High intensity intermittent exercise: effect on young people's cardio-metabolic health and cognition

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Funding Disclosures/conflicts of interest:

The authors declare no conflicts of interest and do not have any financial disclosures

Abstract

With only a quarter of young people currently meeting physical activity guidelines, two key areas of concern are the effects of exercise on cardio-metabolic health and cognition. Despite the fact that physical activity in young people is typically high intensity and intermittent in nature; much of the literature examines traditional endurance type exercise. This review provides an update on the effects of high intensity intermittent exercise on young people’s cardio-metabolic health and cognition. High intensity intermittent exercise has acute beneficial effects on endothelial function and postprandial lipemia and chronic positive effects on weight management. In addition, there is emerging evidence regarding chronic benefits on blood lipid profile, blood pressure and pro- and anti-inflammatory cytokines. Furthermore, emerging evidence suggests beneficial acute and chronic effects of high intensity intermittent exercise on cognition. However, further research is required in both cardio-metabolic health and cognition, particularly regarding the impact of school-based interventions in adolescents.

Keywords: High intensity intermittent exercise; young people; health; cognitive function; academic achievement

Summary statement: Review of emerging evidence of the benefit of high intensity intermittent exercise for cardio-metabolic health and cognition in young people

1. Introduction

Physical activity levels in young people have decreased significantly in recent times, as evidenced by only 27% of young people (aged 5-19) in the United States (16) and 21% of boys and 16% of girls (aged 5-15) in the United Kingdom (6) currently meeting the recommended guidelines of 60 minutes of moderate to vigorous physical activity per day. These low levels of physical activity have been implicated in the relatively high prevalence of overweight and obesity in young people, with 31% of young people (aged 2-19) in the United States (48) and 29% of young people (aged 2-15) in the United Kingdom (35) reported as being overweight or obese. Strategies aimed at increasing physical activity levels have thus become a major public health concern, with evidence suggesting that endurance-based exercise has beneficial effects upon health in young people (61). However, the beneficial effects of physical activity go beyond physical health and extend to psychosocial benefits (26), beneficial effects on mental health (7) and enhanced cognitive function and academic achievement (29).

Despite the majority of the literature surrounding the effects of exercise in young people focusing on endurance type activity, such activity is actually very rare in young people. Evidence suggests that the activity patterns of young people are much more sporadic and rarely consist of sustained moderate or vigorous intensity activity (1). Specifically, it has been suggested that 95% of physical activity bouts in young people are less than 15 s in duration (3) and thus young people’s activity patterns are typically high intensity and intermittent in nature. In addition to the ecological validity of high intensity intermittent exercise in young people, it is also an attractive exercise model as it is time efficient and can be incorporated in to games-based activity (43) which enhances both enjoyment and adherence to exercise programs (38). It is important to note however that if the exercise is perceived as excessively challenging this could have the opposite effect on participation in physical activity and thus it is vital that high intensity intermittent exercise is carefully implemented in young people. This review will focus upon the potential beneficial effects of well-implemented high intensity intermittent exercise on two key areas of concern in young people; cardio-metabolic health and cognitive function.

2. Cardio-Metabolic Health

In adults, physical inactivity is related to a multitude of non-communicable diseases including cardiovascular disease, type 2 diabetes mellitus and metabolic syndrome (2). Whilst such diseases typically present during the fifth decade of life (46), the risk factors associated with their development are present during childhood and track through into adulthood (27,59). Therefore, the effects of high intensity intermittent exercise on these risk factors in young people are of great interest and are reviewed in this section.

2.1: Weight Management

It has been well established that continuous modes of aerobic exercise, such as walking, running and cycling augment weight loss in overweight and obese children and regulate weight management in individuals categorised as being normal weight (44,63). Furthermore, high intensity intermittent exercise has been proposed to induce superior physiological and health-related benefits in contrast to continuous modes of exercise, due to the greater peripheral vascular and cellular stress induced (33).

To appropriately assess the effect of high intensity intermittent exercise training on weight regulation, it is important to distinguish between studies that have investigated children and adolescents categorised as normal weight, overweight and obese. To date the effect of high intensity intermittent exercise training on the physical characteristics of children and adolescents classified as a normal weight remains relatively unexplored. However, Buchan et al. (10,11) have recently conducted a series of studies assessing the effect of 7 weeks of high intensity intermittent exercise training upon cardio-respiratory fitness, power, speed and weight regulation in healthy weight adolescents (boys and girls, aged 16.7 ± 0.6 years). Interestingly, the progressive 7 week high intensity intermittent running exercise programme failed to induce changes in body composition, yet proved successful in enhancing the cardiorespiratory fitness (assessed using the multi-stage fitness test) of the participants who completed the intervention (10,11). The authors suggested that the lack of change in body composition was unsurprising given the short duration (7 weeks) of the exercise programme and the healthy weight of the adolescents at baseline; but that the study provided further evidence that enhancing cardiorespiratory fitness is important in reducing cardiovascular disease risk factors in young people (10).

Lambrick et al. (43) further investigated the effect of high intensity intermittent games-based exercise training on body composition, in children (boys and girls, aged 8-10 years) categorised as normal weight or obese based on baseline body composition. Children from both groups were randomly allocated to complete either 6 weeks of high intensity intermittent exercise or the maintenance of their habitual physical activity levels. For the normal weight children there was no change in body mass or waist circumference, whilst for the obese children completing the intervention there was a 3.2% decline in waist circumference and a 5.8% increase in muscle mass. Of particular note for this study was that the high intensity intermittent exercise intervention was incorporated into child specific games, which may have implications for motivation and uptake of physical activity.

In recent years there has been a greater body of literature assessing the role of high intensity intermittent exercise training on weight loss in overweight and obese adolescents (23,30,43). Studies have typically contrasted the benefits of high intensity intermittent exercise training and endurance training (8,23,30). Specifically, it was reported that 6 months of progressive high intensity intermittent running exercise training in obese adolescents elicited a significantly greater decline in waist circumference than light aerobic exercise; with a 6.7% reduction in waist circumference following high intensity exercise and a 2.8% increase with light endurance training (30). Furthermore, a 12 week high intensity intermittent running training programme has been reported to augment the decline in body mass in obese children (aged 10 years) in comparison to an endurance training intervention with reductions of 2.6% and 1.3%, respectively (23). Whilst in all of the above studies endurance training has been successful in attaining weight reduction, it appears that the superior physiological demands and cellular stress of high intensity intermittent exercise permits significantly greater reductions in body mass and waist circumference.

2.2: Cardiovascular Disease Risk

Cardiovascular disease (CVD) risk during adolescence is characterised by hypertension, dyslipidaemia and low-grade chronic inflammation (41). The majority of research relating to physical activity and CVD risk during adolescence has focused on traditional risk factors such as blood pressure, the blood-lipid profile and fasted glucose and insulin (9,11,30). In contrast, there is limited research addressing the role of physical activity, particularly the acute effects of high intensity intermittent exercise, or the effect of high intensity intermittent exercise training on novel markers of inflammation (24), heart rate variability and recovery (9,23) and flow mediated dilation (9,54) during adolescence.

The acute effects of high intensity intermittent exercise on pro-inflammatory and anti-inflammatory cytokines remains relatively unexplored to date. A small number of studies have examined the effect of high intensity intermittent exercise on inflammatory cytokines in middle-aged men (24,47). In both studies, high intensity intermittent exercise induced a significant increase in pro-inflammatory cytokines (interleukin 6 and interleukin 10) and in the anti-inflammatory cytokine, interleukin 1-receptor antagonist (24,47), whilst the moderate intensity exercise failed to affect the inflammatory biomarkers. The exploration of the acute effects of high intensity intermittent exercise in children, adolescents and adults is important for developing physiological understanding as to how high intensity intermittent exercise, if of a tolerable intensity, for children and adolescents, elicits superior adaptations in contrast to moderate intensity exercise and research is required on this topic.

In contrast, the acute effects of high intensity intermittent exercise on endothelial function have been assessed in adolescent boys, aged 12-14 years (54). The consumption of a high fat breakfast and lunch reduced flow-mediated dilation by 20% and 27%, respectively. Interestingly, if repeated sprints were performed the day prior to the consumption of the high fat meals, postprandial endothelial dysfunction did not occur in the young boys (54). These finding are consistent with those reported a few years earlier when assessing the role of moderate intensity exercise in adolescent boys (53). However, it is yet to be determined whether high intensity intermittent exercise elicits superior benefits above those of moderate intensity exercise and thus this is an area future research must address. Finally, as yet there have been no studies examining the effects of sprint or game-type activity on endothelial function in adolescent girls.

The effect of short-term (2 weeks or less) high intensity intermittent cycling exercise training on both traditional and novel markers of CVD risk has recently been assessed in healthy normal weight adolescents (9). A two-week high intensity intermittent exercise training programme failed to elicit an effect on traditional markers of CVD risk with blood pressure, plasma lipids (cholesterol and triacylglycerol) and fasted glucose remaining unaffected. In contrast, the intervention improved endothelial function and heart rate variability, despite such effects being lost 3 days following the final training session, raising the question as to whether the benefits seen were a result of training or from the acute effects of the last exercise bout. Thus, the effects of high intensity intermittent exercise training on traditional and other markers of CVD risk remains elusive with discrepancies between the recent Bond et al. (9) study and other earlier short-duration high intensity intermittent exercise training studies in healthy adolescents where improvements in blood pressure were shown (11).

Recent studies have observed mixed effects of longer-duration (> 4 weeks) high intensity intermittent exercise on a variety of risk factors associated with cardiovascular disease in adolescents (11,23,30). Novel markers of CVD risk, such as heart rate variability, have been improved with 6 months of high intensity intermittent running exercise (boys and girls aged 14-15 years) (30). Furthermore, high intensity intermittent running exercise programmes have proved successful in attenuating systolic blood pressure in contrast with endurance training programmes (boys and girls, aged 10 years) (23) and control conditions whereby participants maintained baseline levels of physical activity (11). However, the same training programmes have also proved to be ineffective in reducing blood lipids and inflammatory cytokines such as C-reactive protein, adiponectin, total cholesterol and triacylglycerol in adolescents aged 16-17 years (11). Thus, the argument for further research in relation to determining the time course in which high intensity intermittent exercise elicits health benefits is justified.

2.3: Postprandial Lipemia

Elevated plasma triacylglycerol (TAG) concentrations are associated with increased risk of atherosclerosis and the likelihood of a cardiovascular event during later life (4). The Westernised lifestyle is characterised by the ingestion of high fat meals, which results in elevated postprandial TAG concentrations in adolescents (53). Moderate intensity exercise performed the day prior to ingesting high fat meals has previously been reported to reduce postprandial TAG in adolescent girls (56). However, as high intensity intermittent exercise has been reported as superior to moderate intensity exercise in many other health related domains, research has progressed to assess the effect of such exercise and training on postprandial lipemia (54). Sedgwick et al. (54) demonstrated that high intensity intermittent exercise performed 14 hours prior to the ingestion of high fat meals successfully reduced postprandial plasma TAG in adolescent boys. This was the first study to determine that repeated sprints elicit health benefits in adolescent boys; however, the same research team had previously reported that games-based activity also reduced postprandial lipemia in adolescent boys (5).

3. Cognitive Function and Academic Achievement

In addition to the aforementioned beneficial effects of high intensity intermittent exercise on cardio-metabolic health in young people, another area of great interest is the effect of such exercise on cognitive function and academic achievement, with academic achievement of particular importance to schools and school policy makers. Cognitive function is defined as a great variety of brain-mediated functions and processes which allow us to perceive, evaluate, store, manipulate and use information (52). Cognitive function is commonly split in to six domains; memory, attention, executive function, perception, psychomotor functions and language skills; which are sometimes sub-divided further (e.g. visual, verbal, spatial and auditory memory). Therefore, it is unsurprising that cognitive function has been suggested to be particularly important for academic achievement in young people (57). Thus factors that may enhance cognitive function in young people, such as exercise, are of particular interest. The following section will therefore review the evidence regarding both the acute and chronic effects of high intensity intermittent exercise on cognitive function and academic achievement in young people.

3.1: Acute Effects of Exercise on Cognitive Function

There is a substantial body of literature to suggest that an acute bout of exercise has beneficial effects on cognitive function in young people (29,57). However, there are a number of variables that confound the exercise-cognition relationship including; the domains of cognitive function examined, the exact cognitive function tests used, the timing of the tests relative to exercise, and the exercise characteristics (e.g. duration, intensity and modality). Of particular interest in this review is the effect of high intensity intermittent activity on cognitive function in young people, given that this is the mode of exercise that young people most frequently engage in (1,3,38).

Many of the studies examining the effect of exercise on young people's cognitive function have focussed upon continuous exercise models such as walking (25), running (18,19) and cycling (28). The consensus from this literature is that there is a small, but positive, acute effect of moderate intensity exercise on young people's cognition (57). However, more recently studies have started to examine the effect of exercise of differing exercise intensities on cognitive function.

It is logical that exercise of differing intensities will have differing effects on cognitive function, given the mechanisms believed to moderate the exercise-cognition relationship. For example, in an adult population, Winter et al. (62) have demonstrated that high intensity running (2 x 3 min sprints) was more beneficial for cognitive function (learning performance) than moderate intensity exercise (40 min steady running) and a resting control condition. Interestingly, Budde et al. (13) also found that higher intensity exercise was more beneficial for attention (as assessed by the d2 test), but only in the more physically fit young adults. However, given that these studies were conducted in adult populations they must be applied to young people with caution given that age is a moderating variable in the exercise-cognition relationship (17).

One of the key mechanisms that may be responsible for high intensity exercise being particularly beneficial for cognitive function is the higher brain-derived neurotrophic factor (BDNF) and catecholamine concentrations induced by high intensity exercise (62). Whilst no studies to date have examined the acute effects of exercise on BDNF concentrations in young people, Lee et al. (45) have reported that adolescents who regularly exercise have higher concentrations of neurotrophic factors such as BDNF and interestingly, also superior cognitive function when compared to controls. Therefore, it seems that neurotrophic factors such as BDNF do at least have some role to play in affecting cognitive function in young people, although this still requires further investigation.

A number of studies have demonstrated positive effects of high-intensity intermittent exercise on cognitive function in young people (20,32,49,58). Specifically, in 13-15 year old boys and girls Travlos (58) found that mathematics ability was enhanced following high intensity (>85% of age predicted maximum heart rate) running exercise, but only when this exercise was performed early in the school day. Similarly, data from our own laboratory demonstrate that sprint-based exercise (10 x 10 s maximal running sprints, interspersed with 50 s active recovery) performed mid-morning is beneficial for the speed of executive function (Stroop test) both immediately and 45 min post-exercise (20). These findings in young people are thus in line with the adult literature suggesting that high intensity exercise is particularly beneficial for cognitive function.

An interesting form of high intensity intermittent exercise in young people is games-based activity, given this is a mode of exercise that not only elicits a high intensity but as previously described, it is also an attractive exercise model for young people. Games-based activity is potentially particularly beneficial for cognitive function due to the co-ordination and decision making (with a clear cognitive component) required, with Budde et al. (12) reporting an acute bout of co-coordinative exercise to enhance attention in adolescents (boys and girls, 13-16 years old) when compared to a normal sports lesson and a resting control condition. Furthermore, Pesce et al. (49) have also reported that memory was enhanced following team games in boys and girls aged 11-12, when compared to aerobic based exercise, with the authors suggesting that this may be due to cognitive involvement in the decision making process during games play. However, unpublished data from our research group failed to replicate these findings and found no difference between a circuit of coordinative exercise and a resting control condition across a range of domains of cognitive function.

More recently, Gallotta et al. (32) compared the effects of physical exertion (PE class), cognitive exertion (normal school lesson) and mixed physical and cognitive exertion (coordinative PE lesson) on attention in 8-11 year old boys and girls. The authors reported that all three conditions enhanced attention when compared to baseline, but in contrast to the above findings (12,49), they reported that mixed physical and cognitive exertion had less of a beneficial effect when compared to physical or cognitive exertion alone. The authors speculated that this could be due to an excessive physical and cognitive load/stress being placed on the young people in the mixed exertion condition (32), which could have been too much for the 8-11 year old boys and girls in the study of Gallotta et al. (32), whilst enhancing cognition in male and female adolescents (12,49).

In conclusion, there is emerging evidence that high intensity intermittent exercise (particularly games-based activity) is beneficial for cognitive function in young people. However, this is an area that warrants further investigation, specifically concerning the effect in different age ranges (e.g. children vs. adolescents) and the effect on different domains of cognitive function. Furthermore, the time course of the changes in cognitive function following high intensity intermittent exercise is yet to be reported, so it is unknown how long the beneficial effects of exercise persist for.

3.2: Chronic Effects of Exercise on Cognitive Function and Academic Achievement

In addition to the acute effects of exercise on cognition, the chronic effects of exercise training are also of interest, especially given that athletes have been shown to have enhanced executive function when compared to non-athletes (39). Therefore, the subsequent section of this review will explore whether chronic high intensity intermittent exercise training exhibits beneficial effects on cognitive function in young people. As chronic training studies are difficult to conduct in children and adolescents and are relatively sparse, cross-sectional studies examining the cognitive function of children and adolescents who are well-trained (and thus physically fit) with those of a typical school-child are also reviewed.

The effect of chronic exercise training on cognition, like the acute effects of exercise on cognition may be influenced by a number of variables, such as the domain of cognitive function examined and the level/type of physical activity (21). In young people, exercise training has been suggested to have beneficial chronic effects on cognitive function in both children (36) and adolescents (29). However, the evidence in this area is difficult to synthesise due to suggestions that the effects may be sex specific, the wide variety of exercise interventions/classifications used (including the intensity, duration and modality of exercise) and the fact that the majority of studies in the area are cross-sectional and thus have the potential for many confounding variables to affect the findings.

A number of studies have examined the effects of exercise on both cognitive function and academic achievement in young people, with academic achievement being of particular interest for schools and school policy makers. The Centre for Disease Control and Prevention (15) undertook a large-scale review of this topic and concluded that of 251 effects identified in previous studies, just over half (50.5%) demonstrated a positive effect of exercise on academic performance, whilst very few studies (1.5%) demonstrated a negative effect. This effect persisted across school-based, classroom-based and extra-curricular interventions. The reasonably high prevalence of null findings led to Keeley & Fox (42) to surmise that although there is no conclusive evidence that exercise enhances academic achievement, there is also no evidence of negative effects and thus further research is required. Interestingly, a recent study suggests that whilst chronic exercise training per se had no effect on academic achievement in 15-17 year old boys, enhanced physical fitness (achieved by greater levels of exercise training) was correlated with higher academic achievement (40). A further study has also demonstrated that high fit and normal weight students (12-14 year old boys and girls) had a greater chance of being high academic achievers when compared to low fit and overweight students (51). However, these were both cross-sectional studies and thus the causal nature of the relationship could not be established.

In addition to the above studies examining the effects of chronic exercise on academic achievement, a number of studies have examined the effects on cognitive function directly through a range of cognitive function tests. Ruiz et al. (50) documented a positive association between participation in sports during leisure time and cognitive performance (using the SRA-Test of Educational Ability) in 13-18 year old boys and girls, but failed to demonstrate an association between time devoted to study, television viewing or playing video games with cognition. More specifically, an association between moderate-vigorous physical activity and attention (using the d2 test) has been demonstrated in 12-17 year old boys and girls, with a threshold of > 41 $min \cdot d^{-1}$ moderate intensity physical activity and > 12 $min \cdot d^{-1}$ vigorous intensity physical activity suggested as the threshold for improvements in attentional capacity

(60). However, both of these studies are cross-sectional in nature and thus could not demonstrate causation between exercise and cognitive performance in young people.

To address this, a limited number of studies have implemented exercise interventions and examined the effects on cognitive performance in young people. For example, a 9-month afterschool program focused on improving aerobic fitness enhanced cognitive flexibility, inhibition and executive control (measures of executive function, using modified Stroop and Flanker tasks) in 7-9 year old boys and girls (37). In a similar population of boys and girls aged 7 to 9, Castelli et al. (14) have also demonstrated that high-intensity activity may confer additional benefits over moderate intensity activity for attention and executive function (as assessed using the Stroop test). However, no studies have examined the effects of chronic high intensity training in an adolescent population where there may be particular benefit given the decline in physical activity seen during adolescence (34).

Given that team games are an attractive model of high-intensity intermittent exercise for young people (as previously discussed), the effects of games-based interventions on cognition are of great importance. The competitive nature of games could be important, given that a 10-week competitive computer gaming intervention has been shown to enhance executive functions in adolescents to a greater extent than a cooperative gaming intervention (55). Furthermore, Fox et al. (31) have demonstrated an association between sports team participation and academic achievement. However, this was again a cross-sectional study and there is the potential for a number of confounding variables to have affected the study outcomes. Interestingly, in a 6 month intervention study designed to challenge children both cognitively and physically using open skill development, findings demonstrated enhanced executive function in 9-10 year old boys and girls, but that this effect was more pronounced in children classed as overweight (22). However, this is the only study in this area to date and thus warrants further investigation, particularly regarding the effects og exercise interventions in overweight young people.

Overall, the evidence reviewed above suggests that, in addition to the acute benefits discussed earlier, there are also chronic beneficial effects of exercise on cognitive function and academic achievement in young people. However, despite suggestions in the literature that interventions based around high-intensity intermittent exercise would be beneficial for cognition and academic achievement, no studies have specifically addressed this, particularly in an adolescent population.

4. Conclusions and Recommendations for Future Research

The evidence reviewed here suggests that high intensity intermittent exercise is highly beneficial for cardio-metabolic health in young people, as evidenced by beneficial effects on a number of risk factors, including weight regulation, endothelial function and postprandial lipemia. However, the effect of high intensity intermittent exercise on risk factors such as blood pressure, blood lipid profile and pro- and anti-inflammatory cytokines remains either inconclusive or unexplored. Therefore, further research is required in this area to further our understanding. The evidence reviewed here also suggests that high intensity intermittent exercise has both acute and chronic benefits on cognitive function and academic achievement. However, further research is required to elucidate the effects across the various domains of cognitive function and to examine how long the beneficial effects of high intensity intermittent exercise persist for.

In the areas of both cardio-metabolic health and cognitive function, more intervention-based studies are required. As discussed, intervention-based studies face several challenges and are difficult to conduct, but the authors feel that schools provide an ideal intervention target as interventions would be accessible by large numbers of children and multiple intervention settings can be used (e.g. classroom-based, recess time and extra-curricular). A further consideration is the 'control' condition used in both acute and chronic studies, with the literature to date using a mixture of resting and endurance-type activities as the control condition to compare to high intensity intermittent exercise. In addition, further research is required in adolescents and girls, as most studies to date have examined younger children (<11 years old) and boys. Furthermore studies should further examine the suggestion in the literature that exercise has particular benefits in young people classed as overweight/lower fit.

Overall, the evidence is encouraging that high intensity intermittent exercise has beneficial effects on both cardio-metabolic heath and cognitive function/academic achievement in young people, when implemented safely, at a tolerable intensity and in an enjoyable environment. The authors recommend that this area be explored further, particularly regarding the use of games-based activities as an attractive exercise model to implement high intensity intermittent exercise based interventions in young people.

References

1. Armstrong N, Welsman JR. The physical activity patterns of European youth with reference to methods of assessment. *Sports Med*, 2006;36:1067-86.
2. Artero EG, Ruiz JR, Ortega FB, Espana-Romero V, Vicente-Rodriguez G, Molnar D, Gottrand F, Gonzalez-Gross M, Breidenassel C, Moreno LA, Gutierrez A. Muscular and cardiorespiratory fitness are independently associated with metabolic risk in adolescents: the HELENA study. *Pediatr Diabetes*, 2011;12:704-12.
3. Bailey RC, Olson J, Pepper SL, Porszasz J, Barstow TJ, Cooper DM. The level and tempo of children's physical activities: an observational study. *Med Sci Sports Exerc*, 1995;27:1033-41.
4. Bansal S, Buring JE, Rifai N, Mora S, Sacks FM, Ridker P. Fasting compared with nonfasting triglycerides and risk of cardiovascular events in women. *J Am Med Soc*, 2007;298:309-16.
5. Barrett LA, Morris JG, Stensel DJ, Nevill ME. Exercise and postprandial plasma triacylglycerol concentrations in healthy adolescent boys. *Med Sci Sports Exerc,* 2007;39:116-22.
6. British Heart Foundation. Physical activity statistics 2015. Oxford, UK. British Heart Foundation Centre on Population Approaches for Non-Communicable Disease Prevention; 2015. 128 p.
7. Biddle SJH, Asare M. Physical activity and mental health in children and adolescents: a review of reviews. *Br J Sports Med*, 2011;45:886-95.
8. Boer PH, Meeus M, Terblanche E, Rombaut L, Wandele ID, Hermans L, Gysel T, Ruige J, Calders P. The influence of sprint interval training on body composition, physical and metabolic fitness in adolescents and young adults with intellectual disability: a randomized controlled trial. *Clin Rehabil*, 2014;28.3:221-31.
9. Bond B, Cockcroft EJ, Williams CA, Harris S, Gates PE, Jackman SR, Armstrong N, Barker AR. Two weeks of high-intensity interval training improves novel but not traditional cardiovascular disease risk factors in adolescents. *Am J Physiol*, 2015; 309:H1039-47.
10. Buchan DS, Young JD, Simpson AD, Thomas NE, Cooper SM, Baker JS. The effects of a novel high intensity exercise intervention on established markers of cardiovascular disease and health in Scottish adolescent youth. *J Public Health Res*, 2012;1:e24.
11. Buchan DS, Ollis S, Young JD, Cooper SM, Shield JPH, Baker JS. High intensity interval running enhances measures of physical fitness but not metabolic measures of cardiovascular disease risk in healthy adolescents. *BMC Public Health, 2013;13:498.*
12. Budde H, Voelcker-Rehage C, Pietraβyk-Kendziorra S, Ribiero P, Tidow W. Acute coordinative exercise improves attentional performance in adolescents. *Neurosci Lett*, 2008;441:219-23.
13. Budde H, Brunelli A, Machado S, Velasques B, Ribeiro P, Arias-Carrion O, Voelcker-Rehage C. Intermittent maximal exercise improves attentional performance only in physically active students. *Arch Med Res*, 2012;43:125-31.
14. Castelli DM, Hillman CH, Hirsch J, Hirsch A, Drolette E. FIT kids: time in target heart rate zone and cognitive performance. *Prev Med*, 2011;52:S55-9.
15. Centres for Disease Control and Prevention. The association between school-based physical activity, including physical education, and academic performance. Atlanta, GA: US. Department of Health and Human Services; 2010. 84 p.
16. Centres for Disease Control and Prevention. State indicator report on physical activity, 2014. Atlanta, GA: US. Department of Health and Human Services; 2014. 128 p.

17. Chang YK, Labban JD, Gapin JJ, Etnier JL. The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Res*, 2012;1453:87-101.
18. 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;5:183-90.
19. Cooper SB, Bandelow S, Nute ML, Morris JG, Nevill ME. Breakfast glycaemic index and exercise: combined effects on adolescent's cognition. *Physiol Behav*, 2015;139:104-11.
20. Cooper SB, Bandelow S, Nute ML, Dring KJ, Stannard RL, Morris JG, Nevill ME. Sprint-based exercise and cognitive function in adolescents. *Under review*.
21. Cox EP, O'Dwyer NO, Cook R, Vetter M, Cheng HL, Rooney K, O'Connor H. Relationship between physical activity and cognitive function in apparent health young to middle-aged adults: a systematic review. *J Sci Med Sport*, 2015; epub.
22. Crova C, Struzzolino I, Marchetti R, Masci I, Vannozzi G, Forte R, Pesce C. Cognitively challenging physical activity benefits executive function in overweight children. *J Sports Sci*, 2014;32:201-11.
23. De Araujo ACC, Roschel H, Picanco AR, Prado DMLD, Villares SMF, Pinto ALDS, Gualano B. Similar health benefits of endurance and high intensity interval training in obese children. *PLOSOne*, 2012;7:e42747.
24. Dorneles GP, Haddad DO, Fagundes VO, Vargas BK, Kloecker A, Romao PRT, Peres A. High intensity interval exercise decrease IL-8 and enhances the immunomodulatory cytokine interleukin-10 in lean and overweight-obese individuals. *Cytokine*,2016;77:1-9.
25. Drolette ES, Scidder MR, Raine LB, Moore RD, Saliba BJ, Pontifex MB, Hillman CH. Acute exercise facilitates brain function and cognition in children who need it most: an ERP study of individual differences in inhibitory control capacity. *Dev Cog Neurosci*, 2014;7:53-64.
26. Eime RM, Young JA, Harvey JT, Charity MJ, Payne WR. A systematic review of the psychological and social benefits of participation in sport for children and adolescents: informing development of a conceptual model of health through sport. *Int J Behav Nut Phys Act*, 2013;10:98-119.
27. Eisenmann JC, Welk GJ, Ihmels M, Dollman J. Fatness, fitness and cardiovascular disease risk factors in children and adolescents. *Med Sci Sports Exerc*, 2007;39:1251-56.
28. Ellemberg D, St-Louis-Deschênes M. The effect of acute physical exercise on cognitive function during development. *Psychol Sport Exerc*, 2010;11:122-6.
29. Esteban-Cornejo I, Tejero-Gonzalez CM, Sallis JF, Viega OL. Physical activity and cognition in adolescents: a systematic review. *J Sci Med Sport*, 2014:18;534-9.
30. Farah BQ, Ritti Dias, Balagopal PB, Hill JO, Prado WL. Does exercise intensity affect blood pressure and heart rate in obese adolescents? A 6-month multidisciplinary randomized intervention study. *Pediatr Obesity*, 2012;9:111-20.
31. Fox CK, Barr-Anderson D, Neumark-Sztainer D, Wall M. Physical activity and sports team participation: associations with academic outcomes in middle school and high school students. *J School Health*, 2010;80:31-7.
32. Gallota MC, Guidetti L, Francioisi E, Emerenziani GP, Bonavolonta V, Baldari C. Effects of varying types of exertion on children's attention capacity. *Med Sci Sports Exerc*, 2012;44:550-5.
33. Gibala MJ, Little JP, MacDonald MJ, Hawley JA. Physiological adaptations to low-volume, high-intensity interval training in health and disease. *J Physiol*, 2012;590:1077-84.
34. Harding SK, Page AS, Falconer C, Cooper AR. Longitudinal changes in sedentary time and physical activity during adolescence. *Int J Behav Nut Phys Act*, 2015;12:44-51.
35. Health and Social Care Information Centre. Statistics on obesity, physical activity and diet: England 2015. Leeds, UK. Health and Social Care Information Centre; 2015. 103 p.

36. Hillman CH, Kamijo K, Scudder M. A review of chronic and acute physical activity participation on neuroelectric measures of brain health and cognition during childhood. *Prev Med*, 2011;52:S21-8.
37. Hillman CH, Pontifex MB, Castelli DM, Khan NA, Raine LB, Scudder MR, Drolette ES, Moore RD, Wu CT, Kamijo K. Effects of the FITKids randomized control trial on executive control and brain function. *Pediatrics*, 2014; 134:e1063-71.
38. Howe CA, Freedson PS, Feldman HA, Osganain SK. Energy expenditure and enjoyment of common children's games in a simulated free-play environment. *J Pediatr*, 2010;157:936-42.
39. Jacobson J, Matthaeus L. Athletics and executive functioning: how athletic participation and sport type correlate with cognitive performance. *Psych Sport Exerc*, 2014;15:521-7.
40. Kalantari HA, Esmaeilzadeh S. Association between academic achievement and physical status including physical activity, aerobic and muscular fitness tests in adolescent boys. *Environ Health Prev Med*, 2016;21:27-33.
41. Kassi E, Pervanidou P, Kaltsas G, Chrousos G. Metabolic Syndrome: definitions and controversies. *BMC Med,* 2011;9:48.
42. Keeley TJH, Fox KR. The impact of physical activity and fitness on academic achievement and cognitive performance in children. *Int Rev Sport Exerc Psych*, 2009;2:198-214.
43. Lambrick D, Westrupp N, Kaufmann S, Stoner L, Faulkner J. The effectiveness of a high-intensity games intervention on improving indices of health in young children. *J Sports Sci,* 2015;34:190-8.
44. Lee S, Bacha F, Hannon T, Kuk JL, Boesch C, Arslanian S. Effects of aerobic versus resistance exercise without caloric restriction on abdominal fat, intrahepatic lipid and insulin sensitivity in obese adolescent boys: A randomized, controlled trial. *Diabetes,* 2012;61:2787-2795.
45. Lee TMC, Wong ML, Lau BWM, Lee JCD, Yau SY, So KF. Aerobic exercise interacts with neurotrophic factors to predict cognitive functioning in adolescents. *Psychoneuroendocrinology*, 2014;39:214-24.
46. Magnussen CG, Niinikoski H, Juonala M, Kivimaki M, Ronnemaa T, Vilkari JS, Simell O, Raitakari OT. When and how to start prevention of atherosclerosis? Lessons from the cardiovascular risk in the Young Finns Study and the Special Turku Coronary Risk Factor Intervention Project. *Pediatri Nephrol*, 2012;27:1441-52.
47. Mendham AE, Duffield R, Marino F, Coutts AJ. Differences in the acute inflammatory and glucose regulatory responses between small-sided games and cycling in sedentary, middle-aged men. *J Sci Med Sport*, 2014;1089:1440.
48. Ogden CL, Carroll MD, Kit BK, Flegal KM. Prevalence of childhood and adult obesity in the United States, 2011-2012. *J Am Med Asooc*, 2014;311:806-14.
49. Pesce C, Crova C, Cereatti L, Casella R, Bellucci M. Physical activity and mental performance in preadolescents: effects of acute exercise on free-recall memory. *Mental health Phys Act*, 2009;2:16-22.
50. Ruiz JR, Ortega FB, Castillo R, martin-Matillas M, Kwak L, Vicente-Rodriguez G, Noriega J, Tercedor P, Sjostrom M, Moreno LA. Physical activity, fitness, weight status and cognitive performance in adolescents. *J Pediatr*, 2010;157:917-22.
51. Sardinha LB, Marques A, Martins S, Palmeira A, Minderico C. Fitness, fatness, and academic performance in seventh-grade elementary school children. *BMC Pediatr*, 2014;14:176-85.
52. Schmitt JAJ, Benton D, Kallus KW. General methodological considerations for the assessment of nutritional influences on human cognitive functions. *Eur J Nutr*, 2005;44:459-64.

53. Sedgwick MJ, Morris JG, Nevill ME, Tolfrey K, Nevill A, Barrett LA. Effect of exercise on postprandial endothelial function in adolescent boys. *British J Nutr*, 2013;110:301-9.
54. Sedgwick MJ, Morris JG, Nevill ME, Barret LA. Effect of repeated sprints on postprandial endothelial function and triacylglycerol concentrations in adolescent boys. *J Sports Sci*, 2015;33:806-16.
55. Staiano AE, Abraham AA, Calvert SL. Competitive versus cooperative exergame play for African American adolescents' executive function skills: short-term effects in a long-term training intervention. *Develop Psych*, 2012;48:337-42.
56. Tolfrey K, Bentley C, Goad M, Varley J, Willis S, Barrett L. Effect of energy expenditure on postprandial triacylglycerol in adolescent boys. *Eur J App Physiol*, 2012;112:23-31.
57. Tomporowski PD, McCullick B, Pendleton DM, Pesce C. Exercise and children's cognition: the role of exercise characteristics and a place for metacognition. *J Sport Health Sci*, 2015;4:47-55.
58. Travlos AK. High intensity physical education classes and cognitive performance in eighth grade students: an applied study. *Int J Sport Ex Psych*, 2010;8:302-10.
59. Twisk JWR, Kemper HCG, Mechelen WV. Tracking of activity and fitness and the relationship with cardiovascular disease risk factors. *Med Sci Sports Exerc*, 2000;32:1455-61.
60. Vanhelst J, Beghin L, Duhamel A, Manios Y, Molnar D, De Henauw S, Moreno LA, Ortega FB, Sjostrom M, Widhalm K, Gotrand F. Physical activity is associated with attention capacity in adolescents. *J Pediatr*, 2015;168:123-31.
61. Warburton DER, Nicol CW, Bredin SSD. Health benefits of physical activity: the evidence. *Can Med Ass J*, 2006;174.6:801-9.
62. Winter B, Breitenstein C, Mooren FC, et al. High impact running improves learning. *Neurobiol Learn Memory*, 2007;87:597-609.
63. Zorba E, Cengiz T, Karacabey K. Exercise training improves body composition blood lipid profile and serum insulin levels in obese children. *J Sports Med Phys Fitness*, 2011;51:1-6.