Psychological Research (2015) 79:715–728
DOI 10.1007/s00426-014-0612-2

ORIGINAL ARTICLE

The relationship of moderate-to-vigorous physical activity to cognitive processing in adolescents: findings from the ALSPAC birth cohort

Dominika M. Pindus · Robert D. Moore Davis ·
Charles H. Hillman · Stephan Bandelow · Eef Hogervorst ·
Stuart J. H. Biddle · Lauren B. Sherar

Received: 28 March 2014 / Accepted: 13 September 2014 / Published online: 29 October 2014

Abstract The aim of this study was to assess the relations of daily moderate-to-vigorous physical activity (MVPA) to cognitive functions in 15-year-old adolescents from the Avon Longitudinal Study of Parents and Children while controlling for aerobic fitness. A sub-sample of 667 adolescents ($M_{\text{age}} = 15.4 \pm 0.16$ years; 55 % females) who provided valid data on variables of interest, were used in the analyses. MVPA was objectively assessed using an Actigraph GT1M accelerometer and aerobic fitness was expressed as physical work capacity at the heart rate of 170 beats per minute from a cycle ergometer test. A computerized stop-signal task was used to measure mean reaction time (RT) and standard deviation of RT, as indicators of cognitive processing speed and variability during an attention and inhibitory control task. MVPA was not significantly related to cognitive processing speed or variability of cognitive performance in hierarchical linear regression models. In simple regression models, aerobic fitness was negatively related to mean RT on the simple go condition. Our results suggest that aerobic fitness, but not MVPA, was associated with cognitive processing speed under less cognitively demanding task conditions. The results thus indicate a potential global effect of aerobic fitness on cognitive functions in adolescents but this may differ depending on the specific task characteristics.

Introduction

The adverse physical health consequences of physical inactivity in youth are well understood (Gutin & Owens, 2011; Hallal, Victora, Azevedo, & Wells, 2006; Iannotti, Kogan, Janssen, & Boyce, 2009). However, the relations of daily (i.e. accumulated throughout the entire day) physical activity to cognitive functions in youth are less well understood. Thus far, the majority of research has focused on aerobic fitness as a proxy for regular physical activity. The results of these studies indicate that relative to lower fit children, higher fit children modulate attention more efficiently in relation to task demands (Pontifex et al., 2011); demonstrate greater inhibitory control over pre-potent responses (Chaddock et al., 2012a); and are less affected by task difficulty and conditional manipulations (Voss et al., 2011). That is, higher fit children demonstrate greater performance on tasks requiring cognitive control, particularly for tasks that modulate attentional demands. Cognitive control (also known as executive control or executive function) refers to higher order computational processes underlying perception, memory and action, which serve to regulate and optimize goal-directed behaviors (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Norman & Shallice, 1986; Meyer & Kieras, 1997). Its core processes include: planning and mental flexibility, working memory and

D. M. Pindus (✉) · S. Bandelow · E. Hogervorst ·
S. J. H. Biddle · L. B. Sherar
School of Sport, Exercise and Health Sciences, Loughborough
University, Loughborough, LE 11 3TU, UK
e-mail: D.M.Pindus@lboro.ac.uk

D. M. Pindus · R. D. M. Davis · C. H. Hillman
Department of Kinesiology and Community Health, University
of Illinois at Urbana-Champaign, 317 Freer Hall, 906 South
Goodwin Avenue, Urbana, IL 61801, USA

S. J. H. Biddle
The NIHR Leicester-Loughborough Diet, Lifestyle and Physical
Activity Biomedical Research Unit, Leicester, UK

Present Address:
S. J. H. Biddle
Institute of Sport, Exercise & Active Living (ISEAL),
Victoria University, Melbourne, Australia

inhibition/interference control (Braver, Paxton, Locke, & Barch, 2009; Luna & Sweeney, 2004; Miller & Cohen, 2001). Cognitive control functions have been identified as an important target for early intervention (Diamond & Lee, 2011) due to their positive associations with children's academic achievement (Monette, Bigras, & Guay, 2011; St Clair-Thompson & Gathercole, 2006; Best, Miller, & Naglieri, 2011), as well as their ability to predict future health, socio-economic status, and income (Moffitt et al., 2011). Therefore, research demonstrating the benefit of aerobic fitness for cognitive development suggests that higher aerobic fitness may prime children and adolescents' chances for life success in a variety of domains. Although these studies have helped elucidate the benefits of aerobic fitness on neurocognitive development, a child's aerobic fitness is in part genetically determined (Bouchard, Blair, & Haskell, 2012), and only moderately related to daily physical activity ($0.15 \leq r$'s ≤ 0.47 across studies; Dencker & Andersen, 2011). Consequently, the relation of daily physical activity to children's (and adolescents') neurocognitive development remains unclear.

A better understanding of the relation between physical activity and cognitive development can be gained from intervention studies, which test the influence of regular aerobic exercise on children's cognitive function (Chaddock-Heyman et al., 2013; Davis et al., 2011; Kamijo et al., 2011). While only a few randomized controlled trials have been conducted, the results are encouraging, demonstrating that involvement in daily aerobic exercise ranging from 3 to 9 months can lead to significant improvements in children's cognitive function. Specifically, improvements on tasks requiring planning and mental flexibility (Davis et al., 2011), working memory (Kamijo et al., 2011) and inhibition/interference control (Chaddock-Heyman et al., 2013) have been observed. Thus, similar to cross-sectional analyses of aerobic fitness, physical activity interventions of moderate-to-vigorous intensity also appear to benefit cognitive control functions during development. Preliminary evidence further suggests a dose–response relation, with greater exercise durations leading to greater improvements in attention and cognitive control (Davis et al., 2011).

Intervening across the whole day to increase overall time in moderate-to-vigorous physical activity (MVPA) may initially be a more realistic policy goal than implementing aerobic exercise interventions, which are not easily incorporated into the school day. The need for such an approach has recently been voiced in the United States, where integrating MVPA across the whole school day (including active transport, active breaks, recess and increases in high quality physical education) is advocated (National Research Council, 2013). Its rationale stems from evidence that small increases in objectively measured MVPA during recess, the introduction of active breaks into curriculum, and mandatory physical education can add up to 47 min of daily MVPA (Bassett et al., 2013). Thus, bringing the majority of children closer to the recommended daily 60 min of MVPA (Department of Health, 2011; The US Department of Health and Human Services, 2008; National Research Council, 2013). As such, studies assessing the relation between daily accumulation of MVPA and cognition in developing populations are warranted. Furthermore, to our knowledge, no studies have assessed the relation of daily MVPA, while controlling for aerobic fitness. This is important as the driving hypothesis within the field of physical activity and cognition is that the effects of MVPA on cognitive performance are mediated by aerobic fitness (Colcombe & Kramer, 2003; Etnier, 2006). The tenets of this hypothesis are yet to be confirmed (Etnier, 2006). Thus, it remains unclear in children and adolescents whether increased aerobic fitness is necessary for the associations between MVPA and cognition to emerge. We, therefore, sought to evaluate whether MVPA accumulated throughout the day would uniquely contribute to cognitive performance beyond aerobic fitness. More specifically, we sought to evaluate the relation of daily MVPA (assessed by accelerometer) to cognitive processing in adolescents drawn from the Avon Longitudinal Study of Parents and Children (ALSPAC).

Thus far, most studies examining aerobic fitness and cognition have used measures of central tendency (i.e., mean RT and accuracy) as indicators of cognitive performance. However, fluctuations in cognitive performance as indexed by the standard deviation of reaction time (SDRT) may provide a useful complementary measure of cognitive stability, as increases in task difficulty have been associated with increased performance variability across the lifespan (West, Murphy, Armilio, Craik, & Stuss, 2002; Walhovd et al., 2011). Although only two studies have assessed response variability in relation to aerobic fitness, the results of both studies suggest that more aerobically fit children not only respond more accurately, but also more consistently during conditions requiring the up-regulation of cognitive control (Moore et al., 2013; Wu et al., 2011). To date, there are no studies evaluating response variability as a function of daily MVPA in developing populations. Accordingly, the study also sought to inspect the association between accelerometer-assessed daily MVPA and response variability using a task that taps cognitive control.

Attention and inhibitory control were assessed using a stop-signal task, which consists of two conditions that vary the degree to which they engage cognitive control (Logan, Cowan, & Davis, 1984; Verbruggen & Logan, 2008). Based on previous research demonstrating a positive relation between regular aerobic exercise and cognitive performance during more cognitively demanding conditions, we hypothesized that adolescents who engage in greater daily MVPA would show better performance (expressed as shorter and less variable reaction times) for the stop-signal condition, which requires the up-regulation of attention and cognitive control.

Methods

ALSPAC study population

Avon Longitudinal Study of Parents and Children is a prospective birth cohort study of parents and children from the Bristol area of the UK (Boyd et al., 2012). A detailed description of the study together with information on attrition and study compliance is available elsewhere (Mahmood et al., 2013). Briefly, all pregnant women from the former County of Avon in the UK (South West region) whose expected delivery date fell between 1st of April 1991 and 31st of December 1992 were eligible and enrolled in the study. The total ALSPAC sample comprised of 15,458 fetuses, 14,775 were live births and 14,701 were alive at 1 year of age. Data were routinely collected with questionnaires and ten percent of children were also invited to attend research clinics ("Children in Focus"), where more in-depth physical and psychological assessments were performed. The current study is based on a sub-sample of adolescents attending research clinics at age 15 years. Please note that the study website contains details of all the data that is available through a fully searchable data dictionary (Avon Longitudinal Study of Parents and Children. Data dictionary, 2014).

Participants

In total 5,515 adolescents contributed data to the research clinics at 15 years of age (approximately 37.5 % of the core ALSPAC cohort). Figure 1 shows the number of participants included in the study. To be included in the analyses, participants were required to have a valid accelerometer file [i.e., spurious data files were excluded using similar methods as reported in Sherar et al., 2011; only files with a minimum of 10 h of accelerometer wear per day on at least 4 days were included; $n = 1{,}604$, 54 %] and cognitive data (i.e., RT within three standard deviations of the mean, and overall accuracy greater than 50 % on go and stop-signal conditions). The sample was further restricted to adolescents with: (1) the full scale intelligence score of at least 85 on the Wechsler Abbreviated Scale of Intelligence (WASI; Oldfield, 1971), (2) valid aerobic fitness data, (3) no clinical diagnosis of Attention Deficit Hyperactivity Disorder (ADHD), (4) no history of epilepsy or meningitis, as reported by parents, (5) English as a first language, and (6) no special provisions as indicated by Special Education Needs status. Socio-economic status was estimated based on maternal education yielding four categories: '1' = GCSE D–F/CSE/none, technical qualifications; '2' = O-Level/GSCE A–C; '3' = A-Level/ Vocational Qualification; and '4' = university degree (Gutman & Feinstein, 2008). To minimize variance associated with cognitive maturation, participants' age was restricted to 15 years. Seven participants were excluded due to the lack of anthropometric data (body weight)

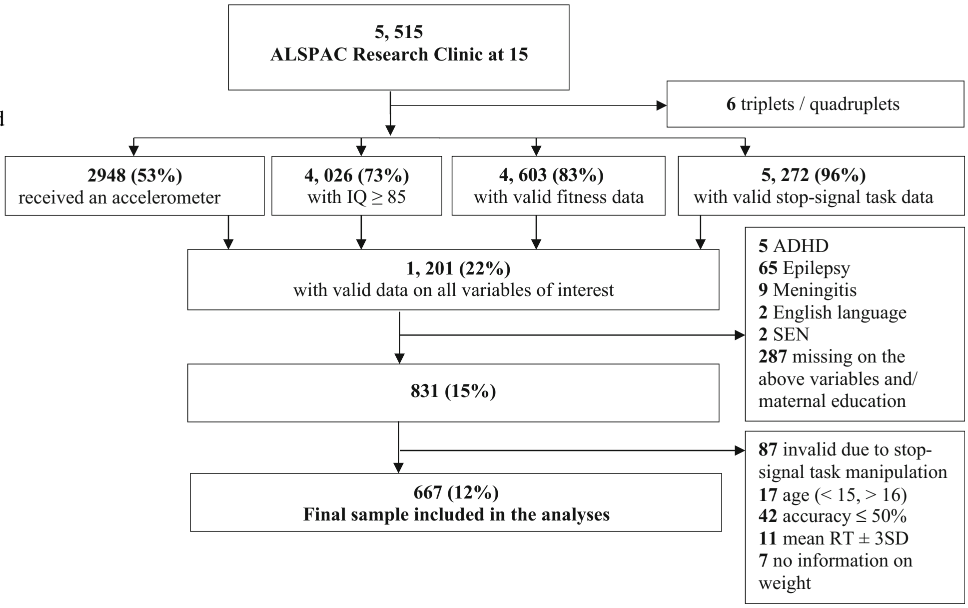

Fig. 1 Number of participants from the Avon Longitudinal Study of Parents and Children (ALSPAC) research clinic at 15 years excluded from the study on physical activity and cognitive control. *RT* reaction time, *ADHD* attention deficit and hyperactivity disorder, *SEN* special educational needs

required to compute weight-adjusted values of aerobic fitness. The final sample included in the analyses comprised of 667 participants (12 %; Fig. 1). The majority of adolescents ($n = 560$, 83.9 %) had normal or corrected-to-normal vision; 97 participants who reported ever wearing glasses or contact lenses did not use vision correction during testing. Information on vision was not available for 10 participants.

Measures

Anthropometrics and body composition

Height was measured to the nearest millimeter using a Harpenden stadiometer (Holtain Ltd., Crosswell, UK) and weight to the nearest 0.1 kg using a calibrated Tanita scale (THF 300GS body fat analyser; Tanita UK Ltd, Yewsley, Middlesex, UK). Total body fat mass was measured using Dual X-ray Absorptiometry (DXA; GE Healthcare, Bedford, UK). Percent total body fat mass (TBFM) was calculated as 100 × total body fat mass/body mass (total bone mass + total lean mass + total fat mass; Ong et al., 2009).

Cognitive task

Attention and inhibitory control were measured with a stop-signal task (Logan, 1994; Logan et al., 1984). The stop-signal task consisted of two conditions: a go condition and a stop-signal condition. The go condition is a dual choice reaction time (RT) task, which requires a response to a visual stimulus (either a letter X or a letter O) appearing focally on the computer screen. Responses to the stimuli were mapped onto two response boxes marked X and O. Participants responded with a right index finger to an X and with a left index finger to an O. The stimuli X and O were equiprobable and were presented at random. Participants were presented with 30 trials and instructed to respond as quickly as possible. For the ‘go’ condition, a fixation point was presented focally for 500 ms, followed by a stimulus (X or O) presented for 1,000 ms, followed by a blank screen presented for 500 ms and another fixation point. Thus, the inter-stimulus interval was equal to 1,000 ms. The stop-signal condition consisted of 64 go and 32 (33 %) randomly interspersed stop-signal trials. Participants were instructed to withhold an already initiated response if they heard an auditory cue (a tone) presented at varied delays relative to the go signal. Two (short and long) equiprobable stop-signal delays (SSDs) were calculated for each participant. SSDs were expressed as the difference between participant’s mean RT on the go condition and either a 150 ms (i.e. long SSD = MRT − 150 ms) and 250 ms (i.e. short SSD = MRT − 250 ms) subtrahend. These parameters were successfully employed in previous research with ALSPAC cohorts (Handley, Capon, Beveriddge, Dennis, & Evans, 2004; Kothari, Solmi, Treasure, & Micali, 2013). The objective of varied SSDs is to bias the probability of inhibition towards chance (Logan et al., 1984). However, due to high probabilities of inhibition (87.8 %) observed under these task conditions, the subtrahends used to calculate SSDs were adjusted, leading to inconsistent task manipulation across participants. First, smaller subtrahends (50 and 150 ms to derive long and short SSDs, respectively) were used. This manipulation resulted in even higher probabilities of response inhibition (91.7 %). Therefore, the subtrahends were further increased. Subsequently two sets of subtrahends were tested: (1) 250 and 350 ms, and (2) 250 and 400 ms, for long and short SSDs, respectively. The latter adjustment resulted in the lowest probabilities of response inhibition (83.9 %) and was, therefore, retained for further testing. Only participants who received either the original or the final set of subtrahends (in total 88.7 % of those who contributed the data to a computer session) were included in the current analyses. Consequently, a sample split based on a subtrahend set used to calculate long and short SSDs was deemed necessary and analyses were carried out on two groups. In group one, 150 ms was used to calculate longer and 250 ms to calculate shorter SSDs. In group two, 250 and 400 ms subtrahends were used, for longer and shorter SSDs, respectively. Thus, participants in group one received on average longer SSDs, relative to the go signal, than participants in group two. If the resulting delay was negative, go and stop signals were presented concurrently. Approximately 50 % of participants in group two received a stop signal concurrently with a go signal on 50 % of stop-signal trials, which resulted in quantitatively and qualitatively different task condition than for group one (further justifying the sample split).

Accelerometry

The details of accelerometer deployment in ALSPAC have been previously described (Mattocks et al., 2007; Mattocks et al., 2008). All adolescents attending research clinics at 15 years were asked to wear an Actigraph GT1M accelerometer (Actigraph LLC, Fort Walton Beach, FL, USA) around their waist, over the right hip for seven consecutive days. Data were recorded as accelerometer counts and averaged across a 60 s interval (epoch) to create counts per minute (CPM). Raw Actigraph data files were re-processed in 2012 to derive outcome variables using a custom made data reduction software (KineSoft, ver 3.3.67, Loughborough, UK; http://www.kinesoft.org). Non-wear time was defined as 60 min of consecutive zero counts, allowing for 2 min of non-zero interruptions (Troiano et al., 2008). The variables of interest were: MVPA, defined as ≥1,963 CPM (Freedson, Melanson, & Sirard, 1998).

Aerobic fitness

Aerobic fitness was measured with a three stage sub-maximal test using an electronically braked cycle ergometer (Lode Rechor P, Groningen, The Netherlands). Workload was increased every 3 min (20, 40 and 60 W), when measures of a heart rate (HR) were taken using a chest mounted HR monitor (Polar S180). Aerobic fitness was expressed as predicted physical working capacity at the heart rate of 170 beats per minute (bpm; PWC-170) relative to adolescent's body weight (kg). PWC-170 was estimated with linear regression models based on the mean HR at the last 30 s of each stage. The data were included in the analyses if the HR was at least 80 and 150 bpm, at the end of the first and the last stage, respectively. These criteria were applied to ensure that the physiological response to the workload was achieved (Lawlor et al., 2008). Weight-adjusted PWC-170 based on a 3-min protocol has been shown to have good convergent validity based on the correlations with maximal oxygen consumption ($r = 0.56$, $p \leq 0.01$; Bland et al., 2012).

Statistical analyses

All analyses were conducted using IBM SPSS Statistics software version 20.0.1. An alpha level of 0.05 was used to define statistical significance. Data were screened for normality and outliers. The differences in demographic, physical activity variables, mean RT and SDRT between the study samples and cases excluded from the analyses were compared using independent-sample *t* tests, analyses of covariance (adjusting for accelerometer wear time) and Chi-square statistics, where appropriate. Group differences on all variables of interest were also inspected. Further, intra-individual differences in task performance on stop signal relative to go condition were assessed with related samples Wilcoxon signed-rank test. The relation between mean RT, SDRT and demographic variables (age, sex, maternal education), aerobic fitness, percent total body fat mass, BMI and IQ were inspected using Spearman's rank order correlation coefficients. The relations of daily MVPA (controlling for accelerometer wear time), aerobic fitness, mean RT and SDRT were explored with partial and bivariate correlations, for MVPA and aerobic fitness, respectively. Multiple hierarchical regression models were employed to examine the associations between daily minutes spent in MVPA and mean RT and SDRT for the go and stop-signal conditions controlling for aerobic fitness. Four models were tested: two models for each of the cognitive variables (go mean RT and go SDRT), for each of the samples (group one with on average longer SSDs and group two with on average shorter SSDs). In all models, aerobic fitness was entered in step one, confounders which were significantly associated with the outcome in zero-order correlations were entered in step two, and MVPA was entered in step three. In models with SDRT, mean RT was entered in the first step, followed by aerobic fitness in step two, remaining confounders were entered in step three, and MVPA in step four. Based on bivariate correlations, the direct relations of aerobic fitness to mean go RT and SDRT were also tested with hierarchical regression models; aerobic fitness was entered in step one and relevant confounders in step two. All models were assessed for multi-collinearity and distributional normality of error terms. Where appropriate data were log transformed.

Results

Descriptive characteristics

Adherence

1,604 (54 %) of the participants had four or more valid days of accelerometer data and thus were retained for analyses. Of these, 12, 20, 28 and 40 % provided 4, 5, 6 and 7 valid days of data, respectively. The remaining participants in the current study had higher IQ, higher CPM, wear time, and daily MVPA than those who had fewer than four valid days of wear time.

Group differences

Tables 1 and 2 present descriptive statistics for group one (i.e., those who received longer SSDs) and group two (i.e. those who received shorter SSDs), respectively. Groups did not differ on demographic or anthropometric characteristics ($p > 0.25$; Table 2); however, adolescents included in group one had significantly higher IQ ($\Delta M = 1.97$, $\mathrm{SE} = 0.75$, $t(664) = 2.64$, $p = 0.01$), aerobic fitness ($\Delta M = 0.15$, $\mathrm{SE} = 0.05$, $t(665) = 3.11$, $p = 0.002$), time spent in light physical activity ($\Delta M = 12.4$, $\mathrm{SD} = 4.57$, $F(1, 664) = 7.42$, $p = 0.007$; Table 2), but lower sedentary time ($\Delta M = -13.1$, $\mathrm{SE} = 5.53$, $F(1, 664) = 5.59$, $p = 0.018$). No further group differences were noted (p's > 0.26).

Sex differences

No sex differences were noted for age, IQ or socio-economic status in group one or two (p's > 0.07; Tables 1, 2). Boys in group one were significantly taller ($\Delta M = 9.95$, $\mathrm{SE} = 0.68$, $t(355) = 14.6$, $p < 0.001$), heavier ($\Delta M = 5.14$, $\mathrm{SE} = 1.09$, $t(355) = 4.73$, $p < 0.001$) and more aerobically fit ($\Delta M = 0.82$, $\mathrm{SE} = 0.05$, $t(318) = 16.1$,

Table 1 Descriptive characteristics of 15-year-old ALSPAC participants who received stop signals at longer delays (group one)

	Males ($n = 166$, 46.5 %)		Females ($n = 191$, 53.5 %)		Overall sample ($n = 357$)	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Age (years)	15.4 (0.16)	[15.0–15.9]	15.4 (0.17)	[15.0–15.9]	15.4 (0.17)	[15.0–15.9]
Height (cm)	174.4 (7.0)**	[151.5–192.3]	164.5 (5.8)	[146.8–177.3]	169.1 (8.1)	[146.8–192.3]
Weight (kg)	63.0 (11.2)**	[37.6–111]	57.8 (9.3)	[39.2–95.5]	60.2 (10.5)	[37.6–111.0]
BMI (kg/m^2)	20.6 (3.02)*	[14.7–33.1]	21.3 (3.0)	[14.9–33.0]	21.0 (3.0)	[14.7–33.1]
% OW/OB	15.7		17.8		16.8	
% TBFM	16.9 (8.28)**	[5.9–42]	30.1 (7.5)	[13.2–50.2]	24.0 (10.3)	[5.9–50.2]
Maternal education						
University (%)	19.3		23		21.3	
Ethnicity (% non-white)	2.4		3.1		2.9	
IQ	102.1 (10.92)	[85–131]	101.4 (10.2)	[85–129]	101.7 (10.5)	[85–131]
AEF (W/kg)	2.54 (0.52)**	[1.2–4]	1.72 (0.42)	[0.92–3.3]	2.10 (0.62)	[0.92–4.0]
CPM	490.2 (197.2)*	[147.6–1,729.9]	399.9 (145.4)	[100.1–962.8]	441.9 (177.0)	[100.1–1,729.9]
Wear time (min)	829.0 (54.8)	[674.6–952.6]	822.8 (60.7)	[676.5–1,031.2]	825.7 (58.1)	[674.6–1,031.2]
Sedentary time (min)	476.4 (81.5)**	[161–671]	499.2 (79.7)	[298–728.4]	488.6 (81.2)	[161.0–728.4]
LPA (min)	288.4 (65.2)	[146.1–466.2]	275.0 (65.0)	[92.9–471.2]	281.2 (65.3)	[92.9–471.2]
MVPA (min)	64.2 (33.4)**	[12–280.2]	48.6 (24.1)	[8.17–139.3]	55.8 (29.8)	[8.2–280.2]

OW/OB overweight/obese, *TBFM* total body fat mass, *IQ* intelligence quotient, *AEF* aerobic fitness, *CPM* accelerometer counts per minute, *LPA* light physical activity ($100 < \text{LPA} < 1{,}963$ CPM), *MVPA* moderate-to-vigorous physical activity ($\geq 1{,}963$ CPM)

* $p < 0.05$, ** $p \leq 0.001$, † $0.05 < p < 0.1$

$p < 0.001$) than girls in group one. In each group, girls had significantly higher BMI (group one: $\Delta M = 0.72$, $\text{SE} = 0.32$, $t(355) = 2.23$, $p = 0.026$; group two: $\Delta M = 1.18$, $\text{SE} = 0.36$, $t(308) = 3.32$, $p = 0.001$) and percent total body fat mass (group one: $\Delta M = 13.24$, $\text{SE} = 0.84$, $t(354) = 15.8$, $p < 0.001$; group two: $\Delta M = 14.6$, $\text{SE} = 0.88$, $t(308) = 16.6$, $p < 0.001$) than boys. In group one, no sex differences in accelerometer wear time were noted ($p = 0.32$); however, boys in group one accrued more CPM ($\Delta M = 90.3$, $\text{SE} = 18.2$, $t(300) = 4.86$, $p < 0.001$), daily MVPA ($\Delta M = 15.2$ min, $\text{SE} = 3.04$, $F(1, 354) = 25.1$, $p < 0.001$) and less sedentary time ($\Delta M = -26.2$ min, $\text{SE} = 7.87$, $F(1, 354) = 11.1$, $p = 0.001$) than girls. Similar sex differences were noted in group two (CPM: $\Delta M = 98.7$, $\text{SE} = 16.8$, $t(236) = 5.6$, $p < 0.001$; accelerometer wear time: $p = 0.75$; MVPA: $\Delta M = 16.5$ min, $\text{SE} = 2.93$, $F(1, 307) = 31.8$, $p < 0.001$; light physical activity: $\Delta M = 15.4$ min, $\text{SE} = 6.36$, $F(1, 307) = 5.91$, $p = 0.016$; sedentary time: $\Delta M = -32.0$ min, $\text{SE} = 7.44$, $F(1, 307) = 18.5$, $p < 0.001$; Table 2).

Task performance

No differences in cognitive performance were noted between adolescents whose data on vision were either missing or who reported ever wearing glasses or contact lenses but did not do so during testing ($p > 0.32$). All task performance data are summarized in Table 3. The inspection of accuracy scores on stop-signal trials revealed mean accuracies of 88.8 % (Mdn = 90.6 %) and 83.8 % (Mdn = 87.5 %) in groups one and two, respectively. These values are significantly higher than a chance level performance and above the usual cutoff used to ascertain the validity of stop-signal manipulation (Band et al., 2003; Logan, 1994). Further inspection of the mean SSDs indicated that on average in group one a stop signal was presented at 157.5 ms (SD = 53.2 ms) or 257.5 ms (SD = 53.2 ms; for a shorter and longer delay, respectively) relative to a go signal; in group two, the mean SSDs were 30.5 ms (SD = 42.9 ms) and 165.9 ms (SD = 57.4 ms). Given the mean response latencies to a go signal of 516.8 ms (59.2; group one) and 603.3 ms (SD = 64.2 ms; group two), participants had on average at least 259.3 ms (group one) and 437.4 ms (group two) to override their initial response. Thus, the parameter manipulations failed to reduce the high probability of behavioral inhibition and yielded the overall probability of inhibiting the response of 86.4 %. This precluded a valid computation of stop-signal reaction time, which requires a chance level accuracy on stop-signal trials (Logan et al., 1984; Band et al., 2003). Consequently, task manipulation aimed to elicit behavioral inhibition was deemed invalid and further analyses focused on go mean RT and SDRT on

Table 2 Descriptive characteristics of 15-year-old ALSPAC participants who received stop signals at shorter delays (group two)

	Males (n = 132, 42.6 %)		Females (n = 178, 57.4 %)		Overall sample (n = 310)		Mean difference (Gr1–Gr2)
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	
Age (years)	15.4 (0.16)	[15.1–16.0]	15.4 (0.15)	[15.1–16.0]	15.4 (0.16)	[15.1–16.0]	−0.00 (0.01)
Height (cm)	174.8 (7.1)**	[155.3–196.0]	164.6 (5.8)	[150.0–181.2]	168.9 (8.1)	[150.0–196.0]	0.16 (0.63)
Weight (kg)	63.0 (10.3)**	[42–93.8]	59.0 (10.0)	[35.2–113.7]	60.7 (10.3)	[35.2–113.7]	−0.51 (0.81)
BMI (kg/m^2)	20.6 (2.7)**	[15.3–28.9]	21.8 (3.3)	[14.9–39.0]	21.2 (3.1)	[14.9–39.0]	−0.24 (0.24)
% OW/OB	13.7		18.5		16.4		
% TBFM	16.5 (7.9)**	[5.1–40.5]	31.1 (7.5)	[14.1–54.7]	24.9 (10.5)	[5.1–54.7]	−0.93 (0.81)
Maternal education							
% University	24.2		22.5			23.2	
Ethnicity							
% Non-white	2.4		0.6			1.2	
IQ	100.8 (8.4)	[85–127]	99.0 (9.1)	[85–126]	99.8 (8.8)	[85–127]	1.97 (0.75)*
AEF (W/kg)	2.39 (0.53)**	[1.24–4.0)	1.63 (0.41)	[0.80–3.3]	1.9 (0.60)	[0.80–4.0]	0.15 (0.05)*
CPM	484.3 (168.1)**	[160.1–1,008.2]	385.6 (128.6)	[113.2–931.3]	427.6 (154.4)	[113.2–1,008.2]	14.2 (13.0)
Wear time (min)	828.4 (72.1)	[672–1,302.7]	826.0 (60.0)	[698.6–1,042.6]	827.0 (65.3)	[672.0–1,302.7]	−1.32 (4.8)
Sedentary time (min)	484.9 (82.6)**	[261.7–896.5]	515.4 (71.1)	[328.8–751.1]	502.4 (77.6)	[261.7–896.5]	−13.1 (5.5)^{a,*}
LPA (min)	278.4 (60.5)*	[140.8–452.7]	262.3 (56.2)	[134.3–479.5]	269.2 (58.5)	[134.3–479.5]	12.4 (4.6)^{a,*}
MVPA (min)	64.9 (30.5)**	[2.43–152.2]	48.2 (23.0)	[6.43–130.4]	55.3 (27.7)	[2.4–152.2]	0.63 (2.2)^{a}

OW/OB overweight/obese, *TBFM* total body fat mass, *IQ* intelligence quotient, *AEF* aerobic fitness, *CPM* accelerometer counts per minute, *LPA* light physical activity (100 < LPA < 1,963 CPM), *MVPA* moderate-to-vigorous physical activity (≥1,963 CPM)

* $p < 0.05$, ** $p \leq 0.001$

[a] Adjusted for wear time

Table 3 Performance of 15-year-old ALSPAC participants on the stop-signal task

	Group 1			Group 2		
	SSD = MRT − 150/−250 ms			SSD = MRT − 250/−400 ms		
	Mean (SD)	Min	Max	Mean (SD)	Min	Max
Go block						
MRT (ms)	407.5 (53.2)	296.6	566.0	415.9 (57.4)	279.1	586.9
SDRT (ms)	88.0 (28.7)	37.9	192.7	88.5 (27.4)	41.5	180.8
Accuracy (%)	90.3 (10.5)*	53.3	100	86.1 (11.9)	53.3	100
Stop-signal block						
Go MRT (ms)	516.8 (59.2)*	360.0	693.0	603.3 (64.2)	393.7	799.1
SDRT (ms)	102.7 (21.7)*	56.7	187.2	119.0 (19.7)	62.3	177.4
SSD short (ms)	157.5 (53.2)*	46.7	316.0	30.5 (42.9)	0.0	186.9
SSD long (ms)	257.5 (53.2)*	146.7	416.0	165.9 (57.4)	29.1	336.9
Overall accuracy (%)	86.2 (10.6)*	53.1	100	78.8 (10.3)	51.0	97.9
Accuracy (stop-signal trials; %)	88.8 (10.8)*	40.6	100	83.8 (13.0)	31.2	100
Accuracy (go trials; %)	84.8 (16.5)*	29.7	100	76.3 (16.6)	31.2	100

SSD stop-signal delay, *MRT* mean reaction time, *SDRT* standard deviation of the reaction time

* Mean difference between groups significant at: $p < 0.001$

go and stop-signal conditions (Tables 4, 5). However, to provide contextual information, performance characteristics of the samples on accuracy measures and their associations with MVPA and aerobic fitness are also presented.

In general, participants had significantly longer mean go RTs on stop signal relative to go condition (group one: $Z = -16.3$, $p < 0.001$, $r = 0.61$; group two: $Z = -15.3$, $p < 0.001$, $r = 0.61$). However, their performance on a

Table 4 Spearman's rank order correlations between the performance of ALSPAC adolescents on stop-signal task, demographic characteristics, cognitive and anthropometric variables and aerobic fitness (group one)

	Age	Sex	SES	IQ	AEF	%TBFM	BMI
Go condition							
MRT (ms)	−0.06	0.09†	−0.12*	−0.19***	−0.06	0.13**	0.10†
SDRT (ms)	−0.06	0.04	−0.05	−0.05	−0.02	0.01	−0.01
Stop-signal condition							
Go MRT (ms)	−0.02	0.09†	−0.11*	−0.09†	−0.02	0.10†	0.11*
Go SDRT (ms)	−0.05	−0.07	−0.10†	−0.12*	0.06	−0.01	0.04

SES socio-economic status, *IQ* intelligence quotient, *AEF* aerobic fitness, *TBFM* total body fat mass, *MRT* mean reaction time, *SDRT* standard deviation of the reaction time

* $p < 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, † $0.051 > p > 0.074$

Table 5 Spearman's rank order correlations between the performance of ALSPAC adolescents on stop-signal task, demographic characteristics, cognitive and anthropometric variables and aerobic fitness (group two)

	Age	Sex	SES	IQ	AEF	%TBFM	BMI
Go condition							
MRT (ms)	−0.04	0.15**	−0.01	−0.09	−0.15**	0.15**	0.07
SDRT (ms)	−0.07	0.11†	−0.01	0.01	−0.12*	0.12*	0.09
Stop-signal condition							
Go MRT (ms)	0.05	0.13*	0.01	−0.12*	−0.09	0.13*	0.06
SDRT (ms)	−0.02	0.05	−0.03	−0.05	−0.04	0.06	0.02

SES socio-economic status, *IQ* intelligence quotient, *AEF* aerobic fitness, *TBFM* total body fat mass, *MRT* mean reaction time, *SDRT* standard deviation of the reaction time

** $p \leq 0.01$, * $p < 0.05$, † $p = 0.06$

stop signal relative to go condition was also more variable as indicated by larger SDRTs (group one: $Z = -8.77$, $p < 0.001$, $r = 0.33$; group two: $Z = -12.33$, $p < 0.001$, $r = 0.49$). Relative to group two (i.e., adolescents who received shorter SSDs), participants in group one (i.e., those who received longer SSDs) responded more quickly ($U = 93{,}142$, $p < 0.001$, $r = 0.59$) and more consistently ($U = 79{,}270$, $p < 0.001$, $r = 0.37$) during the stop-signal condition. No significant group differences in performance on go condition were noted (mean RT: $U = 59{,}685.5$; SDRT: $U = 56{,}065$, $ps \geq 0.08$).

Associations between daily MVPA, aerobic fitness and cognitive processing

MVPA was moderately related to aerobic fitness in both groups: group one $pr = 0.36$, group two: $pr = 0.43$, $ps < 0.001$). Consistent with the predictions, no significant associations were noted between daily minutes spent in MVPA (log transformed) and either mean RT[1] (group one: $pr = 0.02$; group two: $pr = -0.01$, $ps > 0.76$), SDRT (group one: $pr = -0.08$; group two: $pr = -0.06$, $ps > 0.11$) or accuracy (group one: $pr = 0.00$, group two: $pr = 0.02$, $ps \geq 0.76$) during the go condition. Contrary to our predictions, however, MVPA was not significantly related to mean RT (group one: $pr = -0.04$; group two: $pr = -0.01$, $ps > 0.44$), SDRT (group one: $pr = -0.09$; group two: $pr = -0.06$, $ps \geq 0.07$) or accuracy[2] (group one: $pr = -0.06$, group two: $pr = -0.08$, $ps \geq 0.15$) during the stop-signal condition (go trials).

---

[1] In partial correlation analyses with MVPA all cognitive variables except for accuracy were log transformed.

[2] Due to the limitations of task manipulation and its effects on accuracy measures, our hypotheses focused on the speed and not accuracy of performance. However, we provide further details of the analyses for accuracy measures for interested readers. The analyses of the accuracy data for the stop-signal trials revealed a significant correlation in group one for MVPA (log transformed; $pr = 0.12$, $p = 0.02$; accounting for accelerometer wear time). However, this association was not significant in a generalized linear model ($B = 0.00$, SE $= 0.00$, Wald's $\chi^2_{(1, N = 357)} = 0.04$, $p = 0.84$, LR $\chi^2_{(5, N = 357)} = 8.23$, $p = 0.14$; accounting for sex, maternal education, aerobic fitness and wear time, $ps \geq 0.18$). The associations were tested using generalized linear models for binary and event data with a probit link function. Accuracy data were expressed as the number of responses correct within a set of 32 stop-signal trials. No further significant correlations between MVPA ($p = 0.64$, group two) or aerobic fitness ($ps \geq 0.06$) and accuracy on stop-signal trials were observed.

Table 6 A summary of regression analyses for variables predicting mean RT and response variability on stop-signal task (group two)

Step/predictors	Mean go MRT		*t*	Step/predictors	Mean go SDRT		*t*
	ΔR^2	β			ΔR^2	β	
Step 1	0.026*			Step 1	0.15**		
AEF (W/kg)		−0.16	2.88*	Mean go RT		0.38	7.28**
Step 2	0.01			Step 2	0.00		
AEF (W/kg)		−0.07	0.84	Mean go RT		0.37	7.00**
Sex		0.07	0.92	AEF (W/kg)		−0.06	1.18
% TBFM		0.07	0.79	Step 3			
				Mean go RT	0.00	0.37	6.96**
				AEF (W/kg)		−0.06	0.91
				Sex		0.00	0.02

AEF aerobic fitness, *TBFM* total body fat mass, *MRT* mean reaction time, *SDRT* standard deviation of the reaction time

* $p < 0.01$, ** $p < 0.001$

Interestingly, in group two aerobic fitness was inversely related to mean RT ($r_S = -0.15$, $p = 0.01$), and SDRT ($r_S = -0.12$, $p = 0.03$) during the go condition, suggesting that aerobic fitness may yield global benefits to adolescents' cognitive processing speed at least in some adolescents. No such relationships were noted in group one (mean RT: $r_S = -0.06$; SDRT: $r_S = -0.02$, $ps \geq 0.26$). In contrast, aerobic fitness was significantly and negatively related to accuracy on the go condition in group one ($r_S = -0.13$, $p = 0.01$)[3] but not in group two ($r_S = -0.04$, $p = 0.45$). Aerobic fitness was not associated with mean RT, SDRT or accuracy on a more cognitively demanding stop-signal condition (go trials)[3] in either group ($ps \geq 0.13$).

Based on the a priori hypotheses on the associations between MVPA, aerobic fitness and cognitive processing, hierarchical regression models were conducted to further explore the data. In group one, MVPA did not predict mean RT during go condition ($\beta = -0.01$, $t(349) = 0.17$, $p = 0.87$, $\Delta R^2 = 0.00$, $F(6,\ 349) = 3.96$, $p = 0.001$), while controlling for aerobic fitness ($p = 0.31$), accelerometer wear time ($p = 0.70$), maternal education ($p = 0.29$), IQ ($\beta = -0.18$, $t(349) = 3.28$, $p = 0.001$) and percent total body fat mass ($\beta = 0.17$, $t(349) = 2.34$, $p = 0.02$). As expected, MVPA did not predict response variability (SDRT) on the go condition ($\beta = 0.02$, $t(352) = 0.45$, $p = 0.65$, $\Delta R^2 = 0.00$, $F(4,\ 352) = 23.02$, $p < 0.001$), while controlling for mean go RT ($\beta = 0.45$, $t(352) = 9.55$, $p < 0.001$), aerobic fitness, and accelerometer wear time ($ps > 0.48$). Inconsistent with the predictions, however, MVPA failed to predict mean RT during the stop-signal condition ($\beta = 0.06$, $t(351) = 1.14$, $p = 0.25$, $\Delta R^2 = 0.00$, $F(5,\ 351) = 1.85$, $p = 0.10$), when aerobic fitness, accelerometer wear time, IQ and maternal education were accounted for ($ps > 0.10$). Furthermore, MVPA also failed to predict response variability during the stop-signal condition ($\beta = -0.01$, $t(350) = 0.16$, $p = 0.87$, $\Delta R^2 = 0.00$, $F(6,\ 350) = 16.01$, $p < 0.001$), while controlling for mean go RT ($\beta = 0.43$, $t(350) = 9.03$, $p < 0.001$), aerobic fitness, accelerometer wear time, IQ and maternal education ($ps > 0.08$).

In group two, MVPA did not predict mean RT during the go condition ($\beta = 0.01$, $t(304) = 0.15$, $p = 0.88$, $\Delta R^2 = 0.00$, $F(5,\ 304) = 2.22$, $p = 0.052$), while controlling for aerobic fitness, accelerometer wear time, sex and percent total body fat mass ($ps > 0.34$). Likewise, MVPA did not predict response variability during the go condition ($\beta = 0.07$, $t(304) = 1.18$, $p = 0.24$, $\Delta R^2 = 0.00$, $F(4,\ 305) = 14.03$, $p < 0.001$), while controlling for mean go RT ($\beta = 0.37$, $t(304) = 6.98$, $p < 0.001$), aerobic fitness and accelerometer wear time ($p \geq 0.12$). Contrary to our hypothesis, MVPA also failed to predict mean RT on the stop-signal condition ($\beta = 0.05$, $t(303) = 0.78$, $p = 0.43$, $\Delta R^2 = 0.00$, $F(6,\ 303) = 2.12$, $p = 0.05$), when aerobic fitness, accelerometer wear time, sex ($p > 0.34$), IQ ($\beta = -0.11$, $t(303) = 1.98$, $p = 0.049$) and percent total body fat mass were accounted for ($p > 0.26$). No significant relation was found between MVPA and response variability during the stop-signal condition ($\beta = 0.11$, $t(305) = 1.65$, $p = 0.10$, $\Delta R^2 = 0.01$, $F(4,\ 305) = 1.15$, $p = 0.33$), while controlling for mean go RT ($\beta = 0.07$, $t(304) = 1.18$, $p = 0.24$), aerobic fitness ($p = 0.27$), and accelerometer wear time ($p \geq 0.68$). Thus, our results suggest that in older

---

[3] The follow-up analyses revealed that aerobic fitness was a significant predictor of accuracy on the go condition in group one ($B = -0.17$, $SE = 0.07$, Wald's $\chi^2_{(1, N = 357)} = 6.68$, $p = 0.01$, LR $\chi^2_{(2, N = 357)} = 7.74$, $p = 0.02$; after controlling for sex, $p = 0.35$). The association was tested using a generalized linear model for binary and event data with a probit link function. Accuracy data were expressed as the number of responses correct within a set of 30 trials.

adolescents from ALSPAC, daily MVPA was not related to the speed or consistency of responding under either task condition.

Since aerobic fitness in group two was significantly correlated with mean RT and SDRT during the go condition, these relations were further inspected with hierarchical regression models. A summary of the models is presented in Table 6. When aerobic fitness was entered as a sole predictor in step one, it accounted for 2.6 % of variance in mean RT on the go condition, $F(1,308) = 8.28, p = 0.004$. In the second step, although aerobic fitness, sex, or percent total body fat mass did not predict mean RT ($ps > 0.36$), together they explained 3.5 % of variance in mean RT during the go condition, $R^2 = 0.035$, $F(3, 306) = 3.66$, $p = 0.01$. This result may point to a possible interaction effect of sex and adiposity on the relation between aerobic fitness and cognitive processing in the group of ALSPAC adolescents who received a stop signal at on average shorter SSDs (i.e., group two). However, when interaction terms between aerobic fitness and sex, and aerobic fitness and percent total body fat mass were entered into the model, they failed to explain variance in mean go RT ($ps > 0.77$), $R^2 = 0.035$, $\Delta R^2 = 0.00$, $F(5, 304) = 2.20$, $p = 0.054$. Aerobic fitness did not predict response variability during the go condition, when mean go RT and sex were accounted for, $F(3, 306) = 18.1, p < 0.001$.

Discussion

This study is the first to assess the relation between objectively measured daily MVPA and cognitive function in adolescents while controlling for the effects of aerobic fitness. Contrary to our predictions, neither daily MVPA nor aerobic fitness was related to task performance during the stop-signal condition, which required the up-regulation of attention and cognitive control. Interestingly, in one group of adolescents from ALSPAC (i.e. those who received shorter SSDs), aerobic fitness was associated with cognitive processing speed during the go condition, which required lower levels of cognitive control. Although the validity of the stop-signal manipulation limits the interpretability of the current results relative to inhibitory control, our results suggest that higher levels of aerobic fitness may benefit cognitive processing speed in some adolescents. These associations, however, need to be considered in relation to possible factors, such a sex and adiposity.

Our findings suggest that aerobic fitness levels were related to processing speed in some, but not all adolescents from ALSPAC, during task conditions requiring minimal cognitive resources. Our results align with previous research indicating that higher aerobic fitness has global benefits to children's cognitive processing speed (Chaddock et al., 2012b; Hillman, Castelli, & Buck, 2005). Thus, our study supports the contention that in addition to specific effects, aerobic fitness may also have global effects on cognition in developing populations. Although, aerobic fitness, sex or adiposity on their own were not significantly related to RT during the go condition, their combined independent effects were all significant. This effect could not be explained by the interactions between aerobic fitness and sex or adiposity. Given that previous findings in children and adults related adiposity (Davis & Cooper, 2011; Kamijo et al., 2012) and sex (Der & Deary, 2006; Tun & Lachman, 2008) to cognitive control and choice RT, respectively, it is important that future research accounts for these associations. Specifically, higher adiposity was associated with a cognitive disadvantage in children. Likewise, sex differences in choice reaction time have been consistently reported in adult studies, indicating that men have shorter RT latencies than women across the lifespan (Der & Deary, 2006; Tun & Lachman, 2008; Tremblay et al., 2010). Together with the inverse associations of aerobic fitness to adiposity in youth (Carnethon, Gulati, & Greenland, 2005; Burns, Hannon, Brusseau, Shultz, & Eisenman, 2013; Ortega et al., 2007; Rodrigues, Leitão, & Lopes, 2013), and sex differences in aerobic fitness among children and adolescents (Dencker et al., 2007; Tremblay et al., 2010), these studies suggest that sex and adiposity may help explain the observed associations between aerobic fitness and cognitive processing speed.

The lack of associations between daily MVPA and attentional control found in our study stands in contrast to the results of Booth et al. (2013) who found positive associations between percent of time spent in MVPA (accelerometry) and normative scores on tasks that require the up-regulation of attention and cognitive control (selective attention and task switching) in 11-year-old adolescents from ALSPAC. The discrepancy between our findings and those of Booth et al. (2013) may be attributed to differences in task characteristics and cognitive maturation between the two samples. Booth et al. (2013) utilized a cognitive task that was normalized for use in adolescents of similar age (Test of Everyday Attention, TEA-Ch; Manly et al., 2001). In contrast, our results suggest that the mean RT on the go trials within the stop-signal condition did not differentiate between higher and lower active adolescents due to issues in the experimental manipulation as indicated by high rates of response inhibition and substantially longer RTs on go trials on the stop signal relative to the go condition. Specifically, high accuracies on the stop-signal trials indicate that response inhibition was dominant over response execution. In combination with significantly longer latencies on the go trials within the stop signal relative to the go condition, these results suggest that participants slowed their responses in proactive anticipation of a stop signal (Bissett & Logan, 2011; Logan, 1994). Therefore, inhibitory control could not be adequately assessed in the current study, which might have contributed to the null results. It also remains possible that this measure is not sensitive enough to differentiate between higher and lower physically active individuals. In confirmation, in a recent study employing a stop-signal paradigm, Padilla, Perez, Andres, and Parmentier (2013) observed the differences between lower and higher physically active young adults (self-report) on the speed of the inhibition (stop-signal reaction time) but not on the latency of responses to the go trials.

These results must be interpreted with caution, however, as both studies (Booth et al., 2013; Padilla et al., 2013) present methodological considerations. Specifically, Booth et al. (2013) did not control for the effects of aerobic fitness. This is an important limitation, as it is unclear whether the associations between the percentage of time spent in MVPA and the indices of cognitive control could not be accounted for by aerobic fitness. Further, in the cross-sectional analyses the authors used only normative scores to assess cognitive control, which were derived from a small sample of children (approximately 100 children over two age bands; Manly et al., 2001; Manly, Robertson, Anderson, & Nimmo-Smith, 1998). The results of Padilla et al. (2013) are also limited in their conclusive power, as the authors based their physical activity groupings (passive versus active) on self-reported physical activity over the past 4 years. Inaccuracies in recall, and self-report bias render these measures inaccurate methods for the quantification of intensity or volume of physical activity (Prince et al., 2008), thus limiting the interpretability of the reported relations between daily MVPA and cognitive control. As such, further research examining the relation between daily MVPA and cognitive control in developing populations is warranted.

Strengths and limitations

The strengths of our study include a large sample size, objective measurement of daily MVPA, aerobic fitness and adiposity, and controlling for important confounders (IQ, maternal education, objectively assessed adiposity, ADHD status based on clinical assessments). Our study is also one of a few (Hillman et al., 2006) to inspect the relations of physical activity to cognitive function in older adolescents. The main limitation of the current study is the compromised validity of the stop-signal task, which did not allow for the adequate assessment of response inhibition. It also resulted in inconsistent application of task parameters within the ALSPAC sample from the research clinics at 15 years.

In conclusion, this was the first study to assess the relations of objectively measured MVPA to cognitive function in adolescents whilst controlling for the effects of aerobic fitness. Although compromised task validity limits the interpretation of some results, we were able to assess the associations between adolescents' daily MVPA, aerobic fitness and cognitive processing speed during less attentionally demanding task condition. Our results suggest that aerobic fitness (but not daily MVPA) in combination with lower adiposity may benefit cognitive processing speed, and that these effects may vary by sex. These results thus point to potential role of adiposity and sex in the relation between aerobic fitness and cognitive processing. Notwithstanding the limitations of the study, our results add to the scant body of evidence on the associations between objectively measured MVPA, aerobic fitness and cognitive processing, which may have implications for cognitive development and academic achievement (Rohde & Thompson, 2007).

Acknowledgments We are extremely grateful to all the families who took part in this study, the midwives for their help in recruiting them, and the whole ALSPAC team, which includes interviewers, computer and laboratory technicians, clerical workers, research scientists, volunteers, managers, receptionists and nurses. The UK Medical Research Council and the Wellcome Trust (Grant ref: 092731) and the University of Bristol provide core support for ALSPAC. We also would like to thank the reviewers for their constructive comments which significantly contributed to the manuscript. This publication is the work of the authors and Dominika M. Pindus, Robert D. Moore, Charles H. Hillman, Stephan Bandelow, Eef Hogervorst, Stuart J. H. Biddle, and Lauren B. Sherar who will serve as guarantors for the contents of this paper.

Ethical standard Ethical approval for the study was obtained from the ALSPAC Ethics and Law Committee and the Local Research Ethics Committees. Thus, the study was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. The manuscript does not contain clinical studies or patient data.

References

Avon Longitudinal Study of Parents and Children. Data dictionary (2014). http://www.bris.ac.uk/alspac/researchers/data-access/data-dictionary/. Accessed 05 March 2014.

Band, G. P. H., van der Molen, M. W., & Logan, G. D. (2003). Horse-race model simulations of the stop-signal procedure. *Acta Psychologica, 112*(2), 105–142. doi:10.1016/S0001-6918(02)00079-3.

Bassett, D. R., Fitzhugh, E. C., Heath, G. W., Erwin, P. C., Frederick, G. M., Wolff, D. L., et al. (2013). Estimated energy expenditures for school-based policies and active living. *American Journal of Preventive Medicine, 44*(2), 108–113. doi:10.1016/j.amepre.2012.10.017.

Best, J. R., Miller, P. H., & Naglieri, J. A. (2011). Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample. *Learning and Individual Differences, 21*(4), 327–336. doi:10.1016/j.lindif.2011.01.007.

Bissett, P. G., & Logan, G. D. (2011). Balancing cognitive demands: control adjustments in the stop-signal paradigm. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 37*(2), 392–404. doi:10.1037/a0021800.

Bland, J., Pfeiffer, K., & Eisenmann, J. (2012). The PWC170: comparison of different stage lengths in 11–16 year olds. *European Journal of Applied Physiology, 112*(5), 1955–1961. doi:10.1007/s00421-011-2157-z.

Booth, J. N., Tomporowski, P. D., Boyle, J. M., Ness, A. R., Joinson, C., Leary, S. D., et al. (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. doi:10.1016/j.mhpa.2013.09.002.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624–652. doi:10.1037//0033.295X108.3624.

Bouchard, C., Blair, S. N., & Haskell, W. L. (2012). *Physical activity and health*. Champaign: Human Kinetics.

Boyd, A., Golding, J., Macleod, J., Lawlor, D. A., Fraser, A., Henderson, J., et al. (2012). Cohort profile: the 'Children of the 90 s'—the index offspring of the Avon Longitudinal Study of Parents and Children. *International Journal of Epidemiology, 42*(1), 111–127. doi:10.1093/ije/dys064.

Braver, T. S., Paxton, J. L., Locke, H. S., & Barch, D. M. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. *Proceedings of the National Academy of Sciences, 106*(18), 7351–7356. doi:10.1073/pnas.0808187106.

Burns, R., Hannon, J. C., Brusseau, T. A., Shultz, B., & Eisenman, P. (2013). Indices of abdominal adiposity and cardiorespiratory fitness test performance in middle-school students. *Journal of Obesity,*. doi:10.1155/2013/912460.

Carnethon, M. R., Gulati, M., & Greenland, P. (2005). Prevalence and cardiovascular disease correlates of low cardiorespiratory fitness in adolescents and adults. *Journal of American Medical Association, 294*(23), 2981–2988. doi:10.1001/jama.294.23.2981.

Chaddock, L., Erickson, K. I., Prakash, R. S., Voss, M. W., VanPatter, M., Pontifex, M. B., et al. (2012a). A functional MRI investigation of the association between childhood aerobic fitness and neurocognitive control. *Biological Psychology, 89*(1), 260–268. doi:10.1016/j.biopsycho.2011.10.017.

Chaddock, L., Hillman, C. H., Pontifex, M. B., Johnson, C. R., Raine, L. B., & Kramer, A. F. (2012b). Childhood aerobic fitness predicts cognitive performance one year later. *Journal of Sports Sciences, 30*(5), 421–430. doi:10.1080/02640414.2011.647706.

Chaddock-Heyman, L., Erickson, K.I., Voss, M., Knecht, A., Pontifex, M.B., Castelli, D., et al. (2013). The effects of physical activity on functional MRI activation associated with cognitive control in children: a randomized controlled intervention. *Frontiers in Human Neuroscience*, *7*, 1–13. doi:10.3389/fnhum.2013.00072.

Colcombe, S., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychological Science, 14*(2), 125–130. doi:10.1111/1467-9280.t01-1-01430.

Davis, C. L., & Cooper, S. (2011). Fitness, fatness, cognition, behavior, and academic achievement among overweight children: do cross-sectional associations correspond to exercise trial outcomes? *Preventive Medicine, 52*, S65–S69. doi:10.1016/j.ypmed.2011.01.020.

Davis, C. L., Tomporowski, P. D., McDowell, J. E., Austin, B. P., Miller, P. H., 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*(1), 91–98. doi:10.1037/a0021766.

Dencker, M., & Andersen, L. B. (2011). Accelerometer-measured daily physical activity related to aerobic fitness in children and adolescents. *Journal of Sports Sciences, 29*(9), 887–895. doi:10.1080/02640414.2011.578148.

Dencker, M., Thorsson, O., Karlsson, M. K., Lindén, C., Eiberg, S., Wollmer, P., et al. (2007). Gender differences and determinants of aerobic fitness in children aged 8–11 years. *European Journal of Applied Physiology, 99*(1), 19–26. doi:10.1007/s00421-006-0310-x.

Department of Health (2011). UK physical activity guidelines. Fact sheet 3: children and young people (5–18 years). In Department of Health (Ed.). London: GOV.UK.

Der, G., & Deary, I. J. (2006). Age and sex differences in reaction time in adulthood: results from the United Kingdom Health and Lifestyle Survey. *Psychology and Aging, 21*(1), 62–73. doi:10.1037/0882-7974.21.1.62.

Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science, 333*(6045), 959–964. doi:10.1126/science.1204529.

Etnier, J. L. (2006). Are we ready to prescribe physical activity to promote cognitive function? *Medicine and Science in Sports and Exercise, 38*(5), S29–S30.

Freedson, P. S., Melanson, E., & Sirard, J. (1998). Calibration of the computer science and applications, Inc. accelerometer. *Medicine and Science in Sports and Exercise, 30*(5), 777–781. doi:10.1097/00005768-199805000-00021.

Gutin, B., & Owens, S. (2011). The influence of physical activity on cardiometabolic biomarkers in youths: a review. *Pediatric Exercise Science, 23*(2), 169–185.

Gutman, L. M., & Feinstein, L. (2008). Parenting behaviours and children's development from infancy to early childhood: changes, continuities and contributions. *Early Child Development and Care, 180*(4), 535–556. doi:10.1080/03004430802113042.

Hallal, P. C., Victora, C. G., Azevedo, M. R., & Wells, J. C. K. (2006). Adolescent physical activity and health: a systematic review. *Sports Medicine, 36*(12), 1019–1030. doi:10.2165/00007256-200636120-00003.

Handley, S. J., Capon, A., Beveriddge, M., Dennis, I., & Evans, J. S. B. T. (2004). Working memory, inhibitory control and the development of children's reasoning. *Thinking & Reasoning, 10*(2), 175–195.

Hillman, C. H., Castelli, D. M., & Buck, S. M. (2005). Aerobic fitness and neurocognitive function in healthy preadolescent children. *Medicine and Science in Sports and Exercise, 37*(11), 1967–1974. doi:10.1249/01.mss.0000176680.79702.ce.

Hillman, C. H., Motl, R. W., Pontifex, M. B., Posthuma, D., Stubbe, J. H., Boomsma, D. I., et al. (2006). Physical activity and cognitive function in a cross-section of younger and older community-dwelling individuals. *Health Psychology, 25*(6), 678–687. doi:10.1037/0278-6133.25.6.678.

Iannotti, R. J., Kogan, M. D., Janssen, I., & Boyce, W. F. (2009). Patterns of adolescent physical activity, screen-based media use, and positive and negative health indicators in the U.S. and Canada. *Journal of Adolescent Health, 44*(5), 493–499. doi:10.1016/j.jadohealth.2008.10.142.

Kamijo, K., Khan, N. A., Pontifex, M. B., Scudder, M. R., Drollette, E. S., Raine, L. B., et al. (2012). The relation of adiposity to cognitive control and scholastic achievement in preadolescent children. *Obesity, 20*(12), 2406–2411. doi:10.1038/oby.2012.112.

Kamijo, K., Pontifex, M. B., O'Leary, K. C., Scudder, M. R., Wu, C.-T., Castelli, D. M., et al. (2011). The effects of an afterschool physical activity program on working memory in preadolescent children. *Developmental Science, 14*(5), 1046–1058. doi:10.1111/j.1467-7687.2011.01054.x.

Kothari, R., Solmi, F., Treasure, J., & Micali, N. (2013). The neuropsychological profile of children at high risk of developing an eating disorder. *Psychological Medicine, 43*(07), 1543–1554. doi:10.1017/S0033291712002188.

Lawlor, D., Cooper, A., Bain, C., Davey Smith, G., Irwin, A., Riddoch, C., et al. (2008). Associations of birth size and duration of breast feeding with cardiorespiratory fitness in childhood: findings from the Avon Longitudinal Study of Parents and Children (ALSPAC). *European Journal of Epidemiology, 23*(6), 411–422. doi:10.1007/s10654-008-9259-x.

Logan, G. D. (1994). On the ability to inhibit thought and action: a users' guide to the stop signal paradigm. In D. Dagenbach & T. H. Carr (Eds.), *Inhibitory processes in attention, memory, and language* (pp. 189–239). San Diego: Academic Press.

Logan, G. D., Cowan, W. B., & Davis, K. A. (1984). On the ability to inhibit simple and choice reaction time responses: a model and a method. *Journal of Experimental Psychology: Human Perception and Performance, 10*(2), 276–291. doi:10.1037/0096-1523.10.2.276.

Luna, B., & Sweeney, J. A. (2004). The emergence of collaborative brain function: fMRI studies of the development of response inhibition. *Annals of the New York Academy of Sciences, 1021*(1), 296–309. doi:10.1196/annals.1308.035.

Mahmood, O. M., Goldenberg, D., Thayer, R., Migliorini, R., Simmons, A. N., & Tapert, S. F. (2013). Adolescents' fMRI activation to a response inhibition task predicts future substance use. *Addictive Behaviors, 38*(1), 1435–1441. doi:10.1016/j.addbeh.2012.07.012.

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*(8), 1065–1081. doi:10.1111/1469-7610.00806.

Manly, T., Robertson, I. H., Anderson, V., & Nimmo-Smith, I. (1998). *Test of everyday attention for children (TEA-Ch)*. Bury St Edmunds: Thames Valley Test Company.

Mattocks, C., Leary, S., Ness, A., Deere, K., Saunders, J., Tilling, K., et al. (2007). Calibration of an accelerometer during free-living activities in children. *International Journal of Pediatric Obesity, 2*(4), 218–226. doi:10.1080/17477160701408809.

Mattocks, C., Ness, A. R., Leary, S. D., Tilling, K., Blair, S. N., Shield, 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 & Health, 5*(Suppl 1), S98–S111.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: part I. *Basic mechanisms. Psychological Review, 104*(1), 3–65. doi:10.1037/0033-295x.104.1.3.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*(1), 167–2002. doi:10.1146/annurev.neuro.24.1.167.

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., et al. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences, 108*(7), 2693–2698. doi:10.1073/pnas.1010076108.

Monette, S., Bigras, M., & Guay, M.-C. (2011). The role of the executive functions in school achievement at the end of Grade 1. *Journal of Experimental Child Psychology, 109*(2), 158–173. doi:10.1016/j.jecp.2011.01.008.

Moore, R. D., Wu, C.-T., Pontifex, M. B., O'Leary, K. C., Scudder, M. R., Raine, L. B., et al. (2013). Aerobic fitness and intra-individual variability of neurocognition in preadolescent children. *Brain and Cognition, 82*(1), 43–57. doi:10.1016/j.bandc.2013.02.006.

National Research Council (2013). Educating the student body. Taking physical activity and physical education to school. Washington, DC: The National Academies Press.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation* (Vol. 4, pp. 1–18)., Advances in research and theory New York: Plenum Press.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh Inventory. *Neuropsychologia, 9*(1), 97–113.

Ong, K. K., Emmett, P., Northstone, K., Golding, J., Rogers, I., Ness, A. R., et al. (2009). Infancy weight gain predicts childhood body fat and age at menarche in girls. *Journal of Clinical Endocrinology and Metabolism, 94*(5), 1527–1532. doi:10.1210/jc.2008-2489.

Ortega, F. B., Tresaco, B., Ruiz, J. R., Moreno, L. A., Martin-Matillas, M., Mesa, J. L., et al. (2007). Cardiorespiratory fitness and sedentary activities are associated with adiposity in adolescents. *Obesity, 15*(6), 1589–1599. doi:10.1038/oby.2007.188.

Padilla, C., Perez, L., Andres, P., & Parmentier, F. B. R. (2013). Exercise improves cognitive control: evidence from the Stop Signal task. *Applied Cognitive Psychology, 27*(4), 505–511. doi:10.1002/acp.2929.

Pontifex, M. B., Raine, L. B., Johnson, C. R., Chaddock, L., Voss, M. W., Cohen, N. J., et al. (2011). Cardiorespiratory fitness and the flexible modulation of cognitive control in preadolescent children. *Journal of Cognitive Neuroscience, 23*(6), 1332–1345. doi:10.1162/jocn.2010.21528.

Prince, S., Adamo, K., Hamel, M., Hardt, J., Gorber, S., & Tremblay, M. (2008). A comparison of direct versus self-report measures for assessing physical activity in adults: a systematic review. *International Journal of Behavioral Nutrition and Physical Activity, 5*(1), 56. doi:10.1186/1479-5868-5-56.

Rodrigues, L. P., Leitão, R., & Lopes, V. P. (2013). Physical fitness predicts adiposity longitudinal changes over childhood and adolescence. *Journal of Science and Medicine in Sport, 16*(2), 118–123. doi:10.1016/j.jsams.2012.06.008.

Rohde, T. E., & Thompson, L. A. (2007). Predicting academic achievement with cognitive ability. *Intelligence, 35*(1), 83–92. doi:10.1016/j.intell.2006.05.004.

Sherar, L., Griew, P., Esliger, D., Cooper, A., Ekelund, U., Judge, K., et al. (2011). International children's accelerometry database (ICAD): design and methods. *BMC Public Health, 11*(1), 485.

St Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: shifting, updating, inhibition, and working memory. *The Quarterly Journal of Experimental Psychology, 59*(4), 745–759. doi:10.1080/17470210500162854.

The US Department of Health and Human Services (2008). *2008 physical activity guidelines for Americans: Be active, healthy, and happy* (Vol. Chapter 3, pp. 13–19). Washington.

Tremblay, M. S., Shields, M., Laviolette, M., Craig, C. L., Janssen, I., & Connor Gorber, S. (2010). Fitness of Canadian children and youth: results from the 2007–2009 Canadian Health Measures Survey. *Health Reports, 21*(1), 7–20.

Troiano, R., Berrigan, D., Dodd, K., Masse, L., Tilert, T., & McDowell, M. (2008). Physical activity in the United States measured by accelerometer. *Medicine and Science in Sports and Exercise, 40*, 181–188. doi:10.1249/mss.0b013e31815a51b3.

Tun, P. A., & Lachman, M. E. (2008). Age differences in reaction time and attention in a national telephone sample of adults: education, sex, and task complexity matter. *Developmental Psychology, 44*(5), 1421–1429. doi:10.1037/a0012845.

Verbruggen, F., & Logan, G. D. (2008). Response inhibition in the stop-signal paradigm. *Trends in Cognitive Sciences, 12*(11), 418–424. doi:10.1016/j.tics.2008.07.005.

Voss, M. W., Chaddock, L., Kim, J. S., Vanpatter, M., Pontifex, M. B., Raine, L. B., et al. (2011). Aerobic fitness is associated with greater efficiency of the network underlying cognitive control in preadolescent children. *Neuroscience, 199*, 166–176. doi:10.1016/j.neuroscience.2011.10.009.

Walhovd, K. B., Westlye, L. T., Amlien, I., Espeseth, T., Reinvang, I., Raz, N., et al. (2011). Consistent neuroanatomical age-related volume differences across multiple samples. *Neurobiology of Aging, 32*(5), 916–932. doi:10.1016/j.neurobiolaging.2009.05.013.

West, R., Murphy, K. J., Armilio, M. L., Craik, F. I. M., & Stuss, D. T. (2002). Lapses of intention and performance variability reveal age-related increases in fluctuations of executive control. *Brain and Cognition, 49*(3), 402–419. doi:10.1006/brcg.2001.1507.

Wu, C.-T., Pontifex, M. B., Raine, L. B., Chaddock, L., Voss, M. W., Kramer, A. F., et al. (2011). Aerobic fitness and response variability in preadolescent children performing a cognitive control task. *Neuropsychology, 25*(3), 333–341. doi:10.1037/a0022167.