Review of High-Intensity Interval Training for Cognitive and Mental Health in Youth

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ABSTRACT

LEAHY, A. A., M. F. MAVILIDI, J. J. SMITH, C. H. HILLMAN, N. EATHER, D. BARKER, and D. R. LUBANS. Review of High-Intensity Interval Training for Cognitive and Mental Health in Youth. *Med. Sci. Sports Exerc.*, Vol. 52, No. 10, pp. 2224–2234, 2020. **Purpose:** High-intensity interval training (HIIT) has emerged as a time-efficient strategy to improve children's and adolescents' health-related fitness in comparison to traditional training methods. However, little is known regarding the effects on cognitive function and mental health. Therefore, the aim of this systematic review was to evaluate the effect of HIIT on cognitive function (basic information processing, executive function) and mental health (well-being, ill-being) outcomes for children and adolescents. **Methods:** A systematic search was conducted, and studies were eligible if they 1) included a HIIT protocol, 2) examined cognitive function or mental health outcomes, and 3) examined children or adolescents (5–18 yr). Separate meta-analyses were conducted for acute and chronic studies, with potential moderators (i.e., study duration, risk of bias, participant age, cognitive demand, and study population) also explored. **Results:** A total of 22 studies were included in the review. In acute studies, small to moderate effects were found for executive function (standardized mean difference [SMD], 0.50, 95% confidence interval [CI], 0.03–0.98; $P = 0.038$) and affect (SMD, 0.33; 95% CI, 0.05–0.62; $P = 0.020$), respectively. For chronic studies, small significant effects were found for executive function (SMD, 0.31; 95% CI, 0.15–0.76, $P < 0.001$), well-being (SMD, 0.22; 95% CI, 0.02–0.41; $P = 0.029$), and ill-being (SMD, −0.35; 95% CI, −0.68 to −0.03; $P = 0.035$). **Conclusions:** Our review provides preliminary review evidence suggesting that participation in HIIT can improve cognitive function and mental health in children and adolescents. Because of the small number of studies and large heterogeneity, more high-quality research is needed to confirm these findings. **Key Words:** EXERCISE, COGNITION, WELL-BEING, ILL-BEING, HEALTH PROMOTION

The benefits of physical activity for children's and adolescents' physical health are well established (1). There is also strong evidence to suggest that regular physical activity can improve a range of mental health outcomes (e.g., self-esteem, anxiety, and depression) (2). In addition to the physical and mental health benefits of physical activity, accumulating evidence suggests that regular engagement in physical activity to improve cardiorespiratory fitness (CRF) may enhance cognitive function in children and adolescents (3). Of note, the associated benefits of physical activity are largely influenced by the nature of the intervention delivered (i.e., acute and chronic physical activity). Acute interventions involve a single bout of physical activity (between 5 and 60 min) and are typically associated with temporary improvements (i.e., increased affect, release of endorphins, enhanced cerebral blood flow) (4). Conversely chronic interventions typically involve multiple physical activity sessions per week for an extended period of time (e.g., two sessions per week for 10 wk), yielding physiological adaptations (e.g., enhanced brain structure and function) (5). Despite these extensive benefits, 80% of adolescents worldwide are not meeting the international physical activity guideline recommendation of 60 min of daily moderate-to-vigorous physical activity (6). Furthermore, review-level evidence suggests that physical activity levels decline approximately 7% per year during adolescence (7).

The decline in physical activity may also contribute to increased prevalence of mental health disorders (e.g., anxiety, depression) that emerge during late adolescence (i.e., 15–19 yr) (8). Worldwide, mental and substance use disorders are the leading cause of disability among youth, accounting for at least a quarter of years lived with disability (9). Participation in physical activity is important for children's and adolescents'

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mental health, which includes both positive and negative constructs. In this review, we use the term well-being to describe positive constructs (e.g., psychological well-being, self-esteem, positive affect, life satisfaction, quality of life, and psychological resilience) and ill-being to represent preclinical psychological states and clinically diagnosed mental health disorders (e.g., depression and anxiety) (4,10). As previously mentioned, it seems that physical activity and fitness are important for the development of cognitive function, which may serve as a core foundation upon which mental health is established (4). Of note, poor cognitive performance during childhood is associated with current and future mental health problems (i.e., generalized anxiety disorder) (11,12).

Cognitive function refers to the set of mental processes that contribute to perception, memory, intellect, and action (3). Although cognitive function tasks are often dichotomized into two broad categories (basic information processing and executive function) (13), it is important to note that cognitive tasks exist on a continuum, from basic information processing at one end, to tasks requiring high levels of executive function at the other end. Basic information processing requires limited resources and therefore represents a lower level of cognitive function (e.g., simple motor speed/information processing tasks) (14). By contrast, executive functions represent higher-order cognitive processes that contribute toward purposeful, goal-directed behavior. Executive function consists of three core dimensions that are critical for planning, problem solving, and learning (15). These include inhibition, working memory, and cognitive flexibility. Evidence suggests that executive functions are essential for success in school, vocation, and life (5). To date, the majority of physical activity research has demonstrated selective and disproportionately greater effects for executive function tasks as opposed to those that are less executive in nature (14). Recent systematic reviews in school-aged youth (16) and older adults (17) have demonstrated that activity of vigorous intensity improves cognition to a greater extent than activity of moderate and light intensity. One of the clear benefits of engaging in regular physical activity is the development of physical fitness (i.e., CRF, muscular fitness, favorable body composition). There is sufficient evidence to suggest that children and adolescents should participate in vigorous physical activity, as it provides greater health benefits in comparison to light and moderate intensity physical activity (18,19). A useful approach for accumulating vigorous physical activity is high-intensity interval training (HIIT). HIIT is a form of exercise that typically involves alternating relatively short intervals (from <45 s to 2–4 min) of high-intensity activity (i.e., >85% max heart rate) with periods of active recovery or rest, or reoccurring bouts of maximal sprint efforts, interspersed by a prolonged rest period (20). HIIT has emerged as a novel and time-efficient strategy for improving children's and adolescents' health-related fitness in comparison to traditional training methods (20,21). HIIT has gained significant international interest in recent years and was the second highest fitness trend for 2020 (top 5 since 2014) (22). Furthermore, the recent Scientific Report of the 2018 Physical Activity Guidelines Advisory Committee highlighted, for the first time, the need to examine the effects of novel forms of physical activity such as HIIT on health outcomes in youth (23). Despite this, no previous review has focused on the benefits of HIIT for children's and adolescents' cognitive function and mental health.

Two previously published meta-analyses have explored the effects of HIIT on cognitive (24) and mental health (25) outcomes in a range of populations. However, during childhood and adolescence, the brain undergoes dramatic functional and structural changes (26). It is therefore difficult to draw firm conclusions regarding the specific effects of HIIT in children and adolescents. Furthermore, these reviews focused solely on the acute effects of HIIT; however, the chronic effects of HIIT are relatively unknown. Therefore, the primary aim of our review was to evaluate the acute and chronic effects of HIIT on cognitive function (basic information processing, executive function) and mental health (well-being, ill-being) in children and adolescents. A secondary aim was to identify potential moderators of effects (i.e., study duration, risk of bias, age of participants, cognitive demand of HIIT, type of comparison group, and study population).

METHODS

Search strategy. This review aligns with the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) guidelines and was registered with the International Prospective Registry of Systematic Reviews (registration number CRD42017067394). A structured electronic search of all publication years (through August 1, 2019) using Academic Search Ultimate, PubMed, EMBASE, CINAHL Complete, MEDLINE, SPORTDISCUS with Full Text, Psychology and Behavioral Sciences Collection, and SCOPUS was conducted (see Table, Supplemental Digital Content 1, for search strings, http://links.lww.com/MSS/B967). These strings were limited to peer-reviewed publications written in English. Firstly, titles, and abstracts identified in the search were screened for suitability. Secondly, full-text articles were screened against study selection criteria. Finally, reference lists from full-text articles were searched to identify any additional publications not found in the initial search.

Selection criteria. The criteria for study inclusion were as follows: 1) population: children and adolescents (5–18 yr), 2) study design: randomized controlled trial or randomized crossover trial (both chronic and acute studies), 3) type of intervention: structured HIIT (i.e., >85% maximum heart rate) protocol delivered in any setting (e.g., school, laboratory, or community facility), and 4) primary outcomes: quantitative assessment of cognitive function or mental health outcomes. The exclusion criteria were as follows: 1) studies involving adult participants, 2) cross-sectional or longitudinal studies without the evaluation of a HIIT protocol, and 3) studies published in conference abstracts, dissertations, protocol papers, literature reviews, gray literature, and theses. Studies that included participants with atypical development (e.g., cerebral palsy) were not excluded.

Data extraction. Data from included studies were extracted independently by two reviewers (A. A. L. and M. F. M.). The following key study characteristics were extracted: study population (children or adolescents), sample size, age, study location (country of origin), study setting, study duration, HIIT dose (i.e., frequency, intensity, time [i.e., duration], type [i.e., mode of HIIT]), control condition, cognitive function, well-being, ill-being outcome(s), study results, follow-up time points, and retention rates. In the cases of disagreement, both reviewers undertook discussion until a consensus was reached.

Risk of bias. Two reviewers (A. A. L. and M. F. M.) independently assessed the risk of bias of studies that met inclusion criteria using the Cochrane Risk of Bias Tool (RoB 2.0) (27). A third reviewer (D. R. L.) was consulted and consensus reached in the event of disagreement. The studies were assessed based on their "effect of assignment to an intervention." Risk of bias was obtained from journal articles with results of the trial and trial protocols (if provided). Each study was assessed against criteria from five domains: (i) randomization process, (ii) deviations from intended interventions, (iii) missing outcome data, (iv) measurement of the outcomes, and (v) selection of the reported results. Signaling questions within each domain had the following response options, "not applicable," "yes/probably yes," "no/probably no," and "no information," and were used to generate domain-specific judgments of either "low risk," "some concerns," or "high risk" of bias. An overall bias was calculated for each journal article by assessing each of the five domains mentioned previously, and assigned either "low risk," "some concerns," or "high risk" for overall risk of bias. Studies were rated low risk of bias if all five domains were judged to be low risk, some concerns if at least one domain was judged to have some concern regarding bias, and high risk if at least one domain was judged to be of high risk.

Strategy for data synthesis. To determine the effect of HIIT on children's and adolescents' cognitive function and mental health outcomes, we conducted a random effects meta-analysis for outcomes where there were four or more study samples. Posttest mean values and their SD were converted to Cohen *d* effect sizes and analyzed using Comprehensive Meta-Analysis software, Version 2 for Windows (Biostat Company, Englewood, NJ). The magnitude of the pooled effect sizes (hereafter referred to as standardized mean differences or SMDs) was classified as small (SMD, 0.2), medium (SMD, 0.5), and large (SMD, 0.8) (28). For studies that compared multiple HIIT groups to a single control, the sample size of the shared control was split to avoid double counting. This approach prevents effect size estimates from having artificially narrow confidence intervals (CI). When data were not provided in the articles or not provided by the corresponding author upon request, we utilized graph reader software (Web Plot Digitizer V4.2) to extract values.

We conducted six separate meta-analyses to assess the acute and chronic effects of HIIT. Meta-analyses for acute studies examined executive function and well-being (which focused exclusively on affect rather than other well-being outcomes). Therefore, as only one indicator of well-being was examined in acute studies, we use the term "affect" as opposed to well-being. Meta-analyses for chronic studies examined basic information processing, executive function, well-being, and ill-being outcomes. For studies that examined cognitive function outcomes, HIIT was compared with alternative exercise or sedentary control conditions. Three reviewers (A. A. L., M. F. M., D. R. L.) evaluated all studies included in the meta-analysis to determine the demand of cognitive function outcomes. Outcomes were classified as either basic information processing or executive function. As there were not enough studies to conduct separate meta-analyses for the different executive function subdomains (e.g., inhibition, working memory, and cognitive flexibility), tasks exhibiting greater executive function (e.g., incongruent trials of a flanker task, 2-back condition of an *n*-back task, etc.) were converted to Cohen *d*, and an average was included in the meta-analysis as a measure of overall executive function. A similar approach was used for basic information processing with tasks exhibiting lower-order cognitive processes (e.g., congruent trials in the flanker task, 1-back condition in the *n*-back task) were converted to Cohen *d* and then averaged to provide an overall effect on basic information processing. For outcome variables, where lower values are desirable (e.g., reaction time, number of errors), the sign of the effect size was reversed so that positive values represent a beneficial effect for all outcomes. If multiple postexercise values were reported, we extracted the first value between 10 and 60 min after exercise completion, based on evidence showing initial decrements in cognitive performance postexercise followed by improvements during this window (29).

In regard to mental health outcomes, much of the literature on the acute effects of HIIT on affect has compared HIIT with other exercise conditions (e.g., moderate-intensity continuous training [MICT]). However, the aim of our analysis was to determine the effects of HIIT on affect relative to no exercise. As such, comparisons between HIIT and MICT (or other modes/intensities of exercise) were not included. Affective responses during and immediately after high-intensity/strenuous exercise are almost universally negative (30). However, there is a rebound effect whereby feeling state improves thereafter (31). As such, we avoided values reported during and immediately after HIIT and instead extracted the next recorded value (e.g., 5 min after exercise cessation). For both acute and chronic outcomes, when studies used several measures to assess well-being (e.g., self-esteem and quality of life) or ill-being (e.g., depression, perceived stress), an average effect size was calculated and used in the meta-analysis. For studies that included child and parent-reported values for the same outcome, the average of the two values was used in the analyses.

Heterogeneity was determined by Cochrane Q statistic and I^2 values, whereby values of <25%, 50%, and 75% were be considered to indicate low, moderate, and high levels of heterogeneity, respectively. Publication bias was analyzed using Rosenthal's classic fail-safe N, which provides an indication

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of the number of studies needed with a mean effect of zero before the overall effect would no longer be statistically significant. Subgroup moderator analyses were conducted if HIIT effects differed according to the duration of the study (i.e., <8 wk vs ≥ 8 wk), risk of bias (i.e., low vs moderate-to high), age of participants (i.e., children vs adolescents), and type of cognitive demand (i.e., low vs moderate-to-high cognitive demand), with the threshold for significance set at $P < 0.1$.

RESULTS

The search yielded 5282 studies (Figure, Supplemental Digital Content 2, PRISMA flow diagram, http://links.lww.com/MSS/B968). Once duplicates were removed, abstracts (n = 2665), and full-text articles (n = 144) were screened. A total of 22 studies were included in the systematic review and 19 in the meta-analyses. Three studies (32–34) were not included in the meta-analysis because of lack of data availability or control group (see Table, Supplemental Digital Content 3, for study characteristics, http://links.lww.com/MSS/B969).

Study Characteristics and Participants

Studies were published between January 2010 (35) and May 2019 (36,37) including randomized crossover (or other matched; n = 10 [45%]), and parallel group (cluster randomized or individually randomized; n = 12 [55%]) trials. Sample sizes ranged from 13 (38) to 616 (37) participants, totaling up to 2092 children and adolescents. Four studies included only male participants (33,38–40) and 2 studies did not report sex of participants (32,41), whereas the remaining 16 studies included both male and female participants. A majority of the included studies (32,34–39,41–50) assessed adolescent populations (13–18 yr), whereas five studies were conducted with children (33,40,51–53). The majority of studies included typically developing participants apart from three studies that involved children with cerebral palsy (43), children with attention deficit hyperactivity disorder (40), and adolescents with asthma (37). Only three studies specifically recruited athletes (football players (32,40) and sailors [50]).

Studies were conducted in Australia (43,44), Canada (52), Finland (49), Germany (32,40), Greece (35), Lithuania (50), New Zealand (53), Norway (43), Spain (36,47,48), Switzerland (39), Tunisia (33,41), and United Kingdom (37,38,42,45,46,51). The intervention component of studies was conducted at schools (33,35–37,39,42–49,52,53) (n = 15; 68%), in laboratories (38,40,43,51) (n = 4; 18%), and in practical settings such as football fields (32,41) or athletics tracks (50) (n = 3; 14%). Acute studies (33,35,38,39,42,45,46,48,51,52) (i.e., single session) and chronic studies (32,34,36,37,39,41,43,44,47,49,50,53) (range, 2 wk [49] to 6 months [37]) were included. The duration of HIIT sessions ranged from 4 min (52) to 30 min (37,50). For chronic studies, the frequency of sessions ranged from two (36) to five (53) sessions per week. Heart rate monitoring technology was utilized in the majority of studies (32–34,36–39,41–44,48–50) to ensure appropriate exercise intensity (n = 14; 64%).

Studies utilized a variety of physical activity modalities to engage participants in HIIT including maximal sprint running (32,41,42), running (33,35,50), cycling (45,46), treadmill walking/running (38,43,51), circuit training (39), a combination of a variety of aerobic- (e.g., shuttle runs, jumping jacks) and/or resistance-based exercises (e.g., squats, triceps dips) (43,44), video-based intervention delivery involving simple movements (e.g., squats, jumping jacks, running on the spot) (52,53), or cooperative HIIT (e.g., burpees in pairs, coordination ladder back and front) (36,47,48). Two studies included a combination of modalities (e.g., circuit training and running [49] and circuit and game-based activities [37]). In acute studies, HIIT protocols were compared with sedentary activities (including static stretching) (35,39,42,48,52) or alternative physical activity conditions (33,38,46,51). For clarity, in the acute meta-analysis examining affect, one study was not included because of insufficient data (33), and we only examined within-group changes for HIIT conditions (i.e., did not compare HIIT with alternative exercise condition) in two studies (38,46). In chronic studies, HIIT protocols were compared with sedentary activities (36,37,44,47,49,50,53) or alternative exercise conditions (including regular physical education classes or football training) (32,40,41,43). Only one study did not include a control group (43) and was therefore not included in the meta-analysis.

Outcome Measures

Half of the included studies (35,39,43,47–54) measured a component of cognitive function (e.g., basic information processing, executive function; n = 11 [50%]). Of note, all 11 of these studies provided a measure of executive function, whereas only 5 provided data for basic information processing (39,42,43,49,50). Indicators of well-being (i.e., self-concept, quality of life, affect) were also measured in half of the included studies (33,34,36–38,40,41,43–46). Indicators of ill-being (i.e., stress) were measured in four studies (32,41,43,44).

Adherence and Retention

Most studies failed to report data regarding intervention adherence. For those that reported adherence (32,43,44), adherence was problematic in two studies (32,43) and satisfactory in one study (44). Retention rates less than 90% were reported in eight studies (32,36,37,43,48–50,52), whereas in three studies, retention values were not reported (39,40,47).

Risk of Bias

Risk of bias was assessed against criteria from five domains (Fig. 1). Only three studies (43,49,53) were characterized as having "low risk" overall. Bias from randomization process was the most problematic domain, with only five studies (42–44,49,53) evaluated as "low risk." However, all studies were assigned "low risk" for selection of the reported results. Participant and assessor blinding were included only when it was conducted at all time-points. Participant blinding was reported in four studies (36,42,47,48), whereas three studies

	Outcome	Randomization process	Deviations from intended interventions	Missing outcome data	Measurement of the outcome	Selection of the reported result	Overall
Cooper (2016)	Cognitive function	+	+	?	+	+	?
Costigan (2016)	Cognitive function	+	+	+	+	+	+
	Well-being/Ill-being	+	+	+	?	+	?
Faude (2014)	Ill-being	?	?	?	?	+	?
Jebali (2013)	Well-being	?	?	?	?	?	?
Lambrick (2016)	Cognitive function	?	?	+	+	+	?
Lauglo (2016)	Well-being	−	?	?	?	+	−
Leahy (2019)	Well-being/Ill-being	+	+	+	?	+	?
Ludyga (2019)	Cognitive function	?	?	+	+	+	?
Ma (2015)	Cognitive function	?	?	?	+	+	?
Malik (2018a)	Well-being	?	?	+	?	+	?
Malik (2018b)	Well-being	?	?	+	?	+	?
Malik (2019)	Well-being	?	?	+	?	+	?
Martínez-López (2018)	Cognitive function	?	+	+	+	+	?
Messler (2018)	Well-being	?	?	?	?	+	?
Mezcua-Hidalgo (2019)	Cognitive function	?	+	+	+	+	?
Moreau (2017)	Cognitive function	+	+	+	+	+	+
Ruiz-Ariza (2019)	Well-being	?	+	+	?	+	?
Selmi (2018)	Well-being/Ill-being	−	?	+	?	+	−
Stenman (2017)	Cognitive function	+	+	+	+	+	+
Travlos (2010)	Cognitive function	?	?	+	+	+	?
Venckunas (2016)	Cognitive function	−	?	?	+	+	−
Winn (2019)	Well-being	?	?	+	?	+	?

FIGURE 1—Risk of bias assessment. + denotes low risk; ?, some concerns; −, high risk.

(43,44,49) reported assessor blinding. Only one study (53) reported double blinding (participants and assessors). The bias due to deviations from intended interventions was low in five studies (42–44,49,53). The bias due to missing outcome data was fulfilled in all studies apart from seven (32,33,40,42,43,50,52) characterized with "some concerns or high risk." In one study (43), the criteria varied from "low risk" to "some concerns" based on the type of outcome (i.e., computerized program or self-reported data). All studies apart from one (33) met the criteria of bias in selection of the reported results ("low risk").

A priori power calculations were reported in 10 studies (34,37,38, 43–46,51–53).

Meta-analysis

Acute effects of HIIT. Data from the meta-analysis of the acute effects are presented in Table 1. Two separate meta-analyses were conducted for executive function and affect. There were not enough studies to conduct meta-analyses for basic information processing and ill-being.

TABLE 1. Meta-analysis of the acute and chronic effects of HIIT on cognitive function, well-being and ill-being.

	Effect Size and Precision					Heterogeneity				
Outcomes	*k*	*N*	Estimate	95% CI	*P*	*Q*	*df* (*Q*)	*P*	I^2	Fail-Safe *N*
Acute studies										
Executive function	6	508	0.504	0.029 to 0.979	0.038	6.87	5	0.231	27.18	4
Affect	6	88	0.334	0.052 to 0.615	0.020	9.90	5	0.078	49.48	11
Chronic studies										
Basic information processing	4	102	0.290	−0.116 to 0.695	0.162	1.34	3	0.719	0.00	—
Executive function	6	591	0.313	0.149 to 0.760	<0.001	4.82	5	0.439	0.00	3
Well-being	8	696	0.217	0.022 to 0.411	0.029	9.24	7	0.236	24.22	6
Ill-being	4	156	−0.350	−0.675 to −0.025	0.035	2.97	3	0.396	0.00	2

The pooled SMD for the acute effects of HIIT on executive function was 0.50 (95% CI, 0.03–0.98; $P = 0.038$; Figure, Supplemental Digital Content 4, forest plot, http://links.lww.com/MSS/B970), and heterogeneity was relatively low ($I^2 = 27.18$). However, publication bias was considered possible, with only four unpublished studies with an effect size of zero required to reduce the pooled effect to nonsignificance. There were no significant moderators (Table, Supplemental Digital Content 5, moderator analysis, http://links.lww.com/MSS/B971).

The pooled SMD (95% CI) for the acute effects of HIIT on affect was 0.33 (95% CI, 0.05–0.62; $P = 0.020$; Figure, Supplemental Digital Content 6, forest plot, http://links.lww.com/MSS/B972). Heterogeneity was moderate ($I^2 = 49.48$), and the fail-safe *N* was 11 studies. There were no significant moderators (Table, Supplemental Digital Content 7, moderator analysis, http://links.lww.com/MSS/B973).

Chronic effects of HIIT. Data from the meta-analysis are presented in Table 1. Four separate meta-analyses were conducted for chronic studies (i.e., basic information processing, executive function, well-being, and ill-being).

The pooled SMD (95% CI) for the effects of HIIT on basic information processing was 0.29 (−0.12 to 0.70; Fig. 2), and heterogeneity was found to be zero. There were no significant moderators (Table, Supplemental Digital Content 8, moderator analysis, http://links.lww.com/MSS/B974).

The pooled SMD for the effects of HIIT on executive function was 0.31 (95% CI, 0.16–0.76; $P < 0.001$; Fig. 3), and heterogeneity was found to be zero. However, publication bias was considered possible, as Rosenthal's classic fail-safe *N* indicated that only three unpublished studies with an effect size of zero would be required to make the observed effect no longer significant. Cognitive demand of HIIT was a significant moderator, with stronger effects observed for more cognitively demanding HIIT programs (Table, Supplemental Digital Content 9, moderator analysis, http://links.lww.com/MSS/B975).

The pooled SMD for the effects of HIIT on well-being was 0.22 (95% CI, 0.02 to 0.41; $P = 0.029$; Fig. 4), and heterogeneity was found to be low ($I^2 = 24.22$). Rosenthal's classic fail-safe *N* indicated that only six unpublished studies with an effect size of zero would be required to make the observed effect no longer significant. Study duration and cognitive demand of HIIT were significant moderators of intervention effects. Specifically, stronger effects were seen for studies less than 8 wk in duration and for HIIT programs with lower levels of cognitive demand (Table, Supplemental Digital Content 10, moderator analysis, http://links.lww.com/MSS/B976). However, there was only one low-demand study, so this finding should be interpreted with caution.

The pooled SMD for the effects of HIIT on ill-being was −0.35 (95% CI, −0.66 to −0.03; $P = 0.035$; Fig. 5), and heterogeneity was found to be zero. However, publication bias was considered possible, as Rosenthal's classic fail-safe *N* indicated that only two unpublished studies with an effect size of zero would be required to make the observed effect no longer significant. There was no variability across studies assessing the effects of HIIT on ill-being, and moderator analyses were therefore not conducted.

DISCUSSION

The aim of our review was to synthesize the available evidence surrounding the efficacy of HIIT for improving cognitive function and mental health in children and adolescents. Our meta-analysis results suggest that HIIT can produce moderate acute effects (SMD, 0.50) for executive function and small acute effects (SMD, 0.30) for well-being. In addition, we found small significant chronic effects for executive function

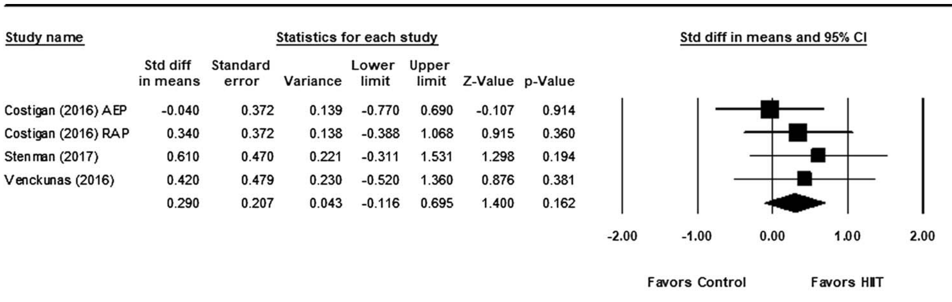

FIGURE 2—Forest plot of the chronic effects of HIIT on basic information processing.

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
	Statistics for each study						
Costigan (2016) AEP	0.060	0.372	0.139	-0.670	0.790	0.161	0.872
Costigan (2016) RAP	0.160	0.370	0.137	-0.565	0.885	0.433	0.665
Stenman (2017)	-0.460	0.465	0.217	-1.372	0.452	-0.988	0.323
Venckunas (2016)	0.000	0.474	0.225	-0.930	0.930	0.000	1.000
Moreau (2017)	0.330	0.115	0.013	0.104	0.556	2.862	0.004
Martinez-Lopez (2018)	0.460	0.149	0.022	0.167	0.753	3.079	0.002
	0.313	0.083	0.007	0.149	0.476	3.748	0.000

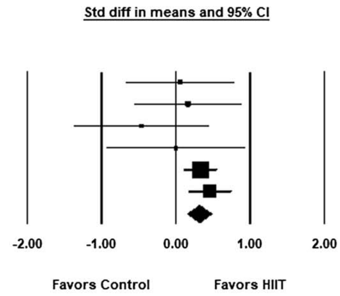

FIGURE 3—Forest plot of the chronic effects of HIIT on executive function.

(SMD, 0.31), well-being (SMD, 0.22), and ill-being (SMD, −0.35), and a small nonsignificant effect for basic information processing (SMD, 0.29). A secondary aim was to identify potential moderators of HIIT effects. Study duration emerged as a significant moderator of chronic physical activity studies on well-being, with stronger effects observed for studies with <8 wk in comparison to those ≥8 wk in duration. Stronger effects for executive function were evident with studies that implemented moderate-to-high cognitively demanding HIIT protocols, whereas stronger effects on well-being were observed for studies that implemented low cognitively demanding HIIT protocols. However, given the relatively small number of studies included in the meta-analyses, our findings should be interpreted with caution.

We found that participation in HIIT had a moderate acute effect (SMD, 0.50) on executive function, which is larger than previously reported (24). Of note, Moreau and Chou (24) conducted a meta-analysis of the acute effects of high-intensity exercise on executive function. In their review, the authors observed a small, positive effect ($d = 0.24$) on overall executive function; however, this effect was moderated by the type of comparison group. A significant effect was only evident when comparing high-intensity exercise to resting conditions, but not when comparing high-intensity exercise to lower-intensity conditions (i.e., moderate-intensity). Regardless, the results suggest that high-intensity exercise is an effective method for improving executive function, and the effects are comparable to those observed with moderate-intensity exercise (55). The additional benefit of high-intensity exercise is that the same effects can be obtained in significantly shorter duration of exercise. Although the mechanisms for these effects are less understood, it has been proposed that higher concentrations of several neurochemicals (i.e., brain-derived neurotrophic factor and catecholarmines [e.g., dopamine, epinephrine]) induced by exercise, and in particular high-intensity exercise, may improve cognitive performance (56). It should also be acknowledged that, although the meta-analysis conducted by Moreau and Chou (24) did not focus exclusively on the effects of HIIT (but rather any form of high-intensity exercise). Interestingly, their moderator analysis revealed comparable effects between high-intensity continuous and intermittent protocols. These results suggest that both forms of training are effective for gaining benefits. However, the lower training volume offered by HIIT provides a time-efficient alternative to induce short-term benefits.

In addition, it has consistently been demonstrated that high-intensity exercise evokes feelings of displeasure as individuals work at, or toward, their functional limits (30,57). According to the Dual Model Theory, aversive psychological feelings experienced during exercise lead to greater rates of exercise dropout (58). Although the effect of in-task affect is well established, the current study aimed to examine the "rebound effect" after a bout of HIIT. Overall, we found a small, significant effect in favor of HIIT (SMD, 0.33). Our results are similar to those observed in a previous meta-analysis focused predominantly on adults (SMD, 0.19; 95% CI, −0.17 to 0.56) (25). It is important to note that in their meta-analysis, the authors examined the effects of between group changes (e.g., HIIT vs MICT), whereas in the current study, we focused on within-group changes, which may explain our larger effect size. Because of the small number of studies included in the current review, it is unclear whether adolescents have the same

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
	Statistics for each study						
Costigan (2016) AEP	-0.180	0.373	0.139	-0.911	0.551	-0.483	0.629
Costigan (2016) RAP	-0.360	0.372	0.138	-1.089	0.369	-0.968	0.333
Leahy (2019)	0.120	0.257	0.066	-0.383	0.623	0.468	0.640
Messler (2018)	0.500	0.393	0.154	-0.270	1.270	1.273	0.203
Ruiz-Ariza (2019)	0.330	0.148	0.022	0.039	0.621	2.223	0.026
Selmi (2018)	0.990	0.387	0.150	0.232	1.748	2.559	0.010
Winn (2019) Asthma	0.270	0.249	0.062	-0.218	0.758	1.084	0.278
Winn (2019) Non-asthma	0.130	0.134	0.018	-0.134	0.394	0.967	0.334
	0.217	0.099	0.010	0.022	0.411	2.180	0.029

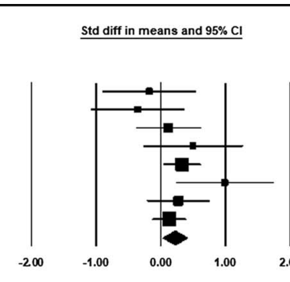

FIGURE 4—Forest plot of the chronic effects of HIIT on well-being.

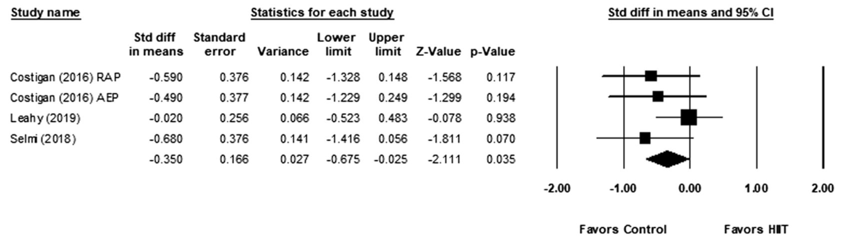

FIGURE 5—Forest plot of the chronic effects of HIIT on ill-being.

affective response to HIIT as adults. Although the immediate negative dose–response effects arising during exercise can reduce exercise adherence, there are no long-term studies conducted with children and adolescents to support this argument. To further our understanding, prospective studies should aim to address this gap in the literature by directly comparing different exercise modalities (i.e., HIIT vs MICT) for adherence to exercise over extend periods of time (e.g., >6 months). We also observed a significant moderator for the level of cognitive demand. Stronger effects were observed for HIIT protocols with low cognitive demand. However, only one study (40) was categorized as involving low cognitive demand; therefore, this finding should be interpreted with caution. It is possible that the demographic of the study population (i.e., elite football players) and nature of the HIIT protocol (i.e., sprint interval training) contributed to the significant moderator effect.

Our meta-analysis revealed that chronic HIIT had a small effect on cognitive function (i.e., both basic information processing and executive function) in children and adolescents. Our findings are consistent with those reported in previous reviews examining children and adolescents (3,59,60). Specifically, Alvarez-Bueno and colleagues (59) reported an effect size of 0.20 for executive functions, whereas Singh et al. (60) found that chronic physical activity interventions improved overall executive functions (SMD, 0.20) and inhibitory control (SMD, 0.26). Considering the relatively small number of studies included in our meta-analyses, our findings should be interpreted with caution. It is important to acknowledge that studies with high-quality designs and larger samples may contribute the strongest evidence for the effects of HIIT on cognitive function. For example, one high-quality study involving more than 300 children (53) contributed more than 50% of the effect size in our meta-analysis. The significant intervention effect observed by Moreau and colleagues is promising, but more high-quality experimental research is needed.

The effect to which physical activity influences cognition may be dependent on a number of parameters such as duration, intensity, and type of activity (4). As the majority of research has focused on the effects of moderate-intensity activity (61), it is difficult to interpret whether activities of varying intensities (i.e., vigorous-intensity) produce similar effects. Findings from the current study suggest that engaging in bouts of vigorous-intensity activity can produce chronic benefits in cognitive function and builds on prior review-level evidence demonstrating an association between vigorous physical activity and cognitive performance in adolescents (62). However, the underlying mechanisms are less understood (4). Vigorous-intensity physical activity seems to be more strongly associated with fitness in youth (19), which in turn may serve to promote improvements in cognitive outcomes via neurobiological outcomes (i.e., structural and functional changes within the brain) (4). Of note, cross-sectional research has demonstrated the children with higher levels of fitness have greater hippocampal volume and memory performance compared with lower-fit children (63). Furthermore, engaging in chronic bouts of physical activity stimulates angiogenesis and neurogenesis in areas of the brain, which ultimately influence cognitive performance (5).

Pesce (64) has suggested that the effect of physical activity on cognition may differ according to the qualitative characteristics of the movement task (i.e., coordinative complexity and cognitive demand). Activity that requires a greater allocation of attention and cognitive effort (known as cognitive engagement) is suggested to improve cognition to a greater extent than activities with low cognitive engagement (e.g., continuous running) (65). This argument, known as the "cognitive stimulation hypothesis," posits that activities that are coordinatively demanding, stimulate similar areas of the brain that are responsible for higher-order cognitive processes (66). Results from our moderator analysis provide some support for this view, with greater effects on cognitive function observed for studies with moderate-to-high levels of cognitive engagement. Benefits may arise from physical activity that is "cognitively demanding" (e.g., activity such as learning new dance moves). However, as this is an emerging area of research, there are not enough studies to draw firm conclusions at this time. In addition, there is a lack of consensus regarding the definition or threshold of what constitutes "cognitively demanding physical activity" (or "noncognitively demanding physical activity" for that matter). Finally, there is considerably more evidence available for positive effects of physical activity that improves CRF on cognitive outcomes (3,67,68).

Finally, results from our meta-analysis revealed that HIIT can improve both well-being and ill-being outcomes. A total of six studies were included in the meta-analysis for well-being, and we found a small positive effect in favor of HIIT (SMD, 0.22). Our findings are consistent with previous reviews conducted in children and adolescents, which have reported small-to-moderate positive effects for physical activity on measures of well-being (10,69). A variety of mechanisms may explain this effect. For example, participation in physical exercise is thought to stimulate neurobiological responses via the release of endogenous opioids (e.g., endorphins). The "endorphin hypothesis" ascribes the positive changes in mood after exercise to the increased release of β-endorphins (70,71). In their conceptual model, Lubans and colleagues (4) identified physical activity intensity as a potential moderator of this effect. Considering that HIIT produces comparable if not superior health benefits than moderate-intensity activity (20,21), it is plausible to suggest that HIIT may stimulate greater neurobiological effects than that of lower-intensity activities.

Our study revealed that HIIT can reduce ill-being (SMD, −0.35) in children and adolescents. In an earlier review, Larun et al. (72) reported significant moderate effect sizes for vigorous-intensity activity interventions on depressive symptoms in youth ($d = -0.66$). However, unlike the current review, the inclusion of children and adolescents with major depressive symptoms may have contributed to a larger effect size. Notably, study participants included in our ill-being meta-analysis were all relatively healthy, therefore limiting the potential for large effects. Findings from our study are consistent with a recent meta-analysis that reported a small significant effect of exercise on psychological ill-being (effect size, −0.13), with stronger effects in children compared with adolescents. Although we were unable to test this hypothesis because of lack of variability, it is possible that the effect of HIIT is stronger in adolescents compared with children, as this is typically the time period for onset of common mental disorders such as anxiety and depression (8).

Similar to traditional types of physical activity (e.g., continuous aerobic activity), engaging in HIIT may also enhance self-efficacy. The authors of a recent review examining the psychological responses to interval training concluded that HIIT can enhance self-efficacy (73). Similarly, a study conducted by Boyd and colleagues (74) found that after 3 wk of HIIT, participants felt confident to schedule and participate (i.e., task self-efficacy) in regular HIIT. It is possible that short bursts of activity interspersed by rest periods are more manageable than bouts of continuous activity, which may enhance self-efficacy. Future studies are needed to test the hypothesis that improvements in self-efficacy act as a mechanism for enhancing well-being in adolescent populations.

Future studies are needed to explore strategies that optimize the effect of HIIT on children's and adolescents' cognitive function and mental health. Effect sizes may be optimized by focusing on the psychosocial, behavioral, and neurobiological mechanisms responsible for the effects of HIIT on brain-related outcomes. Of note, the SAAFE (supportive, active, autonomous, fair and enjoyable) principles provide a framework for the design and delivery of exercise sessions (75). Guided by self-determination theory, these principles have been successfully applied in two recent HIIT studies (43,44). Although the vigorous nature of HIIT can be aversive, HIIT sessions may be perceived as more enjoyable to children and adolescents if they are designed explicitly to satisfy basic psychological needs (i.e., autonomy, competence, relatedness). For example, providing participants with choice of the included exercises and/or work and rest interval durations may satisfy autonomy. Moreover, the provision of encouragement and positive feedback may enhance participants' perceptions of competence. Performing HIIT in groups with friends is more enjoyable and can satisfy perceptions of relatedness. Other simple strategies, such as using music, and exercising in desirable natural environments (e.g., park or beach), may also optimize the cognitive and mental health benefits of HIIT.

Strengths and limitations. This is the first systematic review to quantitatively analyze the effects of HIIT on cognitive function and mental health outcomes in children and adolescents. Strengths of our review include the adherence to PRISMA guidelines, use of the Cochrane ROB criteria, and the inclusion of meta-analyses with moderation analyses. However, there are also some limitations that should be acknowledged: First, as the majority of studies included healthy participants, it was not possible to conduct separate meta-analyses for healthy and unhealthy populations, therefore limiting the generalizability of our findings. Second, given the variability in study measures used for cognitive outcomes, it was not possible to determine the effects on specific domains of executive function (inhibition, working memory, cognitive flexibility). Finally, although promising effects were observed for cognitive function and mental health outcomes after HIIT, it should be acknowledged that the majority of studies did not prescribe an active control group (i.e., moderate-intensity training). Because of the small number of studies included in our review, we were unable to perform a moderator analysis for exercise modality (e.g., HIIT vs MICT). Therefore, we were unable to directly compare the effects of HIIT with an alternative exercise modality for all review outcomes. As interest in this area continues, understanding the specific effects of alternative exercise intensities and modalities would be useful to help inform future physical activity interventions.

CONCLUSIONS

Our study has provided preliminary review evidence suggesting that participation in HIIT can improve children's and adolescents' cognitive function and mental health. In general, the acute effects of HIIT were stronger than the chronic effects for cognitive function. Importantly, both well-being and ill-being were improved after HIIT interventions. Although promising, because of the small number of studies and large heterogeneity, more high-quality research is needed to confirm these findings.

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The authors have no conflict of interest to declare.

The data sets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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A. A. L. and M. F. M. conducted the literature search, assessed studies for eligibility, conducted risk of bias assessment, and wrote the manuscript. C. H. H. and N. E. participated in drafting and revising the manuscript. D.B. provided guidance for the statistical analysis of the review. J. J. S. and D. R. L. were involved in conception and design of the review, conducted data analysis (meta-analysis) and interpretation, and participated in drafting and revising the manuscript. All authors provided critical review and endorsed the final version of the manuscript.

REFERENCES

1. Janssen I, Leblanc AG. Systematic review of the health benefits of physical activity and fitness in school-aged children and youth. *Int J Behav Nutr Phys Act*. 2010;7:40.
2. Biddle SJ, Asare M. Physical activity and mental health in children and adolescents: a review of reviews. *Br J Sports Med*. 22011;45(11):886–95.
3. Donnelly JE, Hillman CH, Castelli D, et al. Physical activity, fitness, cognitive function, and academic achievement in children: a systematic review. *Med Sci Sports Exerc*. 2016;48(6):1197–222.
4. Lubans D, Richards J, Hillman C, et al. Physical activity for cognitive and mental health in youth: a systematic review of mechanisms. *Pediatrics*. 2016;138(3). pii: e20161642.
5. de Greeff JW, Bosker RJ, Oosterlaan J, Visscher C, Hartman E. Effects of physical activity on executive functions, attention and academic performance in preadolescent children: a meta-analysis. *J Sci Med Sport*. 2018;21(5):501–7.
6. Guthold R, Stevens GA, Riley LM, Bull FC. Global trends in insufficient physical activity among adolescents: a pooled analysis of 298 population-based surveys with 1.6 million participants. *Lancet Child Adolesc Health*. 2020;4(1):23–35.
7. Dumith SC, Gigante DP, Domingues MR, Kohl HW. Physical activity change during adolescence: a systematic review and a pooled analysis. *Int J Epidemiol*. 2011;40(3):685–98.
8. Beauchamp MR, Puterman E, Lubans DR. Physical inactivity and mental health in late adolescence. *JAMA Psychiatry*. 2018;75(6):543–4.
9. Erskine HE, Moffitt TE, Copeland WE, et al. A heavy burden on young minds: the global burden of mental and substance use disorders in children and youth. *Psychol Med*. 2015;45(7):1551–63.
10. Rodriguez-Ayllon M, Cadenas-Sánchez C, Estévez-López F, et al. Role of physical activity and sedentary behavior in the mental health of preschoolers, children and adolescents: a systematic review and meta-analysis. *Sports Med*. 2019;49(9):1383–410.
11. Hatch SL, Jones PB, Kuh D, Hardy R, Wadsworth MEJ, Richards M. Childhood cognitive ability and adult mental health in the British 1946 birth cohort. *Soc Sci Med*. 2007;64(11):2285–96.
12. Martin LT, Kubzansky LD, LeWinn KZ, Lipsitt LP, Satz P, Buka SL. Childhood cognitive performance and risk of generalized anxiety disorder. *Int J Epidemiol*. 2007;36(4):769–75.
13. Chang YK, Chu CH, Chen FT, Hung TM, Etnier JL. Combined effects of physical activity and obesity on cognitive function: independent, overlapping, moderator, and mediator models. *Sports Med*. 2017;47(3):449–68.
14. Colcombe S, Kramer AF. Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychol Sci*. 2003;14(2):125–30.
15. Diamond A. Executive functions. *Annu Rev Psychol*. 2013;64:135–68.
16. Daly-Smith AJ, Zwolinsky S, McKenna J, Tomporowski PD, Defeyter MA, Manley A. Systematic review of acute physically active learning and classroom movement breaks on children's physical activity, cognition, academic performance and classroom behaviour: understanding critical design features. *BMJ Open Sport Exerc Med*. 2018;4(1):e000341.
17. Northey JM, Cherbuin N, Pumpa KL, Smee DJ, Rattray B. Exercise interventions for cognitive function in adults older than 50: a systematic review with meta-analysis. *Br J Sports Med*. 2018;52(3):154–60.
18. Costigan SA, Lubans DR, Lonsdale C, Sanders T, Del Pozo Cruz B. Associations between physical activity intensity and well-being in adolescents. *Prev Med*. 2019;125:55–61.
19. Hay J, Maximova K, Durksen A, et al. Physical activity intensity and cardiometabolic risk in youth. *Arch Pediatr Adolesc Med*. 2012;166(11):1022–9.
20. Costigan SA, Eather N, Plotnikoff RC, Taaffe DR, Lubans DR. High-intensity interval training for improving health-related fitness in adolescents: a systematic review and meta-analysis. *Br J Sports Med*. 2015;49(19):1253–61.
21. Eddolls WTB, McNarry MA, Stratton G, Winn CON, Mackintosh KA. High-intensity interval training interventions in children and adolescents: a systematic review. *Sports Med*. 2017;47(11):2363–74.
22. Thompson WR. Worldwide survey of fitness trends for 2020. *ACSM Health Fit J*. 2019;23(6):10–8.
23. 2018 Physical Activity Guidelines Advisory Committee. *2018 Physical Activity Guidelines Advisory Committee Scientific Report*. Washington (DC): US Department of Health and Human Services; 2018.
24. Moreau D, Chou E. The acute effect of high-intensity exercise on executive function: a meta-analysis. *Perspect Psychol Sci*. 2019; 14(5):734–64.
25. Oliveira BRR, Santos TM, Kilpatrick M, Pires FO, Deslandes AC. Affective and enjoyment responses in high intensity interval training and continuous training: a systematic review and meta-analysis. *PLoS One*. 2018;13(6):e0197124.
26. Mundkur N. Neuroplasticity in children. *Indian J Pediatr*. 2005; 72(10):855–7.
27. Higgins JPT, Sterne JAC, Savovic J, et al. A revised tool for assessing risk of bias in randomized trials. *Cochrane Database Syst Rev*. 2016;10(1 Suppl):29–31.
28. Cohen J. *Statistical Power Analysis for the Behavioural Sciences*. 2nd ed. Hillsdale (NJ): Lawerence Erlbaum Associates; 1998. 567 p.
29. Chang YK, Labban JD, Gapin JI, Etnier JL. The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Res*. 2012; 1453:87–101.
30. Ekkekakis P, Hall EE, Petruzzello SJ. Variation and homogeneity in affective responses to physical activity of varying intensities: an alternative perspective on dose-response based on evolutionary considerations. *J Sports Sci*. 2005;23(5):477–500.
31. Jung ME, Bourne JE, Little JP. Where does HIT fit? An examination of the affective response to high-intensity intervals in comparison to continuous moderate- and continuous vigorous-intensity exercise in the exercise intensity-affect continuum. *PLoS One*. 2014;9(12):e114541.
32. Faude O, Steffen A, Kellmann M, Meyer T. The effect of short-term interval training during the competitive season on physical fitness and signs of fatigue: a crossover trial in high-level youth football players. *Int J Sports Physiol Perform*. 2014;9(6):936–44.
33. Jebali T, Moalla W, Elloumi M, Padulo J, Baquet G, Chamari K. The relevant use of the traditional Tunisian game "raqassa" for cardiovascular stimulation in schoolchildren. *Biol Sport*. 2013; 30(3):219–25.
34. Lauglo R, Vik T, Lamvik T, Stensvold D, Finbråten A, Moholdt T. High-intensity interval training to improve fitness in children with cerebral palsy. *BMJ Open Sport Exerc Med*. 2016;2:e000111.
35. Travlos AK. High intensity physical education classes and cognitive performance in eighth-grade students: an applied study. *Int J Sports Exerc Psychol*. 2010;8(3):302–11.
36. Ruiz-Ariza A, Suárez-Manzano S, Lopez S, Martínez-López EJ. The effect of cooperative high-intensity interval training on creativity and emotional intelligence in secondary school: a randomised controlled trial. *Eur Phy Educ Rev*. 2019;25(2):355–73.
37. Winn CON, Mackintosh KA, Eddolls WTB, et al. Effect of high-intensity interval training in adolescents with asthma: the eXercise for Asthma with Commando Joe's® (X4ACJ) trial. *J Sport Health*

Sci [Internet]. 2019 [cited 30 May 2019]. Available from: http://www.sciencedirect.com/science/article/pii/S2095254619300717. https://doi.org/10.1016/j.jshs.2019.05.009.
38. Malik AA, Williams CA, Weston KL, Barker AR. Perceptual responses to high- and moderate-intensity interval exercise in adolescents. *Med Sci Sports Exerc*. 2018;50(5):1021–30.
39. Ludyga S, Puhse U, Lucchi S, Marti J, Gerber M. Immediate and sustained effects of intermittent exercise on inhibitory control and task-related heart rate variability in adolescents. *J Sci Med Sport*. 2019;22(1):96–100.
40. Meßler CF, Holmberg HC, Sperlich B. Multimodal therapy involving high-intensity interval training improves the physical fitness, motor skills, social behavior, and quality of life of boys with ADHD: a randomized controlled study. *J Atten Disord*. 2018;22(8):806–12.
41. Selmi W, Rebai H, Chtara M, Naceur A, Sahli S. Self-confidence and affect responses to short-term sprint interval training. *Physiol Behav*. 2018;188:42–7.
42. Cooper SB, Bandelow S, Nute ML, et al. Sprint-based exercise and cognitive function in adolescents. *Prev Med Rep*. 2016;4:155–61.
43. Costigan SA, Eather N, Plotnikoff RC, Hillman CH, Lubans DR. High-intensity interval training for cognitive and mental health in adolescents. *Med Sci Sports Exerc*. 2016;48(10):1985–93.
44. Leahy AA, Eather N, Smith JJ, et al. Feasibility and preliminary efficacy of a teacher-facilitated high-intensity interval training intervention for older adolescents. *Pediatr Exerc Sci*. 2019;31(1):107–17.
45. Malik AA, Williams CA, Weston KL, Barker AR. Perceptual and prefrontal cortex haemodynamic responses to high-intensity interval exercise with decreasing and increasing work-intensity in adolescents. *Int J Psychophysiol*. 2018;133:140–8.
46. Malik AA, Williams CA, Weston KL, Barker AR. Perceptual and cardiorespiratory responses to high-intensity interval exercise in adolescents: does work intensity matter? *J Sports Sci Med*. 2019;18(1):1–12.
47. Martinez-Lopez EJ, Torre-Cruz MJ, Suarez-Manzano S, Ruiz-Ariza A. 24 sessions of monitored cooperative high-intensity interval training improves attention-concentration and mathematical calculation in secondary school. *J Phys Educ Sport*. 2018;18:1572–82.
48. Mezcua-Hidalgo A, Ruiz-Ariza A, Suarez-Manzano S, Martinez-Lopez EJ. 48-Hour effects of monitored cooperative high-intensity interval training on adolescent cognitive functioning. *Percept Mot Skills*. 2019;126(2):202–22.
49. Stenman M, Pesola A, Laukkanen A, Haapala E. Effects of two-week high-intensity interval training on cognition in adolescents—a randomized controlled pilot study. *Hum Mov*. 2017;18(2):15–20.
50. Venckunas T, Snieckus A, Trinkunas E, et al. Interval running training improves cognitive flexibility and aerobic power of young healthy adults. *J Strength Cond Res*. 2016;30(8):2114–21.
51. Lambrick D, Stoner L, Grigg R, Faulkner J. Effects of continuous and intermittent exercise on executive function in children aged 8–10 years. *Psychophysiology*. 2016;53(9):1335–42.
52. Ma JK, Le Mare L, Gurd BJ. Four minutes of in-class high-intensity interval activity improves selective attention in 9- to 11-year olds. *Appl Physiol Nutr Metab*. 2015;40(3):238–44.
53. Moreau D, Kirk IJ, Waldie KE. High-intensity training enhances executive function in children in a randomized, placebo-controlled trial. *Elife*. 2017;6. pii: e25062.
54. Cooper SB, Bandelow S, Nute ML, Morris JG, Nevill ME. The effects of a mid-morning bout of exercise on adolescents' cognitive function. *Ment Health Phys Act*. 2012;5(2):183–90.
55. Ludyga S, Gerber M, Brand S, Holsboer-Trachsler E, Puhse U. Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: a meta-analysis. *Psychophysiology*. 2016;53(11):1611–26.
56. Cooper SB, Dring KJ, Nevill ME. High-intensity intermittent exercise: effect on young people's cardiometabolic health and cognition. *Curr Sports Med Rep*. 2016;15(4):245–51.
57. Parfitt G, Hughes S. The exercise intensity–affect relationship: evidence and implications for exercise behavior. *J Exerc Sci Fit*. 2009;7:S34–41.
58. Biddle SJH, Batterham AM. High-intensity interval exercise training for public health: a big HIT or shall we HIT it on the head? *Int J Behav Nutr Phys Act*. 2015;12:95.
59. Alvarez-Bueno C, Pesce C, Cavero-Redondo I, Sanchez-Lopez M, Martinez-Hortelano JA, Martinez-Vizcaino V. The effect of physical activity interventions on children's cognition and metacognition: a systematic review and meta-analysis. *J Am Acad Child Adolesc Psychiatry*. 2017;56(9):729–38.
60. Singh AS, Saliasi E, van den Berg V, et al. Effects of physical activity interventions on cognitive and academic performance in children and adolescents: a novel combination of a systematic review and recommendations from an expert panel. *Br J Sports Med*. 2019;53(10):640–7.
61. Erickson KI, Hillman C, Stillman CM, et al. Physical activity, cognition, and brain outcomes: a review of the 2018 physical activity guidelines. *Med Sci Sports Exerc*. 2019;51(6):1242–51.
62. Esteban-Cornejo I, Tejero-Gonzalez CM, Sallis JF, Veiga OL. Physical activity and cognition in adolescents: a systematic review. *J Sci Med Sport*. 2015;18(5):534–9.
63. Chaddock L, Erickson KI, Prakash RS, et al. A neuroimaging investigation of the association between aerobic fitness, hippocampal volume, and memory performance in preadolescent children. *Brain Res*. 2010;1358:172–83.
64. Pesce C. Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. *J Sport Exerc Psychol*. 2012;34(6):766–86.
65. Vazou S, Pesce C, Lakes K, Smiley-Oyen A. More than one road leads to Rome: a narrative review and meta-analysis of physical activity intervention effects on cognition in youth. *Int J Sport Exerc Psychol*. 2019;17(2):153–78.
66. Best JR. Effects of physical activity on children's executive function: contributions of experimental research on aerobic exercise. *Dev Rev*. 2010;30(4):331–551.
67. Khan NA, Hillman CH. The relation of childhood physical activity and aerobic fitness to brain function and cognition: a review. *Pediatr Exerc Sci*. 2014;26(2):138–46.
68. Pontifex MB, Raine LB, Johnson CR, et al. Cardiorespiratory fitness and the flexible modulation of cognitive control in preadolescent children. *J Cogn Neurosci*. 2011;23(6):1332–45.
69. Biddle SJH, Ciaccioni S, Thomas G, Vergeer I. Physical activity and mental health in children and adolescents: an updated review of reviews and an analysis of causality. *Psychol Sport Exerc*. 2019;42:146–55.
70. Saanijoki T, Tuominen L, Tuulari JJ, et al. Opioid release after high-intensity interval training in healthy human subjects. *Neuropsychopharmacology*. 2018;43(2):246–54.
71. Yeung RR. The acute effects of exercise on mood state. *J Psychosom Res*. 1996;40(2):123–41.
72. Larun L, Nordheim LV, Ekeland E, Hagen KB, Heian F. Exercise in prevention and treatment of anxiety and depression among children and young people. *Cochrane Database Syst Rev*. 2006;3:CD004691.
73. Stork MJ, Banfield LE, Gibala MJ, Martin Ginis KA. A scoping review of the psychological responses to interval exercise: is interval exercise a viable alternative to traditional exercise? *Health Psychol Rev*. 2017;11(4):324–44.
74. Boyd JC, Simpson CA, Jung ME, Gurd BJ. Reducing the intensity and volume of interval training diminishes cardiovascular adaptation but not mitochondrial biogenesis in overweight/obese men. *PLoS One*. 2013;8(7):e68091.
75. Lubans DR, Lonsdale C, Cohen K, et al. Framework for the design and delivery of organized physical activity sessions for children and adolescents: rationale and description of the 'SAAFE' teaching principles. *Int J Behav Nutr Phys Act*. 2017;14(1):24.