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Moderate-to-Vigorous Physical Activity, Indices of Cognitive Control, and Academic Achievement in Preadolescents

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Objective To assess whether preadolescents' objectively measured moderate-to-vigorous physical activity (MVPA) is associated with cognitive control and academic achievement, independent of aerobic fitness.

Study design A sample of 74 children ($\text{Mean}_{\text{age}} = 8.64$ years, SD = .58, 46% girls) were included in the analyses. Daily MVPA (min/d) was measured over 7 days using ActiGraph wGT3X+ accelerometer. Aerobic fitness was measured using a maximal graded exercise test and expressed as maximal oxygen uptake ($\text{mL*kg}^{-1}\text{*min}^{-1}$). Inhibitory control was measured with a modified Eriksen flanker task (reaction time and accuracy), and working memory with an Operation Span Task (accuracy scores). Academic achievement (in reading, mathematics, and spelling) was expressed as standardized scores on the Kaufman Test of Educational Achievement. The relationships were assessed using hierarchical regression models adjusting for aerobic fitness and other covariates.

Results No significant associations were found between MVPA and inhibition, working memory, or academic achievement. Aerobic fitness was positively associated with inhibitory control ($P = .02$) and spelling ($P = .04$) but not with other cognitive or academic variables (all $P > .05$).

Conclusions Aerobic fitness, rather than daily MVPA, is positively associated with childhood ability to manage perceptual interference and spelling. Further research into the associations between objectively measured MVPA and cognitive and academic outcomes in children while controlling for important covariates is needed. *(J Pediatr 2016;173:136-42)*.

Physically inactive children may be missing opportunities for optimizing their cognitive and academic potential.[1-4] That is, increasing children's engagement in regular, structured, and sustained moderate-to-vigorous physical activity (MVPA) (namely, aerobic exercise) can benefit cognitive functions, which are implicated in self-regulation, goal-directed behavior, and academic achievement (ie, cognitive control).[1,2] Likewise, regular increases in school physical activity can benefit academic achievement.[3-6] However, little evidence exists on whether children's daily, lifestyle-embedded MVPA (ie, MVPA accumulated throughout the entire day) is related to cognitive control and academic achievement.

Extant studies using objective monitoring of physical activity yield equivocal results in relation to both cognitive control and academic achievement. That is, either null[7-9] or select positive associations have been observed.[10-12] However, their conclusions remain limited, as these studies did not statistically control for aerobic fitness and/or IQ.[10-12] More aerobically fit children perform better cognitively (ie, have greater working memory and can better control distractions)[13,14] and academically,[15,16] as do those with higher intellectual ability.[17,18] In one study, a positive relationship between physical activity emerged only after mediation via aerobic fitness had been considered.[5] Consequently, not accounting for inter-individual differences in these variables could occlude or confound the underlying associations.

To address this limitation, we aimed to assess the associations between accelerometer-measured daily MVPA, cognitive control, and academic achievement in a sample of preadolescent children while controlling for aerobic fitness and IQ. We measured two aspects of cognitive control, which are most consistently related to academic achievement: inhibitory control and working memory.[19] We hypothesized that: (1) greater daily MVPA would be related to

ADHD	Attention deficit hyperactivity disorder	OSPAN	Operation Span Task
BMI	Body mass index	PCL	Partial credit load
CPM	Counts per minute	PCU	Partial credit unit
HR	Heart rate	RCT	Randomized controlled trial
MVPA	Moderate-to-vigorous physical activity	RT	Reaction time
		SES	Socioeconomic status
		VO_{2max}	Maximal oxygen consumption

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better performance on measures of cognitive control and standardized tests of academic achievement (reading, mathematics, and spelling); (2) cognitive control would mediate the relationship between daily MVPA and academic achievement in reading and mathematics; and (3) aerobic fitness would mediate the relationship between daily MVPA and academic achievement in mathematics as indicated by previous findings.[5]

Methods

Children aged 7-9 years (n = 103; 48.5% girls; $\text{Mean}_{\text{age}} = 8.66 \pm 0.56$) were recruited from 7 schools in East Central Illinois, US between June and October in 2013 and in 2014. Approximately 1800 children were reached via flyers, mailings, and local events, an average of 225 responded (12.5%) and of those, 139 (61.8%) qualified for the study, and 103 (46%) completed measurements. The study was approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign. Parents provided written consent, and children provided written assent. To qualify for the study, the children had to be free of neurologic disorders, physical disability, and clinical diagnosis of attention deficit hyperactivity disorder (ADHD; as disclosed by parents; in addition, legal guardians completed ADHD Rating Scale IV[20]). In addition, to be included the children had to: (1) have an IQ score >85 on the Brief Intellectual Ability of the Woodcock-Johnson III Tests of Cognitive Abilities[21]; and (2) provide ≥3 days of valid accelerometer data (≥10 hours of valid accelerometer wear).[22] One child with an IQ of 84 (not a statistical outlier) was included in the analyses (the exclusion of this child's data did not change the results). After exclusions (<3 valid days of accelerometer wear [n = 10], <50% accuracy on cognitive tests [n = 13], missing data [n = 6: cognitive variables n = 4, ADHD n = 1, fitness n = 1]), data from 74 children (46% girls, $\text{Mean}_{\text{age}} = 8.64 \pm .58$) were analyzed. Children visited a laboratory on 2 separate occasions to complete neuropsychological and cognitive testing. Accelerometers were issued on one of the testing days and returned by a parent upon completion of wear.

Standing height was measured with a Seca telescopic stadiometer model 220 (Seca, Birmingham, United Kingdom) to the nearest millimeter and weight was assessed with a Seca 769 electronic column scale (Seca) while children were in lightweight clothing and shoes. Body mass index (BMI) (weight (kg) * $[\text{height } (\text{m}^2)]^{-1}$) percentiles were calculated based on Centers for Disease Control growth charts.[23]

Physical activity was measured over 7 consecutive days with a triaxial ActiGraph accelerometer model wGT3X+ (ActiGraph, Pensacola, Florida) worn on the waist at the right anterior axillary line on an elastic, nylon belt. Data were collected at 100 Hz resolution, integrated into 15-second epochs using ActiLife (v 6.7.1-6.10.0; ActiGraph), processed with KineSoft software v 3.3.76 (KineSoft, Loughborough, United Kingdom), and screened following the procedures described by Sherar et al.[24] Nonwear was defined as 60 minutes of consecutive zero counts, allowing for 2-minute interruptions.[25] To exclude the overnight wear, the analyses were limited to data collected between 6 a.m. and 11 p.m. MVPA was defined based on age specific cut points[26] (for 8-year-old children) using 4 metabolic equivalents as a threshold.[27] Sedentary time was defined as <100 counts per minute (CPM).[28]

Maximal oxygen consumption ($\text{VO}_{2\text{max}}$) was measured during a graded treadmill test using a computerized indirect calorimetry system (True Max 2400; ParvoMedics, Sandy, Utah). Averages of $\text{VO}_{2\text{max}}$ and respiratory exchange ratio were taken every 20 seconds, while children walked or ran (92T; LifeFitness, Schiller Park, Illinois). Heart rate (HR) (polar HR monitor, Polar WearLink+31; Polar Electro, Kempele, Finland) and perceived exertion (children's OMNI scale[29]) were monitored throughout the test. Relative $\text{VO}_{2\text{max}}$ ($\text{mL*kg}^{-1}\text{*min}^{-1}$) was determined by a plateau in oxygen consumption (>2 $\text{mL*kg}^{-1}\text{*min}^{-1}$ despite an increase in workload[30]) or at least one of the following: (1) a HR ≥185 beats per minute[30]; (2) a HR plateau[31]; (3) respiratory exchange ratio ≥1.0[32]; and/or (4) a score of ≥8 on the children's OMNI scale.[29] $\text{VO}_{2\text{max}}$ percentiles were computed based on normative values.[33]

Socioeconomic status (SES) was calculated using a trichotomous index based on parental reports of: (1) child's participation in free or reduced price lunch program at school; (2) the highest level of education obtained by the mother and father; and (3) the number of parents who work full time.[34] Pubertal stage was assessed by parental ratings on a pictorial scale based on photographs of secondary sexual characteristic standards (5 stages).[35,36] Stage 1 indicates prepubertal state (no overt signs of secondary sex characteristics); stage 5 indicates the full mature state.

Inhibitory control was assessed with a modified Eriksen flanker task,[37] which measures ability to suppress distractors and attend to relevant information. Participants were asked to respond as quickly and accurately as possible with a thumb press to the directionality (left or right) of a centrally positioned target fish amid an array of congruous (facing in the same direction) or incongruous (facing the opposite direction) flanker fish.[1] Following 40 practice trials, participants completed 2 blocks of 84 experimental trials with equiprobable congruency and directionality. The stimuli were 3-cm tall yellow fish presented focally (using Neuroscan Stim 2 software; Compumedics, Charlotte, North Carolina) for 250 ms on a blue background with equiprobable interstimulus intervals of 1600, 1800, or 2000 ms. Measures of mean reaction time (RT), accuracy, and 2 measures of interference control (accuracy and RT interference, expressed as the differences between congruent and incongruent values with higher values indicative of poorer performance) were taken. High test re-test reliability (Intraclass Correlation Coefficient = 0.95) and convergent validity (r = 0.48) have been observed using an abbreviated version of the task.[38]

Working memory was measured with the Operation Span Task (OSPAN).[39,40] A trial consisted of individual words printed on a computer screen followed by a simple arithmetic problem (eg, 1 + 2 = 3). Participants were instructed to read both aloud, indicate whether an arithmetic problem was correctly solved, and to write down all words in the order of presentation during a recall phase. Four blocks of 4 sets of trials (set size: 1-4 trials) were presented at random (40 trials across 16 sets). Words were presented focally on a computer screen (Neuroscan Stim 2 software; Compumedics) for 1000 ms followed by an interstimulus interval of 1100 ms and an arithmetic problem displayed for up to 10 seconds. Scoring criteria[40] included scores which did (all-or-nothing credit) and did not require (partial credit) correct and sequential recall of all items in a set: (1) all-or-nothing unit score (the number of sets correct divided by the total number of sets); (2) all-or-nothing load score (the proportion of the sum of trials correct to the total number of trials); (3) partial credit unit (PCU) score (the average of the summed proportions of trials correct to the set size); and (4) partial credit load (PCL) score (the proportion of trials correct to the total number of trials). OSPAN tasks have high test-re-test reliability (r = .88[41]) and good convergent validity (r's = .40-.60[42]; adult data).

Academic achievement in reading, mathematics, and spelling was assessed with 5 subtests from the Kaufman Test of Educational Achievement, Second Edition.[43] Composite standardized scores (Mean = 100, SD = 15) for reading (word recognition and reading comprehension) and mathematics (math concepts, applications, and computation), and standardized score for spelling subscale were included. Kaufman Test of Educational Achievement, Second Edition subtests have very high internal consistencies, interrater reliabilities, and internal validity (r's = .91-.97[43]).

Statistical Analyses

Independent sample *t* tests, ANCOVA, and χ^2 statistics were used to evaluate group differences in demographic, anthropometric, physical activity, cognitive, and academic achievement variables, as appropriate. Within participant differences on the flanker task were assessed with Wilcoxon signed-rank test. Pearson correlation coefficients were used to inspect bivariate associations, and partial correlations (controlling for wear time) were used to assess relationships with MVPA. Where appropriate, variables were transformed to comply with normality. The relationships were further inspected with 3 sets of multiple hierarchical regression models. In minimally adjusted models, outcomes were predicted from MVPA adjusting for wear time only. Partially adjusted models were additionally adjusted for covariates (eg, age, sex, IQ, ADHD ratings, birth weight) if they were significantly related to cognitive and/or academic achievement outcomes in bivariate correlations. Fully adjusted models were adjusted for covariates as per partially adjusted models and additionally for aerobic fitness. All models were assessed for multicollinearity and normal distribution of error terms. Where appropriate, variables were log- or square root-transformed to conform to the assumption of normality of distribution. IBM SPSS Statistics v 23.0.0.1 (IBM Corp, Armonk, New York) was used to conduct all the analyses. The alpha level was set at .05.

Results

No differences were noted between children who were excluded (n = 29) and those included (n = 74) in the study with regards to demographic (age, sex, ADHD ratings) or anthropometric (height, weight, BMI) variables, pubertal stage, aerobic fitness, percent lower or higher fit, or overweight and obese ($Ps \geq .09$). Children included in the analyses did not differ from those excluded in any of the physical activity variables (CPM, time sedentary, light PA, or MVPA; $Ps \geq .07$). Those included in the analyses had, on average, higher IQ ($\text{Mean}_{\text{incl}}$ = 112, $\text{Mean}_{\text{excl}}$ = 102, $P = .002$), and those excluded were more likely to come from a lower SES background (OR = 2.89, $P = .02$).

Descriptive characteristics of participants stratified by sex are presented in **Table I**. No significant sex differences were noted for age, anthropometric (height, weight, BMI, BMI percentile) ADHD, IQ ($Ps \geq .29$), or physical activity variables (CPM, wear time, sedentary time, MVPA; $Ps \geq .11$). As expected, boys had higher relative VO_{2max} ($P = .044$) but did not differ from girls on VO_{2max} percentile ($P = .52$). No sex differences were noted for SES, overweight/obese status, or percent of higher and lower fit ($Ps \geq .22$). Girls were more likely to be classed as prepubertal (OR = 3.1, $P = .18$). Boys were more accurate ($\text{Mean}_{\text{boys}}$ = 83.6%) than girls ($\text{Mean}_{\text{girls}}$ = 77.4%, $P = .01$) on the congruent flanker condition. No further sex differences were noted in performance on either cognitive tasks or academic achievement tests ($Ps \geq .15$).

The majority of participants (n = 64, 86.5%) wore the accelerometer for at least 5 days, 2 (2.7%), 8 (10.8%), 16 (21.6%), 26 (35.1%), and 22 (29.7%) participants provided data for 3, 4, 5, 6, and 7 days, respectively. Average daily wear time was 13.3 hours (6:00 a.m.-11:00 p.m.; **Table I**). Physical activity was positively and moderately related to aerobic fitness: CPM: r = .37, $P = .001$, MVPA (log transformed): $pr = .37$, $P = .001$. Participants' performance on cognitive tasks and academic achievement tests are summarized in **Table II**. As expected, participants responded, on average, faster and more accurately on congruent than incongruent trials, mean $\text{RT}_{\text{difference}}$: $Z = 7.22$, $P < .001$, r = 0.59; $\text{accuracy}_{\text{difference}}$: $Z = -6.02$, $P < .001$, r = .50.

No significant partial correlations between MVPA and either cognitive or academic achievement variables were noted ($Ps \geq .13$). Aerobic fitness was negatively related to accuracy interference ($r = -.25$, $P = .03$) but not to other cognitive variables or academic achievement ($Ps \geq .11$).

Table III presents the summary of the results (significance levels for model ANOVAs, model R^2s, and standardized parameter estimates for MVPA and fitness, where appropriate; data for covariates not shown) from the

Table I. Mean (SD) values for participants' demographic, anthropometric, aerobic fitness, and physical activity data

	Girls (n = 34)		Boys (n = 40)		Combined (N = 74)	
	Mean (SD)		Mean (SD)		Mean (SD)	
Age (y)	8.63 (.56)		8.66 (.60)		8.64 (.58)	
SES low (n, [%])	8 [23.5]		12 [30.0]		20 [27.0]	
Ethnicity (white n, [%])	25 [73.5]		23 [57.5]		48 [65]	
IQ*	111.4 (11.2)		111.8 (12.6)		111.6 (11.9)	
Height (cm)	135.2 (6.64)		135.6 (7.17)		135.4 (6.89)	
Weight (kg)	35.0 (11.0)		34.1 (9.02)		34.5 (9.93)	
BMI (kg/m^2)	18.9 (4.54)		18.4 (3.73)		18.6 (4.10)	
OW/OB (n, [%])†	12 [35.3]		14 [35.0]		26 [35.1]	
VO_{2max} (mL*kg^{-1}*min^{-1})	41.4 (8.06)		45.1 (7.64)*		43.4 (8.00)	
VO_{2max} percentile	41.6 (34.1)		36.7 (31.1)		38.9 (32.4)	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
CPM	549.6 (151.9)	328.4-925.7	561.7 (167.3)	285.1-996.7	556.2 (159.4)	285.1-996.7
Wear time (min/d)	790.8 (48.8)	673.6-891.7	809.3 (48.0)	712.6-909.6	800.8 (48.9)	673.6-909.6
Sedentary time‡ (min/d)	443.6 (56.0)	328.7-554.2	460.4 (68.3)	338.9-637.5	452.7 (63.1)	328.7-637.5
LPA§ (min/d)	262.1 (40.0)	143.0-339.7	255.7 (34.2)	200.9-346.6	258.6 (36.8)	143.0-346.6
MVPA¶ (min/d)	85.1 (26.4)	46.1-137.5	93.2 (30.6)	45.0-158.7	89.5 (28.9)	45.0-158.7

CPM, accelerometer counts per minute; *LPA*, light physical activity; *OW/OB*, overweight or obese.

Intensity cut points were based on age-specific cut points for 8-year-olds (using a 4 metabolic equivalents threshold) developed by Freedson and first published by Trost et al[26]; sedentary cut point developed by Treuth et al.[28]

*IQ: A composite standardized score of IQ from Woodcock-Johnson III Tests of Cognitive Abilities, Brief Intelligence Assessment[21]; IQ minimum = 84 (n = 1).

†OW/OB category defined based on the CDC growth charts.[23]

‡Sedentary time <100 CPM.

§LPA ≥100, <1638 CPM.

¶MVPA ≥1638 CPM.

minimally (adjusted for wear time), partially (additionally adjusted for covariates), and fully adjusted (additionally adjusted for aerobic fitness) regression models predicting inhibitory control, working memory, and academic achievement from MVPA. MVPA was not related to either measures of inhibitory control (accuracy, mean RT, or interference on the flanker task; $Ps \geq .11$) or working memory (PCU, PCL, all-or-nothing unit, or all-or-nothing load scores on the OSPAN, $Ps \geq .52$) regardless of the adjustment for covariates and aerobic fitness (Table III). Similarly, MVPA was not related to academic achievement in either reading, mathematics, or spelling in minimally, partially, and fully adjusted models ($Ps \geq .20$). Covariates explained significant proportion of variance in models predicting incongruent mean RT and interference accuracy on the flanker task, PCU on the OSPAN, and academic achievement in reading, mathematics, and spelling as indicated by R^2 values and significant ANOVAs for partially adjusted models (Table III). Birth weight and ADHD explained 12% of variance each in incongruent mean RT and accuracy interference ($Ps \leq .02$), and IQ and age explained 21% of variance in PCU on the OSPAN task ($P = .001$). IQ was the strongest predictor of academic achievement, accounting for 20%-34% of variance ($Ps < .001$). Aerobic fitness emerged as a significant predictor of spelling ($P = .04$), predicting 4.6% of variance, and showed a trend for accuracy interference ($P = .06$).

In follow-up regression models, where aerobic fitness was entered as the main predictor, it explained 6.8% of variance in accuracy interference [$\beta = -.26$, $t(71) = 2.40$, $P = .02$, $F(2, 71) = 7.17$, $P = .001$] after controlling for ADHD scores ($\beta = -.32$, $t = 2.99$, $P < .001$) and 4.7% variance in spelling [$\beta = -.22$, $t(71) = 2.12$, $P = .04$, $F(2, 71) = 12.8$, $P < .001$], accounting for IQ [$\beta = .48$, $t(71) = 4.74$, $P < .001$]. Because no significant associations between MVPA and academic achievement variables were noted, mediation analyses were not performed.

Table II. Performance on flanker task, OSPAN, and academic achievement

	Median (IQR)	Range
Flanker congruent		
Mean RT (ms)	518.6 (132.8)*	392.5-827.0
Response accuracy (%)	83.3 (15.5)*	52.4-98.8
Flanker incongruent		
Mean RT (ms)	571.8 (152.5)†	420.9-939.6
Response accuracy (%)	72.6 (17.0)†	51.2-96.4
Flanker interference		
Mean RT (ms)	49.4 (44.5)	−27.6 to 203.0
Response accuracy (%)	8.33 (11.9)	−10.7 to 34.5
OSPAN		
Mean RT (ms)	4618.2 (1555.7)	2093.4-7354.4
Response accuracy (%)	87.5 (13.1)	52.5-100.0
PCU score	0.60 (0.28)	.14-.97
PCL score	0.55 (0.28)	.10-.95
ANU score	0.38 (0.25)	.06-.88
ANL score	0.25 (0.29)	.03-.83
	Mean (SD)	Range
Academic achievement		
Spelling	110.0 (23.0)	79.0-151.0
Reading	118.0 (17.0)	80.0-159.0
Math	109.0 (22.2)	82.0-150.0

PCU, partial-credit unit; *PCL*, partial-credit load score; *ANU*, all-or-nothing unit; *ANL*, all-or-nothing load; *KTEA II*, Kaufman Test of Educational Achievement, Second Edition.[43]

Academic achievement was assessed with the KTEA II[43] and expressed as standardized scores with the mean of 100 and an SD of 15.

*and † Significant within-participant differences across congruent and incongruent conditions ($P < .001$).

Table III. The associations of daily MVPA to cognitive control and academic achievement (N = 74; except for PCU, N = 72 and ANU, N = 71)

	Minimally adjusted					Partially adjusted					Fully adjusted				
Predictors	Model R^2	Model P ANOVA	B	95% CI	*P*	Model R^2	Model P ANOVA	B	95% CI	*P*	Model R^2	Model P ANOVA	B	95% CI	*P*
Model 1: Incon Acc	.08	.06				.08	.06				.09	.08			
VO_{2max}													.15	−.14; .57	.24
MVPA			−.07	−.12; .07	.57			−.07	−.12; .07	.57			−.12	−.15; .05	.33
Model 2: Incon MRT*	.01	.71				**.13**	**.02**				**.13**	**.04**			
VO_{2max}													−.06	−.00; .00	.61
MVPA			.08	.00; .00	.51			.06	.00; .00	.61			.08	.00; .00	.51
Model 3: Acc Interference	.02	.48				**.14**	**.02**				**.18**	**.01**			
VO_{2max}													−.22†	−.48; .01	.06
MVPA			−.12	−.10; .03	.30			−.18	−.12; .01	.11			−.10	−.10; .04	.43
Model 4: MRT Interference‡	.02	.46				.02	.46				.05	.31			
VO_{2max}													−.18	−.08; .01	.15
MVPA			−.13	−.02; .01	.26			−.13	−.02; .01	.26			−.06	−.02; .01	.62
Model 5: OSPAN PCU§	.00	.89				**.21**	**.00**				**.22**	**.01**			
VO_{2max}													−.13	−.01; .00	.27
MVPA			−.05	−.00; .00	.66			.03	−.00; .00	.77			.09	−.00; .00	.48
Model 6: OSPAN ANU	.02	.53				.07	.18				.07	.27			
VO_{2max}													−.07	−.01; .01	.59
MVPA			−.08	−.00; .00	.54			−.05	−.00; .00	.66			−.03	−.00; .00	.84
Model 7: Spelling	.04	.27				**.24**	**.00**				**.29**	**.00**			
VO_{2max}													**−.23**	**−.92;−.02**	**.04**
MVPA			−.10	−.19; .08	.41			−.06	−.15; 09	.58			.03	−.11; .14	.78
Model 8: Reading	.04	.22				**.38**	**.00**				**.39**	**.00**			
VO_{2max}													−.07	−.49; .24	.50
MVPA			−.15	−.19; .04	.20			−.10	−.14; .04	.28			−.08	−.14; .06	.46
Model 9: Mathematics	.01	.68				**.29**	**.00**				**.30**	**.00**			
VO_{2max}													−.11	−.64; .21	.31
MVPA			−.07	−.17; .09	.77			−.03	−.13; .09	.77			.01	−.11; .13	.90

Incon Acc, incongruent accuracy on modified Eriksen flanker task[37]; *Incon MRT*, incongruent mean RT; *PCU*, partial credit unit score; *ANU*, all-or-nothing unit score.
Values are model R^2s, *P* values for model ANOVAs, standardized β and 95% CI. *P* values less than .05 are set in bold.
Analyses were conducted using multiple hierarchical regression models.
Minimally adjusted models were adjusted for accelerometer wear time.
Partially adjusted models were additionally adjusted for birth weight (model 2); ADHD (model 4); age and IQ (model 5); birth weight and IQ (model 6); IQ (models 7-9).
Fully adjusted models were adjusted as in partially adjusted models and additionally for aerobic fitness.
*Log transformed.
†Trend at *P* = .06.
‡Square root transformed.
§Only PCU and ANU scores were included, as load scores were highly correlated with unit scores.

Discussion

Our results in relation to aerobic fitness align with cross-sectional and experimental findings indicating a positive relationship between aerobic fitness and indices of cognitive control in children.[1,2,13,14,45] Specifically, we found a selective relationship between aerobic fitness and children's ability to manage distraction, which is closely related to self-regulation.[46,47] In turn, children's ability to self-regulate cognition, behavior, and emotions can predict future vocational success, health outcomes[48] and academic achievement.[19] The findings further align with the evidence from randomized controlled trials (RCTs) on the positive effects of daily after-school aerobic exercise programs on children's cognitive control.[1,2] The improvements on measures of cognitive control coincided with increments in aerobic fitness.[1,49] Because aerobic fitness is posited as the main mechanism for the effects of chronic exercise on cognitive control[50,51] our findings paired with evidence from the RCTs suggest that regular aerobic exercise resulting in fitness improvements is likely needed to benefit cognition, at least with children.

Our findings indicate that aerobic fitness is positively related to an applied measure of cognition as assessed with standardized achievement test (ie, spelling test). These findings align with previous reports of positive associations between aerobic fitness and standardized measures of achievement in spelling in Dutch[52] and Northern American children[44] of similar age. In contrast, Lambourne et al[5] found no associations between aerobic fitness and spelling (assessed with standardized test of academic achievement). This difference in findings could be related to the difference in covariates included in the models such as IQ. Lambourne et al[5] did not control for IQ in their models. Therefore, some underlying associations might have been missed due to the interindividual variation in IQ which is strongly related to academic achievement.[53] In confirmation, when IQ was excluded from our model, the association between aerobic fitness and spelling was no longer observed.

In our study, accelerometer measured MVPA was not related to cognitive control or academic achievement irrespective of aerobic fitness and IQ. Previous studies reported positive associations with some cognitive[10,11] and academic[3,5,12] measures and null associations with others.[7,8,10,11,54] The discrepancy in results may be related to the heterogeneity of cognitive measures, and tested covariates. In contrast to our findings, Booth et al[12] and Syväoja et al[10] found significant associations between the time spent in MVPA (accelerometry) and indices of inhibitory control (selective attention, interference,[12] and impulsivity[10]) in English and Finnish adolescents, respectively. However no relationship was noted for working memory.[10] We found no associations on either measures of inhibition or working memory using sensitive computerized tasks. Although these studies are important, as they are among the first to report on the associations between objectively measured daily MVPA, cognition,[10,12] and academic achievement[5,6,8,12,54] in young people, their conclusions remain limited, as the relative contributions of aerobic fitness and/or IQ to these relationships could not be assessed. One study, which did control for both factors, was also limited in its conclusions because of the constraints of the cognitive task.[7] Our study contributes to these previous findings by showing that adjustment for aerobic fitness did not modulate null findings in relation to the associations between MVPA and either cognitive control or academic achievement. Emergent evidence from the RCTs suggests a positive effect of physical activity interventions on academic achievement in school-aged children.[3,4] However, to make specific health and policy recommendations, further research is needed into the dose-response relationship between MVPA and both academic achievement and cognition. Such research needs to consider what dose of MVPA (in terms of mode, frequency, and duration) is necessary to yield academic benefits and how such a dose may change depending on a child's baseline physical activity.

Several limitations of the current study should be recognized. First, the cross-sectional design precludes causal inferences. Second, it may be suggested that the intensity cut point used in our study was lower than cut points previously used and could have captured light physical activity as well as MVPA. However, when we performed the same analyses with a higher intensity threshold (3000 CPM), the results remained unchanged. Further, the majority of children in our study were tested during summer holidays, when the levels of physical activity are higher compared with autumn or winter months.[55] Thus, the results may not be representative of the school year. Owing to limitations of accelerometry, we were unable to capture swimming; in addition, cycling may not be accurately quantified. Therefore, accelerometry may have underestimated children's daily MVPA given that these activities are more prevalent during the summer months because of organized summer camps and fair weather.

Future research should examine the dose-response relationship between MVPA, cognitive control, and academic achievement to ascertain whether aerobic exercise (which aims to increase aerobic fitness), bouts of daily MVPA, or specific MVPA daily volume are sufficient for cognitive and academic benefits to emerge. ■

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References

1. Hillman CH, Pontifex MB, Castelli DM, Khan NA, Raine LB, Scudder MR, et al. Effects of the FITKids randomized controlled trial on executive control and brain function. Pediatrics 2014;134:e1063-71.
2. Davis CL, Tomporowski PD, McDowell JE, Austin BP, Miller PH, Yanasak NE, et al. Exercise improves executive function and achievement and alters brain activation in overweight children: a randomized, controlled trial. Health Psychol 2011;30:91-8.
3. Donnelly JE, Greene JL, Gibson CA, Smith BK, Washburn RA, Sullivan DK, et al. Physical Activity Across the Curriculum (PAAC): a randomized controlled trial to promote physical activity and diminish overweight and obesity in elementary school children. Prev Med 2009;49:336-41.
4. Fedewa AL, Ahn S, Erwin H, Davis MC. A randomized controlled design investigating the effects of classroom-based physical activity on children's fluid intelligence and achievement. Sch Psychol Int 2015;36:135-53.
5. Lambourne K, Hansen DM, Szabo AN, Lee J, Herrmann SD, Donnelly JE. Indirect and direct relations between aerobic fitness, physical activity, and academic achievement in elementary school students. Ment Health Phys Act 2013;6:165-71.
6. Van Dijk ML, De Groot RH, Savelberg HH, Van Acker F, Kirschner PA. The association between objectively measured physical activity and academic achievement in Dutch adolescents: findings from the GOALS study. J Sport Exerc Psychol 2014;36:460-73.
7. Pindus DM, Davis RM, Hillman CH, Bandelow S, Hogervorst E, Biddle SJH, et al. The relationship of moderate-to-vigorous physical activity to cognitive processing in adolescents: findings from the ALSPAC birth cohort. Psychol Res 2015;79:715-28.
8. Syväoja HJ, Kantomaa MT, Ahonen T, Hakonen H, Kankaanpaa A, Tammelin TH. Physical activity, sedentary behavior, and academic performance in Finnish children. Med Sci Sports Exerc 2013;45:2098-104.
9. Hansen DM, Herrmann SD, Lambourne K, Lee J, Donnelly JE. Linear/nonlinear relations of activity and fitness with children's academic achievement. Med Sci Sports Exerc 2014;46:2279-85.

10. Syväoja HJ, Tammelin TH, Ahonen T, Kankaanpää A, Kantomaa MT. The associations of objectively measured physical activity and sedentary time with cognitive functions in school-aged children. PLoS One 2014;9:e103559.
11. Booth JN, Tomporowski PD, Boyle JM, Ness AR, Joinson C, Leary SD, et al. Associations between executive attention and objectively measured physical activity in adolescence: findings from ALSPAC, a UK cohort. Ment Health Phys Act 2013;6:212-9.
12. Booth JN, Leary SD, Joinson C, Ness AR, Tomporowski PD, Boyle JM, et al. Associations between objectively measured physical activity and academic attainment in adolescents from a UK cohort. Br J Sports Med 2013;48:265-72.
13. Scudder MR, Lambourne K, Drollette ES, Herrmann SD, Washburn RA, Donnelly JE, et al. Aerobic capacity and cognitive control in elementary school-age children. Med Sci Sports Exerc 2014;46:1025-35.
14. Pontifex MB, Raine LB, Johnson CR, Chaddock L, Voss MW, Cohen NJ, et al. Cardiorespiratory fitness and the flexible modulation of cognitive control in preadolescent children. J Cogn Neurosci 2011;23:1332-45.
15. Van Dusen DP, Kelder SH, Kohl HW, Ranjit N, Perry CL. Associations of physical fitness and academic performance among schoolchildren. J Sch Health 2011;81:733-40.
16. Sardinha LB, Marques A, Martins S, Palmeira A, Minderico C. Fitness, fatness, and academic performance in seventh-grade elementary school students. BMC Pediatr 2014;14:1-9.
17. Demetriou A, Spanoudis G, Shayer M, van der Ven S, Brydges CR, Kroesbergen E, et al. Relations between speed, working memory, and intelligence from preschool to adulthood: structural equation modeling of 14 studies. Intelligence 2014;46:107-21.
18. Deary IJ, Strand S, Smith P, Fernandes C. Intelligence and educational achievement. Intelligence 2007;35:13-21.
19. Jacob R, Parkinson J. The potential for school-based interventions that target executive function to improve academic achievement: a review. Rev Educ Res 2015;85:512-52.
20. DuPaul GJ, Power TJ, Anastopoulos AD, Reid R. ADHD rating scale-IV: Checklists, norms, and clinical interpretation. New York, NY: The Guilford Press; 1998.
21. Woodcock RW, McGrew KS, Mather N. Woodcock-Johnson III tests of cognitive abilities. Rolling Meadows, IL: Riverside Publishing; 2001.
22. Rich C, Geraci M, Griffiths L, Sera F, Dezateux C, Cortina-Borja M. Quality control methods in accelerometer data processing: defining minimum wear time. PLoS One 2013;8:e67206.
23. Kuczmarski RJ, Ogden CL, Guo SS, Grummer-Strawn LM, Flegal KM, Mei Z, et al. 2000 CDC growth charts for the United States: methods and development. Vital Health Stat 11 2002;1-190.
24. Sherar L, Griew P, Esliger D, Cooper A, Ekelund U, Judge K, et al. International children's accelerometry database (ICAD): design and methods. BMC Public Health 2011;11:485.
25. Troiano RP, Berrigan D, Dodd KW, Mâsse LC, Tilert T, McDowell M. Physical activity in the United States measured by accelerometer. Med Sci Sports Exerc 2008;40:181-8.
26. Trost SG, Pate RR, Sallis JF, Freedson PS, Taylor WC, Dowda M, et al. Age and gender differences in objectively measured physical activity in youth. Med Sci Sports Exerc 2002;34:350-5.
27. Harrell JS, McMurray RG, Baggett CD, Pennell ML, Pearce PF, Bangdiwala SI. Energy costs of physical activities in children and adolescents. Med Sci Sports Exerc 2005;37:329-36.
28. Treuth MS, Schmitz K, Catellier DJ, McMurray RG, Murray DM, Almeida MJ, et al. Defining accelerometer thresholds for activity intensities in adolescent girls. Med Sci Sports Exerc 2004;36:1259-66.
29. Utter AC, Robertson RJ, Nieman DC, Kang JIE. Children's OMNI scale of perceived exertion: walking/running evaluation. Med Sci Sports Exerc 2002;34:139-44.
30. Whaley MH, Brubaker PH, Otto RM, Armstrong LE. ACSM's guidelines for exercise testing and prescription. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2006.
31. Freedson PS, Goodman TL. Measurement of oxygen consumption. In: Rowland TW, ed. Pediatric laboratory exercise testing: clinical guidelines. Champaign, IL: Human Kinetics Publishers; 1993. p. 91-113.
32. Bar-Or O. Pediatric sports medicine for the practitioner: From physiologic principles to clinical applications. New York: Springer-Verlag; 1983.
33. Shvartz E, Reibold RC. Aerobic fitness norms for males and females aged 6 to 75 years: a review. Aviat Space Environ Med 1990;61:3-11.
34. Birnbaum AS, Lytle LA, Murray DM, Story M, Perry CL, Boutelle KN. Survey development for assessing correlates of young adolescents' eating. Am J Health Behav 2002;26:284-95.
35. Tanner JM. Growth at adolescence. 2nd ed. Oxford: Blackwell Scientific Publications; 1962.
36. Taylor SJC, Whincup PH, Hindmarsh PC, Lampe F, Odoki K, Cook DG. Performance of a new pubertal self-assessment questionnaire: a preliminary study. Paediatr Perinat Epidemiol 2001;15:88-94.
37. Eriksen BA, Eriksen CW. Effects of noise letters upon identification of a target letter in a non-search task. Percept Psychophys 1974;16:143-9.
38. Weintraub S, Dikmen SS, Heaton RK, Tulsky DS, Zelazo PD, Bauer PJ, et al. Cognition assessment using the NIH Toolbox. Neurology 2013;80:S54-64.
39. Turner ML, Engle RW. Is working memory capacity task dependent? J Mem Lang 1989;28:127-54.
40. Conway AA, Kane M, Bunting M, Hambrick DZ, Wilhelm O, Engle R. Working memory span tasks: a methodological review and user's guide. Psychon Bull Rev 2005;12:769-86.
41. Klein K, Fiss WH. The reliability and stability of the Turner and Engle working memory task. Behav Res Methods Instrum Comput 1999;31:429-32.
42. Kane MJ, Hambrick DZ, Tuholski SW, Wilhelm O, Payne TW, Engle RW. The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. J Exp Psychol Gen 2004;133:189-217.
43. Kaufman AS, Kaufman NL. Kaufman Test of Educational Achievement, KTEA II. 2nd ed. San Antonio, TX: Pearson; 2004.
44. Scudder MR, Federmeier KD, Raine LB, Direito A, Boyd JK, Hillman CH. The association between aerobic fitness and language processing in children: Implications for academic achievement. Brain Cogn 2014;87:140-52.
45. Moore RD, Wu C-T, Pontifex MB, O'Leary KC, Scudder MR, Raine LB, et al. Aerobic fitness and intra-individual variability of neurocognition in preadolescent children. Brain Cogn 2013;82:43-57.
46. Rueda MR, Posner MI, Rothbart MK. The development of executive attention: contributions to the emergence of self-regulation. Dev Neuropsychol 2005;28:573-94.
47. Sporer N, Brunstein JC, Glaser C. Attention control as indicator of self-regulation and its influence on scholastic achievement: results of a longitudinal analysis. Psychologie in Erziehung und Unterricht 2006;53:1-11.
48. Moffitt TE, Arseneault L, Belsky D, Dickson N, Hancox RJ, Harrington H, et al. A gradient of childhood self-control predicts health, wealth, and public safety. Proc Natl Acad Sci U S A 2011;108:2693-8.
49. Davis CL, Tomporowski PD, Boyle CA, Waller JL, Miller PH, Naglieri JA, et al. Effects of aerobic exercise on overweight children's cognitive functioning: a randomized controlled trial. Res Q Exerc Sport 2007;78:510-9.
50. Etnier JL. Are we ready to prescribe physical activity to promote cognitive function? Med Sci Sports Exerc 2006;38:S29-30.
51. Kramer AF, Hahn S, Cohen NJ, Banich MT, McAuley E, Harrison CR, et al. Ageing, fitness and neurocognitive function. Nature 1999;400:418-9.
52. van der Niet AG, Hartman E, Smith J, Visscher C. Modeling relationships between physical fitness, executive functioning, and academic achievement in primary school children. Psychol Sport Exerc 2014;15:319-25.
53. Kaufman SB, Reynolds MR, Liu X, Kaufman AS, McGrew KS. Are cognitive g and academic achievement g one and the same g? An exploration on the Woodcock-Johnson and Kaufman tests. Intelligence 2012;40:123-38.
54. LeBlanc MM, Martin CK, Han H, Newton R, Sothern M, Webber LS, et al. Adiposity and physical activity are not related to academic achievement in school-aged children. J Dev Behav Pediatr 2012;33:486-94.
55. Kristensen PL, Korsholm L, Møller NC, Wedderkopp N, Andersen LB, Froberg K. Sources of variation in habitual physical activity of children and adolescents: the European Youth Heart Study. Scand J Med Sci Sports 2008;18:298-308.