University of Dundee

Associations between executive attention and objectively measured physical activity in adolescence:

Booth, J. N. ; Tomporowski, P. D.; Boyle, J. M. ; Ness, A. R.; Joinson, C.; Leary, S. D.; Reilly, J. J.

Citation for published version (APA):
Booth, J. N., Tomporowski, P. D., Boyle, J. M., Ness, A. R., Joinson, C., Leary, S. D., & Reilly, J. J. (2013). Associations between executive attention and objectively measured physical activity in adolescence:: findings from ALSPAC, a UK cohort. *Mental Health and Physical Activity, 6*(3), 212-219. 10.1016/j.mhpa.2013.09.002

Associations between executive attention and objectively measured physical activity in adolescence: Findings from ALSPAC, a UK cohort☆

J.N. Booth [a, *], P.D. Tomporowski [b], J.M. Boyle [a], A.R. Ness [c], C. Joinson [d], S.D. Leary [c], J.J. Reilly [a]

[a] School of Psychological Sciences and Health, University of Strathclyde, Glasgow G1 1QE, UK
[b] University of Georgia, Athens, GA 30602, USA
[c] School of Oral and Dental Sciences, University of Bristol, Bristol Dental School, Lower Maudlin Street, Bristol BS1 2LY, UK
[d] School of Social and Community Medicine, University of Bristol, Canynge Hall, 39 Whatley Road, Bristol BS8 2PS, UK

ABSTRACT

Studies of relationships between physical activity and children's attention skills are often constrained by small samples, lack of objective measurements and lack of control for confounders. The present study explores the relationship using objective measures of physical activity from a large birth cohort which permits both longitudinal and cross-sectional analyses. Data from 4755 participants (45% male) with valid measurement of physical activity (total volume and intensity) by accelerometry at age 11 from the Avon Longitudinal Study of Parents and Children (UK) were analysed. Attention was evaluated by the Test of Everyday Attention for Children (TEA-Ch) at 11 years and by the Cognitive Drug Research (CDR) computerised cognitive assessment system at 13 years. Males engaged in an average of 29 min (SD 17) of daily moderate-to-vigorous physical activity (MVPA) at age 11 years compared with 18 min (SD 12) among females. In unadjusted models, higher total volume of physical activity was associated with lower performance across attention tasks. When total volume of physical activity and potential confounding variables were controlled for, higher MVPA was associated with better performance at both 11 and 13 years. Correction for regression dilution approximately doubled the standardised β coefficients. We observed complex associations but results suggest that MVPA may be beneficial for attention processes in adolescence, especially in males. This has implications for interventions aimed at improving executive attention but may also be supportive of the benefits of physical activity for educational and mental health outcomes.

© 2013 The Authors. Published by Elsevier Ltd. All rights reserved.

Low levels of physical activity are common in adults and children, so much so, that there has recently been a call for action on the "pandemic of physical inactivity" (Kohl et al., 2012). Engaging in physical activity is well known to be beneficial for physical health. However evidence also suggests that it is related to mental health, including cognitive function (Callaghan, 2004), in populations with and without psychological difficulties and that it can be beneficial for cognitive decline in older adults (see Physical Activity Guidelines Advisory Committee, 2008, for a review). In addition, there is evidence that increased physical activity (PA) leads to improvements in cognition in adults (Colcombe & Kramer, 2003) and children (Hillman, Kamijo, & Scudder, 2011; Sibley & Etnier, 2003; Tomporowski, Naglieri, & Lambourne, 2012), particularly in the area of executive function (Tomporowski, Davis, Miller, & Naglieri, 2008; Tomporowski, Lambourne, & Okumura, 2011).

Executive functions are the higher order processes which direct thought and action. They are generally thought of as an umbrella term which comprises distinct but related processes such as working memory, inhibition and attentional shifting (Miyake et al., 2000; Steele, Karmiloff-Smith, Cornish, & Scerif, 2012). Controversies exist in the literature about the exact relationship between different executive functions and the terms used to refer to them. For example, Diamond (2013) suggests that inhibitory control subsumes processes such as interference control and attention. However, recent investigation of attentional processes in children

has pointed to two distinct but related aspects: selective/sustained attention and executive attention (i.e. attentional shifting) (Steele et al., 2012). A full review of the current controversies is beyond the scope of this paper, however a growing body of research points to the wide reaching importance of executive functions, even with the differing terminologies. For example, a strong relationship has been identified between executive function performance and cognitive reserve in older adults (Roldán-Tapia, García, Cánovas, & León, 2012) and these two closely related constructs of attention and executive function have been implicated in children's mental health (Micco et al., 2009) and in many areas of children's learning (Bull & Scerif, 2001; Christopher et al., 2012; St Clair-Thompson & Gathercole, 2006) with deficiencies identified across a number of developmental difficulties, for example, reading difficulties, ADHD and Autism (c.f. Willcutt, Sonuga-Barke, Nigg, & Sergeant, 2008, for a review). A recent review concluded that making any substantial change to executive function through traditional training programmes is extremely difficult though (Wass, Scerif, & Johnson, 2012). Physical activity interventions, however, have been suggested to be the most promising, in adults at least (Hertzog, Kramer, Wilson, & Lindenberger, 2008). Therefore evidence suggesting whether physical activity can lead to improvements in these areas is of particular importance, especially in young populations where executive functions are still developing (c.f. Diamond, 2012).

Randomised controlled trials have found that increases in moderate to vigorous intensity PA in particular can lead to improvements in certain aspects of executive function in young children (Fisher et al., 2011) and children who are overweight, with evidence for a dose response effect (Davis et al., 2011). Indeed a recent review suggested that the greatest benefits of physical activity for children have been found for working memory, selective attention and inhibition tasks (Guiney & Machado, 2013). However, studies are often constrained by cross-sectional designs, small samples, lack of objective measurement of physical activity, and failure to control for confounders (Biddle & Asare, 2011; Etnier & Chang, 2009; Tomporowski et al., 2012) and so further work aimed at addressing these issues is required, with a particular need for longitudinal studies which can assess the effects of PA over time.

If higher levels of habitual PA can lead to improvements in attention, including executive attention, this would have implications for improvements in academic attainment and potentially inform interventions for those with less efficient executive functions (e.g. those with developmental or psychological difficulties). In addition there are also implications for mental health given the evidence which suggests executive functions are an important factor in young people (e.g. Micco et al., 2009). The present study therefore aims to explore whether objectively measured physical activity at 11 years old is associated with attention and executive function cross-sectionally and longitudinally.

1. Method

1.1. Study cohort

The sample comprised participants from the Avon Longitudinal Study of Parents and Children (Golding, Pembrey, Jones, & ALSPAC, 2001). ALSPAC is an on-going population-based study investigating influences on health and development of children. Ethical approval for the study was obtained from the ALSPAC Law and Ethics Committee and the Local Research Ethics Committees. The phases of enrolment are described in detail in Supplementary material and in the cohort profile paper. Pregnant women resident in the former Avon Health Authority in south-west England, having an estimated date of delivery between 1/4/91 and 31/12/92 were invited to take part, resulting in a cohort of 14,541 pregnancies and 13,988

children alive at 12 months. When the oldest children were aged 7 years, an attempt was made to increase the size of the initial sample with eligible cases that did not join the cohort at the outset. The phases of enrolment are described in more detail in the cohort profile paper (Boyd et al., 2012).

1.2. Study design and procedures

The present study investigates associations between objectively measured total volume of PA and moderate–vigorous intensity PA (MVPA) at an ALSPAC research clinic attended at age 11 years, and attention and executive attention at ages 11 and 13.

1.3. Exposure, outcome measures and covariates

1.3.1. Physical activity measurement

The Actigraph AM 7164 2.2 accelerometer (Fort Walton Beach, Florida) objectively measures free-living PA. The Actigraph has acceptable reliability, high criterion validity, and low reactivity for measurement of physical activity in adolescents (DeVries et al., 2009) and provides greater power to detect associations than measurement which is not objective (Janz, 2006; Reilly et al., 2008).

The Actigraph used is described in detail elsewhere (Mattocks et al., 2008; Ness et al., 2007) with participants requested to wear the accelerometer for 7 consecutive days during waking hours. A monitoring period of at least 3 days and 10 h of wear time per day was required (Mattocks et al., 2007a; Penpraze et al., 2006) with strings of consecutive zero's lasting ten minutes or more removed to account for non-wear time. In order to quantify MVPA from accelerometry output we applied the cut-point of 3600 cpm derived from the validation and calibration study conducted in a sub-sample of ALSPAC participants at 11 years (Mattocks et al., 2007b).

1.3.2. Attention and executive attention tasks

The outcome measures for the present analyses were from the Test of Everyday Attention for Children (TEA-Ch) (Manly, Robertson, Anderson, & Nimmo-Smith, 1998) at 11 years and the Cognitive Drug Research (CDR) computerised cognitive assessment system (United BioSource Corporation) at 13 years (c.f. Wesnes, 2008). Three tasks were selected from the TEA-Ch, each found to load on a different aspect of attention in factor analytic studies: the Sky search task; the sky search dual task; and the opposite-worlds task. The Sky search task has been found to load on selective attention factors in previous research (e.g. Manly et al., 2001). Participants are required to identify pairs of identical "spacecraft" from a page of visually similar stimuli whilst ignoring all distracting stimuli and to circle each pair of identical spaceships. Twenty pairs of spacecraft were identical from 49 displayed. Time and accuracy were recorded and a motor control condition was also performed. An age-corrected normative score was calculated based on the manual instructions, which was also adjusted for motor control. The sky search dual task has been found to load on sustained attention factors (Manly et al., 2001) and followed the same procedure as the sky search task but with the addition of simultaneously presented auditory stimuli which participants had to count whilst performing the sky search task. Normative scores based on time and errors were calculated. In previous research (Manly et al., 2001) the opposite-worlds task has loaded on a factor which was labelled attentional control/switching. It involves two conditions: in the first, participants followed digits (1 and 2 only) printed on a hand out stating the number out loud; in the second condition, participants had to inhibit the prepotent response and this time state "one" when presented with the digit 2, and "two" when

presented with the digit 1. Errors resulted in a time penalty and normative scores were calculated based on this.

At 13 years old, three tasks from the attentional component of the CDR were administered. For the simple reaction time task, the word "yes" was presented thirty times in the middle of a computer screen with varying inter-stimulus intervals and participants had to press a corresponding button whenever it was displayed. For the choice reaction time task, thirty trials were completed where participants were presented with either the word "yes" or the word "no" displayed on a computer screen. The choice of word was selected randomly and there was equal probability of the stimulus being "yes" or "no" with varying inter-stimulus interval. Participants had to respond by pressing the correct corresponding button, inhibiting the prepotent response and attending to the stimuli. In the digit vigilance task, participants were presented with a digit in the middle of the screen which remained constant, and a second digit on the left hand side of the screen which changed at a rate of 150 per minute. When the digits matched, the participant had to press a response button. There were 45 targets. Participants had to inhibit responding when the digits did not match and focus attention on the correct stimuli. Score was based on reaction time and errors.

1.4. Confounders

A series of potential confounders previously identified in the literature as being associated with either physical activity, executive function/attention or both were included in the analyses: age; birth weight; gestation; age of mother at delivery; mother's oily fish intake during pregnancy as assessed by questionnaire at 32 weeks gestation; maternal smoking in the first three months of pregnancy; weight status, expressed as a BMI Z score relative to UK 1990 reference data; pubertal status based on Tanner pubic hair stage for males (stage I [least advanced] to V [most advanced]) and menarche status for females evaluated at age of outcome (Leary et al., 2008; Tanner, 1986; Wiles, Haase, Lawlor, Ness, & Lewis, 2011); ethnicity; socio-economic status based on maternal educational attainment (none/CSE to University degree) and occupational social class as classified by the OPCS in 1991 (classes I [professional/ managerial] to V [unskilled manual workers]) (OPCS., 1991).

1.5. Inclusions and exclusions

The following criteria were used to exclude participants based on potential confounding of executive function performance: a psychiatric diagnosis based on the Development and Well-being Assessment (DAWBA) (Goodman, Ford, Richards, Gatward, & Meltzer, 2000) which provides information to make a DSM-IV (APA, 2000) clinical diagnosis (Ford, Goodman, & Meltzer, 2003); participants with a Statement of Educational Needs as reported by school or parents; participants with Total Difficulties scores of 16 and greater on the teacher-completed version of the Strengths and Difficulties Questionnaire (Goodman, 1997) at age 11.

1.6. Statistical analyses

Three PA variables were calculated which were all adjusted for accelerometer wear time: the total volume of PA as measured in accelerometer counts-per-minute (cpm) made up largely of light intensity PA, average daily number of minutes spent in MVPA and also the percentage of time spent in MVPA.[1] Age-corrected

Table 1
Sample characteristics.

Characteristic	Males		Females	
	n	Mean (SD)	n	Mean (SD)
Age in months at PA monitoring	2128	140.8 (2.8)	2627	140.9 (2.8)
Birth weight (g)	1996	3457.1 (579.6)	2446	3375.2 (490.5)
Gestation (weeks)	2020	39.4 (2.0)	2484	39.5 (1.6)
Age of mother at delivery (years)	2020	29.2 (4.6)	2484	28.9 (4.5)
BMI Z score at 11	2117	0.34 (1.17)	2609	0.27 (1.17)
BMI Z score at 13	1093	0.27 (1.18)	1392	0.18 (1.16)
	n	Percentage	n	Percentage
Ethnicity				
White	1846	95.6	2281	96.4
Non-white	84	4.4	85	3.6
BMI at 11 years				
Normal	1512	71.4	1917	73.5
Overweight	288	13.6	339	13.0
Obese	317	15.0	353	13.5
BMI at 13 years				
Normal	810	74.1	1061	76.0
Overweight	143	13.1	192	13.8
Obese	140	12.8	139	10.0
Mother's oily fish intake				
Never/rarely	714	37.2	900	38.3
Once in 2 weeks	674	35.2	806	34.3
1−3 times a week	508	26.5	615	26.1
4−7 times a week	20	1.0	30	1.3
More than once a day	1	0.1	1	0.0
Mother smoked during pregnancy				
Yes	308	15.5	411	16.8
No	1681	84.5	2029	83.2
Mothers Education				
CSE	244	12.4	310	12.9
Vocational	171	8.7	186	7.8
O level	695	35.4	874	36.4
A level	536	27.3	632	26.3
Degree	317	16.1	397	16.5
Occupational social class				
I (professional)	134	7.8	142	6.8
II	600	35.1	710	34.2
III (non-manual)	734	42.9	894	43.0
III (manual)	103	6.0	121	5.8
IV	122	7.1	180	8.7
V (unskilled)	15	0.1	30	1.4
Armed forces	1	0.1	0	0
Pubertal status at 11				
Experienced menarche	–	–	298	15.0
Tanner stage I	528	39.0	–	–
Tanner stage II	565	41.7	–	–
Tanner stage III	206	15.2	–	–
Tanner stage IV	53	3.9	–	–
Tanner stage V	3	0.2	–	–
Pubertal status at 13				
Experienced menarche	–	–	1123	60.5
Tanner stage I	151	11.9	–	–
Tanner stage II	301	23.7	–	–
Tanner stage III	358	28.2	–	–
Tanner stage IV	398	31.3	–	–
Tanner stage V	62	4.9	–	–

normative scores were employed for tasks from the TEA-Ch. Normative scores were not available for the CDR task scores but following a procedure for analysing these tasks identified in previous literature (Wesnes, 2008), raw scores were subject to a factor analysis. Two separate factors were identified: a reaction speed factor with the simple reaction time, digit vigilance speed and the choice reaction time speed loaded onto it; and an accuracy factor

---

[1] Percentage of time in MVPA = (mins of mvpa/mins of light + mins of moderate + mins of vigorous activity)*100.

which had the digit vigilance targets detected, digit vigilance false alarms and choice reaction time accuracy loaded on it. These factors have previously been identified for the CDR system (Wesnes, 2008; Wesnes, Ward, McGinty, & Petrini, 2000) and factor scores were employed for all further analysis. Associations between PA (all variables adjusted for wear time) and attention tasks were assessed using multiple linear regression. The interaction between gender and PA was formally tested. As evidence suggested interaction effects (p-values < 0.05), all analyses were conducted separately for males and females.

A series of models were used to explore the impact of confounding variables following previous reports of ALSPAC accelerometry. Model 1 (minimally adjusted model) was adjusted for age of participants. Model 2 adjusted for the potential confounders in model 1, plus birth weight and gestation. In model 3, the variables included in model 2 were adjusted for, together with age of mother at delivery, mother's oily fish intake and whether the mother of participants smoked in the first three months of pregnancy. Model 4 adjusted for potential confounding variables in model 3 plus the inclusion of BMI Z score relative to UK 1990 reference data and pubertal stage of participant (recorded at time of outcome). The final model (model 5) adjusted for all confounders in model 4 plus ethnicity, maternal educational attainment and occupational social class.

Models 1–5 were fit separately for total volume of PA (accelerometer cpm), MVPA and percentage of time spent in MVPA and then refit with both total volume of PA and percentage of time spent in MVPA entered simultaneously. This allows conclusions regarding the impact of percentage of time in MVPA, that is, the intensity of PA, to be drawn independently of the total volume of PA and sedentary time (Wiles et al., 2011). As the PA guidelines and previous research highlight the importance of MVPA, the present study shows results for the percentage of time spent in MVPA, with total volume included as a control variable. For ease of interpretation, only results for models 1 (minimally adjusted) and 5 (fully adjusted) are presented in tables with coefficients for each separate model presented in Supplementary material. To assess whether changes in effect sizes identified in models 2–5 were biased by missing data, model 1 was repeated for only those participants who had complete data in model 5 (complete confounder information).

The intra-class correlation coefficient (ICC) was used to make adjustment for regression dilution (Mattocks et al., 2007a). SPSS v19 was used for all analyses.

2. Results

2.1. Characteristics of study participants

Of the 11,952 ALSPAC participants invited to attend the 11-year clinic, 60% attended, 93% of those who attended agreed to wear an Actigraph, and 85% of those, provided valid activity data (Leary et al., 2008; Mattocks et al., 2008; Ness et al., 2007). Data from 4755 participants (2128 males and 2627 females) remained for analyses following the application of all exclusion criteria; Table 1 provides the characteristics of these participants. As reported elsewhere (Leary et al., 2008; Mattocks et al., 2008; Ness et al., 2007), small differences were found when comparisons of characteristics were made between children who attended the clinic and those who did not. This was also the case when those who provided valid accelerometer data were compared to those who did not (Leary et al., 2008; Mattocks et al., 2008; Ness et al., 2007).

Daily number of minutes of MVPA for males was 29 (SD = 17) and for females was 18 (SD = 12) and the percentage of time spent in MVPA was 8% (SD = 4) for males and 5% (SD = 3) for females. The correlation between accelerometer cpm and percentage of time spent in MVPA was 0.73 for males and 0.68 for females. Descriptive

statistics for attention tasks at age 11 and 13 are presented in Table 2. Similar scores were obtained for males and females for all tasks. For normative scores at age 11, females performed slightly better than males. However at age 13, while girls had marginally better accuracy on tasks, the reaction time of boys was quicker.

2.2. Associations with EF at 11

The associations between PA at 11 and attention/executive attention were assessed with linear regression analyses with results shown in Tables 3 and 4. For males, when entered separately, total volume of physical activity (accelerometer cpm) predicted decreased performance on the sky search task; however the percentage of time spent in MVPA predicted increased performance. This pattern continued when total volume of PA (accelerometer cpm) and percentage of time spent in MVPA were entered simultaneously, even after adjusting for confounders. Higher intensity PA was associated with better performance when the total volume of PA was controlled for. The same pattern of associations was found for the dual and the opposite-worlds tasks, and while the associations were not as great for the dual task, they were of a similar magnitude for the opposite-worlds task.

Similar associations were observed for females, with total volume of PA predicting lower performance on all tasks but percentage of time spent in MVPA predicting higher normative scores. While the betas were small in magnitude for the sky search and dual task, they were greater for the opposite-worlds task and remained after controlling for confounders. Thus when total volume of PA was controlled for, the percentage of time spent in MVPA predicted greater performance on the opposite-worlds task.

2.3. Associations with EF at 13

Factor scores were used to examine the associations between physical activity at age 11 and attention/executive attention at age

Table 2
Descriptive statistics for physical activity variables and attention task performance.

Characteristic	Males		Females	
	n	Mean (SD)	n	Mean (SD)
Total volume of PA, Counts-per-minute (cpm)	2128	662 (186)	2627	553 (153)
MVPA minutes per day	2128	29 (17)	2627	18 (12)
Percentage of time spent in MVPA	2128	8 (4)	2627	5 (3)
Attention at 11 years old				
Sky search norm	2120	8.72 (2.23)	2618	9.68 (2.29)
Dual task norm	2090	7.50 (2.25)	2579	8.22 (2.12)
Opposite-worlds norm	2025	18.46 (1.30)	2533	18.65 (1.04)
Attention at 13 years old				
Simple reaction time (s)	1590	292.25 (50.02)	1985	296.61 (47.43)
Digit vigilance speed (s)	1590	426.14 (42.15)	1982	428.93 (41.72)
Digit vigilance targets detected	1590	25.62 (4.04)	1982	26.18 (3.85)
Digit vigilance false alarms	1590	4.50 (5.32)	1982	3.51 (4.95)
Choice reaction time (s)	1585	434.25 (61.02)	1975	450.13 (61.79)
Choice reaction time accuracy	1585	26.98 (2.12)	1975	27.62 (1.91)

Note: cpm = total volume of physical activity measured by accelerometer counts per minute; MVPA = average daily number of minutes spent in moderate-to-vigorous physical activity.

Table 3
Associations between physical activity at 11 years old and executive function at 11 years old in males.

Model	cpm			% time in MVPA			%MVPA adjusted for total volume		
	β	95% CI	p value	β	95% CI	p value	β	95% CI	p value
Sky search									
Minimally adjusted $n = 2120$	0.015	−0.03 to 0.06	0.489	0.060	0.02 to 0.10	0.006	0.105	0.04 to 0.17	0.001
Fully adjusted $n = 1174$	−0.013	−0.07 to 0.04	0.659	0.046	−0.01 to 0.10	0.123	0.122	0.04 to 0.21	0.006
Dual task									
Minimally adjusted $n = 2090$	0.002	−0.04 to 0.04	0.922	0.025	−0.02 to 0.07	0.254	0.050	−0.01 to 0.11	0.116
Fully adjusted $n = 1156$	0.021	−0.04 to 0.08	0.497	0.033	−0.03 to 0.09	0.281	0.038	−0.05 to 0.13	0.395
Opposite-worlds									
Minimally adjusted $n = 2025$	−0.003	−0.06 to 0.05	0.910	0.042	0.00 to 0.09	0.056	0.094	0.03 to 0.16	0.004
Fully adjusted $n = 1126$	−0.052	−0.11 to 0.01	0.091	0.006	−0.05 to 0.07	0.844	0.094	0.01 to 0.18	0.036

Note: Tables include standardised beta coefficients (β) and 95% confidence intervals for physical activity variables predicting executive function task performance. The minimally adjusted model (Model 1) adjusts for age of participants; the fully adjusted model (model 5) adjusts for age plus birth weight, gestation, age of mother at delivery, mother's oily fish intake, whether the mother of participants smoked in the first three months of pregnancy, BMI Z score relative to UK 1990 reference data, pubertal stage of participant (recorded at time of outcome), ethnicity, maternal educational attainment and occupational social class.

Table 4
Associations between physical activity at 11 years old and executive function at 11 years old in females.

Model	cpm			% time in MVPA			%MVPA adjusted for total volume		
	β	95% CI	p value	β	95% CI	p value	β	95% CI	p value
Sky search									
Minimally adjusted $n = 2618$	−0.046	−0.08 to −0.01	0.019	−0.015	−0.05 to 0.02	0.442	0.031	−0.02 to 0.08	0.248
Fully adjusted $n = 1560$	0.004	−0.04 to 0.05	0.864	−0.002	−0.04 to 0.04	0.925	−0.011	−0.08 to 0.06	0.767
Dual task									
Minimally adjusted $n = 2579$	−0.001	−0.03 to 0.03	0.942	0.034	0.00 to 0.07	0.079	0.067	0.01 to 0.12	0.013
Fully adjusted $n = 1538$	0.002	−0.05 to 0.06	0.943	0.021	−0.03 to 0.07	0.421	0.038	−0.03 to 0.11	0.295
Opposite-worlds									
Minimally adjusted $n = 2533$	−0.024	−0.06 to 0.02	0.234	0.025	−0.01 to 0.06	0.204	0.078	0.01 to 0.13	0.004
Fully adjusted $n = 1517$	−0.030	−0.08 to 0.02	0.252	0.016	−0.03 to 0.07	0.536	0.071	0.00 to 0.14	0.050

Note: Tables include standardised beta coefficients (β) and 95% confidence intervals for physical activity variables predicting executive function task performance. The minimally adjusted model (Model 1) adjusts for age of participants; the fully adjusted model (model 5) adjusts for age plus birth weight, gestation, age of mother at delivery, mother's oily fish intake, whether the mother of participants smoked in the first three months of pregnancy, BMI Z score relative to UK 1990 reference data, pubertal stage of participant (recorded at time of outcome), ethnicity, maternal educational attainment and occupational social class.

13, with the beta coefficients shown in Table 5. Factor 1 represented response speed for the attention tasks[2] and for males it was found that total volume of PA (accelerometer cpm) predicted an increase (i.e. participants took longer to respond) whereas MVPA predicted a decrease in factor score suggesting it was predictive of improved performance. This continued after controlling for confounders and when taking account of the total volume of PA.

Factor 2 represents accuracy on the CDR tasks.[3] Total volume of PA (accelerometer cpm) predicted decreased factor score (i.e. less accurate performance) and MVPA predicted higher accuracy for males. In the fully adjusted model this continued to be the case, with the magnitude of the beta attenuating slightly with the inclusion of all confounders. Therefore MVPA was predictive of improved performance across both factors.

An additional adjustment was made to the models in order to take into account MVPA at age 13.[4] The magnitude of the betas for factor 1 were somewhat attenuated and percentage of time spent in MVPA was no longer a robust predictor of CDR response speed ($\beta = -0.085$, $p = 0.193$). However for factor 2, while controlling for MVPA at age 13 attenuated the beta slightly, percentage of time

spent in MVPA at age 11 continued to predicted improved accuracy ($\beta = 0.146$, $p = 0.024$).

A similar pattern of results was found for females for factor 1.[5] Total volume of PA (accelerometer cpm) predicted longer response times whereas MVPA, and percentage of time spent in MVPA, predicted decreased response time (i.e. improved performance). This continued in the fully adjusted models. While a similar pattern of results was found for the accuracy factor,[6] the magnitude of the resulting beta coefficients was small with broad confidence intervals suggesting less robust effects for this factor for females. Further analyses which controlled for MVPA at age 13 resulted in further attenuation of the betas.

To control for bias due to missing data, for each association model 1 was repeated for participants who had complete data at model 5. The resulting regression coefficients were slightly larger than when all available data were included indicating no significant bias (see Supplementary material).

When the standardised regression coefficients for associations with executive function at 13 in the fully adjusted models were corrected for regression-dilution, they decreased from −0.11 to −0.24 for males for factor 1 (speed), and from 0.16 to 0.36 for

---

[2] For males, the correlation between the EF tasks administered at age 11 and Factor 1 of the CDR was: sky search $r = -0.15$, $p < 0.001$; dual task $r = -0.12$, $p < 0.001$; opposite worlds $r = -0.28$, $p < 0.001$.

[3] For males, the correlation between the EF tasks administered at age 11 and Factor 2 of the CDR was: sky search $r = 0.01$ $p > 0.05$; dual task $r = 0.08$ $p < 0.05$; opposite worlds $r = 0.06$, $p < 0.05$.

[4] Correlation between MVPA at age 11 and MVPA at age 13 = 0.39 ($p < 0.001$) in males and 0.34 ($p < 0.001$) in females.

[5] For females, the correlation between the EF tasks administered at age 11 and Factor 1 of the CDR was: sky search $r = -0.20$ $p < 0.001$; dual task $r = -0.07$ $p < 0.05$; opposite worlds $r = -0.16$, $p < 0.001$.

[6] For females, the correlation between the EF tasks administered at age 11 and Factor 2 of the CDR was: sky search $r = 0.05$ $p < 0.05$; dual task $r = 0.16$ $p < 0.001$; opposite worlds $r = 0.11$, $p < 0.001$.

Table 5
Associations between physical activity at 11 years old and executive function at 13 years old.

Model	cpm			% time in MVPA			%MVPA adjusted for total volume		
	β	95% CI	p value	β	95% CI	p value	β	95% CI	p value
Males									
Factor 1 − speed									
Minimally adjusted $n = 1581$	0.030	−0.02 to 0.08	0.238	−0.029	−0.08 to 0.02	0.242	−0.108	−0.18 to −0.04	0.003
Fully adjusted $n = 678$	0.008	−0.07 to 0.08	0.834	−0.044	−0.12 to 0.03	0.263	−0.107	−0.22 to 0.01	0.063
Factor 2 − accuracy									
Minimally adjusted $n = 1581$	−0.075	−0.12 to −0.03	0.003	0.008	−0.04 to 0.05	0.738	0.132	0.06 to 0.20	<0.001
Fully adjusted $n = 678$	−0.040	−0.12 to 0.04	0.305	0.046	−0.03 to 0.12	0.243	0.160	0.05 to 0.27	0.005
Females									
Factor 1 − speed									
Minimally adjusted $n = 1974$	0.001	−0.04 to 0.04	0.963	−0.065	−0.11 to −0.02	0.004	−0.122	−0.18 to −0.06	<0.001
Fully adjusted $n = 889$	0.005	−0.07 to 0.08	0.889	−0.029	−0.10 to 0.04	0.401	−0.061	−0.15 to 0.03	0.196
Factor 2 − accuracy									
Minimally adjusted $n = 1974$	−0.067	−0.11 to −0.02	0.003	−0.002	−0.05 to 0.04	0.933	0.081	0.02 to 0.14	0.008
Fully adjusted $n = 889$	−0.023	−0.09 to 0.04	0.505	0.002	−0.06 to 0.07	0.953	0.034	−0.06 to 0.13	0.474

factor 2 (accuracy). For females for factor 1, the coefficient decreased from −0.06 to −0.14.

3. Discussion

3.1. Main findings and study implications

The present study aimed to explore whether objectively measured physical activity at 11 years old, in particular MVPA, is associated with attention and executive function and to address a number of limitations in the literature by employing a unique longitudinal approach. We observed a complex pattern of associations. While total volume of PA, comprised mostly of light intensity activity, predicted lower performance on tasks at both 11 and 13 years, our findings support the hypothesis that higher MVPA was associated with better executive function performance in adolescent males, with results less convincing for females. Results were not uniform across all tasks administered, suggesting that there may be selective benefits of PA. The finding that total volume of PA (mostly light intensity PA) led to lower predicted executive function performance was unexpected and the reasons for this are unclear from the present study. However, the finding that the intensity of physical activity is important over time, i.e. a beneficial impact of MVPA for some tasks, is of particular importance and is consistent with the emerging body of evidence from intervention studies with children and obese adolescents which suggests that increases in MVPA can lead to improvements in executive function, with evidence for a dose response effect (Davis et al., 2007, 2011; Fisher et al., 2011). Previous literature suffers from a number of limitations, such as a lack of longitudinal studies, small sample sizes, reliance on subjective measures of physical activity and failure to control for confounders. Our study addresses these limitations with a unique longitudinal design and highlights that the intensity of physical activity is an important factor. The findings contribute to recent conclusions suggesting that physical activity is beneficial for some aspects of executive function (Guiney & Machado, 2013) however research which includes a wider array of tasks of executive function is also required. Furthermore, these findings make a promising contribution to the literature investigating interventions to improve executive functions (Wass et al., 2012).

The present results demonstrate the benefits from relatively small increases in MVPA. However, while the effect sizes for the observed associations are modest, it should be noted that levels of objectively-measured free-living MVPA were considerably lower than the recommended level in evidence-based guidelines of 60 min per day, similar to other studies of adolescents in the western world (Ekelund et al., 2012). In boys, a two standard deviation increase in MVPA would have been required in order to reach the recommended 60 min/day and a three standard deviation increase would have been required for girls. Measurement error correction (Mattocks et al., 2007a) approximately doubled standardised beta coefficients and a two SD increase in MVPA at 11 years (to reach an average of 60 min/day in the boys) would translate to predicted increases in executive attention at 13 years of 0.72 SD, for example. This is, however, speculative.

3.2. Study strengths and limitations

This present study has a number of strengths: longitudinal design; large sample size; the broadly socio-economically representative nature of the sample; the objective measurement of the physical activity; adjustment for a range of confounders which address a number of limitations in the current literature. Associations between MVPA and executive function were strongest when the total volume of physical activity was taken into account suggesting that some caution should be taken in interpretation. Additional adjustment to control for type I error was not made due to considerations concerning the balance between type I and type II error (Feise, 2002). One limitation of the present study concerns the use of different assessment tasks at ages 11 and 13. This precluded us from assessing whether MVPA was associated with change in executive function performance over time and instead permitted us to assess whether there were long term associations. While the CDR tasks have been used in previous research, they are not age-corrected standardised tasks and the conclusions which can be drawn are arguably not as convincing as the results of the analysis at age 11. Furthermore, the correlations between task performance at age 11 and age 13 were low, which suggests that different executive/attentional processes were assessed at the different time points. However, the fact that a similar pattern of results were found at 11 and 13 with differing tasks suggests that the effects are robust. Research which employs the same tasks and a longitudinal design would be welcomed in the literature.

Accelerometer assessed PA provides a measure of sedentary time, however this was not addressed in the present analyses. An understanding of the relationship between sedentary behaviour and executive function would add greatly to our understanding of these complex relationships however a lack of knowledge of what participants were doing during sedentary time in the present study (e.g. screen time) precludes conclusions from being drawn.

Furthermore, accelerometry provides a global measure of PA and does not provide information on specific domains such as sports played. Therefore future work should aim to understand these complex relationships.

3.3. Conclusions and implications

Higher levels of free-living moderate–vigorous intensity PA had a beneficial association with attention/executive attention task performance in adolescents, in particular for males. A full RCT is required to understand the nature of this relationship more fully. In particular, further research is needed to examine the dose response required to have a benefit on attention and executive function and to investigate which various executive processes may be differentially affected (Guiney & Machado, 2013). Our findings point to a potentially fruitful avenue of investigation for those who are interested in improving executive function (Diamond & Lee, 2011). Improved attention may also have benefits which extend beyond the academic, for example, risk taking, reward circuits and classroom behaviour (c.f. Hughes, 2011 for a review). Furthermore as executive function is related to developmental and psychological difficulties in children and adults (Micco et al., 2009) and is also related to the extent to which the brain can stem the effects of ageing (Roldán-Tapia et al., 2012), findings which suggest improvements in these areas may have wide reaching impact. If causal, these relationships may also add empirical support to strategies aimed at increasing PA levels in adolescents and may provide parents and policy makers with an additional incentive to implement physical activity programmes. This may in the long term also go some way towards addressing the "pandemic of physical activity" which currently exists (Kohl et al., 2012).

Competing interests

Acknowledgements

Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.mhpa.2013.09.002.

References

APA. (2000). *Diagnostic and statistical manual of mental disorders* (Fourth Text Revision ed.). Washington, DC: American Psychiatric Association.

Biddle, S. J. H., & Asare, M. (2011). Physical activity and mental health in children and adolescents: a review of reviews. *British Journal of Sports Medicine, 45*, 886–895.

Boyd, A., Golding, J., Macleod, J., Lawlor, D. A., Fraser, A., Henderson, J., et al. (2012). Cohort profile: the 'children of the 90s'—the index offspring of the Avon Longitudinal Study of Parents and Children. *International Journal of Epidemiology*, 1–17.

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: inhibition, switching and working memory. *Developmental Neuropsychology, 19*, 273–293.

Callaghan, P. (2004). Exercise: a neglected intervention in mental health care? *Journal of Psychiatric and Mental Health Nursing, 11*, 476–483.

Christopher, M. E., Miyake, A., Keenan, J. M., Pennington, B., DeFries, J. C., Wadsworth, S. J., et al. (2012). Predicting word reading and comprehension with executive function and speed measures across development: a latent variable analysis. *Journal of Experimental Psychology: General, 141*, 470–488.

Colcombe, S., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults. *Psychological Science, 14*, 125–130.

Davis, C. L., Tomporowski, P. D., Boyle, C. A., Waller, J. L., Miller, P. H., Naglieri, J., et al. (2007). Effects of aerobic exercise on overweight children's cognitive functioning: a randomized controlled trial. *Research Quarterly for Exercise and Sport, 78*, 510–519.

Davis, C. L., Tomporowski, P. D., McDowell, J. E., Austin, B. P., Miller, P., Yanasak, N. E., et al. (2011). Exercise improves executive function and achievement and alters brain activation in overweight children: a randomized controlled trial. *Health Psychology, 30*, 91–98.

DeVries, S., VanHirtum, H. W. J. E. M., Bakker, I., Hopman-Rock, M., Hirasing, R. A., & VanMechelen, W. (2009). Validity and reproducibility of motion sensors in youth: a systematic update. *Medicine & Science in Sports & Exercise, 41*, 818–827.

Diamond, A. (2012). Activities and programs that improve children's executive functions. *Current Directions in Psychological Science, 21*, 335–341.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168.

Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science, 333*, 959–964.

Ekelund, U., Luan, J., Sherar, L. B., Esliger, D. W., Griew, P., & Cooper, A. (2012). Moderate to vigorous physical activity and sedentary time and cardiometabolic risk factors in children and adolescents. *The Journal of the American Medical Association, 307*, 704–712.

Etnier, J. L., & Chang, Y. (2009). The effect of physical activity on executive function: a brief commentary on definitions, measurement issues, and the current state of the literature. *Journal of Sport and Exercise Psychology, 31*, 469–483.

Feise, R. J. (2002). Do multiple outcome measures require *p*-value adjustment? *BMC Medical Research Methodology, 2*.

Fisher, A., Boyle, J. M. E., Paton, J. Y., Tomporowski, P. D., Watson, C., McColl, J. H., et al. (2011). Effects of a physical education intervention on cognitive function in young children: randomized controlled pilot study. *BMC Pediatrics, 11*, 97.

Ford, T., Goodman, R., & Meltzer, H. (2003). The British child and adolescent mental health survey 1999: the prevalence of DSM-IV disorders. *Journal of the American Academy of Child and Adolescent Psychiatry, 42*, 1203–1211.

Golding, J., Pembrey, M., Jones, R., & ALSPAC. (2001). ALSPAC – the Avon Longitudinal Study of Parents and Children I. Study methodology. *Paediatric and Perinatal Epidemiology, 15*, 74–87.

Goodman, R. (1997). The strengths and difficulties questionnaire: a research note. *Journal of Child Psychology and Psychiatry, 38*, 581–586.

Goodman, R., Ford, T., Richards, H., Gatward, R., & Meltzer, H. (2000). The development and well-being assessment: description and initial validation of an integrated assessment of child and adolescent psychopathology. *The Journal of Child Psychology and Psychiatry and Allied Disciplines, 41*, 645–655.

Guiney, H., & Machado, L. (2013). Benefits of regular aerobic exercise for executive functioning in healthy populations. *Psychonomic Bulletin & Review, 20*, 73–86.

Hertzog, C., Kramer, A., Wilson, R. S., & Lindenberger, U. (2009). Enrichment effects on adult cognitive development: can the functional capacity of older adults be preserved and enhanced? *Psychological Science in the Public Interest, 9*, 1–65.

Hillman, C. H., Kamijo, K., & Scudder, M. (2011). A review of chronic and acute physical activity participation on neuroelectric measures of brain health and cognition during childhood. *Preventive Medicine, 52*(Suppl. S21–S28).

Hughes, C. (2011). Changes and challenges in 20 years of research into the development of executive functions. *Infant and Child Development, 20*, 251–271.

Janz, K. F. (2006). Physical activity in epidemiology: moving from questionnaire to objective measurement. *British Journal of Sports Medicine, 40*, 191–192.

Kohl, H. W., Craig, C. L., Lambert, E. V., Inoue, S., Alkandari, J. R., Leetongin, G., et al. (2012). The pandemic of physical inactivity: global action for public health. *The Lancet, 380*, 294–305.

Leary, S. D., Ness, A. R., Smith, G. D., Mattocks, C., Deere, K., Blair, S. N., et al. (2008). Physical activity and blood pressure in childhood. *Hypertension, 51*, 92–98.

Manly, T., Anderson, V., Nimmo-Smith, I., Turner, A., Watson, P., & Robertson, I. H. (2001). The differential assessment of children's attention: the Test of Everyday Attention for Children (TEA-Ch), normative sample and ADHD performance. *Journal of Child Psychology and Psychiatry, 42*, 1065–1081.

Manly, T., Robertson, I. H., Anderson, V., & Nimmo-Smith, I. (1998). *The Test of Everyday Attention for Children (TEAch)*. Bury St Edmunds: Thames Valley Test Company.

Mattocks, C., Leary, S., Ness, A., Deere, K., Saunders, J., Kirkby, J., et al. (2007a). Intraindividual variation of objectively measured physical activity in children. *Medicine & Science in Sports & Exercise, 39*, 622–629.

Mattocks, C., Leary, S., Ness, A., Deere, K., Saunders, J., Tilling, K., et al. (2007b). Calibration of an accelerometer during free-living activities in children. *International Journal of Pediatric Obesity, 2*, 218–226.

Mattocks, C., Ness, A., Leary, S., Tilling, K., Blair, S. N., Shied, J., et al. (2008). Use of accelerometers in a large field-based study of children: protocols, design issues, and effects on precision. *Journal of Physical Activity and Health, 5*, S98–S111.

Micco, J. A., Henin, A., Biederman, J., Rosenbaum, J. F., Petty, C., Rindlaub, L. A., et al. (2009). Executive functioning in offspring at risk for depression and anxiety. *Depression and Anxiety, 26*, 780–790.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cognitive Psychology, 41*, 49–100.

Ness, A. R., Leary, S. D., Mattocks, C., Blair, S. N., Reilly, J. J., Wells, J., et al. (2007). Objectively measured physical activity and fat mass in a large cohort of children. *PLoS Medicine, 4*, e97.

OPCS. (1991). *Standard occupational classification*. London: Her Majesty's Stationary Office.

Penpraze, V., Reilly, J. J., MacLean, C., Montgomery, C., Kelly, L. A., Paton, J. Y., et al. (2006). Monitoring of physical activity in young children: how much is enough? *Pediatric Exercise Science, 18*, 483–491.

Physical Activity Guidelines Advisory Committee. (2008). In Department of Health and Human Services (Ed.), *Physical activity guidelines advisory committee report, 2008*. Washington, DC.

Reilly, J. J., Penpraze, V., Hislop, J., Davies, G., Grant, S., & Paton, J. Y. (2008). Objective measurement of physical activity and sedentary behaviour: review with new data. *Archives of Disease in Childhood, 93*, 614–619.

Roldán-Tapia, L., García, J., Cánovas, R., & León, I. (2012). Cognitive reserve, age, and their relation to attentional and executive functions. *Applied Neuropsychology, 19*, 2–8.

Sibley, B. A., & Etnier, J. L. (2003). The relationship between physical activity and cognition in children: a meta-analysis. *Pediatric Exercise Science, 15*, 243–256.

St Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: shifting, updating and inhibition, and working memory. *The Quarterly Journal of Experimental Psychology, 59*, 745–759.

Steele, A., Karmiloff-Smith, A., Cornish, K., & Scerif, G. (2012). The multiple subfunctions of attention: differential developmental gateways to literacy and numeracy. *Child Development, 83*, 2028–2041.

Tanner, J. M. (1986). 1 Normal growth and techniques of growth assessment. *Clinics in Endocrinology and Metabolism, 15*, 411–451.

Tomporowski, P. D., Davis, C. L., Miller, P., & Naglieri, J. (2008). Exercise and children's intelligence, cognition, and academic achievement. *Educational Psychology Review, 20*, 111–131.

Tomporowski, P. D., Lambourne, K., & Okumura, M. (2011). Physical activity interventions and children's mental function: an introduction and overview. *Preventive Medicine, 52*, S3–S9.

Tomporowski, P. D., Naglieri, J. A., & Lambourne, K. (2012). Exercise psychology and children's intelligence. In E. O. Acevedo (Ed.), *Oxford handbook of exercise psychology*. New York: Oxford University Press.

Wass, S. V., Scerif, G., & Johnson, M. H. (2012). Training attentional control and working memory — is younger, better? *Developmental Review, 32*, 360–387.

Wesnes, K. A. (2008). Assessing change in cognitive function in dementia: the relative utilities of the Alzheimer's disease assessment scale — cognitive subscale and the cognitive drug research system. *Neurodegenerative Diseases, 5*, 261–263.

Wesnes, K. A., Ward, T., McGinty, A., & Petrini, O. (2000). The memory enhancing effects of a *Ginkgo biloba/Panax* ginseng combination in healthy middle-aged volunteers. *Psychopharmacology, 152*, 353–361.

Wiles, N., Haase, A., Lawlor, D., Ness, A., & Lewis, G. (2011). Physical activity and depression in adolescents: cross-sectional findings from the ALSPAC cohort. *Social Psychiatry and Psychiatric Epidemiology*, 1–11.

Willcutt, E. G., Sonuga-Barke, E. J. S., Nigg, J. T., & Sergeant, J. A. (2008). Recent developments in neuropsychological models of childhood psychiatric disorders. In T. Banaschewski, & L. A. Rohde (Eds.), *Advanced biological psychiatry: Vol. 24. Biological child psychiatry. Recent trends and developments* (pp. 195–226). Basel: Karger.