_{2max}) EG no. 2: Moderate (50% VO_{2max})	Modified Flanker Task	Executive functions	Pre-test and post-test (less than 2 min after exercise)
Kimura and Hozumi [34]	RCT	EG no. 1: 70.7 (ND) EG no. 2: 71.1 (ND)	EG no. 1: 17 (7M) EG no. 2: 17 (7M) Total: 34 (20F, 14M)	EG no. 1: Combination-style dance EG no. 2: Free-style dance	EG no. 1 and 2: 40 min, including a 10-min warm-up and cool-down	EG no. 1 and 2: Light (40–50% of HR reserve)	The task-switching reaction time test	Executive functions	Pre-test and post-test (within 10 min after exercise)
Netz et al. [40]	Pre-test/post test	Total: 63.7 (3.6)	Total: 20 (20F)	CG: NA EG: Walking on a treadmill	CG: NA EG: 44 min, including a 6-min warm-up and 3-min cool-down	CG: NA EG: Moderate (60% of HR reserve)	Alternative uses test	Executive functions	Pre-test and post-test (5 min and 60 min after exercise)
O'Brien et al. [26]	Quasi-experimental	Total: 69.7 (5.6)	CG: 21 OS: 18 CS: 19 Total: 58 (37F, 21M)	CG: Group meeting, card games OS: Aerobics, tennis, dance CS: Gym or swimming	CG: 60 min OS: 60–80 min CS: 60–80 min	CG: NA OS: Not measured CS: Not measured	Digit span task and Sound-Induced Flash Illusion	Executive functions and audio-visual perception	Pre-test and post-test (within 10 min after exercise or sedentary activity)
Peiffer et al. [25]	Pre-test/post test	Total: 65.8 (3.8)	Total: 11 (11F)	CG: NA EG no. 1 and 2: Walking on a treadmill	CG: NA EG no. 1 and 2: 25 min, including a 5-min warm-up	CG: NA EG no. 1: Moderate (50% VO_{2max}) EG no. 2: Vigorous (75% VO_{2max})	Modified Flanker test and d2 test	Executive functions	Pre-test and post-test (within 2 min and 30 min post-exercise)

Table 1 (continued)

Study	Design	Participants		Exercise intervention			Cognitive outcome		
		Age, years [mean (SD)]	Sample size (sex)	Type of exercise	Duration of exercise	Intensity of exercise	Cognitive task	Cognitive domain(s)	Timing of assessment
Stones and Dawe [27]	RCT	Total: 84.5 (ND)	CG: 10 (ND) EG: 10 (ND) Total: 20 (17F, 3M)	CG: Watched a video EG: Stretching, flexibility and aerobics	CG: 'Similar interval' EG: 19 min, including a 2-min warm-up and cool-down	CG: NA EG: Sedentary to light intensity	Modified set test, word fluency task, symbol digit task	Executive functions	Pre-test and post-test (immediately after and 30 min post-exercise)
Tsuji et al. [36]	Counter-balanced crossover	Total: 65.9 (1.0)	Total: unclear (either 14 or 16, with 9F, 7M)	CG: Resting EG: Cycling	CG: 10 min EG: 10 min	CG: NA EG: Light to moderate (40% of VO_{2max})	Digit working memory task	Executive functions	Pre-test and post-test (10 min after exercise)

SD standard deviation, *RCT* randomized controlled trial, *CG* control group, *EG* exercise group, *F* female, *M* male, *NA* not applicable, *ND* no data, *LFG* lower-fitness group, *HFG* higher-fitness group, *HR* heart rate, *RPE* rate of perceived exertion, *RM* repetition maximum, $VO_{2}max$ maximal oxygen uptake, *OS* open skill, *CS* closed skill, *HRmax* maximum heart rate

Chang et al. [30] and Chu et al. [35] presented different findings from Abe et al. [29], Barella et al. [37], Hyodo et al. [31] and Johnson et al. [32], with results suggesting enhanced performance on both the Stroop congruent (color) subtest and incongruent subtest for both the lower-fitness and higher-fitness groups following 25 min of either light- to moderate-intensity cycling (50–60% of HR reserve) [30] or moderate-intensity cycling (65% of HR reserve) [35]. Effect sizes for all groups and task subtests investigated by Chang et al. [30] and Chu et al. [35] are presented in Table 2. Although both fitness groups benefited from the acute bout of cycling, both studies reported a significantly greater benefit for the higher-fitness group when compared with the lower-fitness group [30, 35].

3.4.2 Verbal Fluencies and Symbol Digit Task

Post-intervention verbal fluency performance was assessed in two studies using the set test for semantically cued verbal fluency and the word fluency test for phonologically cued verbal fluency [27, 38]. Both Dawe and Moore-Orr [38] and Stones and Dawe [27] reported enhanced performance ($d=0.54$) on the set test following a 15-min single bout of sedentary- to light-intensity physical exercise (e.g. range of motion exercises and walking) when compared with a control group who watched a 15-min video. However, neither study observed a significant increase in performance on the phonologically cued word fluency test [27, 38]. Furthermore, Dawe and Moore-Orr [38] and Stones and Dawe [27] also assessed post-intervention visuo-motor performance using a symbol digit task, under the same exercise and control conditions. Both studies reported no significant differences on the symbol digit task performance between the intervention and control groups [27, 38].

3.4.3 The Flanker Task

Kamijo et al. [33] and Peiffer et al. [25] used a modified version of the Eriksen Flanker task to assess executive control. Kamijo et al. [33] investigated bouts of 20 min at one of two levels of exercise intensity—either a light-intensity cycling bout (30% of VO_{2max}) or a moderate-intensity cycling bout (50% of VO_{2max}). Results from Kamijo et al. [33] showed a significant improvement after moderate-intensity exercise on the Flanker task congruent ($d=0.92$) and incongruent ($d=0.69$) subtests, and no significant differences were found following light-intensity exercise [33]. Peiffer et al. [25] also included two levels of exercise intensity: moderate-intensity walking (50% of VO_{2max}) and vigorous-intensity walking (75% of VO_{2max}), but the results were averaged across exercise intensity. A 20-min bout of moderate- to vigorous-intensity walking significantly enhanced the Flanker task total score ($d=0.35$), congruent subtest score ($d=0.22$) and

Table 2 Results of the included studies

Study	Notes	Exercise intervention	Cognitive task—subtest and significant difference (+)		Effect size (95% CI)
Abe et al. [29]	Only the stepping condition is reported here as being an aerobic type of exercise	10 min of stepping exercises	Stroop color subtest	0	$d=-0.10$ (−0.64, 0.45)
			Stroop incongruent subtest	+	$d=0.09$ (−0.45, 0.63)
Barella et al. [37]	Of the 12 time points post-exercise, only the 'immediately after' time point is reported here	20 min of moderate-intensity walking	Stroop color subtest	+	$d=0.54$ (−0.10, 1.16)
			Stroop interference subtest	0	$d=0.14$ (−0.48, 0.76)
			Stroop inhibition subtest	0	$d=0.29$ (−0.34, 0.91)
Chang et al. [30]	This study also recorded event-related desynchronization during the Stroop task	25 min of light- to moderate-intensity cycling	Stroop congruent LFG	+	$d=0.23$ (−0.38, 0.83)
			Stroop incongruent LFG	+	$d=0.13$ (−0.48, 0.73)
			Stroop congruent HFG	+	$d=0.34$ (0.28, 0.94)
			Stroop incongruent HFG	+	$d=0.47$ (−0.15, 1.07)
Chu et al. [35]	Only reaction time results are reported here, not the percentage of accuracy	25 min of moderate-intensity cycling	Stroop congruent LFG	+	$d=0.35$ (−0.23, 0.91)
			Stroop incongruent LFG	+	$d=0.43$ (−0.15, 0.99)
			Stroop congruent HFG	+	$d=0.86$ (0.23, 1.46)
			Stroop incongruent HFG	+	$d=0.91$ (0.27, 1.51)
Dawe and Moore-Orr [38]	Only the immediately post-test data are presented here, not the 30-min post-test	15 min of sedentary- to light-intensity walking, stretching and flexing exercises	Set test	+	$d=0.54$ (−0.38, 1.40)
			Word fluency initial letter cued	0	$d=-0.06$ (−0.94, 0.82)
			Symbol digit test	0	$d=-0.22$ (−1.09, 0.66)
Hatta et al. [39]	This study also investigated mood and salivary alpha-amylase. These results are not reported here	80–120 min of moderate to vigorous walking	WCST category achievement	0	$d=0.43$ (−0.21, 1.05)
			WCST total errors	0	$d=0.52$ (−0.12, 1.13)
			WCST perseverative errors of Nelson	0	$d=0.24$ (−0.38, 0.86)
Hyodo et al. [31]	Only reaction times are reported here, not the error rates and fNIRS data	7 min of moderate-intensity cycling	Stroop neutral condition	0	$d=-0.25$ (−0.94, 0.45)
			Stroop incongruent condition	+	$d=1.05$ (0.28, 1.76)
Johnson et al. [32]	Only results from the aerobic exercise condition are reported and only the 'immediately after' results, not the resistance exercise results and not the 30- and 60-min post-exercise results	10 min of moderate-intensity cycling	Stroop color subtest	0	$d=0.4$ (−0.11, 0.90)
			Stroop interference subtest	0	$d=0.19$ (−0.31, 0.69
			Stroop inhibition subtest	+	$d=0.40$ (−0.11, 0.89)
		30 min of moderate-intensity cycling	Stroop color subtest	0	$d=0.25$ (−0.26, 0.74)
			Stroop interference subtest	0	$d=-0.10$ (−0.60, 0.39)
			Stroop inhibition subtest	+	$d=0.37$ (−0.14, 0.87)
Kamijo et al. [33]	Only the reaction times are reported here and only the results from the older adult group	20 min of light-intensity cycling	Flanker task congruent	0	$d=-0.16$ (−0.65, 0.95)
			Flanker task incongruent	0	$d=-0.38$ (−1.17, 0.44)
		20 min of moderate-intensity cycling	Flanker task congruent	+	$d=0.92$ (0.05, 1.72)
			Flanker task incongruent	+	$d=0.69$ (−0.16, 1.49)

Table 2 (continued)

Study	Notes	Exercise intervention	Cognitive task—subtest and significant difference (+)		Effect size (95% CI)
Kimura and Hozumi [34]	Only the reaction times are reported here, not the accuracy	20 min of light-intensity combination-style dance	Repeat reaction time	+	$d=0.59$ (−0.11, 1.26)
			Switch reaction time	+	$d=0.87$ (0.14, 1.55)
			Switch cost	+	$d=0.43$ (−0.26, 1.10)
		20 min of light-intensity freestyle dance	Repeat reaction time	+	$d=0.51$ (−0.18, 1.18)
			Switch reaction time	+	$d=0.20$ (−0.48, 0.87)
			Switch cost	0	$d=-0.56$ (−1.23, 0.14)
Netz et al. [40]	This study also has a younger adult group and follow-up (60 min) data	35 min of moderate-intensity walking	Alternative uses test mean score	+	Data not available for calculation
O'Brien et al. [26]	Results are presented in comparison with the control group	60–80 min of either aerobics, tennis or dance (open skill)	Digit span task	+	Data not available for calculation
			Sound-Induced Flash Illusion	+	Data not available for calculation
		60–80 min of either gym or swimming (closed skill)	Digit span task	+	Data not available for calculation
			Sound-Induced Flash Illusion	0	Data not available for calculation
Peiffer et al. [25]	Data presented here are regardless of exercise intensity. This study also has follow-up data 30-min post-exercise, which are not presented here	20 min of moderate to vigorous walking	Flanker task total	+	$d=0.35$ (−0.51, 1.18)
			Flanker task congruent condition	+	$d=0.22$ (−0.63, 1.04)
			Flanker task incongruent condition	+	$d=0.44$ (−0.43, 1.26)
			d2 test error rate	+	$d=0.02$ (−0.82, 0.85)
			d2 test GZ value	+	$d=-0.12$ (−0.95, 0.73)
			d2 test SKL value	+	$d=0.10$ (−0.74, 0.93)
Stones and Dawe [27]	Only the immediately post-test data are presented here, not the 30-min post-test	15 min of sedentary- to light-intensity walking, stretching and flexing exercises	Set test	+	$d=0.54$ (−0.38, 1.40)
			Word fluency initial letter cued	0	$d=0.06$ (−0.82, 0.93)
			Symbol digit task	0	$d=0.22$ (−0.67, 1.09)
Tsujii et al. [36]	Nil	10 min of light to moderate cycling	Digit task	+	Data not available for calculation

LFG low-fitness group, *HFG* high-fitness group, *WCST* Wisconsin card sorting test, *fNIRS* functional near-infrared spectroscopy, *GZ* the rate at which participants mark off each d2 and the overall number of marked letters within the d2 test, *SKL* measure of attention (i.e. the standardized number of accurate answers minus confusion errors), *CI* confidence interval incongruent subtest score (d=0.44) of healthy older adults post-exercise [25]. Peiffer et al. [25] also used the d2 test to assess attentional performance of healthy older adults after the same exercise conditions, and also averaged across exercise intensity. Results showed enhanced performance at all three d2 test values (i.e. error rate [d=0.02], the rate at which participants mark off each d2 and the overall number of marked letters within the d2 test [GZ value; d=0.12] and the measure of attention [SKL value; d=0.10]) following exercise [25].

3.4.4 The Digit Span Task

Two studies used a digit span task to assess working memory following an acute bout of aerobic exercise [26, 36]. Results from O'Brien et al. [26] demonstrated that following a 60- to 80-min open skill exercise session (aerobics, tennis or dance), as well as following a 60- to 80-min closed skill exercise session (gym or swimming), performance on the digit span task was enhanced when compared with the control group, which attended a meeting and played card games [26]. The intensity levels of the open and closed skill exercise session were not measured in this study. Tsujii et al. [36] reported that after a 10-min bout of light- to moderate-intensity cycling (40% of VO_{2max}), reaction times of healthy older adults on the digit span task were significantly lower (p <0.05) when compared with a resting control condition, suggesting enhanced performance of working memory abilities [36].

3.4.5 The Wisconsin Card Sorting Test

The WCST was used in one study to assess concept formation and reasoning following a self-paced walking bout of exercise [39]. Performance at the WCST was measured in healthy older adults after an 80- to 120-min bout of moderate to vigorous walking (67.4% ± 8.0% of HR_{max}). Findings suggest no significant main effect of exercise on the performance on all three measures of the WCST (i.e. category achievement, total errors and perseverative errors of Nelson) when compared with pre-test measures [39].

3.4.6 The Alternative Uses Test

Post-exercise cognitive flexibility was assessed using the alternative uses test in a population of healthy older women [40]. Findings from this study suggest a significant improvement (p =0.04) in cognitive flexibility of healthy older adults immediately after a 35-min bout of moderate-intensity walking (60% of HR reserve) when compared with pre-test cognitive measures [40]. Further analysis conducted by Netz et al. [40] indicated that the physical fitness level of participants was correlated with enhanced performance, with a lower level associated with a greater facilitative effect of the single bout of exercise on cognition [40].

3.4.7 Task-Switching Reaction Time Test

Kimura and Hozumi [34] assessed post-exercise executive functions of healthy older adults using a task-switching reaction time test. Two 20-min exercise interventions were tested in this study: a light-intensity (40–50% of HR reserve) combination-style dance and a light-intensity (40–50% of HR reserve) freestyle dance [34]. Results indicate that executive function was facilitated by both exercise conditions, with significantly enhanced performance post-exercise of both the repeat and switch reaction time conditions within the task-switching reaction time test [34]. Effect sizes for each exercise condition and task subtest are presented in Table 2. Findings from Kimura and Hozumi [34] also revealed that the switch cost in the combination-style dance group decreased post-exercise (d = 0.43), whereas no significant difference was found in the freestyle dance group.

3.4.8 Sound-Induced Flash Illusion Task

O'Brien et al. [26] investigated a different cognitive domain: audio-visual perception, using the Sound-Induced Flash Illusion task. Results showed a significant improvement of sensitivity in audio-visual perception within the intervention group performing a 60- to 80-min open skill exercise session [26]. However, no significant differences were found in the performance of the control group playing card games in a group meeting and the intervention group performing a 60- to 80-min closed skill exercise session [26].

3.5 Quality Appraisal

In the 15 included studies, quality scores on the PEDro scale ranged from 2 to 7 (with a mean of 4.1 ± 1.4) of a maximum score of 8. All studies outlined the eligibility criteria of their trial and provided statistical comparisons and valid measures for at least one key outcome measure. Five of the 15 studies reported to have randomly allocated their participants into intervention groups [27, 32, 34, 37, 38]. However, only Kimura and Hozumi [34] reported performing a concealed allocation. Additionally, all reviewed studies provided a baseline similarity measure, with the exception of Chu et al. [35], Hyodo et al. [31] and O'Brien et al. [26]. None of the 15 included studies mentioned the blinding of assessors. Finally, eight studies provided a key outcome measure for more than 85% of their subjects, and only five studies mentioned that all subjects received the exercise condition or the control condition as allocated, suggesting the use of an intention-to-treat analysis. Detailed results from the quality assessment using the PEDro scale are presented in Table 3.

Table 3 Quality rating of included studies using the PEDro scale

Study	Eligibility criteria	Random allocation	Concealed allocation	Baseline similarity	Assessor blinded	Outcome from > 85%	Intention to treat	Statistical comparison	Valid measures	Total score (out of 8)
Abe et al. [29]	Y	N	N	Y	N	N	N	Y	Y	3
Barella et al. [37]	Y	Y	N	Y	N	Y	Y	Y	Y	6
Chang et al. [30]	Y	N	N	Y	N	Y	N	Y	Y	4
Chu et al. [35]	Y	N	N	N	N	N	N	Y	Y	2
Dawe and Moore-Orr [38]	Y	Y	N	Y	N	Y	N	Y	Y	5
Hatta et al. [39]	Y	N	N	Y	N	Y	N	Y	Y	4
Hyodo et al. [31]	Y	N	N	N	N	N	N	Y	Y	2
Johnson et al. [32]	Y	Y	N	Y	N	N	Y	Y	Y	5
Kamijo et al. [33]	Y	N	N	Y	N	N	N	Y	Y	3
Kimura and Hozumi [34]	Y	Y	Y	Y	N	Y	Y	Y	Y	7
Netz et al. [40]	Y	N	N	Y	N	Y	N	Y	Y	4
O'Brien et al. [26]	Y	N	N	N	N	N	Y	Y	Y	3
Peiffer et al. [25]	Y	N	N	Y	N	Y	Y	Y	Y	5
Stones and Dawe [27]	Y	Y	N	Y	N	N	N	Y	Y	4
Tsujii et al. [36]	Y	N	N	Y	N	Y	N	Y	Y	4
Total	15Y/0N	5Y/10N	1Y/14N	12Y/3N	0Y/15N	8Y/7N	5Y/10N	15Y/0N	15Y/0N	Mean 4.1 (SD 1.4)

Y yes, *N* no, *SD* standard deviation, *PEDro* physiotherapy evidence database

4 Discussion

This systematic review identified 15 studies investigating the immediate effects of acute aerobic exercise on cognitive functions of healthy adults aged 60 years and above. As a result of this current review, it is clear that there are an increasing number of studies in this area, with a large number completed in recent years. In fact, 11 of the 15 studies included in this review were published between 2010 and 2018, suggesting an increasing interest in this field of research in countries such as Taiwan, China, Japan, Australia, Ireland, Italy and the US. Of the 15 studies included in this review, 14 have presented findings that suggest a significant enhancement of cognitive performance on at least one subtest of a cognitive task following an acute bout of aerobic exercise.

4.1 Acute Effects of Aerobic Exercise on Cognition

As presented in Sect. 3.4, all 15 included studies examined the immediate effects of a single bout of aerobic exercise on the cognitive domain of executive function. Only one recent study investigated a different cognitive domain—audio-visual perception [26]. There are discrepancies between the results of the six studies that used the Stroop task to assess executive functions [29–32, 35, 37]. Findings from Barella et al. [37] are partly consistent with the literature [51, 52], which suggests that an acute bout of exercise is likely to have a positive effect on response speed (assessed by the Stroop color subtest). However, by showing no effects of acute aerobic exercise on Stroop interference and Stroop inhibition subtests, results from Barella et al. [37] differ from the rest of the literature [51, 52], which suggests that an acute bout of exercise has a positive effect on higher-level executive functions. The exercise intensity level used by Barella et al. [37] is similar to that used by Chang et al. [30], Chu et al. [35], Hyodo et al. [31] and Johnson et al. [32], and therefore it is unlikely that exercise intensity alone could explain this discrepancy in the results. Results from Barella et al. [37] can be partly explained by a potential fatigue and effort–reward imbalance that might have affected participants as a result of having their cognition assessed at 12 time points. Consideration of how additional moderators such as fatigue and motivation might play a role could help better understand the effects of acute aerobic exercise on cognitive functions in the older population.

Results from Abe et al. [29], Hyodo et al. [31] and Johnson et al. [32] suggested a post-exercise enhancement of higher levels of executive functions assessed by the Stroop interference [29, 31] and the Stroop inhibition subtest [32], which is consistent with previous findings in young adults [53, 54]. However, Abe et al. [29], Hyodo et al. [31] and Johnson et al. [32] suggested no enhancement of information processing speed assessed by the Stroop color subtest, which is inconsistent with conclusions from Tomporowski [51] that acute exercise is thought to have an effect across different levels of executive function. Other researchers [55–57] suggest that more demanding tasks are likely to be more sensitive to the effects of physical exercise, in comparison with automatic effortless tasks, which supports the results of Abe et al. [29], Hyodo et al. [31] and Johnson et al. [32].

Results from Chang et al. [30] and Chu et al. [35] suggest a general improvement in multiple cognitive functions measured by the Stroop task, and are consistent with the young adult literature [51, 52]. Results from Chang et al. [30] and Chu et al. [35] have also highlighted the importance of taking into consideration the fitness level of participants at baseline. Findings from both studies suggest a greater benefit on cognition for the higher-fitness group following a single bout of aerobic exercise [30, 35], which is contrary to the findings from Netz et al. [40], who have attributed post-exercise enhancement of cognitive performance to the lower fitness level of their participants [40]. As summarized by Brisswalter et al. [58], contradictory findings exist with regard to the effects of aerobic fitness level on cognitive performance during or after an acute bout of exercise, therefore additional studies would help better understand these effects [58].

Similarities can be found between the results of the two studies that assessed verbal fluency [27, 38]. Results from both studies are consistent and suggest an enhanced performance on the set test, but not on the phonologically cued verbal fluency task or the symbol digit task [27, 38]. As mentioned by Dawe and Moore-Orr [38], the order in which the three cognitive tasks were administered might have influenced performance on the outcome measures. The set test was administered first in both studies, followed by the word fluency task and the symbol digit task. The increase in heart rate was minimal in both studies (i.e. 2 beats/min), meaning benefits from the physiological arousal response were likely to have been limited to the performance on the first test presented (i.e. the set test) [27, 38]. These results highlight the importance of the exercise intensity level used to potentially enhance cognitive performance. Both Dawe and Moore-Orr [38] and Stones and Dawe [27] used a sedentary- to light-intensity level, which might not have been the optimal level of exercise intensity for this specific age group.

The study by Kamijo et al. [33] is the only included study to have specifically investigated the effects of different levels of exercise intensity on cognitive functions of healthy older adults. Kamijo et al. [33] reported that reaction times of older adults following a moderate-intensity cycling bout were shorter relative to a light-intensity cycling bout, suggesting an enhancement in cognitive functions only as a result of moderate-intensity cycling, and further highlighting the potential role of exercise intensity in modulating effects on cognition. Results from the moderate-intensity exercise group of Kamijo et al. [33] and the moderate to vigorous exercise group from Peiffer et al. [25] are consistent overall and suggest enhanced performance for both the congruent and incongruent conditions of the modified Flanker task post-exercise. Results from Peiffer et al. [25] are consistent with previous studies on young adults who have reported larger effects of exercise on the incongruent modified Flanker task condition, since it requires greater executive control compared with the congruent condition [56, 59].

Findings from O'Brien et al. [26] and Tsujii et al. [36] are consistent and suggest that a single bout of aerobic exercise enhances working memory performance of healthy older adults [26, 36], which is consistent with findings in healthy sedentary young adults [60]. O'Brien et al. [26] and Kimura and Hozumi [34] both investigated the effect of different types of aerobic exercise on cognitive functions of healthy older adults. Results from Kimura and Hozumi [34] suggest no differences between dance styles, with both dance styles being beneficial for cognitive functions, which is in line with the results from O'Brien et al. [26] that both open skill exercises (including dance) and closed skill exercises (gym or swimming) can benefit cognitive functions [26]. O'Brien et al. [26] also investigated audio-visual perception, and although they reported a significant effect of open skill exercises on performance at the Sound-Induced Flash Illusion task in comparison with a control group playing card games in a group meeting, they did not report the same effect for closed skill exercises [26]. This lack of effect for closed skills exercises could be partly explained by the use of a control task that required the involvement of cognitive functions (i.e. card games), highlighting the importance of selecting control conditions that cannot interfere with the phenomenon under investigation.

Finally, the study by Hatta et al. [39] was the only included study that did not report enhanced cognitive function measures following a single bout of aerobic exercise. As previously discussed, exercise intensity is thought to play an important role in acute exercise effects [58]. Although Hatta et al. [39] reported an exercise intensity between moderate and vigorous, the self-paced nature of the exercise bout led to participants walking without a specific intensity target. Moreover, another moderator variable that might explain these results is the duration of the exercise bout. The non-significant results from Hatta et al. [39] could be attributed to the fact that the number of steps, the distance and therefore the duration of the exercise bout varied between participants, resulting in a wide duration range (i.e. 80–120 min). Fatigue due to the long duration of the exercise bout is also likely to partly explain the non-significant results obtained by Hatta et al. [39]. Therefore, the lack of effect may, at least in part, be due to these methodological issues [61].

4.2 Quality Appraisal

Results from the quality assessment using a modified version of the PEDro scale suggest that, on average, the 15 included studies are of medium quality (i.e. 4.1/8). These results can be partly explained by the fact that the PEDro scale is designed to specifically assess the methodological quality of randomised controlled trials. Therefore, non-randomised controlled trials inevitably scored lower. Although blinding of assessors could be performed in studies investigating the effects of a single bout of exercise on cognitive performance, it appears to be the only criterion that was not met by any of the included studies. This lack of blinding in combination with the low numbers of randomised controlled trials could partly explain the medium overall quality of the 15 included studies. Therefore, there is a need for more random and concealed allocations with blinding of assessors in order to increase methodological quality when answering this research question.

5 Conclusion

There is increasing evidence suggesting that a single bout of acute aerobic exercise can optimize immediate cognitive performance of healthy older adults. Although this review has provided important insights into this, the limited number of studies included and their heterogeneity, especially with regard to the use of a variety of cognitive assessments, did not allow for a critical analysis of the results for all cognitive functions. While the pool of studies, as well as the sample size of studies identified in this review was quite small, an increasing interest in acute exercise effects on cognition has been noted in the recent years.

The methodological quality rating of included studies in this review was highly varied and there is a need for more comprehensive randomized controlled trials to address this key question before meaningful effects can be precisely identified. In order to advance this field, there is a need for future high-quality studies that employ concealed allocation, blinded assessment, control conditions and common standards of cognitive measures, such as assessments recommended for older patients with dementia [62]. Future studies should also consider additional moderator variables such as fatigue, motivation, baseline fitness level, timing of cognitive assessment and the use of common standards regarding exercise timing, duration and intensity, such as the Norton et al. [41] exercise intensity terminology. This approach would enable comparison across studies and allow us to determine exercise-related factors that influence cognition. Future studies should also further investigate the time course and dose–response of exercise-related effects on cognition in healthy older adults and clinical populations, including immediate effects within 15 min. This would allow to build on current evidence, such as findings from a recent trial with stroke patients, which suggests that the use of short and frequent mobilization following stroke enhances outcomes and chances of regaining independence [63]. Other cognitive domains, such as language and memory, should also be explored in future studies conducted in older adults. Finally, when sufficient studies using the same outcome measures are available, future reviews could focus on performing meta-analyses.

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Compliance with Ethical Standards

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