Original Article

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Effects of high-intensity interval training on executive functions in children and adolescents: A Systematic Review and Meta-analysis

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Abstract

Background: In recent years, research has focused on the effect of high-intensity interval training (HIIT) on cognitive function has strongly increased. However, little is known about the effects of HIIT on executive function (EFs) in children and adolescents. Objective: This systematic review and meta-analysis aimed to evaluate the effects of HIIT on EFs in children and adolescents. Methods: A literature search was performed using four electronic databases: PubMed, Web of Science, Scopus, and EBSCOhost. We included studies published since 2010 that examined HIIT interventions on EFs (Inhibitory Control (IC), Working Memory (WM) and Cognitive Flexibility (CF)) with participants aged between 6 and 18 years. Results: Seven of the 295 studies were included in this review. Analysis of HIIT effects, as well as sensitivity analysis, indicated that participation in HIIT exercise sessions led to a significant improvement in WM (MD = 0.29, 95% CI 0.08; 0.05; z = 2.73, p = 0.01; I^2 = 92%; p < 0.01). However, the analysis of the effects of HIIT on IC indicated that participation in HIIT exercise sessions was not significant (MD = -1.3, 95% CI 20.02; 17.41; p=0.26; z = -0.14, p =0.89; I^2 = 22%; p= 0.26). Conclusion: Our study provides evidence that participation in an HIIT program can improve the working memory of children and adolescents.

Keywords: high-intensity interval training, executive functions, children, adolescents, systematic review

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INTRODUCTION

Growing evidence demonstrates a positive association between physical activity, cognition, and brain function [1–5] and supports the acute and chronic benefits of aerobic exercise on cognitive function in childhood, adulthood, and the elderly [6]. Recent findings have shown a greater improvement in cognitive function when associated with high-intensity physical activity compared to moderate exercise intensity [7,8]. High-intensity interval training (HIIT) consists of relatively brief bouts of vigorous physical activity (i.e., ≥85% of maximal heart rate for brief intervals) interspersed by short periods of rest or low-intensity physical activity for recovery [9]. HIIT protocols are typically performed using treadmills or cycle ergometers, although recent studies on children and adolescents have implemented training sessions using a variety of modalities according to HIIT characteristics [10,11]. HIIT has demonstrated a positive effect on health outcomes such as cardiorespiratory fitness and systolic blood pressure [12,13], with greater enjoyment [14] in youth. In addition to physiological adaptations (e.g., maximal cardiac output, skeletal muscle oxidative enzyme capacity, capillary density, increased red blood cell volume, and hemoglobin mass) [15], the beneficial effects of HIIT have also been found to extend to executive functions (EFs) [16,17]. EFs are a series of cognitive processes that are responsible for organizing and coordinating behaviors to perform complex tasks, especially those that escape routines [18]. The EFs mentally play with ideas, taking the time to think before acting, meeting novel, unanticipated challenges, resisting temptations, and staying focused [19]. Moreover, EFs during childhood are predictors of EFs in adulthood, decisive for school and academic success [20], and for personal fulfillment and quality of life [21]. It is generally accepted that there are three core EFs [22–24]: inhibitory control (IC) (i.e., the ability to selectively focus on task-relevant information while resisting attention to a prepotent but undesirable response), working memory (WM) (i.e., the ability to hold information in mind and mentally work with it or with information no longer perceptually presented), and cognitive flexibility (CF) (i.e., the ability to flexibly change mental representations back and forth between two task demands). Recent systematic reviews [17,25] have explored the acute and chronic effects of HIIT on EFs. The main results showed that acute bouts of HIIT have a positive effect on IC in children and adolescents and that chronic HIIT benefits IC and WM in children. Despite the positive effects observed [16], aspects related to the dosage/modality, between-subject differences, possible underlying mechanisms, and feasibility of translating HIIT to real-world settings in children or adolescents remain unclear [17]. It has also been reported in some studies that high-intensity exercise has a small facilitating effect on cognitive function and that this effect is comparable with that observed for moderate-intensity exercise [26]. Nonetheless, the relevance of high-intensity exercise has been demonstrated in those seeking time-efficient ways to induce immediate cognitive improvements, such as children and adolescents, who are often restricted to sedentary learning environments [26,27]. Despite the growing number of published systematic reviews that were accomplished in this line [17,27], none of them considered a meta-analysis. Therefore, a stronger level of evidence is required for a more comprehensive approach [17], and none of these studies considered a meta-analysis. Thus, the results on the effect size of the implemented acute and chronic HIIT interventions on youth EFs remain unclear. Therefore, the purpose of this systematic review and meta-analysis was to evaluate the effects of HIIT interventions on EFs (IC, WM, and CF) in children and adolescents.

METHODS

Search strategy

This review aligns with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [28] and was registered with the International Prospective Register of Systematic Reviews (PROSPERO) (registration number: CRD42022315524). The search was performed using the following four electronic databases: PubMed, Web of Science, Scopus, and EBSCOhost. The systematic search for studies began on January 1st and ended on the 31st of the same month. Only studies published since 2010 were included because HIIT is a new topic, and the literature initially focused mainly on adults [25]. The search terms were ["high- intensity interval training" OR "high intensity intermittent training" OR "sprint interval training] AND ["children" OR "child" OR "adolescent" OR "youth"] AND ["cognitive function" OR "executive function" OR "executive control"].

Eligibility criteria

Studies were considered eligible if they met all of the following criteria: a) the research involved an intervention study, acute (single session of HIIT) or chronic (repeated session of HIIT weeks, or months), where the HIIT characteristics (e.g., the type of movements involved, intensity, work-to-recovery ratio (WRR), weeks frequency duration of the intervention) were given; b) the reported high intensity rate were either ≥80% heart rate reserve ($HR_{reserve}$), ≥85% heart rate maximal (HR_{max}), ≥90% maximal oxygen consumption (VO_{2max}) or peak power out- put [9,29]; c) randomized designs with controlled trials (RCT) and control trials (CT) were considered; d) the research focused on different subcomponents of executive function based on the definitions from [19], namely, IC, WM, and CF; e) outcome measures involved executive function-related tasks with explicitly defined performance indices (e.g., response accuracy, response times, items recalled), and executive function- related tasks were identified by referring to the studies from [19] and [30]; f) participants of 6 to 18 years healthy and without diagnosed disease or mental disorders; g) Articles with focus in sports, reviews, papers published in conference, dissertations, thesis or in non-peer-reviewed journals were excluded; h) Only research involving humans and written in English were considered.

Study selection

The selection criteria were based on the PICOS criteria used to define the characteristics of the included studies. Population: studies including healthy participants between 6 and 18 years old were included; Intervention: studies evaluating the effect of acute or chronic HIIT on EFs and providing clear HIIT protocol were included; Comparator: studies comparing an active control (e.g., other exercise protocols) or passive control (e.g., watching television, sitting, and resting) were included; Outcomes: studies assessing executive function were included; Study design: studies RCTs and CT were included. Two authors completed the screening and selection of studies in February 2022. First, duplicates were removed and titles and abstracts were examined to identify studies that met the inclusion criteria. Second, the full texts of the eligible studies based on the screened studies were read by three authors (TRA, AB, and MGM) to determine their final inclusion. Disagreements between the two reviewers were resolved through a consensus meeting between the three authors in February 2022. Finally, articles on acute and chronic HIIT interventions and executive function-related tasks were included in this review. Figure 1 provides an overview of the selection process.

Data extraction process and data synthesis

The full texts were analyzed and after confirming the eligibility criteria, the following data were extracted: (a) first authors' name, publication year, and country of data collection; (b) sample size, participants' age, and sex; (c) study design and/or group assignment; (d) details about HIIT intervention (such as exercise intensity, work/rest, session time, frequency, duration of intervention, and modality); (e) subcomponents of EFs assessed; and (f) main findings outcomes. The outcome data were extracted in the form of pre-and post-training intervention means and standard deviations (SD). The dependent variables included were reported in repetitions or milliseconds (if relative values were not reported). In studies that reported intermediate and post-intervention values, only the final EF values were compared with the baseline values. Data from the included studies were extracted independently by two reviewers (TRA and AB), and any discrepancies were resolved by consulting a third reviewer (MGM).

Assessment of risk of bias

Two authors (TRA and AB) assessed study quality according to the PEDro scale [31]. Any disagreements were discussed with a third reviewer (MGM) until consensus was reached. The total PEDro score is obtained by adding points describing the quality of papers, for example, 9–10 (excellent), 6–8 (good), 4–5 (fair), and ≤3 (poor) [31].

Statistical Analysis

A random effects model was used for each outcome. Pooled effect sizes (ES) were presented as unstandardized mean differences (MD) with a 95% confidence interval (95%CI). An overall analysis was performed to determine the effect of the change in the EF of HIIT in each study. Sensitivity analyses were conducted to detect whether any study was responsible for a large proportion of heterogeneity (I^2), which was assessed and qualitatively considered as not important if I^2 = 0-40%, moderate if I^2 = 30–60%, substantial if I^2 = 50–90%, and considerable if I^2 = 75–100% [32]. Publication bias assessment was not performed because the outcome analyses included less than 10 studies [32]. The package “meta” (version 4.11-0) [33] for the R statistical software (version 4.1.0) [34] was used. The overall effects (z-value) were considered statistically significant at $p < 0.05$.

RESULTS

Study selection

A total of 295 studies were initially identified from PubMed, Web of Science, Scopus, and EBSCOhost, and other articles were identified through other sources (n=3; articles considered for the authors; obtained from other systematic reviews) [17,25]. Of these, 62 duplicates were excluded from the analysis. Accordingly, 233 articles were screened by title and abstract, of which 210 were excluded. After the first stage of screening, 23 articles were selected for full-text screening, resulting in a total of 7 full-text articles included in the data extraction and reporting. A flow diagram of the study selection process, following the PRISMA guidelines, is shown in Figure 1. Table 1 summarizes the characteristics and results of the study.

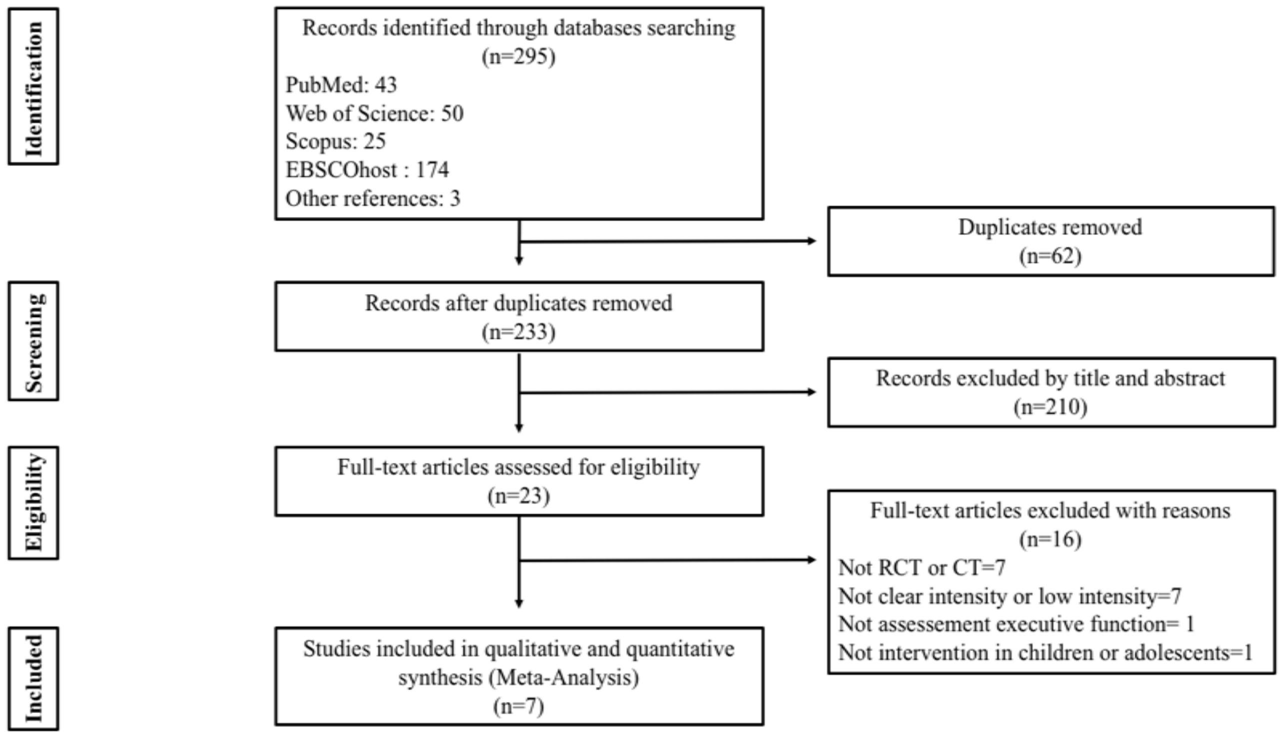

Figure 1. PRISMA flow diagram of each stage of the study selection.

Table 1. Summary table of studies

Authors, Country, Study Design	Sample	Groups (n)	Modality/ Intensity	Work / Rest	Session time	F	D	Assesments	Results
Costigan et al. (2016) [35] Australia RCT	School Children N=65; ♂=45; ♀=20 15.8±0.6 years	HIIT/AEP=21 HIIT//RAP=22 CG=22	AEP: Shuttle runs, jumping jacks, and skipping RAP: Shuttle runs, jumping jacks, skipping, combined with body weight squats, push-ups >85% HRmax CG: PE and usual lunchtime activities	30s /30s	8-10 min	3	8	TMT-B (cognitive flexibility)	AEP: Unclear effect RAP: Possibly beneficial
Lubans et al., (2020) [36] Australia RCT	School Children N=670; ♂=371; ♀= 299 16.0±0.4 years	HIIT=337 CG=333	HIIT: Shuttle runs, jumping jacks, dance sequences, push-ups, squat jumps ≥85% HRmax CG: Usual PE	30s /30s - 20s /10s	8-20 min	3	24	Eriksen Flanker Task (inhibition control) N back-task (working memory)	Null effect
Ludyga et al., (2019) [37] Switzerland RCT	School Children N=94; ♂ 14±0.7 years	HIIE=32 MIE=34 CG=28	HIE and MIE: Jumping jacks, shuttle runs, rope skipping, stepping up and down on a bench, jumping sideways, and dribbling a ball while running ≥85% HRmax CG: Watched an exercises video	HIE: 60s /30s MIE: 30s /30s	16 min	Single session	—	Flanker task (inhibition control)	HIE: null effect MIE: inhibitory control improvements. Effect sustained for 60 min pos-exercise
Tottori et al., (2019) [38] Japan Non-RCT	School Children N=56; ♂=31; ♀=25 10.2±1.0 years	HIIT=29 CG=27	HIIT: Shuttle runs, jumping jacks, vertical jumps, mountain climbers, and plank in and out jumps ≥85% HRmax CG: NR	30s /30s	8-10 min	3	4	DSF/DSB (working memory)	HIIT: working memory improvement
Mezcua et al., (2019) [39] Spain RCT	School Children N=158; ♂=80; ♀= 78; 14.06±1.2years	HIIT=77 CG=81	HIIT: Combination of cardiorespiratory, motor, and coordinative training ≥85% HRmax CG: Static stretching	30s /30s	16 min	Single session	—	Reynolds Intellectual Assessment Scales (working memory)	Both groups: working memory improvement
Martinez et al., (2018) [40] Spain RCT	School Children N= 184; ♂=98; ♀= 86; 13.73±1.3years	HIIT=90 CG=94	HIIT: Combination of cardiorespiratory, speed agility and coordinative training ≥85% HRmax CG: Static stretching	20s /40s - 40s /20s	16 min	2	12	Reynolds Intellectual Assessment Scales (working memory)	No significant differences between groups
Moreau et al., (2017) [41] New Zealand RCT	School Children N=305; ♂=118; ♀=187; 9.9±1.7 years	HIIT=152 CG=153	HIT: Jumping jacks, high knees, squat jumps, squat jacks, leg switches. ≥85% HRmax CG: Blend of board games, computer games, and trivia quizzes	20s /20s – 20s /60s	10 min	5	6	Flanker, Go/no Go test, Stroop (inhibition control) Backward digit span, Backward Corsi blocks, Visual 2-back (Working memory)	Inhibition control and working memory improvements

F, Frequency (week); D, Duration (weeks); HRmax; heart rate maximum; S, second; Min, minutes; TMT-B, trail-making test b; HIIT, high-intensity interval training; RCT, randomized control trials; AEP, aerobic exercise program; RAP, resistance and aerobic program; CG: control group; PE, physical education; HIE, high-intensity intermittent exercise; MIE, moderately intense intermittent exercise; DSF, digital span forward; DSB, digital span backward; ♂, boys; ♀, girls

Description of studies

All the included articles assessed the effects of an acute or chronic HIIT intervention on EFs; an overview of the included studies is provided in Table 1. The present review found that the number of participants in each study ranged from 56 to 670, with ages ranging from 9 to 16 years. These studies were conducted in their respective countries, including Australia [35,36], Switzerland [37], Japan [38], Spain [39,40], New Zealand [41]. Six studies were RCTs [35–37,39–41] and one was a non-RCT [38]. Five studies investigated the chronic effects of HIIT [35,36,38,40,41] while two investigated the acute effects [37,39]. The duration of chronic interventions in the included studies lasted from 4 weeks [38] to 24 weeks [36]. Exercise training sessions were implemented five times a week in one study [41], three times a week in three studies [35,36,38], and twice a week in one study [40]. Two studies included only a single session [37,39]. The type of HIIT intervention consisted of aerobic exercises (e.g., shuttle runs, jumping jacks, and skipping) in five studies [35–38,41] and a combination of cardiorespiratory, motor, and coordinative training in two other studies [39,40]. The effective time of HIIT intervention ranged from 8 min [35,36,38] to 20 min [36]. In terms of the work/recovery time ratio, there was a range between 20-60 seconds for work–10-60 seconds for recovery. Additionally, three EFs components have been categorized: IC, WM, and CF [42]. Regarding the different subcomponents of the EFs, three studies focused on IC [36,37,41], five on WM [36,38–40], and one on CF [35]. Concerning the EFs assessment, WM was estimated through the N back-task test, digital span forward/backward, Reynolds Intellectual Assessment Scales, Backward Corsi blocks, and Visual 2-back [33,35–38, respectively]. IC was estimated using the Eriksen Flaker task, Flaker task, Go/no go, and Stroop [36,37,41], and CF was assessed using the Trail Making Test [35]. Overall, WM was improved in three articles [38,39,41] and IC in one [41], whereas two studies found no differences in WM [36,40], and two studies did not show improvement in IC [36,37]. Also, another article reported the unclear effect of HIIT on CF and classified as "possibly beneficial" [35].

Table 2. Quality assessment/ PEDRo Scale

Study	Score	Quality
Costigan et al., (2016) [35]	9	Excellent
Lubans et al., (2020) [36]	7	Good
Ludyga et al., (2019) [37]	5	Fair
Tottori et al., (2019) [38]	4	Fair
Mezcua et al., (2019) [39]	7	Good
Martinez et al., (2018) [40]	7	Good
Moreau et al., (2017) [41]	8	Good

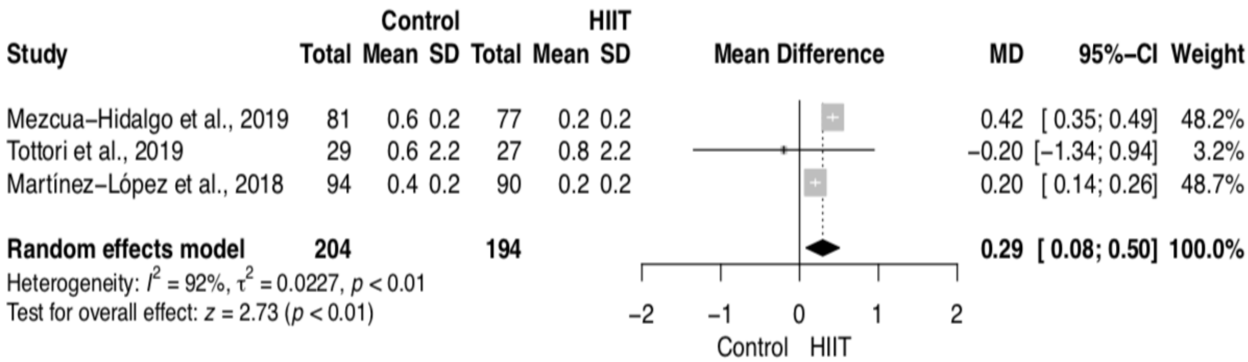

Figure 2. Forest plot of mean difference in WM variable of studies included (Mezcua-Hidalgo et al., 2019 [39]; Tottori et al., 2019 [38]; Martínez-López et al., 2018 [40]).

Table 3. Sensitivity analysis.

Outcome		Studies	MD (95% CI)	I^2 (p)	Z (p)
WM	O	Mezcua–Hidalgo et al., 2019 [39] Tottori et al., 2019 [38] Martínez–López et al., 2018 [37]	0.29 (0.08; 0.05)	92% (0.01)	2.73 (0.01)
	C1	Mezcua–Hidalgo et al., 2019 [39] Martínez–López et al., 2018 [40]	0.31 [0.09; 0.53]	96% (0.01)	2.81 (0.01)
	C2	Mezcua–Hidalgo et al., 2019 [39] Tottori et al., 2019 [38]	0.38 [0.10; 0.67]	11% (0.29)	2.64 (0.01)
	C3	Tottori et al., 2019 [38] Martínez–López et al., 2018 [40]	0.20 [0.14; 0.26]	0% (0.49)	6.5 (0.01)

WM, working memory, O – Overall, C1 – Combination 1, C2 – Combination 3, C3 – Combination 3

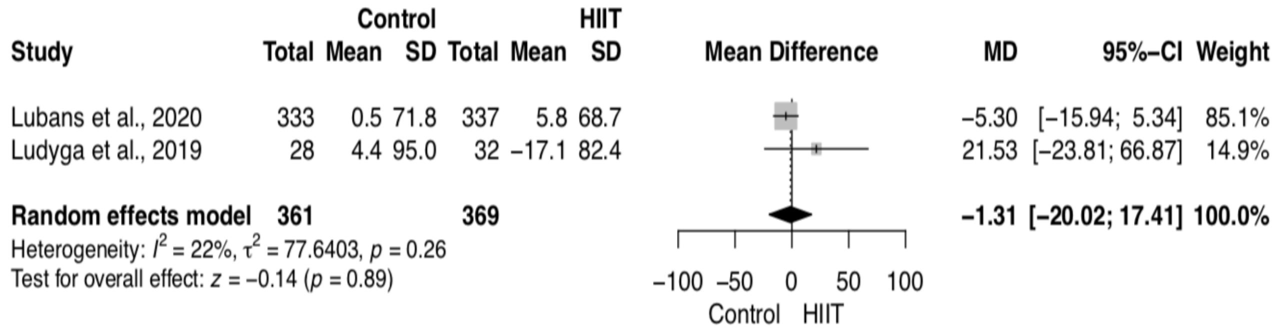

Figure 3. Forest plot of mean difference in IC variable of studies included (Lubans et al., 2020 [36]; Ludyga et al., 2019 [37]).

Sensitivity analysis of the effects of HIIT on working memory

Table 3 shows the sensitivity of the analysis, which presented high I^2. Several subanalyses in different combinations were performed to identify the study that contributed the most to I^2. The first combination after the removal of the [38] study, not decreased I^2 (96%, $p < 0.01$), while MD increased from 0.29 ($p < 0.01$) to 0.31 ($p < 0.01$). The second combination from after the removal of the [40] study, decreased I^2 from 92% ($p < 0.01$) to 11% ($p < 0.29$), while MD increased from 0.29 ($p < 0.01$) to 0.38 ($p < 0.01$). The third combination from after the removal of the [39] study, decreased I^2 from 92% ($p < 0.01$) to 0% ($p < 0.49$), while MD decreased from 0.29 ($p < 0.01$) to 0.20 ($p < 0.01$).

Effects of HIIT on IC

Figure 3 shows the analysis of HIIT effects on IC (milliseconds), indicating that participation in HIIT exercise sessions does not significantly affect IC (MD = -1.3, 95% CI 20.02; 17.41; p=0.26; z = -0.14, p =0.89). Heterogeneity in this analysis was low (I^2 = 22%; p = 0.26).

DISCUSSION

The purpose of this systematic review and meta-analysis was to evaluate the effects of HIIT intervention on EFs (IC, WM, and CF) in children and adolescents. Overall, we found unclear results regarding the effect of an acute or chronic HIIT intervention on EFs because four of the seven articles did not show a significant effect in any of the three domains of the EFs. Concerning WM, most studies that measured this outcome found improvements, and this result agrees with other studies, two with children [38,44] and one with adolescents [45]. These results are particularly important since our meta-analysis suggests that HIIT produces a significant effect on WM; nevertheless, they present high heterogeneity. Despite this, our sensitivity analysis showed in two combinations with both acute and chronic HIIT programs, low heterogeneity, and significant differences in favor to HIIT intervention, this is positive as WM steadily increases throughout infancy and childhood into adolescence [46]. This could be explained by the fact that HIIT increases oxygenation in the prefrontal cortex, the brain region associated with EFs [47,48], inducing higher brain H_2O_2 and TNF-α levels, which activate the signaling of peroxisome proliferator-activated receptor-γ coactivator (PGC-1α) to enhance brain-derived neurotrophic factor (BDNF) synthesis [49] and, consequently, improve responsiveness. However, more studies are needed on high-intensity exercise and EFs, particularly to determine the most suitable modality for children and adolescents [16]. Regarding IC, our review found that only one study out of three reported a significant improvement, which contrasts with other reviews [17,25]. The meta-analysis indicated that HIIT does not produce significant improvements in IC, supporting what has been reported in the literature. The analyzed studies showed low heterogeneity. Our results agree with those of other studies [50], which indicate that there is currently inconclusive evidence for the beneficial effects of the HIIT program on IC in children. Nevertheless, one meta-analysis reported before positive effects of HIIT intervention on IC, the authors pointed out that, considering the relatively small number of studies included in their meta-analysis. Therefore, HIIT interventions in IC should be interpreted with caution [8]. Possible improvements in IC with HIIT could be attributed to an increased state of arousal and an elevated level of cerebral perfusion, as high arousal may indicate better vigilance-sustained attention. It has been postulated that an exercise-induced arousal state would enhance IC performance because executive tasks are highly susceptible to changes in arousal states [47]. Regarding CF, only one study analyzes this outcome and found no significant improvement with the HIIT program. This finding coincides with that reported by other review analyses [17], where one study implemented an 8-week school-based HIIT program in adolescents and verified no effect in CF [35]. This is probably due, perhaps, to the fact that it increases secretions of BDNF post-exercise with acute HIIT which may, in turn, result in stronger neuronal functioning [51,52] in contrast, a chronic HIIT program. Nevertheless, there is evidence that shows improvement in CF with a chronic HIIT program of 6-week [41] and another study of 9 months, but of moderate to high-intensity intervention enhanced CF and IC [53]. However, as there have been few studies outlining this aspect of EFs, more research is needed to verify these findings.

LIMITATIONS

The limitation of this study is related to the variability in study measures used for EFs outcomes, as it was difficult to analyze the effects of HIIT on specific EF domains. Furthermore, it was not possible to include one study [41] because the data were not available. Owing to the limited number of studies included in our review and meta-analysis, the findings should be interpreted with caution.

CONCLUSION

Our study has provided evidence suggesting that participation in an HIIT program can improve children and adolescents' EFs, specifically in WM. These findings have important implications, especially for those seeking time-efficient designs of physical exercise aimed at improving their EFs. Although this result is promising, due to the small number of studies reviewed, more research is needed to further clarify the effects of HIIT interventions on EFs during childhood and adolescence.

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CONFLICT OF INTERESTS

The authors have no conflicts of interest to declare.

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