Title: Are changes in cardiorespiratory fitness resulting from physical activity interventions related to changes in executive function and academic performance in children and adolescents? A systematic review and meta-regression.

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Abstract

Physical activity (PA) interventions in children and adolescents are thought to improve cardiorespiratory fitness (CRF), and possibly executive function (EF), and academic performance (AP). It is thought that the impact of PA upon CRF might be associated with improved EF and AP. However, previous meta-analyses have not examined this relationships. Thus, we conducted a systematic review and meta-regression of intervention studies that reported a pre- and a post-intervention measure of CRF and AP and/or EF and included a control group. A total of 17 studies were included. PA interventions had the following main effects: 0.24 [95% CI=0.09, 0.40] for CRF; 0.11 [95% CI=-0.16, 0.38] for AP; and 0.02 [95% CI=-0.09, 0.13] for EF after removal of influential studies. Meta-regression for CRF changes upon EF outcomes suggested a small effect ranging from negative trivial to moderate (β = 0.26 [95% CI=-0.18, 0.70]). For CRF changes upon AP outcomes the estimate was trivial with poor precision ranging negative to positive large effects (β = -0.04 [95% CI=-1.52, 1.45]). Despite small positive effects upon CRF, the effects upon EF or AP are less clear. Further, it seems unlikely improvements in CRF from PA interventions are associated with changes EF or AP.

1 Introduction

Cardiorespiratory fitness (CRF) can be defined as the overall capacity of cardiovascular and respiratory systems, and the ability to carry out prolonged strenuous exercise (Ortega et al., 2008). The association between poor CRF and a cluster of metabolic risk factors in children and adolescents has been well-described (Ortega et al., 2008; Ruiz et al., 2006). Despite this, there has been a global decline in CRF by 7.3% per decade in high and upper-middle income countries from 1981 to 2000 with levels now seemingly plateaued (Tomkinson et al., 2019). Despite there being a strong genetic component of CRF, and little relation between CRF and habitual physical activity (PA; Armstrong et al., 2011), moderate to vigorous physical activity (MVPA) does appear to influence CRF (Ortega et al., 2006). Indeed, recent work suggests that compared to merely replacing sedentary time with light- to moderate-PA, vigorous PA has a greater association with CRF both cross-sectionally and prospectively (Santos et al., 2018). Further, randomised controlled trials in school-aged children have demonstrated that increasing PA increases CRF (Lavie et al., 2011). Schools are an ideal location to improve children and adolescents CRF as a large proportion of the youth population can be accessed, monitored, and influenced within them for the majority of the year (Tomporowski et al., 2011). However, there is also pressure on schools regarding academic performance in subjects including reading and mathematics, which impact on time spent on physical education (PE) (Coe et al., 2006; Tsai et al., 2009; Arnold er al., 2016). This is despite emerging evidence linking PA and CRF to both executive function (EF) and academic performance (AP; Santana et al., 2017; Donnelly et al., 2016).

EF includes the mental processes required when you have to pay attention or concentrate on a task (Diamond, 2013) and which are needed when relying upon instinct would be ill-advised, insufficient, or impossible (Burgess and Simons, 2005; Espy, 2004; Miller and Cohen, 2001). EF has been associated with AP (Haile et al., 2016), classroom behaviours (Singh et al., 2012), and mental health (Diamond and Ling, 2016) in addition to increased on-task behaviour (the amount of time spent working on a learning task) and improved ability to inhibit off-task behaviour whilst in the classroom (Hofmann et al., 2012). There are three primary sub-domains of EF; inhibition, working memory, and cognitive flexibility (Lehto et al., 2003; Miyake et al., 2000). Inhibition (also called selective attention) involves being able to control attention, behaviour, thoughts, and emotions to override internal instinct and do what is required or appropriate (Diamond, 2013). Working memory involves holding information in one's mind and mentally working with it (Baddeley and Hitch, 1994; Smith and Jonides, 1999). Cognitive flexibility (also called shifting) builds on the other two sub-domains and involves a person being able to change how they think about something and also if they can change their perspectives both spatially and interpersonally (Diamond, 2013)[13]. These sub-domains of EF have also been found to be individually associated with AP in children (St Clair-Thompson and Gathercole, 2006), and adolescents

(Gathercole et al., 2004) and are foundations for higher-order EFs such as reasoning, problem-solving, and planning (Lunt et al., 2012; Collins and Koechlin, 2012).

The cardiovascular fitness hypothesis suggests that CRF is a physiological mechanism explaining physical activity's effect on mental health. Early review of this possible mechanism in exercises effects on depression showed little support (North et al., 1990); however, more recently the hypothesis has been considered more broadly in relation to EF. Improvement in the heart's ability to deliver oxygen to the muscles from more regular MVPA underpins CRF increases (American College of Sports Medicine, 2000) which are thought to be associated angiogenesis in the motor cortex, increased blood flow, and improved brain vascularization (Hillman et al., 2008). Children's white matter integrity is positively related to performance on an inhibition task (Oosterman et al., 2008) and reduced white matter integrity in adults is associated with poorer inhibitory control (Marks et al., 2007). CRF has also been positively associated with white matter integrity (Colombe et al., 2006). Animal studies have shown long term physical exercise induces neurostructural changes and upregulation of neurotrophic factors which influence learning and memory (Voss et al., 2011; Dishman et al., 2006; Ferris et al., 2007; Flöel et al., 2010). Further, Chaddock et al. (2010) found children with higher CRF levels had larger volumes of basal ganglia and hippocampus. Building on this potential link between CRF and EF recent studies have shown a positive association between CRF and AP (Bezold et al., 2014; Wittberg et al., 2012). As such, as the cardiovascular hypothesis suggests, improved CRF resultant from increased PA could lead to improvements in how children perform academically.

An early meta-regression found no significant association between CRF and cognitive performance (Etnier et al., 2006). However, the majority of the studies included were based on adult populations. Recent work has focused on the relationship between CRF with AP and EF in children and youth. Two narrative reviews described research reporting a positive association between AP, EF, and CRF (Haapala, 2013; Keeley and Fox, 2009). Three recent systematic reviews (Santana et al., 2017; Donnelly et al., 2016; Marques et al., 2018; Van Waelvelde et al., 2019) all reported studies suggesting positive associations between CRF and PA with EF and AP, although findings were inconsistent and the majority of studies included used cross-sectional designs. Recently meta-analyses (Alvarez-Bueno et al., 2017a; Alvarez-Bueno et al., 2017b; de Greef et al., 2018; Alvarez-Bueno et al., 2020) have examined the effects of PA upon sub-domains of EF and several aspects of AP finding small significant effects of PA for EF and AP. However, these analyses have primarily, though not exclusively, examined cross-sectional associations between PA/CRF and EF/AP as opposed to intervention studies. Further, it is typically assumed that PA interventions have induced improved CRF despite there being only moderate evidence for this effect in school-based interventions (Pozuelo-Carrascosa et al., 2018). Thus, it is similarly assumed in line with cross-sectional data linking CRF and EF or AP, that it is a mechanism that might be involved in their improvment. However, previous meta-analyses of interventions have not examined the moderating effect of PA induced increases in CRF (compared to a control group) upon changes in EF and AP. Therefore, the aim of this study was to perform a systematic review and meta-analysis of the effects of PA interventions upon CRF, EF, and AP, and to perform a meta-regression to investigate the assaciation between changes in CRF, and changes in EF and AP.

2 Methods

This work developed, performed and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (Liberati et al., 2009; Moher et al., 2012). The protocol was registered with the PROSPERO International prospective register of systematic reviews (http://www.crd.york.ac.uk/PROSPERO/), registration number CRD42017070845.

2.1 Literature Search

2.1.1 Eligibility Criteria

An electronic search of the literature, was conducted using combinations of the search terms below. Only intervention studies were included in this study and they had to include a control group. They were eligible if data were presented on CRF and EF or AP at pre- and post-intervention. The primary sources were peer-reviewed journal articles published in the English language.

2.1.2 Information Sources

Potential articles were identified by searching electronic databases and relevant article reference lists (including previous review articles). Searches were conducted in: Medline/PubMed (EBSCOhost), Science Direct (Elsevier ScienceDirect), Scopus (Scopus), SPORTDiscus (SPORTDiscus), Academic Search Complete, CINAHL Complete, and PsychINFO. The last search was performed on the 10th October 2020.

2.1.3 Search Strategy

Databases were searched using terms that had been developed through discussion within the research team. Search strategies included three groups of key-words/terms: (a) CRF ("fitness," or "cardiorespiratory fitness," or "cardiovascular fitness," or "cardiovascular capacity," or "physical fitness," or "aerobic fitness," or "aerobic capacity,"); (b) academic performance ("academic outcome," or "academic performance," or "academic success," or "academic achievement," or "cognition," or "cognitive function," or "executive function"); (c) children/adolescents ("children," or "adolescents," or "teen," or "school-aged," or "youth"). The search strategy is included in supplementary materials (https://osf.io/pxnu3/).

The literature search, evaluation of quality, and extraction of the data were carried out independently by two researchers (ST & NW). Articles not relevant for the aim of the study were eliminated once the title was examined. Potentially eligible articles abstracts were screened following the inclusion and exclusion criteria. Disagreements between reviewers were resolved by consensus opinion or arbitration by a third reviewer (SM). As noted, reference lists of selected articles and review articles were also. Only original articles were included and authors were contacted via email if full articles were not available or to request additional data if it was not reported in the manuscript (i.e. to facilitate effect size calculcations).

2.2 Inclusion and Exclusion Criteria

2.2.1 Type of Participants

Included studies' participants needed to be apparently healthy (i.e., free from known disease, disability [including learning disabilities], or injury) children and adolescents with a mean age between 5-18 years old. Studies with participants from any country, and studies focussing on a single sex or both were also included.

2.2.2 Types of Studies

The aim of this meta-analysis was to examine the effect of upon CRF, EF, and AP in addition to the association of changes in CRF with changes in EF or AP resulting from PA interventions. Therefore, only studies including CRF as an outcome measure alongside AP and/or EF were included. The meta-analysis included randomised and non-randomised controlled trials that were written in English. Uncontrolled and cross-sectional studies were excluded from the analysis.

2.2.3 Types of Outcome Measures

CRF measures could include: direct measurement of maximal oxygen consumption (VO_{2max}) or direct measurement of peak oxygen consumption (VO_{2peak}) in a maximal graded fitness test on a treadmill or cycle ergometer, indirect measurement of VO_{2peak} in a maximal graded fitness test on a treadmill or cycle ergometer, or maximal field based CRF tests (e.g. 20m Multistage Shuttle Run or Cooper test). EF measures could include: any of the sub-domains of EFs (inhibition, working memory, or cognitive flexibility), a combination of the three, or all three sub-domains of EFs. AP is defined as a domain that refers to the extent to which a student achieves their educational goals (Donnelly et al., 2016) and include the different subjects taught in a school's curricular programme e.g. reading, mathematics, or languages. AP measures could include: standardised or non-standardised methods, including specific tests (e.g. for reading, language, or arithmetic skills etc.), a cluster of achievement tests, or grade point averages, across curricular subjects (Donnelly et al., 2016).

2.2.4 Exclusion Criteria

Articles published in non-English language were excluded. Articles not meeting inclusion criteria or not including findings related to the inclusion criteria were excluded; e.g. a study measured CRF but did not also include a measure of cognitive function or an academic outcome. There were numerous studies that administered a PA intervention and examined the effects of an increase in PA on EF or AP and included a measure of CRF as a marker of health, although often this was only measured or reported at baseline (e.g. Chaddock et al., 2012; Howie et al., 2015).

2.3 Data Extraction

The following data were extracted from all included articles following the Cochrane Consumers and Communication Review Group: (a) author, year of publication, and length of intervention (b) study design and location, (c) sample size and participant characteristics (including age at baseline and sex), (d) measurement tool for CRF, (e) measurement tool for EF or AP, (f) controlled variables, (g) main findings, and (h) pre- and post-test means and standard deviations for CRF variable and AP/EF variable. Extracted data is available in the supplementary materials (https://osf.io/5watg/).

2.4 Study Quality and Risk of Bias

The quality of the studies was assessed independently by two authors (ST & NW) using two scales. The methodological quality and internal validity of randomised controlled trials (RCTs) were assessed using the

Jadad Scale (Jadad et al., 1996), whilst non-RCTs were assessed using the Effective Public Health Practice Project (EPHPP) Quality Assessment Tool for Quantitative Studies (Armiho-Olivo et al., 2012).

2.5 Statistical Analyses

All analysis was performed using the 'metafor' package in R (version 3.5.1; R Core Development Team, https://www.r-project.org/) and analysis code is available in the supplementary materials (https://osf.io/6ds9b/). Some studies collected data over multiple time-points (i.e. multiple years with data collection annually). In these cases the data for the first post-intervention measurements was used. This reduced the variance in study length. Secondly, if a study had two intervention groups then their data were analysed independently with the control group thus yielding multiple effect sizes for that study and outcome. The difference in standardised mean changes for raw scores (pre- to post-intervention) were compared between groups using Hedges *g* and pre-test standard deviations used as the denominator (Morris, 2008). The magnitude of Hedges *g* were interpreted with reference to Cohen's (1988) thresholds; trivial (<0.2) small (0.2 to <0.5), moderate (0.5 to <0.8), and large (>0.8) and positive effect size values indicated higher scores of the outcome in favour of the intervention group. Three separate random effects meta-analyses were performed to examine the effect of PA interventions upon CRF, EF, and AP generating point estimates for pooled effect sizes and precision of those estimates using 95% confidence intervals (CI). Multilevel models with cluster robust estimates were used where multiple effect sizes were derived from the same studies and study groups with both included as random effects. Estimates were weighted by inverse sampling variance to account for this in addition to the between-studies variance (tau-squared), and restricted maximal likelihood estimation was used in all models. EF was also divided into three sub-domains; inhibition, working memory, and cognitive flexibility. Due to the limited number of studies AP was not divided into sub-groups. Mixed-effect meta-regression analyses were carried out on the main effects of EF and AP outcomes where the amount of change in CRF (Hedges *g* for CRF outcomes) between pre- and post-intervention was used as a moderator in order to examine the association of changes in CRF between intervention and control groups with changes in EF and AP outcomes. Exploratory moderation analyses were also performed examining age and the length of intervention. Additionally, sub group comparisons were performed to compare studies where PA intervention took up time in the curriculum that would be used for other academic subjects (Yes v No). A fixed-effects with moderators model was used to compare the two groups of studies to see if there was a significant difference between each set of the two models ($p<0.05$). Influence analyses was performed examining Cook's distances for the main models of CRF, EF, and AP and where there was evidence of influential effect sizes (Cook's *d* ~1.0) models were rerun dropping that effect. Heterogeneity was examined through the Q statistic and the I^2 statistic (Higgins et al., 2003). A significant Q statistic suggested that studies are likely not drawn from a common population. We interpreted I^2 values for degree of heterogeneity in effects as: 0-40% were not important, 30-60% moderate heterogeneity, 50-90% substantial heterogeneity, and 75-100% considerable heterogeneity (Higgins and Green, 2011). Small study bias was examined graphically by contour enhanced funnel plots.

3 Results

3.1 Final Study Selection

The initial search identified a total of 8,430 potential papers, with 3 additional studies identified from reference lists of review articles. After adjusting for duplicates, 6,757 remained. Of these, 6,477 did not meet the criteria after screening the titles. Abstracts of 280 papers were examined and 128 articles remained. Full texts of these papers were reviewed. Of these studies, 111 did not meet the inclusion criteria: 78 of these studies did not have a control group, 4 studies appeared eligible but the authors did not respond or could not provide the additional required data that were requested, 2 studies were cross-sectional designs, 18 studies did not have both pre- and post-intervention measures of CRF, 6 studies did not have both pre- and post-intervention measures of EF or AP, 2 studies had participants who were too young or too old, and 1 study only did one bout of activity. Therefore, a final total of 17 studies were included in this meta-analysis (Figure 1).

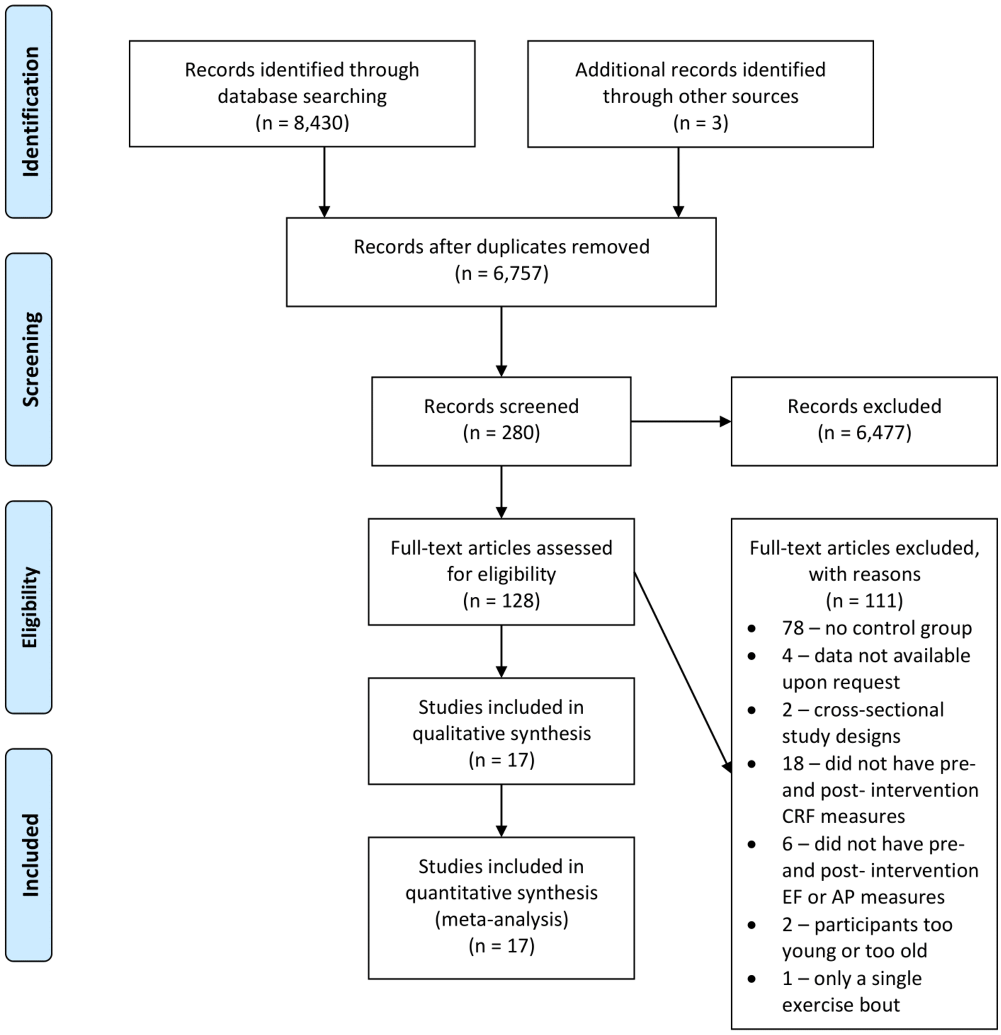

Figure 1. PRISMA flow diagram

3.2 Systematic Review

The 17 studies included in the systematic review are shown in Table 1. Nine studies used a PA intervention to examine its effects upon changes in CRF and EF. Three studies measured the effects of a PA intervention upon changes in CRF and AP The final five studies investigated the effects of a PA intervention upon changes in CRF, and both AP and EF.

3.2.1 Participants

A total of 5,886 children and adolescents took part in the included studies. The sample size for individual studies ranged from 23 to 1076 students. Participants' mean age ranged from 6 to 15 years old. Some studies only only recorded the school grades of the students from which age was inferred. All studies used participants from both sexes. Studies came from the following countries: United States (k=6), Netherlands (k=4), Denmark (k=1), South Africa (k=1), Switzerland (k=1), Norway (k=1), Sweden (k=1), Chile (k=1), and Italy (k=1). Fourteen studies were randomised controlled trials, and three used quasi-experimental designs.

3.3 Study Quality

Methodological quality and internal validity of the fourteen RCT studies that were assessed using the Jadad Scale varied; four studies scored 2 points, five studies scored 3 points, two studies scored 4 points, and one study scored 5 points. Methodological quality of two of the three quasi-experimental studies that were assessed using the EPHPP Quality Assessment Tool for Quantitative Studies was “Weak” and one study was “Moderate”. Study quality scores are available in the supplementary materials (https://osf.io/d9tx6/).

Table 1 Study Characteristics

Reference	Location / Study Design / Length of Study	Participants' Baseline Characteristics	Assessment of CRF	Assessment of EF	Assessment of AP	Control Variables	PA Intervention Details	Main Findings
Donnelly et al. (2017)	US / Randomised controlled trial / 3 years	584 children / 7-9 years old / 2nd-3rd grades / boys and girls	PACER	N/A	Wechsler Individual Achievement Test-Third Edition (WIAT-III) measured AP. Standardised composite scores for mathematics, reading comprehension fluency, and spelling.	Age, BMI, waist circumference, sex, ethnicity, annual household income, baseline differences.	Curricular intervention. 10x10minute active lesson sessions per week. Activities aimed for 4-5 METs per session, but not measured.	AP improved across 3 years in reading, mathematics, and spelling in children in intervention and control schools, with no significant between group differences.
Chaddock-Heyman et al. (2013	United States / Randomised control trial / 9 months	23 children / 8-9 years old / boys and girls	Maximal graded exercise test administered on a treadmill	Flanker task measured inhibition.	N/A	BMI, age, sex, pubertal timing, and SES	After school intervention. 5x120 minute sessions per week. Average 76.8minutes of MVPA per session. Aerobic activities as well as muscle and bone strengthening activities were included through fitness activities and low-organised games.	60+ minutes of physical activity per day for 5 days per week decreases in fMRI brain activation in the right anterior prefrontal cortex coupled with within-group improvements in performance on a task for attentional and interference control.
Crova et al. (2014)	Italy / Randomised control trial / 6 months	70 children / 9-10 years old / boys and girls	20mMSR	Random number generator task measured inhibition and working memory.	N/A	BMI, age, sex, and baseline differences	Non-curricular intervention. 2x60minute sessions of enhanced PE programme of skill based and tennis-specific training per week. Average 49.6% of sessions spent doing MVPA.	Children with higher CRF had higher inhibition and working memory than children with lower CRF.
de Greeff et al. (2018)	Netherlands / Randomised control trial / 2 years	499 children / 5-7 years old / 2nd-3rd grades / boys and girls	20mMSR	Stroop test measured inhibition. Digit span backward and Visual span measured working memory.	N/A	Grade and sex	Curricular intervention. 3x20-30minute sessions per week. 60% of each lesson was spent in MVPA. Exercises were performed whilst solving an academic task.	There was no significant difference between the intervention and control groups for CRF or EF.

				Wisconsin card sorting test measured cognitive flexibility.				
Gall et al. (2018)	South Africa / Randomised control trial / 20 weeks	663 children / 8-13 years old / boys and girls	20mMSR	Selective attention measured by d2 test.	Composite average of end of year results from home language, additional language, mathematics, and life skills.	Sex, stunting, anaemia, intestinal protozoa and soil-transmitted helminth infections, age, BMI, SES, self-reported PA, grip strength, and VO2max	Curricular intervention. The intervention included 2x45minute physical education lessons per week, 1x45minute moving to music class per week, in-class activity breaks, and school infrastructure adaption.	No significant intervention effect found on selective attention. Children with higher CRF had better concentration performance than less fit peers. PA intervention had positive effect on AP. After controlling for confounders, there was no change in AP for intervention group but a decrease in control group.
García-Hermoso et al. (2020)	Chile / Randomised controlled trial / 8 weeks	170 children / 8-10 years old / boys and girls	20mMSR	Attention capacity using the d2 Test of Attention	End of semester grades in mathematics and language	Baseline scores, age, sex, weight status, peak heigh velocity, sedentary time, moderate-vigorous physical activity levels, and school	Non-curricular intervention. Children attended five times per week before their first class (8:00-8:30 AM). Sessions included cooperative physical games in addition to age appropriate sports, playground games, dance, and other recreation.	Neither selective attention nor concentration improved significantly. Effects were trivial. Both language and mathematics grades improved significantly in the intervention group compared to the control group (who decreased) with moderate to large effects
Garst et al., (2020)	US / Randomised controlled trial / 9 months	144 children / 11-14 years old / boys and girls	PACER	N/A	Average school reported grades at end of semester	Sex	Curricular interventions. The control group participated in regular PE. The intervention group replaced PE with a CrossFit workout. Both were performed three times a week for 60 minutes per session.	Significant group by time interactions were found suggesting a reduction in AP for the intervention group and maintenance in the control group
Hillman et al. (2014)	US / Randomised control trial / 9 months	221 children / 7-9 years old / boys and girls	Maximal graded exercise test administered on a treadmill.	Flanker task measured inhibition. Switch task	N/A	Sex and age	Non-curricular intervention. 5x120minute sessions per week. >70minutes of MVPA per session. Sessions were aerobically	The physical activity intervention enhanced EF and brain function during tasks that

				measured cognitive flexibility.			demanding with opportunities to refine motor skills.	required greater executive control.
Kamijo et al. (2011)	US / Randomised control trial / 9 months	43 children / 7-9 years old / boys and girls	Maximal graded exercise test administered on a treadmill.	Sternberg task measured working memory.	N/A	BMI, age, SES, ADHD scores, pubertal status, IQ	Non-curricular intervention. 5x120minute sessions per week. >70minutes of MVPA per session. Sessions were aerobically demanding with opportunities to refine motor skills.	Physical activity intervention led to increases in CRF and Sternberg task performance. The beneficial effects of the physical activity intervention were greater for task conditions that required greater working memory demands.
Kvalø et al. (2017)	Norway / Randomised control trial / 6 months	449 children / 9-10 years old / boys and girls	20mMSR	Stroop test measured inhibition. Digit span test measured working memory. Trail Making Test measured cognitive flexibility.	N/A	Sex, BMI, and waist circumference	Curricular and non-curricular intervention. 2x45minutes physically active lessons, 5x10minute physically active homework, 5x10minute PA during recess. No intensity reported.	Results indicate that increased physical activity in school might improve children's EF, even without improvements in CRF.
Schmidt et al. (2015)	Switzerland / Randomised control trial / 6 weeks	181 children / 10-12 years old / boys and girls	20mMSR	Flanker task measured inhibition. An additional block of the flanker task was used to measure cognitive flexibility. The n-back task measured working memory.	N/A	Physical activity level, pubertal status, SES, BMI z-score, and AP	Curricular intervention. 2x45minute sessions per week. Team Games intervention group: floorball and basketball tailored games to challenge EF. Aerobic Exercise: aerobic exercise that were not cognitively engaging. PA intensities not specified.	The results showed that both the Team Games and Aerobic Exercise interventions improved CRF more than the control group. Only the Team Games intervention significantly improved children's cognitive flexibility performance, and the other two measurements of EF remained unaffected.
Sjöwall et al. (2017)	Sweden / Quasi-experimental design / 2 years	228 children / 6-13 years old / boys and girls	20mMSR	Arithmetic test	N/A	Sex and age	Curricular intervention. 3x40minutes per week of additional PA. Various physical activities. Specified as high intensity but not measured.	No beneficial development of arithmetic for active school compared to control school.

Tarp et al. (2016)	Denmark / Cluster-randomised control trial / 20 weeks	632 children / 12-14 years old / boys and girls	Andersen Test	Flanker task measured inhibition.	AP measured using a custom-made grade specific mathematics test.	Sex and age	Curricular and non-curricular intervention. 5x60minutes extra PA over per week. 60minutes could include class-room PA, structured recess PA, PA homework. Intensity was measured but no requirements were made.	No significant difference in change, when comparing the intervention and control groups in EF. An intervention effect was found for CRF in girls. No significant difference in change, when comparing the intervention and control groups in mathematics. An intervention effect was found for CRF in girls
Torbeyns et al. (2017)	Belgium / Randomised control trial / 5 months	44 children / 14 years old / boys and girls	20mMSR	Rey Auditory Verbal Learning Test to measure working memory. The Stroop test and the Rosvold Continuous Performance Test measured inhibition.	Standardised Dutch (native language) and mathematic tests.	Age, BMI, body fat percentage, waist circumference	Curricular intervention. 4x50minutes per week using a bike desk. Cycling intensity measured but not standardised.	No significant effect of using bike desk in classroom on EF. CRF significantly improved in the intervention group. No significant effect of using bike desk in classroom on AP. CRF significantly improved in the intervention group.
van den Berg et al. (2019)	Netherlands / Randomised control trial / 9 weeks	512 children / 9-12 years old / boys and girls	20mMSR	d2 test of attention, fluency task, attention network task, Stroop task	N/A	Age and baseline score	Curricular intervention. 5x10minute exercise break during class. Moderate to vigorous intensity. Accelerometers and heart rate was monitored and used to measure PA and exercise intensity.	No intervention effects on EF or CRF.
van der Niet et al. (2016)	Netherlands / Quasi-experimental design / 22 weeks	105 children / 8-12 years old / boys and gilrs	20mMSR	Stroop test measured inhibition, visual memory and digit span tests measured working memory, trail making test measured cognitive flexibility and tower of London test	N/A	Age, SES, sex, and baseline scores	Non-curricular intervention. 5x30minutes lunchtime sessions per week. Moderate to vigorous activities including running games, circuit training, and cognitive PA. Heart rate was monitored to measure intensity.	CRF improved for children in both the intervention and control groups, but not significantly. Inhibition and working memory improved significantly in intervention group compared to control group. No other significant effects were found on the other executive functioning measures.

				measured planning.				
Weiss et al. (2015)	US / Quasi-experimental design / 1 year	1076 children / 11-14 years old / 6th-8th grades / boys and girls	PACER	N/A	Standardised test score in mathematics and reading from previous and current year	Baseline differences in BMI, waist circumference, self-esteem, perceived physical confidence, perceived academic differences, perceived peer acceptance	Curricular intervention. 2x45minutes per week. Enhanced PE lessons focussing on moderate intensity activities. No measure of PA.	The results showed that the boys and girls in the intervention groups had significantly improved in CRF (P < 0.05) compared to the control group. Reading and mathematics test scores increased for both boys and girls in the intervention and control groups, although only the boys' control group's reading test score improved significantly (P < 0.05).

3.4 Influence and Small Study Bias

Examination of the contour enhanced funnel plots did not reveal any obvious publication bias (Figure 2). However, van der Niet et al. (2016) appeared to be an outlier when examining EF which was also confirmed when examining Cook's *d* for EF (see https://osf.io/dtmn9/). For comparative purposes, results from meta-analyses for EF was reported both with and without the van der Niet et al. (2016) study included.

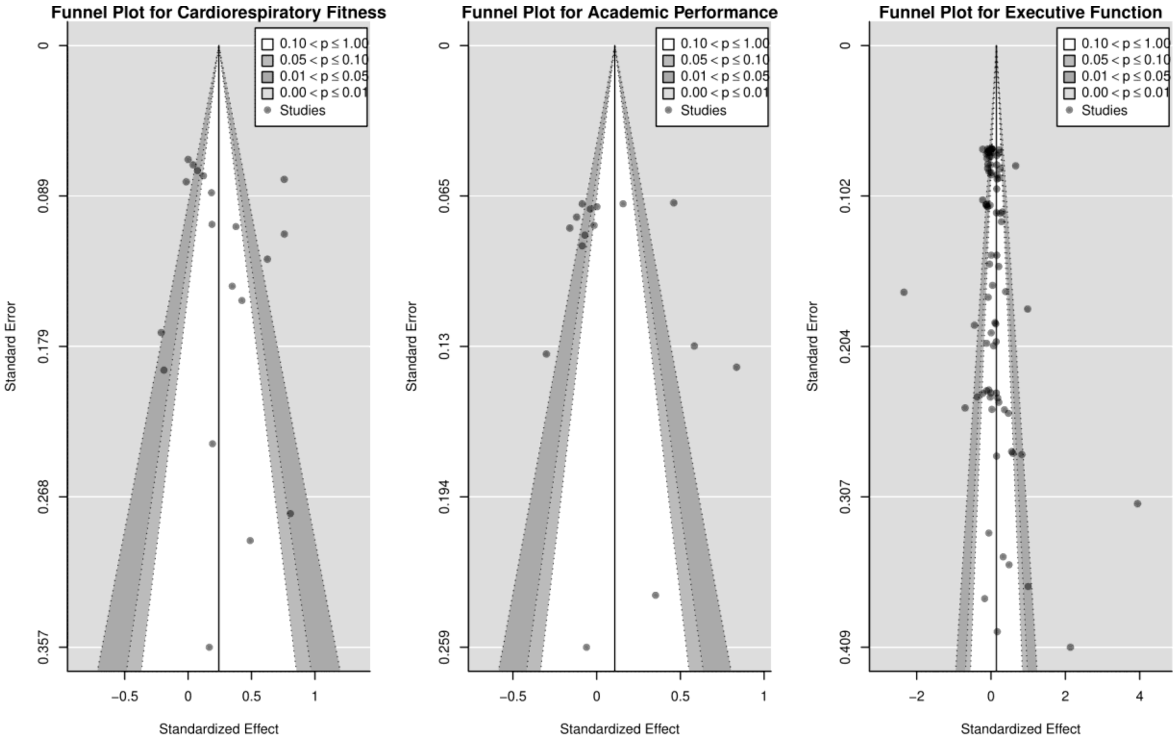

Figure 2. Contour enhanced funnel plots

3.5 Meta-Analysis and Meta-Regression

3.5.1 Cardiorespiratory Fitness

The pooled effect size estimate for CRF was 0.24 [95% CI=0.09, 0.40] (Figure 3) indicating a small effect with reasonable precision indicated by the CIs ranging from trivial to small. Cochrane's Q showed a significant heterogeneity (Q=131.26, df=18, p<0.001) and I^2 showed considerable inconsistency (I^2=86.7%).

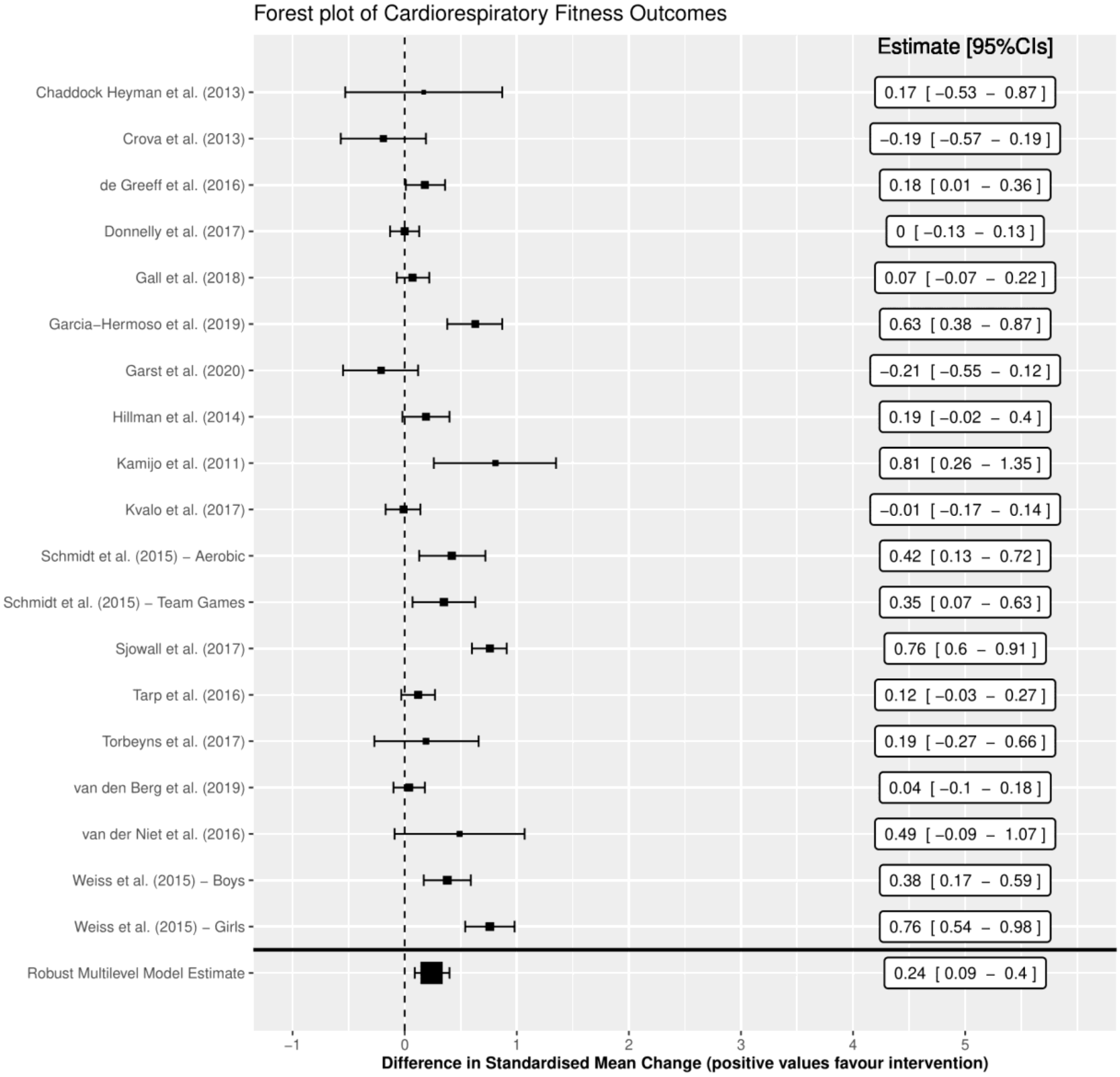

Figure 3. Forest plot of cardiorespiratory fitness outcomes

The effect of age upon CRF outcomes was trivial (β = 0.01 [95% CI=-0.09, 0.07]), and the effect of study duration was essentially null (β = 0.00 [95% CI=-0.00, 0.00]). The effect of whether the intervention was during curriculum time was trivial for curricular interventions (ES=0.18 [95% CI=-0.01, 0.37]), and small for non-curricular interventions (ES=0.45 [95% CI=0.09, 0.80]) but no significant difference between the two models was found (z=1.718, p=0.086). Meta-analytic scatterplots for age (https://osf.io/haemk/), and study length (https://osf.io/gytah/), are available in the supplementary materials.

3.5.2 Executive Function

The pooled effect size estimate for overall EF was 0.15 [95% CI=-0.12, 0.41] indicating a trivial effect with relatively low precision indicated by the CIs ranging from negative trivial to small. Due to the number of effect sizes in the EF model these are presented as a caterpillar plot (Figure 4). Cochrane's Q showed significant heterogeneity (Q=634.57, df=82; p<0.001) and I^2 showed considerable inconsistency (I^2=94.6%). The effect size estimates of the sub-domains of EF are presented in the supplementary materials (https://osf.io/9yejt/). With the study of van der Niet et al. (2016) removed the pooled effect size for overall EF was reduced to 0.02 [95% CI=-0.09, 0.13].

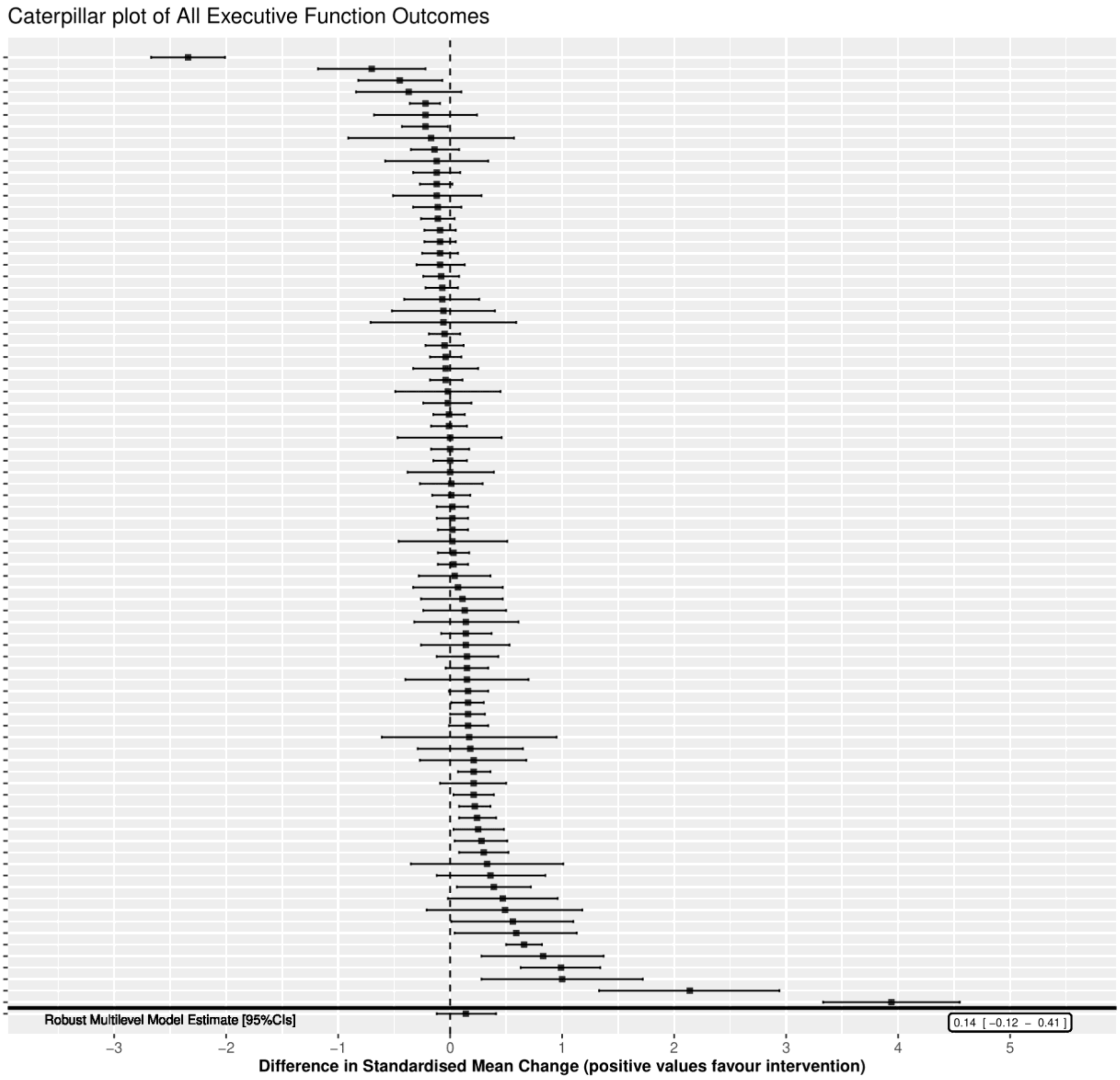

Figure 4. Caterpillar plot of executive function outcomes

The effect of CRF effects upon EF outcomes was moderate (β = 0.51 [95% CI=-0.27, 1.29]) with very poor precision ranging from negative small to positive large effects. The meta-analytic scatterplot of CRF effects upon EF outcomes is shown in Figure 5. With the study of van der Niet et al. (2016) removed the estimated effect decreases in magnitude and increased in precision (β = 0.26 [95% CI=-0.18, 0.70]) suggesting a small effect ranging from a possible negative trivial to moderate effect. However, this still included a possible effect estimate of zero.

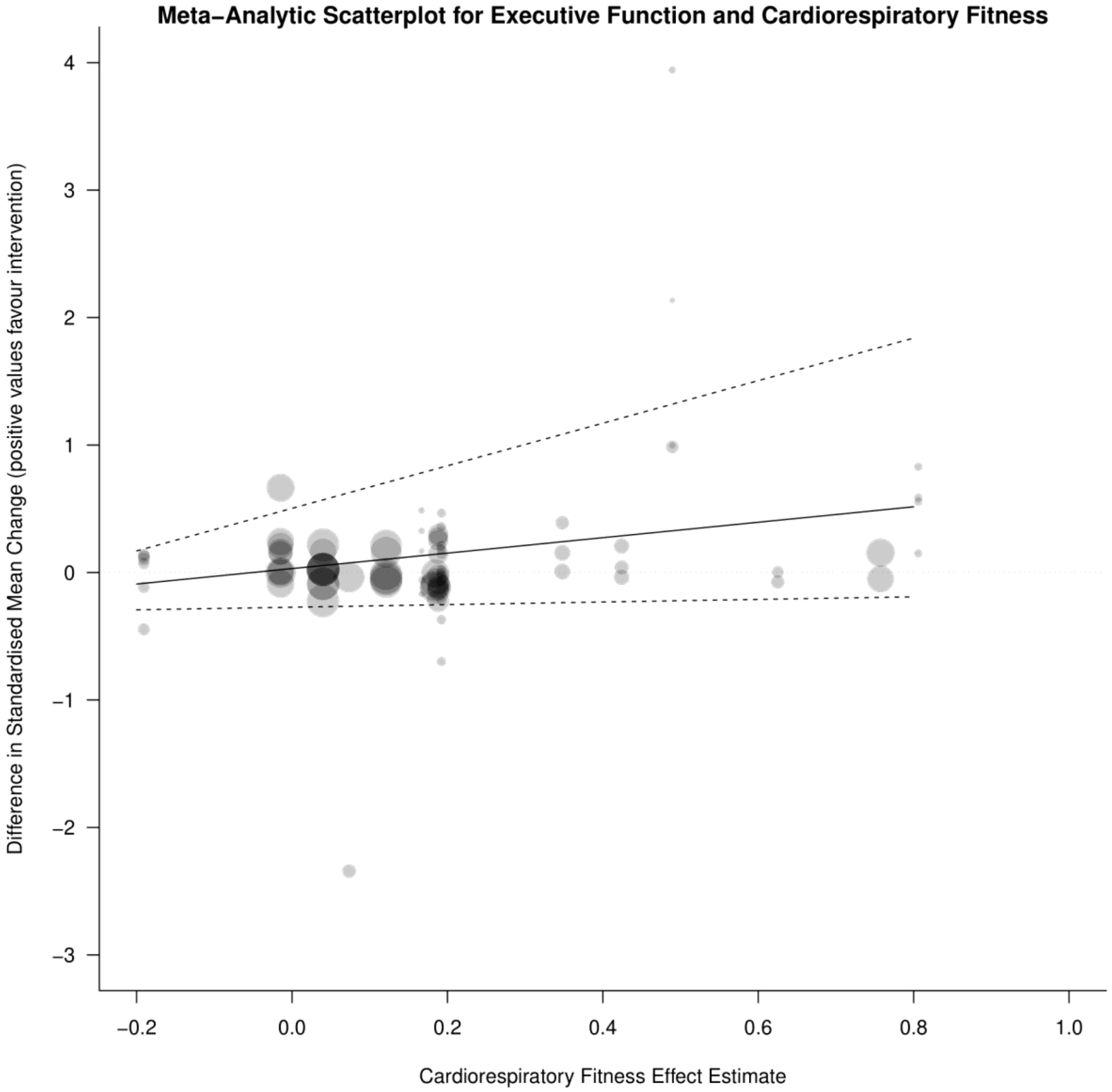

Figure 5. Meta-analytic scatterplot of cardiorespiratory fitness effects on executive function outcomes

The effect of age upon EF outcomes was trivial (β = -0.05 [95% CI=-0.15, 0.06]), and the effect of study duration was essentially null (β = 0.00 [95% CI=-0.01, 0.00]). The effect of whether the intervention was during curriculum time was trivial for curricular interventions (ES=-0.01 [95% CI=-0.13, 0.10]), and small for non-curricular interventions (ES=0.45 [95% CI=-0.24, 1.15]) but no significant difference between the two models was found (z=1.825, p=0.06). Meta-analytic scatterplots for age (https://osf.io/4pw2e/), and study length (https://osf.io/7w4dc/), are available in the supplementary materials. These models were rerun excluding van der Niet et al. [57] and the results are presented in the supplementary materials (https://osf.io/xf6bv/).

3.5.3 Academic Performance

The pooled effect size estimate for overall AP was 0.11 [95% CI=-0.16, 0.38] (Figure 6) indicating a trivial effect with relatively low precision indicated by the CIs ranging from negative trivial to small. Cochrane's Q showed significant heterogeneity (Q=120.89, df=14; p<0.001) and I^2 showed considerable inconsistency (I^2=92.8%).

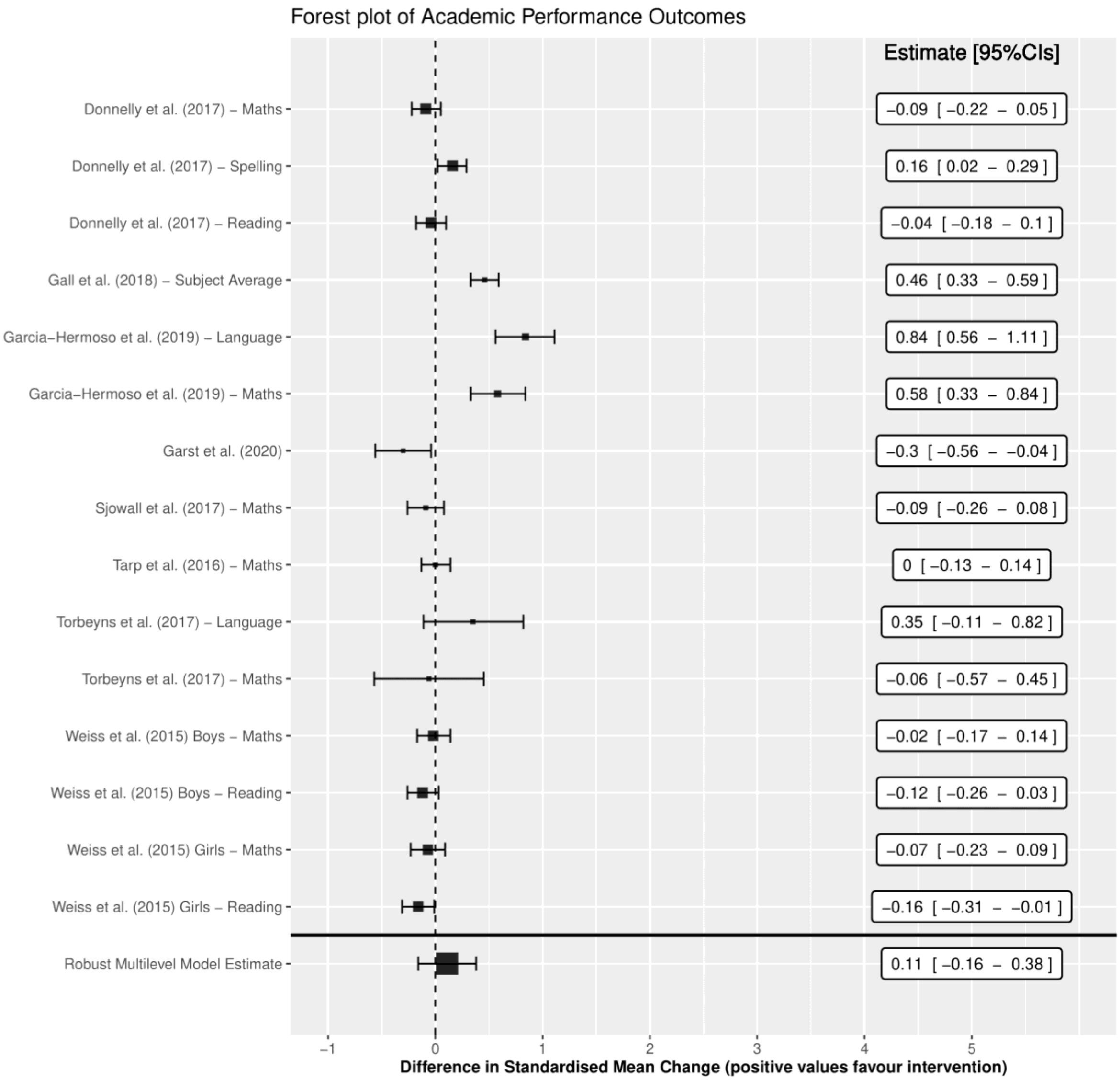

Figure 6. Forest plot of academic performance outcomes

The effect of CRF effects upon AP outcomes was trivial (β = -0.04 [95% CI=-1.52, 1.45]) with very poor precision ranging from negative to positive large effects. The meta-analytic scatterplot of CRF effects upon AP outcomes is shown in Figure 7.

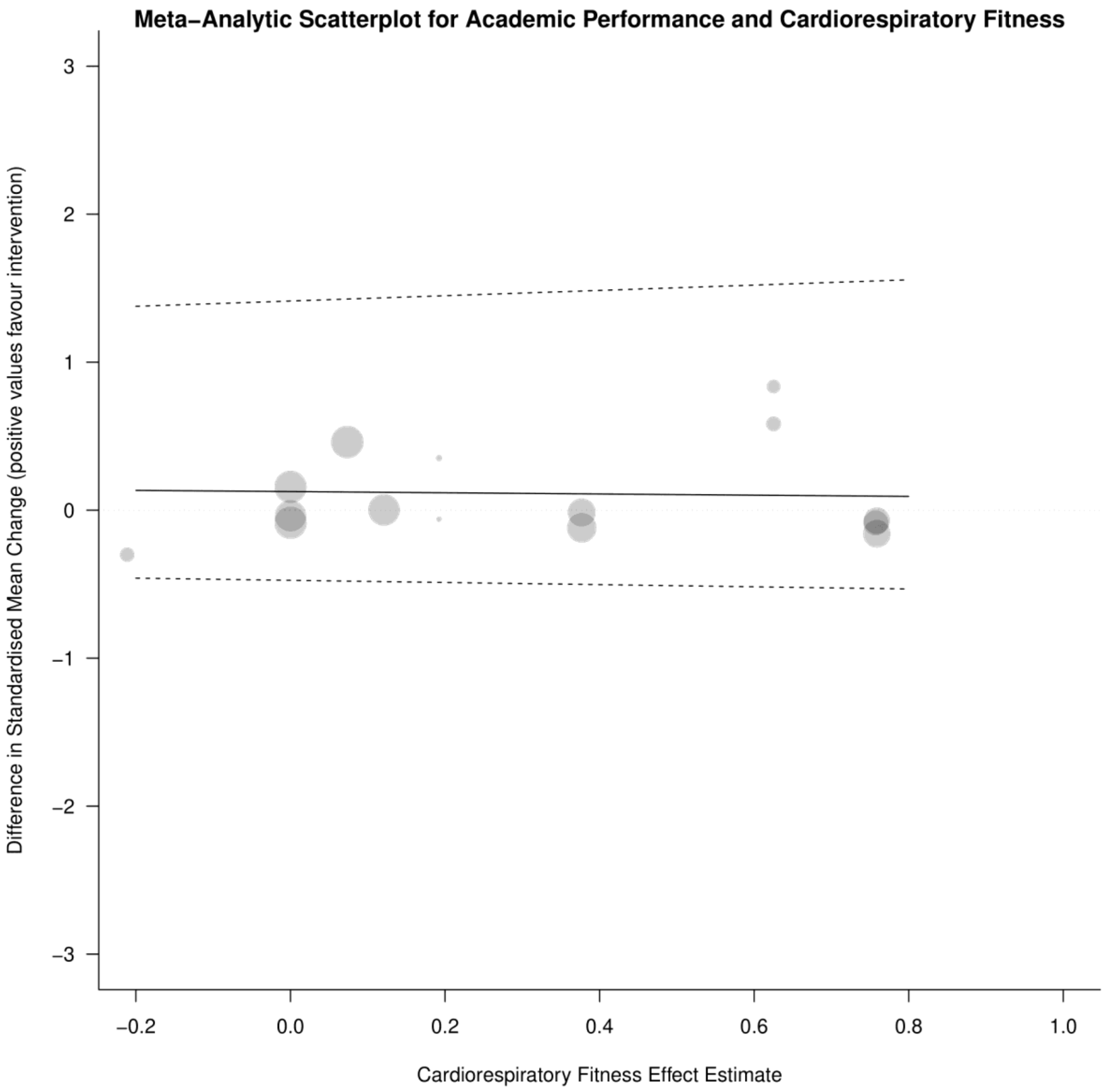

Figure 5. Meta-analytic scatterplot of cardiorespiratory fitness effects on executive function outcomes

The effect of age upon AP outcomes was trivial (β = -0.04 [95% CI=-0.14, 0.07]), and the effect of study duration was essentially null (β = 0.00 [95% CI=-0.01, 0.00]). The effect of whether the intervention was during curriculum time was trivial for curricular interventions (ES=0.05 [95% CI=-0.22, 0.32]), and small for non-curricular interventions (ES=0.30 [95% CI=-4.73, 5.34]) but no significant difference between the two models was found (z=0.616, p=0.538). Meta-analytic scatterplots for age (https://osf.io/95hvn/), and study length (https://osf.io/4qbgv/), are available in the supplementary materials.

4 Discussion

To the best of the authors' knowledge, this is the first systematic review and meta-analysis that aimed to investigate both the impact of PA interventions upon CRF, EF, and AP, in addition to the association of changes in CRF with changes in EF or AP resulting from PA interventions in children and adolescents. Overall, results from the meta-analysis suggest that PA interventions result in small improvements in CRF, but effects upon EF and AP are less clear. Further, though the moderating effect of CRF outcomes upon EF outcomes was initially estimated to be moderate the precision of this estimate was poor and removal of a highly influential study (van der Niet et al., 2016) reduced this to a small imprecise effect. The moderating effect of CRF outcomes on AP outcomes was also trivial and highly imprecise. Thus, although PA interventions might positively impact upon CRF outcomes, these are unlikely to moderate the impact upon EF and AP outcomes both of which seem trivial and unclear.

4.1 Physical Activity, Cardiorespiratory Fitness, and Executive Function

The current meta-analysis found that while participating in a PA intervention resulted in a small improvement in CRF in line with the findings of Pozuelo-Carrascosa et al. (2018); yet, PA interventions seemed to have a trivial yet unclear effect upon EF. This is in contrast to conclusions drawn by Donnelly et al. (2016) whose systematic review found cross-sectional studies with designs accounting for confounding variables showed children with higher CRF performed consistently better in EF tests. However, the result of the current study agrees with those from Verburgh, Königs, Scherder and Oosterlaan (2014), who found no meaningful effect of chronic physical exercise on EF (ES=0.16 [95% CI=-0.07, 0.39]). Verburgh et al. (2014) and the meta-analysis conducted in the present study also contrast with the results of meta-analyses by Álvarez-Bueno et al. (2017b; ES=0.20 [95% CI=0.10, 0.30]) and de Greeff et al. (2018; ES=0.24 [95% CI=0.09, 0.39]) on the positive effects of a PA interventions on EF in children and adolescents; though the results from these latter two meta-analyses suggest at best there may only be small effects. However, considering the effect and interval estimates of the present analysis (0.15 [95% CI=-0.12, 0.41]) our upper interval estimate contains the reported effects from other meta-analyses. Though, in the present study, van der Niet et al. (2016) was removed and analyses reconducted after influence and small study bias analysis which reduced the effect estimates in all models for EF (main model, 0.02 [95% CI=-0.09, 0.13]). However, although this study was not yet published when Verburgh et al. (2014) conducted their meta-analysis and as such was not included, the meta-analyses performed by de Greeff et al. (2018) and Álvarez-Bueno et al. (2017b) did not remove this influential study. At present it seems unclear the extent to which PA interventions impact upon EF which could range from trivial negative effects to small positive effects. Yet, while the magnitude of improvements in CRF resultant from PA interventions may exert a small moderating on EF outcomes (β = 0.26 [95% CI=-0.18, 0.70]), this too is unclear.

4.2 Physical Activity, Cardiorespiratory Fitness, and Academic Performance

Similarly to EF, despite a small effect of PA interventions upon CRF, there was a trivial yet unclear effect upon AP. Again, this result disagrees with two other meta-analyses conducted by Álvarez-Bueno et al. (2017a; ES=0.26 [95% CI=0.07, 0.45]) and de Greeff et al. (2018) (ES=0.26 [95% CI=0.02, 0.49]) both reporting small effects. Again though, considering the effect and interval estimates of the present analysis (0.11 [95% CI=-0.16, 0.38]) our upper interval estimate contains the reported effects from other meta-analyses. At present it also seems unclear the extent to which PA interventions impact upon AP which again could range from trivial negative effects to small positive effects. However, unlike EF, there was little evidence to suggest a moderating effect of CRF changes upon AP outcomes (β = -0.04 [95% CI=-1.52, 1.45]).

4.3 Previously Proposed Mechanisms Linking Physical Activity, Cardiorespiratory Fitness, Executive Function, and Academic Performance

Several underlying mechanisms have been previously proposed to explain the cross-sectional links between PA, CRF, EF, and AP. Firstly, students who achieve better academically may be more orientated for success, and therefore more likely to achieve success both academically, and in PA/fitness (Thøgersen-Ntoumani and Ntoumanis, 2006). This may explain stronger associations in cross-sectional studies. Secondly, a longitudinal PA intervention that increases children's CRF may enhance angiogenesis and neurogenesis in the areas of the brain, that are used for memory and learning, which in turn has been proposed to improve EF and AP (Hillman et al., 2009; Isaacs et al., 1992). Thirdly, cognitively engaging PA is hypothesized to have more of a benefit on EF and AP than repetitive aerobic exercise, such as long-distance running (Vazou et al., 2016). Due to the limited number of studies, sub-group analysis by PA type was not performed. However, Schmidt et al. (2015) investigated the effects of the different types of PA on EF and found that both the "Team Games" and "Aerobic Exercise" groups improved their CRF significantly in comparison to the control group but only the "Team

Games" group increased their EF significantly. These findings are also supported by the meta-analysis conducted by de Greeff et al. (2018) who found a greater effect size for cognitively engaging PA interventions (ES=0.53 [95% CI=0.14, 0.92]) in comparison to aerobic PA (ES=0.29 [95% CI=0.13, 0.45]).

However, despite these plausible mechanisms for the role of PA in improving EF and AP, potentially through its effects upon CRF, the results of the present study do not support this. Our analysis was limited findings from studies that examined both CRF outcomes and EF and/or AP outcomes and suggests that, at best, PA interventions may produce small improvements in CRF whilst having at worst trivial negative impact upon EF or AP. Thus, CRF seems unlikely to mediate any link between PA and EF or AP. Yet, that PA interventions to not negatively impact EF or AP is an important finding as it dispels the often held myth that PA interventions could distract students from pursuits related to the improvement of AP (Coe et al., 2006; Tsai et al., 2009; Arnold et al., 2016). The present study suggests that PA interventions, even those conducted during curricular time, may improve CRF whilst likely avoiding negative impact upon AP. With the future health benefits of improving CRF being well documented (Mintjens et al., 2018), it the possible value of dedicating time during the school day to increasing PA and thus CRF should be considered given it's neglible negative impact upon children's AP

4.4 Limitations

Firstly, some studies were not included in the meta-analysis due to the way the results had been reported in the published article. All authors were contacted to obtain any unpublished data that was required, though some did not reply and others were unable to provide the data requested as the data were not available. Secondly, our search did not consider unpublished studies or include grey literature. Thirdly, measurements of CRF, EF, and AP were standardised by calculating effect sizes, however the validity of and reliability of the individual measures used varies. Fourthly, although some moderators were investigated here and found to have little influence over PA intervention effects (age, and study length) there may be others that influence the response to PA that were not included. One example of this is the intensity of effort of the PA undertaken by the participants in the intervention. Santos et al. (2018) suggested that vigorous PA has a stronger prospective association with changes in CRF. It may be that high intensity of effort intervention impact upon outcomes and moderator relationships. However, this was not included due to most of the studies not using a method to standardise or measure this. It is therefore recommended that future studies monitor the intensity of effort of the PA used in interventions. Fifthly, as the intention of our analysis was to examine the moderating effects of CRF changes upon EF and/ AP changes, we limited our inclusion criteria to only studies measuring both outcomes. As such, the estimates reported from our main models (i.e. without moderation for CRF) should be treated cautiously as they do not include all studies that have examined these outcomes independently. Finally, due to the fact that it is uncommon for correlation matrices or raw data to be available from intervention studies limiting the ability to conduct mediation analysis, we were limited to conducting moderation analyses of the association of changes in CRF with changes in EF or AP at the study/group level. This means that our moderation results reflect only the extent to which CRF changes as associated with PA interventions effects upon EF or AP changes.

5 Conclusions

In conclusion, this meta-analysis has found that, while PA interventions may produce small improvements in CRF in children and adolescents, PA intervention impact impact upon EF or AP is less clear. Further, it seems unlikely that the improvements in CRF produced by PA interventions are associated with changes EF or AP. However, the general lack of negative effect on either AP or EF is noteworthy given that most of the PA interventions examined took place during time normally allotted for curricular activities. This suggests schools can implement PA into the curriculum to improve children's CRF, which is associated with numerous health benefits for children in their present and future, and that concern regarding the negative impact of such interventions may be unfounded.

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Compliance with Ethical Standards

N/A

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Conflicts of Interest

Samuel Tuvey, James Steele, Elizabeth Horton, Xian Mayo, Gary Liguori, Steven Mann, Nadja Willinger and Alfonso Jimenez declare that they have no conflicts of interest relevant to the content of this review.

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